Salt Plugs in the Eastern Zagros, Iran: Results of Regional Geological Reconnaissance

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ABSTRACT. Regional reconnaissance study of salt plugs covered the area of about 50,000 square kilometers (coordinates 53°50' to 56°30' E and 26°30' to 28°15'N). Altogether 68 salt plugs were characterized from the viewpoint of their position in the structure of area, morphological and evolution stages, rock content and mineralization.

Prevailing amount of plugs lies in the flanks of anticline folds and is bounded to fold plunges and sigmoidal bends, where the most favorable conditions are established for the salt plug intrusion. The position of plug is highly influenced by basement tectonics, too.

Hydrogeological works proved the existence of regional and local aquifers. Upper regional aquifers are situated in the Bakhtyari Formation filling most of synclines, the lower is connected with Paleogene limestone units. The weathered zone of salt plugs shows its own hydrogeological regime and aquifers. Groundwater is highly mineralized, sometimes even in the upper aquifer. Waters can be classified as brackish to brines. Numerous are warm springs accompanied with hydrogen sulfide.

Salt plugs were classified into three structural-morphological groups (circular, linear and combined). According to size, plugs are distinguished as small (below 4 km in diameter) and large. Activity of plugs was divided into three traditional groups, i.e. active, passive and ruins, each of groups being subdivided into three subgroups. Completely new criteria were adopted to estimate the activity in the most objective manner. Salt glaciers originated in surficial conditions by increased creep caused by the hydratation of salts. Movement of glaciers can be very fast if supplied in salt from plug vent. No anomalously increased temperature is needed to start the glacier flow. Unbreached salt plugs were discussed. Their occurrence is highly limited. It is shown, that "collapse structures" are connected rather with other processes than solution collapse after leached salt. Tectonic effects, erosion and pedimentation took part substantially in the formation of cauldrons. Linear cauldrons are connected with tension regime in the apical zone of anticlines. Primary and secondary rim synclines have not been yet detected. The origin of salt plugs was multicyclic process active at least since Paleogene. The distribution of exotic blocks in plugs was reinterpreted from satellite images and air photos, indicating that the delineation and deciphering of their lithologies is sometimes possible when the field knowledge is available.

The soliferous Hormoz Complex was deposited in Upper Precambrian (Riphean-Vendian) to Middle Cambrian on rifted continental margins of Arabian Plate in a rectangular basin limited by deep (crustal) faults. New fossils have not been found. The Hormoz Complex represents product of deposition in evaporitic basin with multicyclic nature and repeating horizons of salts and other evaporites within carbonate-clastic-volcanosedimentary accumulations. The percentage and thickness of gypsum and especially of salt decreased from the center of the basin towards its margins. Predominance of acid volcanics and volcanoclastics is bound to the southeastern part of the region close to the Oman line.

KEY WORDS: salt plugs, diapirism, lithology, tectonics, hydrogeology, Hormoz Complex, Zagros Fold Belt, Southeastern Iran.

1. Introduction

(P. Bosák)

The geological exploration of salt plugs in the southeastern Iran (Bandar Abbas area) was performed by the staff of the former GMS (Geoindustria GMS) exploration company from October 1992 to January 1993 (P. Bosák, J. Spudil, P. Sulovský and V. Václavek). The study was concentrated to the geology, structure and position of famous salt plugs and for their economic geological potential. The study was ordered by the Ministry of Plan and Budget, Tehran, Islamic Republic of Iran.

The exploration was divided into two important phases. The first one was concentrated to detailed remote sensing analysis of the area (1991-1992) which was finished by the Final Report on Remote Sensing Phase (Bosák et al. 1992). The second phase (1992/1993) was represented by the field reconnaissance completed by the final report (Bosák et al. 1993).

This contribution deals dominantly with the results of the field phase of the study utilizing general results of the remote sensing analysis. It was edited by P. Bosák. The descriptive chapters were contributed by all authors taking part in the field phase and by Josef Jaroš. Responsible authors of respective chapters and subchapters are mentioned in the text only.

Altogether, 68 identifiable salt plugs and salt veins (Salzgang) occur on the surface (Fig. 1, Tabs. 18 and 19). Only 6 sites were not visited during field operations or seen from helicopter. Other plugs were visited: (1) by car field trips (with field routes on foot), (2) during helicopter landing (with field foot trips, 7 sites), (3) by boat (with field trips on foot and/or car, 2 sites), (4) by combined car trips/helicopter landing (3 sites), (5) by combined car/boat trip (1 site, and (6) by car/foot trips, helicopter landing and boat/foot trips(1 site). Helicopter reconnaissance covered 10 sites. Some salt plugs were surveyed by several visits (*cf.* Tab. A2 in the Appendix). During exploration works, study of groundwaters, springs and surficial streams were carried out, too.

Remote sensing analysis was performed before the start of the field reconnaissance. Following cosmic photos were utilized: LANDSAT MSS (digital, path: 160 and 161, row: 41, photos taken on May 15, 1984 [160/41] and April 29, 1987 [161/41]) and LANDSAT TM (digital, path: 160, row: 41 and 42 floating), both types produced by LANDSAT/EOSAT (USA), SPOT XS (digital, path k: 162, row J: 296, photo taken on May 20, 1988) produced by SPOT IMAGE (France), and KFA 1000 (spectrozonal, analog type of data, film no. 0086, photo no. 17586, photo taken on September 1, 1990) produced by SOYUZKARTA (Russian Federation). Data were processed using specialized system of image analysis PERICOLOR 2001. Data were visualized on PHOTOMATION 1700, RECTIMAT and DURST apparatuses. Spatial information was enhanced by (i) local optimization, (ii) first horizontal derivation, and (iii) Laplace operator. Spectral information was enhanced by (i) calculations of ratios of individual spectral bands, (ii) principal component analysis, and (iii) production of color composite images. Black-and-white products at the scale of 1:250,000 were produced as the principle material for photogeological interpretation and planning of field operations. Air photos at the scale of about 1:60,000 (rows M 111-M 114, M 261-M 263, M 287, M 295-M 300 and M 306 were taken in 1956 and 1957 by American companies) covered nearly whole studied territory, nevertheless they could be used only for photogeology owing to their age and substantially changed surface situation and infrastructure. On the other hand, they allowed to study changes of relief and plugs which started within nearly 40 years. Limited amount of air photos at the scale of about 1:20,000 were available for some salt plugs and their surroundings (Puhal, Zendan, Do-Au and Qalat-e Bala), and for the Khanet Surkh Anticline.

Acknowledgement: We acknowledge the field cooperation of the staff of the Ministry of Plan and Budget, Tehran, Islamic Republic of Iran. The chemical analyses of groundwater were performed in the Laboratory of Water of the Ministry of Power in Bandar Abbas (Islamic Republic of Iran). The chemical analyses of evaporates from groundwater and a part of chemical analyses of rocks were performed in laboratory of MEGA Co. in Strá• pod Ralskem (Czech Republic). The organic carbon and hydrocarbons were analyzed in organic geochemical laboratory of the Czech Geological Institute, Brno (Czech Republic). Thin sections and a part of chemical analyses of rocks were made by the GEMATRIX Ltd., Černošice (Czech Republic). Digital processing of remote sensing data was performed by Mr. Jindřich Rejl, now with Agency of Nature Conservation and Landscape Protection of the Czech Republic, Praha (Czech Republic) and Mr. Stanislav Saic in the Department of Image Processing, Institute of Information Theory and Automatization, Academy of Sciences of the Czech Republic, Praha (Czech Republic). Drawings were finished by Mr. Miroslav Morch, now with Timex Ltd. Zdice and by Mr. Josef Forman. Institute of Geology, Academy of Sciences of the Czech Republic, Praha (Czech Republic). The help of all institutions and persons is acknowledged. The text was carefully and critically read and commented by Prof. Dr. Manfred Fürst (Hallstadt, FRG); his contribution is especially acknowledged.

2. Geographical data

(P. Bosák, J. Spudil and V. Václavek)

The studied area lies in the southern part of the Islamic Republic of Iran near the northern shore of Khalij-e Fars (Persian Gulf). The studied region covers the area of about 50,000 km², and it is limited by coordinates: 26°30'-28°15' N and 53°50'-56°40 (Fig. 1).

The southeastern part of the area belongs mostly to the Hormozgan Province and its districts (sharestans) of Bandar Abbas, Bandar-e Lengeh, Aban (Jazireh-ye Qeshm and adjacent islands). The northwestern part of the area lies in the Fars Province, the district of Lar.

2.1. Morphology (P. Bosák)

The area belongs to the eastern part of the Zagros Mountain Range and the Persian Gulf Platform. Khalij-e Fars is a shallow epicontinental sea with water depths of less than 100 m. Jazirehye Qesh is the largest shore island near the coast. The smaller offshore islands (Hormoz, Larak, Hengam, etc.) are salt plugs, partly fringed by the recent or subrecent coral reefs.

The continental region can be classified as hilly to mountainous. In general, the W-E trending anticlinal mountain ridges and synclinal valleys are the most distinct morphological elements. In detail, the WNW directions prevail in the western part of the studied area and the W-E to NNW ones are more common in the eastern part of the region, including the Jazirehye Qeshm.

The summit of Kuh-e Shu (2,692 m a.s.l.) is the highest point in the region. The common altitudes of the highest summits are about 1,500 m a.s.l. in the coastal zone; they reach up to 1,800 m to 2,100 m a.s.l. further northward.

The synclinal depressions show variable morphology. For the dominant amount of valleys is typical the flat bottom (Ushaped valleys) filled with young alluvial sediments deposited in meandering to braided river systems. Others have character of deep, canyon-like or V-shaped valleys, formed by the entrenchment of rivers deeply to synclinal structures (especially along some of structural systems). The slopes of hills and ranges are dissected by a network of gorges and trenches (mostly Vshaped). Deep antecedent valleys, common in higher zones of Zagros Mountains (Oberländer 1965), are relatively rare. Foots of ranges are often contoured by telescoping alluvial fans.

The geological structure, lithology and tectonics strongly control landscape morphology. The relief is very young, the principal folding is only of middle Pliocene to Pleistocene in age, and the movement has been continuing up to the present time with relatively high intensity. Vita-Finzi (1979) calculated 1.9 mm of annual uplift in Gachin and Qeshm areas.

Planation surfaces are developed only in small scale, owing to very young and still active uplift. Some erosional downcuts are connected with indistinct pediments and glacis (Oberländer 1965, Fürst 1970). Planation surfaces on soft lithologies (marls, claystones, e.g., Anguru Member) are connected with the development of valley systems and lateral pedimentation in semiarid climatic periods with somewhat decelerated uplift. Such surfaces are gently inclined and they occur at different altitudes. Sometimes they are covered by substantially thick deposits of alluvial fans (renewed uplift and erosion). The cyclic uplift of the region and the sea level changes are documented by both river and marine terrace systems. Several levels of terraces in the area of Kuh-e Shu lie at +100 to +80 m, +60 m, +30 m, +15 to +10 m and +10 to +5 m above recent riverbeds (Fürst 1970). The highest terrace level is covered by 20 to 30 m thick layer of block scree and gravel. The middle terrace level is covered only by 5 to 6 m thick coarse-grained deposits. The terraces of the lower group contain only a thin cover of coarse-grained clastics (2 to 5 m).

The slope angles of anticlines are associated principally with strata dips (relatively flat summits and steeper slopes). Resistant rock types (limestones, dolostones, sometimes conglomerates) form sharp cuestas (see Tab. 2) or triangular bedding facetes, forming several lines along the range slope. Soft and less cemented rocks (evaporites, shales, marls, sometimes conglomerates) build depressions and soft morphologies of the relief. When they are not dissected by young erosion, mountain ridges are formed by structural surfaces of antiforms. Where more intensive areal erosion occurred there are outliers, rest hills and inselbergs, sometimes built of less resistant rock types capped by more resistant interbeds.

The salt plugs of this region have a special morphology, forming sometimes highly positive forms and sometimes negative forms of relief. Their morphology and evolution are described below.

The shore of the Persian Gulf is flat, gently rising from the sea to the foot of mountains from 0 up to approx. 40 to 50 m a.s.l., at 3 to 5° angles. Relics of abrasion and/or accumulation marine terraces are visible along the present sea coast and on some of the small islands in the Persian Gulf. Coastal terrace is gently rising from the sea level to the foothills of anticlinal mountains. The best example is developed between Puhal and Lashtegan. This plain can be classified as an accumulation marine terrace comparable with the abrasion terrace at +15 m on Jazirehye Hormoz (*cf.* Gansser 1960). Higher terraces at +25 to +30 m a.s.l. occur also on Jazireh-ye Hormoz, and Quaternary conglomerate and beach sand can be found even as high as at +100 m a.s.l. on Jazireh-ye Furur (Gansser 1960). This provides evidence for young vertical movements of the area and an uplift of salt plugs (*cf.* Kent 1958) in this region.

There is a relatively broad tidal zone (hundreds of metres to first kilometres) with tidal channels and strips of salt marshes with mangroove-like low vegetation. Two large deltas are situated in the region, i.e. the delta of Rud-e Mehran River, and the common delta of Rud-e Gowdar and Rud-e Kul Rivers. Deltas are flat, mostly salty, with shallow downcuts of individual tributary channels.

The large island, Jazireh-ye Qeshm, more than 120 km long, follows the shoreline of the Persian Gulf. It is not far from the principal land. Its landscape is also distinctly geologically affected. Between the shore and the island, there is a system of muddy marshes, shallow marine channels and vegetated flat islands, a product of delta systems and nearshore tidal currents. Other islands inside and outside the region studied, i.e. Jazirehye Furur, Jazireh-ye Bani Furur, Jazireh-ye Tanb-e Bozorg, Jazireh-ye Tanb-e Kuchak (inside), and Jazireh-ye Hormoz and Jazireh-ye Larak (outside) are small with more or less oval to circular shape. They are built up by salt plugs and some sedimen-



tary rims with relatively low morphology and abrasional shore formations.

In the text here and below, we will use some geographical names (mostly of anticlinal ridges, salt plugs, settlements etc.) which can be pronounces also other form. They are listed in Table 1.

Name used mostly in this report	Synonyms
Bustaneh	Bostanu, Bustanu, Bustanou Gachin
Kuh-e Barn	Kuh-e Padal
KuheBavyiun	Kuhe Bawun, Kuhe Hilu
Gachin	see Bustaneh
Kuh-e Cenow	Kuh-e Ginau
Kuhe Ceshu	Kuhe Anguru, Kuhe Gashu, Kuhe Gishu
Kuh-e Quniz	Kuh-e Gardesh Siah
Kuhellchen	KuheIrche
Kuh-e Shu	Kuhe Harmo
Puhal	Pohal, Pahel
Rud-e Gowdar	Ruche Cowder, Ruche Rasul
Rude Ku	Rude Ka

Table 1.Synonyms of geographical names (modified from
Bosák and Václavek 1988).

2.1.1. Geomorphic features of individual lithological units

(P. Bosák)

The lithology reflected in variable mechanical properties of individual units appear to control the character of structural forms, morphology of salt plugs and geomorphic features of the whole area.

Geological structure, lithology and tectonics strongly influence the landscape morphology. The relief is very young, owing to the principal folding only during the mid-Pliocene to Pleistocene. Table 2 summarizes the geomorphic importance of individual rock units in the stratigraphic succession. The principal feature-forming units are limestones of the Asmari Formation, the Guri Member, and the conglomerates of the topmost Agha Jari and of the basal Bakhtyari Formations. The landscape formed on the Pabdeh Formation and the Anguru Member has a character of badlands.

The most distinct features of the relief are structural surfaces of large anticlines. Their surface, if not dissected by young erosion (gullies), is formed by upper bedding plane of some of feature-forming units, or of more resistant interbeds in low relief units. A majority of anticlines show such surfaces, e.g., Kuhe Geshu, Kuh-e Kishi, Kuh-e Champeh. Some anticlines are deeply eroded. Here, feature-forming units build parallel runs of distinct cuestas and triangular rocky facets, e.g., in Kuh-e Ilchan, the closure of Kuh-e Khamir, an outer zone of Kuh-e Champeh.

Large areas of badlands on anticline flanks are developed on the Anguru Member and the Agha Jari Formation, e.g., in the northern flank of Kuh-e Champeh, the southern flank of

Feature forming rock unit	Low weathering rock unit
SURMEH FORMATION	
lower limestones	
upper limestones	
	HITH ANHYDRITE
FAHLIYAN FORMATION	
limestones	
	GADVAN FORMATION
	limestones, marlstones
DARIYAN FORMATION	
limestones	
	KAZHDUMI FORMATION
	limestones, marls
SARVAK FORMATION	SARVAK FORMATION
middle limestones	upper limestones
	SURGAH FORMATION
	shales, marls, limestones
	ILAM FORMATION
	limestones, shales
	GURPI FORMATION
	marls
TARBUR FORMATION	
limestones	
	PABDEH FORMATION
	marls, shales
JAHROM FORMATION	
upper dolostones	
ASMARI FORMATION	
limestones	
	CHECHEL MEMBER
	evaporites
CHAMPEH MEMBER	
limestones	
	MOL MEMBER
	marls, evaporites
GURI MEMBER	
limestones	
ANGURU MEMBER	ANGURU MEMBER
lower limestones	marls
AGHA JARI FORMATION	AGHA JARI FORMATION
upper conglomerates	lower clastics
BAKHTYARI FORMATION	BAKHTYARI FORMATION
basal conglomerates	conglomerates

 Table 2.
 Geomorphic importance of rock units.

Kuh-e Khamir, the area among Kuh-e Shu - Kuh-e Guniz - Kuhe Geshu, etc. Some badlands occur also in cores of deeply eroded anticlines, e.g., on Mesozoic marls in Kuh-e Khamir.

2.2. Climate (J. Spudil and P. Bosák)

The area belongs to an arid type of climate (hot and dry), locally modified by the mountains (lower temperature, higher rainfall) and by the Khalij-e Fars (higher air humidity, hot summers).

Annual average precipitation varies from 50 to 350 mm. There are places in some mountain ranges with more than 600 mm. Generally, the volume of precipitation increases from the SE to the NW. Rain falls mainly in winter and spring. It is brought by western winds blowing from the Mediterranean. The highest ranges are covered by several centimeters of snow periodically in winter season. In summer dry passat winds from the continental Asia prevail. The relative air humidity varies from 26 to 98%.

The average annual temperature is about 27 °C. The coldest month's average temperature being in January and February (about 16 °C). In the lowest daily temperature can decrease below zero in this season. The warmest months are July and August (about 36 °C), in some days of this months more than 50 °C.

2.3. Hydrology (J. Spudil, V. Václavek and P. Bosák)

The region is basically drained by three large rivers into Khalije Fars, respectively to Khoran Bostanu. The eastern part is drained by Rud-e Kul (in several river segments named also Rud-e Shur) which flows from the North to the South, in general, crossing geological structures. Its most important right bank tributary is Rud-e Shur. Central-western part of the region is drained by Rud-e Gowdar (Rasul) flowing along basic geological structures, i.e. from the WNW to ESE. Rud-e Kul and Rude Gowdar form common delta near Puhal. The prevailing portion of the southwestern part of the region is drained to the ESE again parallel to geological structures by Rud-e Mehran which forms large, well developed delta. Marginal part on the SW belongs to Rud-e Tang-e Khur basin, which empties directly into Khalij-e Fars. The eastern part of the region is drained by several shorter streams (Rud-e Khurjal, Rud-e Jamas, resp. Rude Jalabi or Hasan Langi, resp. Rud-e Shaghar), flowing directly to Khalij-e Fars from the North to the South.

Closed depression with intermittent lake Mehregan Shur-e Zar lies to the North of the port of Bandar-e Lengeh. It is drained by short stream emptying into the sea gulf near Bandar-e Charak. Other closed depressions occur in the western vicinity of Lar, i.e. near Dashti village and north of Evaz.

The Jazireh-ye Qeshm Island is separated from the mainland only by narrow and shallow strait of Khoran Bostanu thanks to material brought by rivers. Transport of material in the strait of Khoran Bostanu is generally from the West to the East. The material is laid down forming numerous flat low-elevated muddy islands which appear mostly during low tide (e.g., in the vicinity of Bandar-e Khamir).

Owing to the character of precipitation, discharge in large rivers is relatively low during the year (several litres per second). Riverbeds of smaller streams are mostly without water in dry season. The distinct increase of the discharge can be registered only in winter months, when riverbeds of smaller streams are also periodically filled with water. Owing to unpoised course of stream and resulted high river gradients, a huge amount of material is redeposited in wet season.

Numerous springs occur in the region due to morphological and lithological conditions. Their yields are highly variable depending on annual season, i.e. on precipitation. The yield of some springs is relatively stable, connected with deep water circulation. Such spring can be classified as thermal. Water of a major part of spring is highly mineralized. The mineralization of springs, but also of all surface waters including intermittent springs, is high in general.

3. Geology

(P. Bosák and J. Jaroš)

The history of the geological investigation of the area north of the Persian Gulf has a long tradition. Tavernier's description (1642) of the salt of Jazireh-ye Hormoz belongs to the earliest recorded geological observation made in Iran. Two studies from the 19th Century, i.e. those of Beke (1835) and Blanford (1872) mark the beginning of modern geological investigation in the area. Remarkable are reports by Pilgrim (1908, 1922, 1924) and Stahl (1914), containing abundant observations and interpretations valid also for the present authors.

3.1. Review of previous investigations (J. Jaroš)

The Eastern Zagros has been intensively studied owing to the salt diapirism and structural framework in particular. The position of region studied in the geological structure of the Iran has been evaluated in synthetic studies dealing (1) with the whole Iranian territory and/or with its substantial part (e.g., de Böckh, Lees and Richardson 1929; Schroeder 1944; Lees 1938; Stöcklin 1968a, 1974; Gansser 1955; Harrison 1968; Berberian 1973; Crawford 1972; Vialon, Houchmand-Zadeh and Sabhezi 1972; Takin 1972; Haynes and McQuillan 1974, etc.), or (2) with the structure and evolution of the Zagros or its fold belt in particular (e.g., Pilgrim 1924; Clapp 1940; Falcon 1961, 1967a,b, 1969, 1974a, b; Kamen-Kaye 1970; Fürst 1970; Pilger 1971; Nowroozi 1972; Kashfi 1976, 1980; Ricou, Braud and Brunn 1977; Farhoud 1978; Adib 1978; Pamič, Sestini and Adib 1979; Murris 1980; Jaroš 1981; Coleman 1981). The application of the geosynclinal model of the classical geology had been typical for a long time, but the application of plate tectonic model has prevailed since seventies and eighties. Stratigraphy and lithology of sediments in the Zagros Fold Belt was compiled especially by the British Petroleum Co. (1956), James and Wynd (1965), Fürst (1970), Huber (1977). Some formations were described in detail also by other authors (e.g., the Gachsaran Formation by Gill and Ala 1972). Short review synthesis of stratigraphy, tectonics and hydrogeology was made by Bosák and Václavek (1988) for the region studied.

As it was mentioned above, the first report on salt plugs is dated back to the 17thCentury (Tavernier 1642). Salt plugs were than described several times during the first stage of Zagros investigation in the 19th and the very beginning of the 20thCentury (e.g., Blanford 1872; Pilgrim 1908).

The second stage of investigation was carried out in twenties to forties of the 20th Century with relatively abundant studies on salt plugs (e.g., Busk and Mayo 1918; Pilgrim 1924; Richardson 1926, 1928; Lees 1927, 1931; Krejci 1927; Asklund 1927; de Böckh, Lees and Richardson 1929; Harrison 1930, 1931; Fulda 1930; King 1930, 1937; Harrison and Falcon 1936; Hirshi 1944; Lehner 1944, 1945; Schroeder 1946) looking for their connection with the Hormoz Salt Formation underlying the Phanerozoic pile of the Eastern Zagros. Some of authors noted occurrences of exotic blocks in salt (acid and mafic to ultramafic magmatic rocks).

The expansion of geological research, mapping, economic geology and other disciplines since the early fifties has been connected with the oil boom along the Persian Gulf. Numerous oil companies have been operating in the area. This fact result9

ed in the detailed view on the geology of the Persian Gulf region. Salt diapirism is still in the center of interest (e.g., in studies of O'Brien 1955, 1957; Harrison 1956; Humphrey 1958; Kent 1958, 1966, 1970, 1979; Wolf 1959; Walther 1960, 1972; Gansser 1960, 1969; Stöcklin 1961, 1968, 1976; Player 1965, 1969; Fürst 1970, 1976; Wolfart 1972; Trusheim 1974; Ala 1974). Several thematic symposia contributed substantially to our knowledge of salt plugs and diapirism (i.e. symposia in London 1931, Tulsa 1968 and Tehran 1990). Numerous studies already mentioned here were published in the first and second symposia proceedings. The last one brought the new information, especially on salt plugs in the Eastern Zagros (e.g., Ahmadzadeh Heravi, Houshmandzadeh and Nabavi, Darwishzadeh, Momenzadeh and Heidari, Espahbod, Mohajer, Samadian, Davoudzadeh, Fürst, Samani, Koyi, Sabzehei, Talbot). The carbonatite occurrences connected with salt diapirism has been noted by Watters and Alavi (1973).

The analyzed region is covered by official geological and tectonic maps published by the IOOC (1959, scale of 1:2,500,000), the GSI (1984, 1:2,500,000), the GSI (1973, Stöcklin {Ed.}, scale of 1:2,500,000, tectonic), the IOOC (1969, 1:1,000,000, sheet South-West Iran) and the NIOC (1977, Huber {Ed.}, scale of 1:1,000,000, sheet No. 5 - South-Central Iran). The map of the IOOC (1956, Perry, Setudehnia and Nasr {Eds.}, scale of 1:250,000, sheet South-East Fars) was not at disposal.

3.2. Geological setting (P. Bosák and J. Jaroš)

The studied region belongs to the part of the Alpine-Himalayan system, represented by the southern Zagros-Dinaride branch of the orogenic belt (Ilhan 1967, Jaroš 1981). The Zagros Mountains is an orogenic segment NW-SE trending to a distance of nearly 1,500 km. The following orogenic zones can be distinguished in the cross section through the Zagros Mountains *s.l.* (Jaroš 1981): (0) *molasse foredeep zone* (Persian Gulf); (1) *sedimentary fold zone*; (2) *Zagros suture* (imbricated {crushed} ophiolitic zone, Main Zagros Thrust and wrench fault); (3) *metamorphic zone*; (4) *zone of inner molasse basins*, and (5) *volcano - plutonic zone*.

3.2.1. Foothils

The Foothils represent badlands of the Miocene Fars Group sediments, sheared off from the hidden base of the Asmari Limestone along decollement thrusts in the Gachsaran Formation. To the E and N, the Foothills are limited against the Fold Belt by the Mountain Front Flexure (Falcon 1961) and by the S-N trending Kazerun Fault. Toward the S, the zone gradually passes into unfolded Quaternary molasse fill of the Persian Gulf platform.

3.2.2. Fold Belt

The Zagros Fold Belt, also called the Fars-Larestan fold belt (Huber 1977), of the Zagros system is composed of huge, elon-

gated whale-back or box-shaped anticlinal mountains, penetrated by salt plugs of the Hormoz Complex. The structures generally trend in the NW-SE direction, but the WSW-ENE trend is typical for the area north of Bandar Abbas (Fig. 2). The total compression rate, asymmetry and linearity of fold structures rise from the S to the N in the correspondence with the idea of southward tectonic transport of Phanerozoic sedimentary fold zone. The intensity of overfolding of anticlines over synclines simultaneously increases in the same direction due to the transition of the Fold Belt into the Imbricated Zone of Zagros, which is cropping out only in the NE corner of the region studied. Besides gently dipping overthrusts, folds are dissected also by subvertical faults, i.e. normal faults and wrench faults.

The Zagros fold system is overthrusted along and cut off by the Zandan Thrust, a branch of the Zagros Main Thrust, approximately 75 km east of Bandar Abbas. The Fold Belt is cut by the NNW-SSE lineaments, associated with salt plugs. Hidden basement structures traverse the Fold Belt in the WSW-ENE to SW-NE directions. Some salt plugs are associated with them.

The Fold Belt can be, similarly to other regions, subdivided into southern coastal subzone of "low" folds and into the northern subzone of "high" folds. The criterion for this is represented not only by altitudes of anticlinal ridges but also the age of rocks uncovered in cores of anticlines. The oldest exposed sequences are represented mostly by Jurassic to Lower Cretaceous Khami Group, sometimes even by Paleozoic to Triassic strata, and the youngest sediments incorporated into the fold structure are those of the Bakhtyari Formation, sometimes also up of younger Pleistocene in age (*cf.* Samadian 1990).

The southern part of the Fold Belt is formed by the coastal ranges from Kuh-e Gisakan to Kuh-e Khamir, with altitudes up to 1,500 m a.s.l. These anticlines, partly with Cretaceous and Jurassic cores, form two to three separate ranges. To the SW of Bandar Abbas, the ENE trending anticlines of Kuh-e Shu, Kuhe Anguru and Kuh-e Genow (altitudes from 2,300 to nearly 2,700 m a.s.l.), rise with Cretaceous and Jurassic cores, and Eocene to Oligocene limestone carapaces high above the surrounding Fars Group badlands. To the NE of the coastal ranges, a subcoastal depressions with principally Fars Group sediments and altitudes of 500 to 800 m a.s.l. extends from Khest to Lar. It contains some higher anticlines with exposed Paleogene and partly Cretaceous cores. Farther to the N/NW, there are four to five parallel rows of anticlines, terminating in the complicated, fault- and thrust-dissected area of Kuh-e Muran, Kuh-e Gahkum and Kuh-e Furghun where Carboniferous to Triassic sequences crop out.

Review of the geological evolution (P. Bosák)

The Zagros Fold Belt is the northeastern continuation of the Arabian Platform. The north trending Oman line (Gansser 1955) terminates its southeastern extension (Fig. 2). The Belt, extends 1,500 km northeastward and ranges in width from 200 km in the N to 300 km in the SE. It is separated from the Sanandaj-Sirjan zone on its northeastern side by the north-dipping Main Zagros Thrust. The Main Zagros Thrust represents two parallel lines, which, in places, coalesce (Braud and Ricou 1971).

Unlike at the SW edge of the Arabian Platform, the Precambrian basement is exposed nowhere in the Zagros Fold Belt, even in deeply eroded sections of the High Zagros Mountains (Falcon 1967). However, the Precambrian rocks have been transported upward within the Infracambrian Hormoz salt that reaches the surface in some large antiform structures as salt plugs (Stöcklin 1968, 1974). Observations of Haynes and McQuillan (1974) concerning the blocks of basalt and gabbro in the emergent salt plugs suggested a probable basement of the oceanic crust. Bosák and Václavek (1988) observed a variety of "exotic" blocks inside the Hormoz salt from mafic to ultramafic volcanic/plutonic rocks to acidic volcanics, metamorphics and different sediments.

Phanerozoic sedimentary deposits of the Zagros Fold Belt consist of limestone, shale, marl, sandstone, dolostone, and evaporite, quite similar but thicker than the deposits of the Arabian Platform proper. The Hormoz Formation itself is not exposed in the Zagros Fold Belt, except at its extreme southern end (Jazireh-ye Hormoz), where disturbed fragments are present within the breached salt domes (Stöcklin 1968b). The uppermost Precambrian and Lower Cambrian rocks are exposed in the northeastern part of the Belt. The oldest sedimentary rocks exposed in the SE part of the Fold Belt (out of area under interest) are represented by Silurian graptolithic shales and basal conglomerates containing pebbles of red chert, dolostone, and fine-grained sandstone, probably derived from the Infracambrian Hormoz Formation. A widespread Permian transgression of shallow marine carbonates across the Arabian Platform marked the beginning of a long period of quiescent deposition and the final coalescence of the Pangea. The Permian transgression is a boundary of the pre-Permian and post-Permian developments of the area as stated by Lees (1950). A continuous marine sedimentation is recorded in the Zagros Fold Belt from the Late Triassic onward

A comparison of the stratigraphic sequences on either side of the Zagros Suture has shown that the sedimentary deposits are continuous and that the platform extended from Arabia into Iran during the Paleozoic as a part of Pangea (Stöcklin 1968b, 1974). Rapid facies changes occur along the distinct northward and northeastward trends in nearly all of the Zagros Fold Belt sedimentary sequences. Deposition within the Zagros Fold Belt had its axis along the present-day Persian Gulf, from the Triassic onward. The thickness of the folded Zagros sedimentary pile ranges from 8,000 m in the High Zagros up to 18,000 m in the Dezful embayment to the North of the Persian Gulf.

The Pangea started drifting along the N boundary of the Arabian Platform during the Upper Permian to the Triassic. A local Tethys seaway occurred within the rifted zone formed by the drift of the Eurasia away from the Gondwana. Seafloor spreading appeared at least during the Middle Cretaceous, but had started earlier, during the Lower Cretaceous. The spreading has been inactive since 95 Ma, ceasing during Coniacian (Coleman 1981). The seafloor spreading was connected up until the late Middle Cretaceous with a subduction of the Arabian Lithospheric Plate beneath the Persian Plate.

The northward drift of Africa (together with Arabia) reached approx. 10° and was combined with an opposite rotation of the Eurasia and Africa during Late Cretaceous. The movement led to the closure of the Tethys, and caused a broad regional unconformity in the Late Cretaceous (Coleman 1981). As a result of the Late Cretaceous movements, not quite synchronous facies changes in different sectors of the area took place, as stated by Kashfi (1976). So along the northeastern boundary of the Zagros Fold Belt, within the Zagros Crushed (Imbricated) Zone, there are schuppen structures of radiolarites, detrital limestones, colored melange, and ophiolites tectonically emplaced over





Turonian platform sediments of the Belt (Ricou, Braud and Brunn 1977). These allochthonous sequences represent fragments of the Tethyan Sea obducted onto the continental margin of the Arabian Platform during its Late Cretaceous closure (Coleman 1981).

The Arabian and the Persian Platforms coalesced during the Campanian or the Early Maastrichtian; the Zagros was not longer the continental margin (Stöcklin 1974). But the Arabian Platform was separated from Africa during the Miocene, and has since rotated anticlockwise by some 9°. This would imply a northwestern displacement of the southern Arabia relative to Africa by as much as 400 km, at an average rate some 2 cm per year. This movement of Arabian Platform coincides precisely with the period of mountain building in the southern Iran. The formation of the Zagros Fold Belt would undoubtedly have been facilitated by sliding over the supposedly Infracambrian salt lubricant (Wells 1968).

During the further northward movement of the Arabian Platform in Pliocene, the thick wedge of sediments was squeezed between the two continents. As the edge of the Persian Platform offered a resistant barrier, the sediments at the frontal edge of the Arabian Platform were subjected to the greatest compression. This resulted in extensive thrusting and overfolding in the Imbricated (crushed) Zone. Farther to the SE, the compression was lower, and the rocks of the Zagros Fold Belt were less intensively folded (Haynes and McQuillan 1974). The Infracambrian Hormoz salt was squeezed plastically into zones of weakness and formed the outcropping salt plugs (Falcon 1969) at the same time.

After the principal Pliocene folding, conglomerates of the Bakhtyari Formation were deposited in the synclinal depressions. More recent movements have tilted and folded these sediments, and the present seismic activity in the southern Iran indicates that compression is still taking place (Nowroozi 1971, 1972). Jacob and Quittmeyer (1979) showed present-day northward slip vectors of 4 to 5 cm per year along the Zagros and Makran, respectively (subduction of the Arabian Platform under the Eurasian Plate).

The Zagros tectonic styles are a structural record of two geodynamically different orogenic stages in the orogenic history of the mountain range (Jaroš 1981): (1) Paleoalpine stage with an orogenic record in the subduction zone of type B (Benioff type), i.e. subduction of the oceanic lithosphere of the presumably narrow Neotethys beneath the southwestern margin of the Persian Platform (Plate). The paleoalpine mountain range (Protozagros), formed above the subduction zone, can be correlated with the cordillera-type or, in places, island arc-type of orogeny; and (2) Neoalpine stage with an orogenic record of the subduction in a Type A zone (Alpine type), i.e. subduction of the Arabian Platform beneath the Persian Platform, i.e. beneath the Protozagros and its margin. The intracrustal subduction in this continental collision zone seems to be flat and shallow, and can be compared with subductions reported from root zones of the Alpine superficial nappes. The detachment of the Phanerozoic sequence of the Arabian shelf along the Infracambrian salt during the folding process through the mechanism of flexure and flexure slip resembles the structural development in sub-Alpine mountains, specifically in the Jura Mountains of France and Switzerland.

The Alpine movements started at the beginning of the Triassic, during the Ladinian. Since that time, tectonic instability has ensued and numerous movement phases have occurred (Stöcklin 1968b, 1974). Falcon (1967b) reported the following phases: (1) Triassic (possibly Upper Triassic to Jurassic, i.e. Cimmerian movements; Ilhan 1967); (2) Upper Jurassic to Lower Cretaceous, which preceded the beginning of intensive diastrophism (Ilhan 1967); (3) Upper Cretaceous orogenic phase, reaching its peak in the Campanian to Early Maastrichtian; Ilhan (1967) reported some continuation of the movement up to the Paleocene and some activity even during the Upper Eocene to Lower Oligocene; (4) Miocene-Pliocene. The Zagros Fold Belt was folded entirely in the last, Mio-Pliocene orogenic phase, i.e. the whole Infracambrian to Neogene sequence was squeezed (Stöcklin 1968b). The folding also influenced the migration of sedimentary troughs and basins in the NE-SW direction (Falcon 1967b).

The pre-orogenic period was characterized by movements resulting in a very gentle, large-scale undulations of the sea floor. It is noteworthy that these undulations were aligned parallel with the N-S (Arabian) trend rather than with the Zagros trend (Stöcklin 1968b). An extensive flexure along the inner part of the Fold Belt originated during the youngest Plio-Pleistocene movements. The flexure trends in the NW-SE direction. Its amplitude is 12,000 m, decreasing to 6,000 m northwestward, and to 9,000 m southeastward. The origin of the flexure is connected with an isostatic effect owing to deep-seated movements of the Earth crust (Falcon 1967a). For the near-surface sediments of the Zagros Fold Belt, the associated crustal shortening is about 80 km (Falcon 1967b), i.e. the lateral shortening is equal to 6.5 to 15.5 %, max. 20 %, in average 10 % (Falcon 1974b).

Very interesting are the views of different authors on the nature of the thick sedimentary pile of the Zagros Fold Belt. Commonly, these sediments are reported to have resulted from the deposition in a geosynclinal subsiding area. Haynes and McQuillan (1974) interpreted this area as a miogeosynclinal wedge. Kamen-Kaye (1970) supposed the thick sedimentary sequence to be deposited on a platform rather than in a geosyncline, in spite of the widespread subsidence in the linear Cretaceous to Tertiary foredeep. Stöcklin (1968a) considered the Folded Belt maybe as a marginal, mobile, sedimentary trough superimposed on the Arabian Platform. Kashfi (1976) in his refusal of the plate tectonic model, noted that the simple crust subsidence and the sediment accumulation in the subsiding trough, coupled with simple isostatic balance and compressional movements, had been sufficient to produce the Zagros geosyncline.

The thick sedimentary sequence represents, in its early stages, the platform development (Infracambrian to Middle Triassic, *cf.* Stöcklin 1968) and, in its later stages, the differentially subsiding continental margin (*cf.* e.g., Stöcklin 1974) of the Arabian Platform during the seafloor spreading, ocean closure and subduction. In the late stages of the development, molasse sediments accumulated, representing syn- and post-orogenic deposits (Middle Miocene to Holocene).

4. Stratigraphy and structure

(P. Bosák, J. Jaroš and P. Sulovský)

Two structural levels can be distinguished in the region investigated: (1) basement level and (2) platform cover. The basement is of Proterozoic age representing epi-Pan African Platform which is an integral part of the Arabian Shield. It is supposed, that platform cover started with the deposition of the Hormoz Complex over peneplanated basement (Davoudzadeh, Lensch and Weber-Diefenbach 1986). Platform cover is represented by over 10,000 m thick sedimentary pile. Several evolutionary stages can be stated in the platform cover: (1) early stage, mostly evaporitic, (2) transitional stage and (3) real platform stage. The early stage is represented by evaporite-clastic-carbonate megacycle of the Hormoz Complex and correlative formations (late Precambrian to Middle? Cambrian). The transitional stage encloses very complex periods characterized by numerous breaks and sometimes by weak metamorphism ending by the extensive Permian transgression (cf. Lees 1950, Coleman 1981). Since Permian, stable platform conditions prevailed. Sedimentary sequences are mostly composed of platform carbonates, passing in Cenozoic to evaporite-clastic and evaporite-carbonate units and terminating by clastic late Cenozoic to Quaternary deposits

4.1. Basement level (P. Bosák)

Only little is known on the internal structure of the Precambrian basement in Iran as Stöcklin (1968b) noted. Since this time, no substantial achievements has been published on Iran. As the Precambrian basement is exposed nowhere in the Zagros Fold Belt unlike only at the western edge of the Arabian Platform (Falcon 1967a), the deduction of an early history will be given on last studies from Arabian peninsula. Nevertheless, the basement can be characterized as epi-Pan African neoplatform (quazicraton). Owing to its higher mobility and oscillatory movements connected with thick sedimentary cover and polycyclic orogeny with fault tectonics, the platform basement is close to a paraplatform in the sense of some Chinese authors. Folding of sedimentary cover is a result of other circumstances not connected with the platform evolution, i.e. incorporation (eventually reworking) into collisional system of Alpine-Himalayan orogenic belt in younger evolution of the region.

The basement consolidation is connected with major continental collision on the eastern side of the Arabian Platform terminating at about 600 Ma ago (Coleman 1981). The crust was metamorphosed, granitized, folded and faulted during Pan African (also Hijaz or Katangan) Orogeny (Stöcklin 1968b, 1974, Berberian and King 1981, Coleman 1981, Davoudzadeh, Lensch and Weber-Diefenbach 1986, Husseini 1988, 1989, Samani 1988a, 1988b) which is dated to 960-600 Ma ago (Berberian and King 1981). Husseini (1988) connects the platform consolidation with the Idsas collision along the Idsas suture (around 680-640 Ma). It was followed by intense deformation and metamorphism (640-600 Ma) coinciding with ductile (and possibly dextral) early movements of the Najd system which influenced in later stages the character of the Hormoz Complex and correlative deposits. After 600 Ma the crust progressively "relaxed", with the intrusion of post-tectonic granite diapirs and brittle left-lateral movement on the Najd fault system (Husseini 1988) which can be correlated with the termination of the episode of plate collision and arc magmatism at about 600-550 Ma according to Berberian and King (1981). Nevertheless, observations of Haynes and McQuillan (1974) in the Zagros Fold Belt suggested a basement of probably oceanic character owing to finds of ultrabasic rocks in exotic blocks in Hormoz plugs. Farhoudi (1978) further proposed that it becomes increasingly oceanic from the SE to the NW. In general, according to Berberian and King (1981) and Farhoudi (1978), it was supposed that basement has a character of calc-alkaline island arcs. Our data support the idea of origin of basic volcanics rather in withinplate to transitional volcanic arc/within-plate collision type of environment.

4.1.1. Lithology and petrology (P. Sulovský)

Salt plugs of the Eastern Zagros represent typical tectonic windows. As such they have dragged to the surface a broad palette of rocks of various petrological character, origin, and age. This assemblage includes rocks of Precambrian basement. Exotic blocks in the Hormoz diapirs composed of deeply metamorphosed or magmatic Precambrian rocks occur occasionally. Schists and gneisses are reported by Richardson (1926, 1928), serpentine garnetiferous limestone and mylonite by Harrison (1930, 1931), tonalite gabbro and migmatite-granite by Gansser (1960), schistose rocks by Kent (1970), metamorphosed mudstone by (Kent 1979), soda-feldspar granite porphyry, quartz-biotite porphyry, quartz porphyry, biotite-quartz keratophyre, dolerite, alkaline rhyolite, tuff ignimbrite, and spilites with pilow structures by Samani (1988b). Basalt and gabbro blocks are reported by Haynes and McQuillan (1974) as basement rocks, too. The emplacement of pre-Hormoz blocks into Hormoz diapirs is connected with olistostromes by Gansser (1960) or with cut of basement along basement fault scarps during plug ascend by some other authors. Finds of presumably pre-Hormoz rocks during our survey were rather scarce: biotite gneiss (Puhal plug) and granitoid rocks (coarse-grained granite - Do-au plug, hornblende granodiorite - Chahal, Siah Tagh and Gahkum plugs, aplite and plagiaplite - Chah Banu plug, quartz monzodiorite, monzonite and tonalite - Zendan, Champeh, Bam and Tang-e Zagh plugs).

Igneous rocks

Due to multitude of overprinting and overlapping processes to which almost all igneous rocks brought to surface by diapirism were subjected, it is practically impossible to identify undisputedly those whose origin can be put in Precambrian, or, rather, which date before the deposition of evaporite/volcanosedimentary sequence named conventionally the Hormoz Complex. Many observations exclude from the group of Precambrian rocks those of apparent effusive origin, recognized usually by typical massive or vesicular structure and often porphyritic texture with fine-grained groundmass. They use to be classified as rhyolite, andesite, ignimbrite, trachyte, basalt, melaphyre and their tuffs. Their petrology is described in detail in chapter concerning the Hormoz Complex.

Less unequivocal is the dating of dark green fine- to coarsegrained massive igneous rocks. Authors of previous papers dealing with the petrology of Zagros salt plugs call them usually diabase, indicating thus subvolcanic origin, probably coeval with formation of the Hormoz Complex. This may be in many cases true. But this group of rocks often includes coarse-grained rocks with gabbroic texture, which may be suspected rather of abyssolithic or hypabyssolithic origin. According to results of geochemical analysis, they most probably belong to the basement sequences. The uncertainty in datation of gabbroic rocks applies also to abyssal to hypabyssal intermediate rocks, classified according to their composition as diorites and quartz diorites of the tonalite type. Owing to uncertainties, the rocks are all described in the part concerning the composition of the Hormoz Complex, although they probably belong to the basement structures.

Light-colored dike rocks similar in appearance to granites can usually be described as pegmatite or aplite. They have sometimes more basic composition, corresponding to plagiaplites. Fine-grained varieties often exhibit graphic textures. Coarsegrained granitic rocks are rather scarce (Do-au plug).

Metamorphic rocks

Metamorphic rocks found among plug material during our field mission include sericite-biotite schist, biotite schist, biotite gneiss, metadiabase, quartzite, zoisite-hornfels, actinolite-bearing rock, calc-silicate hornfels (erlan), and porcellanite. Earlier authors (e.g., Richardson 1926, 1928, Harrison 1930, Hirschi 1944, Kent 1970) report occurrences of principally the same assemblage of metamorphic rocks. They can generally be divided into two groups: regionally metamorphosed rocks and contact metamorphic rocks.

Regionally metamorphosed rocks have probably formed under two distinctly different pressure/temperature combinations (Fig. 3). The first group, involving mica schists and metadiabases, belongs to the greenschist facies (biotite zone), possibly also to metamorphically higher almandine zone of the epidote-amphibolite facies (gneisses), i.e. metamorphism of medium to low pressures (P_{TOTAL} = 200 - 500 MPa) and moderate temperatures (250 - 500 °C). The rocks of the second group - zoisitehornfelses and similar rocks with abundant occurrences of blue fibrous alkaline amphibole, may have been formed under low-T/high-P conditions. Magnesioriebeckite forms also up to several centimeters thick veins in such rocks. Rock crystals occurring in fissures of such rocks often contain so abundant blue amphibole inclusions, that they acquire sky-blue color (Fig. 3). These rocks probably belong to the blueschist facies. The almost joint occurrence of blueschist rocks with rocks of the greenschist facies can be explained by rapid changes of pressure conditions over relatively short distances (tens to hundreds of meters). Rocks with blue alkaline amphibole had to form in zones with strong oriented pressure, which combined its action with pressure of the overburden and with water pressure. Such conditions would be fulfilled in zones with swift changes of pressure within narrow (tectonic) zones. Sharp drops in pressure can be responsible for the genesis of potassium metasomatism, too (see below). The zones of high-pressure glaucophane metamorphism may also be intracontinental (Dobretsov 1978). The spatial distribution of rocks with blue fibrous amphibole indicates they are strictly bound to the northeastern part of the studied area, close to the Zagros Thrust zone.

It is necessary to consider also another process leading to

formation of alkaline amphiboles - alkaline metasomatism. Evidences of this process in various magmatic as well as metamorphic rocks are numerous. Similar assemblage of host rocks and subsequent alterations by alkaline metasomatism has been for example reported by Garson et al. (1984) from Scotland, where metasediments, gneisses, amphibolites, Caledonian granitic rocks and meta-limestones are veined or replaced by metasomatic assemblage of blue fibrous magnesioriebeckite, aegirinic pyroxene, albite, calcite, hematite and anatase.

Contact metamorphosed rocks have been registered in several salt plugs (Hormoz, Hengam, Berkeh-ye Suflin, Moguieh) already by previous authors, e.g., by Richardson (1930). We can name finds of garnetiferous calc-silicate rocks, reported from Hengam, Berkeh-ye Suflin and Moguieh plugs. We have confirmed them in Berkeh-ye Suflin plug and in Moguieh. They represent very interesting rocks, consisting of quartz, carbonate, clinopyroxene, plagioclase, potash feldspar, and deep green garnet. The last named mineral possesses very specific features (poikilitic fabric, strong optical anisotropism) and composition, characterizing it as hydrogrossular. This indicates pronounced role of water during contact metamorphism. The mineral assemblage and chemical composition of these rocks suggest they have originated either by allochemical metamorphism of carbonate sediments or by progressive regional metamorphism of rocks of appropriate composition (marls and tuffaceous rocks). The isotopic composition of carbonate carbon of these rocks (three samples of a scattered erlan block in the Berkeh-ye Suflin plug) display a remarkable spread of values: from $d^{13}C = 0.6$ % (PDB) and $d^{18}O = 22.8$ % (SMOW) to $d^{13}C = -6.2$ % (PDB) and $d^{18}O = 34.2$ ‰ (SMOW), indicating locally very variable temperature of contact metamorphism and/or input of carbon from the magmatic rock.

Sedimentary rocks

Certain sedimentary rocks may be considered as Precambrian, too. Quite substantiated is such classification in case of red, well solidified, perhaps even slightly metamorphosed conglomerates or sandstones with psephitic admixture, occurring quite abundantly in the Do-au, Chah Musallem and Khain plugs. Their mineral composition comprises: quartz, microcline, plagioclase, fragments of chalcedony rocks and laminated silicites (lydites), muscovite (incl. mica schists), gypsum fragments.

4.1.2. Structure (P. Bosák)

The basement structure can be deciphered from the structural plan of the platform cover. It is supposed, that most of large fault systems dissecting the platform sedimentary cover are projections of basement structures, often revealing higher seismicity with epicenters in a 50 to 100 km depth (Falcon 1967b, Nowroozi 1971, 1972). Numerous salt plugs are associated with them, and, on the other hand, these fault lines of the basement are important for the origin of salt diapirs (Humphrey 1958).

Old, N-S basement trends of the Arabian Platform are distinguishable in Zagros as zones of normal and transcurrent faulting with associated facies changes and anticlinal plunges. The most important N-S lineament is the Oman line, representing the zone of dextral movement of 120 km (Crawford 1972). This line affected Alpine structures of the eastern Iran and limited the eastern margin of the Hormoz Salt Formation (Stöcklin





1974b, Coleman 1981). This line trends from the southern Oman to Elborz Mountains (Falcon 1967b). West of the Oman line, the Arabian Platform under the Persian Gulf is dissected by meridional structures into blocks. Another important manifestation of this trend is the Qatar-Kazerun line, and some other lines with presumably dextral character (Falcon 1967b, 1969). Antithetic Riedel shear zones affecting the plug position are interpreted by Fürst (1990) also as projection of basement tectonics. The deep-seated Precambrian basement was probably little affected by the Alpine movements (Henson 1951, Stöcklin 1968b).

In some places, younger Zagros trends are superimposed on the older, N-S trends (e.g., Jazireh-ye Lavan, *cf.* Henson 1951; Mina, Razaghnia and Paran 1967). The effect of the two superimposed trends is typical only for the boundary of the unfolded zone and the folded Zagros Fold Belt (Kamen-Kaye 1970).

In the studied area, there are relatively numerous manifestations of the SW-NE trending structures, parallel with trends in the Dasht-e Kevir area (i.e. the trend prevailing in the eastern Elborz). It is clearly visible in the coastal region between Bandar-e Lengeh and Surdo, and from the delineation of some salt plugs. This trend, roughly perpendicular to the Zagros trend, caused also the bending and plunging of some anticlines.

The seismicity of area can serve to detect the character of faults and their principal trends, especially those projected from the basement level (e.g., Tchalenko and Braud 1974; Canitez 1969). The entire folded zone and its crustal basement are associated with a seismic zone covering a roughly rectangular area from the northern shore of the Persian Gulf to the southern boundary of the Zagros Thrust and from the Strait of Hormoz to the southern Iraq.

The large earthquakes at Lar, lying in the region studied, were investigated in detail by Afshar (1960), Gansser (1969) and Nowroozi (1972). Epicenters of the 1960 earthquake constitute clusters which show a roughly NW alignment. Another belt stretches from Lar to the E and ends at the N-S fault zone reflecting the Oman line just east of Bandar Abbas. Epicenters to Northeast of Lar generally have the S-N alignment, too (Gansser 1969). Gansser (1969) concluded that none of very numerous Zagros epicenters conform to the surface structures or run parallel to the Zagros Thrust zone. They seem to reflect a rejuvenation of the old N-S trend of the Arabian Foreland, documented by the Qatar alignment and the Oman trend in particular. The Lar cluster of epicenters furthermore falls into the rather abrupt change from the SE striking to the NE striking structures. Large salt plugs are particularly numerous in this area.

Nowroozi (1971) showed that a majority of earthquakes of the Zagros Fold Belt was confined to a slab nearly 60 km thick that generally dips between 10° and 20° to the north. Focal plane mechanism solutions were obtained for five earthquakes in the Zagros Fold Belt (Nowroozi 1972). The conclusions are as follows: (1) all of the solutions show a northward slip vector; (2)all show that the compression axis is nearly perpendicular to the trend of the Zagros, and (3) all show a shallow angle thrust mechanism. The type of faulting, the directions of the slip vectors and of the compression axes respectively, together with the confinement of earthquakes within a slab dipping to the N/NE, indicate that the relative displacement of the Arabian Platform with respect to the Persian Platform is, at least partially, accounted for by a wide subduction zone along the Zagros Fold Belt. The thickness of the seismic zone is about twice the thickness of continental crust. This may suggest that the northeastern boundary of the Arabian Platform is being thrust under the Fold Belt.

Geophysical data allow to reconstruct character of basement surface in studied area. Data compiled by Yousefi and Friedberg (1978) and Yousefi (1989) indicate that basement top ascends from the S to the N in general, i.e. from the axis of Khalije Fars where lies at depth of 12,000 m b.s.l. in direction to the Main Zagros Thrust where occurs at about only 4,000 to 5,000 m b.s.l. Behind the Main Thrust, basement abruptly rises to about 0 m.

Geophysical material provides numerous less or more intensive anomalies, which can be interpreted in various ways. Distinct is subdivision of the area studied into two parts along NE-SW trending anticlinal structure (Bastak to Kuh-e Shu) in depths of 4,000 to 8,000 m b.s.l. Its N flank is highly reduced (steep), probably broken by slightly oblique expressive fault structure (ENE-WSW). The fault structure trends from Kuh-e Gavbast - Kuh-e Shu - Kuh-e Muran. The movement amplitude is about 1,000 to 2,000 m with dip to the NNW. Behind this line, in the W part of the area, the general trend is disturbed with depression at 8,000 to 11,000 m b.s.l. interpreted as syncline with axis from Lar to Gahkum. The important and generally NE-SW trending tectonic line of semicircular course of unknown dip is interpreted in Lar area.

Some positive anomalies (i.e. shallow magnetic bodies) are related to phenomena in the upper part of the upper structural level.

4.2. Platform level (P. Bosák)

The platform stage started after the carbonization of basement structures, i.e. at about 600 Ma ago. Evolution of young platform was characterized by complex taphrogenic evolution (Husseini 1988, 1989, Samani 1988a,b) imprinted in the complicated facies pattern of late Precambrian (Infracambrian) to Middle Cambrian units in the Arabian peninsula as well as in Iran. Facies puzzle can be deciphered only with problems, which makes difficulties in the correlation and dating of the Hormoz Complex.

As we stated above, the platform cover can be divided into three stages, in general. The **early stage** is represented by evaporite-clastic-carbonate megacycle of the Hormoz Complex and correlative formations (late Precambrian to Middle Cambrian) and influenced by taphrogenic post-orogenic platform evolution connected with movements along the Najd fault system.

The **transitional stage** encloses very complex period characterized by numerous hiatuses and sometimes by weak metamorphosis terminating by the extensive Permian transgression (*cf.* Lees 1950, Coleman 1981). The second stage started in Middle Cambrian when first fully marine carbonates were deposited and when the disappearance of the salt pseudomorphs indicates a steady subsidence of the Cambrian sedimentary basins (Berberian and King 1981). This datum corresponds with period in which the Arabian crust became tectonically quiescent for a long period of time as peneplanation of the area progresses (Husseini 1988, p. 99). Nevertheless, numerous unconformities and disconformities occur within Ordovician to Carboniferous sequences indicating unrest connected with epeirogenesis during Caledonian and Variscan movements.

Since Permian, **real stable platform** conditions prevailed. Sedimentary sequences are composed mostly of platform carbonates, passing in Cenozoic to evaporite-clastic and evaporite-carbonate units and terminating by clastic late Cenozoic to Quaternary deposits. Also in this period, tectonic unrest is common since upper Triassic, connected with paleo-Alpine and neo-Alpine structural evolution (*cf.* Falcon 1967b, Ilhan 1967, Stöcklin 1968b, 1974, Jaroš 1981).

4.2.1. Early platform stage

Late Precambrian formations were deposited in basins on the presumably peneplanated Arabian basement (Berberian and King 1981, Davoudzadeh, Lensch and Weber-Diefenbach 1986). Taphrogenic evolution, associated with alkali-rift volcanism accompanied by some basic effusives, divided the region into a system of interconnected rift basins limited by important fault systems (e.g., Main Zagros, High Zagros, Nayband, Chapedony, Posht-e Badam, Berberian and King 1981; meridional faults and pre-Zagros swell, Davoudzadeh, Lensch and Weber-Diefenbach 1986; the N-S trends, i.e. Oman high and the NW-SE trends, Stöcklin 1968). These faults, especially Oman-Lut trend (Stöcklin 1974) and present Main Zagros Thrust (Stöcklin 1968), which represented at that time normal fault according to Berberian and King (1981) appear to have acted as facies dividers separating evaporitic basins from coeval nonevaporitic facies (Berberian and King 1981, cf. also Husseini 1988, 1989). All features indicate the evolution in an extensional phase.

According to the model of Husseini (1988, 1989), movements along left-lateral, predominantly brittle, Najd strike-slip system in Saudi Arabia occurred in 600 to 540 Ma ago. It was accompanied by the formation of broad grabens and rift basins in the northern Egypt, southern Oman, Pakistan and in the Arabian Gulf and Zagros Mountains. The left-lateral displacement and the kinematic plate translation in the NW direction, may have transformed formerly active Idsas suture into a passive fault within the Arabian Platform. The emplacement of posttectonic granitic plutons in a relaxed Arabian crust together with the deposition of clastics, shallow marine carbonates and thick evaporites over most of the Arabian Plate is connected with the rifting, as well as with alkali-rift volcanism. These patterns are consistent with the development of a regional extensional system of continental break-up along the margin of the Pangea Infracambrian plate accompanied by typical subsequent volcanism

The Hormoz salt and related sediments were deposited in an isolated, NW-trending, rectangular basin which developed during 300 km of right-lateral displacement along the Zagros fault. Since this evaporitic basin was geometrically bounded to the E by the Zagros fault and the S by the Dibba fault, it is evident that these two faults had a normal component. The "Infracambrian" Zagros fault can be interpreted as a divergent, rightlateral fault, the Arabian Gulf and Zagros Mountains as a rift basin, and finally the Hawasina fault as a transform fault (Husseini 1988).

The oldest deposits connected with this extensional evolution in Oman are dated to 654 Ma ago, i.e. in the Huqf Group. Here clastics with volcanic interbeds of Abu Mahara Formation overlie Precambrian basement and terminate by the Buah dolomite. This dolomitic member is correlated with saline Ara Formation outcropping in the Gaba Basin as salt diapirs. Ara Formation is correlated with the Hormoz evaporites of the Arabian Gulf and Zagros Mountains (Husseini 1989). Upper Proterozoic and Cambrian represent the complete tectonic cycle with the accretion and collision (720-620 Ma), following by the collapse and extension (620-540 Ma). By the close of Cambrian up to lowermost Ordovician (500 Ma), the Arabian Platform was peneplanated stable margin of Gondwana (Husseini 1988).

The early stage of platform evolution is represented by the Hormoz Complex in the studied region. The complex is built mostly of evaporites, clastic and chemogenic sediments, volcanics of variable provenience including agglomerates, ignimbrites, tuffs and tuffites. In some portions acidic volcanics dominate, in some regions basic types are more dominant, but both types occur together. The complex outcrops as salt diapirs in complicated structural patterns. As the complex is described in individual chapters below, detailed information should be found there.

4.2.2. Transitional platform stage

The transitional stage encloses complex sequences representing evolution of passive continental margin at least up to about 400 Ma (Berberian and King 1981). As stated above, this stage started in about Middle Cambrian, when first fully marine environment appeared and terminated by the extensive Permian transgression. The platform sequence is represented by marine clastic and carbonate units showing some unconformities and disconformities in the central and northern Iranian regions. Weak metamorphosis to greenschist facies in Oman Mountains is dated to about 327 Ma (*cf.* Coleman 1981), indicating Variscan orogenic event. As rocks of these stage do not occur in superficial structure of the area studied, they are not characterized as concerns their lithology, petrology, structure, etc.

4.2.3. Real platform stage

Real platform stage resulted in a very thick pile of sediments overlying previous early and transitional platform levels (stages) with total thickness of about 8,000 to 12,000 m.

The stratigraphic sequence of this stage can be subdivided in to: (1) Permian to Triassic, (2) Triassic to Turonian/Maastrichtian, (3) topmost Cretaceous to Paleogene, (4) Lower to Middle Miocene and (5) Middle/Upper Miocene to Quaternary. Different levels reflect structural-evolutionary megacycles connected with individual phases of Alpine Orogeny. This subdivision according to orogenic phases nicely fit with stratigraphic subdivision of the Permian to Quaternary sequence into seven depositional megacycles.

Permian to Triassic level is supposed to be the real platform development, while younger levels represent differentially subsiding continental margin (Stöcklin 1968). It is clear, that this period is the most quiescent era of the platform evolution (e.g., Stöcklin 1974). Carbonate deposition dominated.

Triassic to Turonian/Maastrichtian level is connected with paleo-Alpine evolution of the region. Starting with the first more intensive, i.e. Cimmerian movements, in Upper Triassic and Jurassic (Falcon 1967, Ilhan 1967) (older phases) and continuing in Upper Jurassic to Lower Cretaceous (younger phases), preceding intensive diastrophism (Ilhan 1967). The termination of this level is connected with cessation of active sea floor spreading at about 95 Ma (Coleman 1981) and subduction of the Benioff type, i.e. subduction of the oceanic lithosphere beneath the Persian Platform (Plate, Jaroš 1981). Sediments are characterized by prevalence of carbonate platform sediments

with transitions to deeper marine marlstones and claystones locally.

The topmost Cretaceous to Paleogene level is characterized by rearrangement of sedimentary basins and by complicated facies patterns. Basinal marlstones and claystones pass into evaporitic facies with gypsum-anhydrite and to dolomitized carbonate sequences and terminates by dominantly nummulitic carbonates with some evaporite and sandstone members.

Lower to Middle Miocene represents continuing rearrangement of sedimentary basins owing to more intensive subduction of the Alpine type, i.e. subduction of the Arabian Platform beneath the Protozagros and its margin (Jaroš 1981). Evaporitic-carbonate, evaporitic-clastic, red bed and related facies dominate in lower part of the level being overlain by thick limestone-claystone sequence. The influence of piercing salt plugs became more distinct in paleogeography, than in previous Lower Tertiary period.

Middle/Upper Miocene to Quaternary level is connected with intensive folding due to accelerated subduction of Arabia under Persia. The character of deposits changed to molasselike equal to syn- and post-orogenic clastics. As movements continue also recently, Holocene deposits are also tilted and Plio-Pleistocene clastics are even highly squeezed in synclines.

4.2.4. Stratigraphy and lithology

The stratigraphic division (Tab. 3) of the Phanerozoic platform deposits is based on lithostratigraphy complemented by biostratigraphy. Therefore, each different facies development has its own stratigraphic name in the rank of member and/or formation units. This state results from a common practice of exploration divisions of oil companies and reflects the exploration aims, methods and style of data interpretation.

In the region studied, there are exposures starting only with Carboniferous. Silurian rocks were reported from Gahkum and Furghun Anticlines as small outcrops. Carboniferous to Triassic rocks are exposed only in limited extent in the same anticlines along regional thrusts. Younger platform sequences form seven large megacycles separated by more or less distinct disconformities and unconformities: (1) Permian (Permo-Carboniferous) to Triassic, (2) Lower Jurassic to Lower Cretaceous; (3) Lower to Upper Cretaceous; (4) Upper Cretaceous; (5) Upper Cretaceous to Eocene; (6) Eocene to Middle Pliocene, and (7) middle Upper Pliocene to Quaternary. On an average, each megacycle is 600 to 1,500 m thick. Our interpretation of stratigraphy based on natural limits, i.e. megacycles, erosion phases, etc. differs somewhat from older interpretations. Therefore, there are applied some working stratigraphic names not occurring in older schemes.

The Bangestan Group is newly subdivided into *Lower Bangestan Subgroup* (Kazhdumi and Sarvak Formations) and into the *Upper Bangestan Subgroup* (Surgah and Ilam Formations). Both Subgroups are separated by an important tectono-erosional so-called "post-Cenomanian" event of orogenic nature accompanied by subaeric erosion, paleokarstification and even bauxite formation. The Lower Bangestan Subgroup represents the top of the second megacycle, the Upper Bangestan Subgroup forms the lower part of the third megacycle.

The Mishan Formation has been subdivided (James and Wynd 1965 and others) into the Guri Limestone Member and undivided Mishan Formation. Because this state does not represent the real situation in the region studied, the Formation was subdivided by Bosák and Václavek (1988) into: (1) lower part, i.e. the Guri Member (limestones), and (2) upper part, the Kermaran Member (mostly marls). The name Kermaran Member, although reflecting real geological situation and geographical position, is not proper from the priority point of view, because James (1961) used term Anguru Marl. Therefore, we are returning to this older name. Upper marly sequence of the Mishan Formation is named here as the *Anguru Member*.

The subchapter deals only with groups, formations and members occurring on and/or at the Earth surface in the region of interest. The individual lithostratigraphic units are described from older to younger ones. The descriptions are based mostly on James and Wynd (1965), Perry, Setudehnia and Nasr (1965), Fürst (1970, 1976), Setudehnia (1977), Stöcklin (1977a) and Huber (1977).

Hormoz Formation

The Hormoz Formation is a sequence of lithologically variable evaporitic-volcanic rocks in salt plugs. The thickness of the formation is more than 1,000 m in the Kuh-e Shu area. The salt plug cores are composed of salt, anhydrite, dolostone, basic igneous rocks and red siltstones (i.e. the lower Hormoz Formation). The salt plug rims are composed of evaporites alternating with dark dolostones, rhyolites, tuffaceous and micaceous sandstones and mudstones, rarely also of conglomerate beds (i.e. the upper Hormoz Formation, 600 to 800 m thick).

Harrison (1930) and Gansser (1960) described occurrences of *in situ* intrusions of acid volcanics in the sequence of the Hormoz salt. These rocks are represented by soda-granite porphyry and quartz-biotite porphyry (Puhal plug; Harrison 1930) or by trachytic to rhyolitic rocks (Jazireh-ye Hormoz, Jazirehye Hengam, Jazireh-ye Tomb-e Bozorg; Gansser 1960). In some places, volcanics are accompanied by tuffs and agglomerates. Acid volcanic and magmatic rocks occur also as blocks in salt, or replaced into young Tertiary to Quaternary sediments. The find of a 3,000 cubic meter block of amphibole granite to granodiorite on Jazireh-ye Hengam (Gansser 1960) is noteworthy.

The occurrence of mafic to ultramafic rocks has been reported by numerous authors since the first notice by Pilgrim (1908). They can be found as exotic boulders to large blocks in salt plugs and their vicinity. The most common rocks are basalt, diabase, dolerite and gabbro. Rocks are often authometamorphosed, altered or decomposed and contain abundant secondary minerals (zoisite, etc.; Ulrych pers.comm. 1988). The primary position, i.e. the intrusion of mafic to ultramafic rocks, was reported by Pilgrim (1908), Richardson (1928), and de Böckh, Lees and Richardson (1929). They supposed a salt deposition concurrent with the volcanism. The latest description of in situ intrusions was presented by Gansser (1960) from several islands in the Persian Gulf. For example, on Jazireh-ye Tombe Bozorg, doleritic basalt with a pillow texture is reported. On Jazireh-ye Furur and Jazireh-ye Bani Furur, there are outcrops of amphibole and zoisite-amphibole diabase, in the former island intruding into dark bituminous limestones associated often with salt. Basic igneous rocks show cooling effect near salt contacts (Gansser 1960).

The origin of volcanic and magmatic rocks within the salt plugs has not yet been satisfactorily explained. Some authors suppose their primary origin, others suppose that the formed deeply buried topographic elevations of degraded volcanic cones, probably of the Cambrian age (Kent 1958), or that they occur only as exotic blocks without any direct intrusion into

	Age		Group Subgroup Formation Member	Known thick ness, avera- ge value (m)	Thickness in the area (m)			
Quaternary			Quaternary deposit	1- X00	400			
	Pliocene		Kharg Limestone Bakhtyari Formation	? 0-2400	? 300-2000			
			Lahbari Member	0-1570	?			
		Upper	Agha Jari Formation	200-3000	200-2000			
		N: 331 -	Anguru Member	2500	1900			
		MIGGIE	Guri Member Misban Formation	5- 050 150-3000	20- 100			
Neogene	Miocene		Razak Formation	300-1000	1000			
			Mol Member	0- 52	50			
			Champeh Member	110	100- 110			
		Lower	Chechel Member	300-1000	300			
			Gachsaran Formation	100-1000	470			
	Upper		Fars Group Asmari Formation	120- 610	250			
Paleogene	Middle		Jahrom Formation		0-600			
	and		Padden Formation	150-1200	080			
	TOMET		Sachun Formation	1400	0- 300			
			Gurpi Formation	25- 400	150 -400			
			Tarbur Formation	500- 850	0-200			
	Upper		Ilam Formation	30- 280	100			
			Surgah Formation	200	60- 90			
			Upper Bangestan Subgroup					
			Abmadi Nember	0- 60	2			
			Mauddud Member	61-122	· ?			
Cretaceous			Sarvak Formation	30- 820	800			
			Kazdhumi Formation	65- 225	90			
			Lower Bangestan Subgroup		400 ? 300-2000 1900 20-100 2000 1000 50 100-110 300 470 250 0-600 680 0-300 150-400 0-200 100 60-90 150-200 100 60-90 150-200 100 20-100 200 100 200 100 200 200 200			
			Bangestan Group					
	Lower		Dariyan Pormation	205	150- 250			
	TOMET		Gadvan Formation	100- 150	130-250			
			Fabliyan Formation	360	300- 350			
			Upper Khami Subgroup					
	Upper		Hith Anhydrite	90	90			
			Surmeh Formation	450-1800	450			
Jurassic	Middle		Lower Khami Subgroup					
	& Lower		Khami Group	100 0-0				
			Neyriz Formation	100- 350	?			
Triassic			Khaneh Kat Formation	364-1000	365			
Permian			Khuff Formation	1000	1000			
Carboniferous			Carboniferous sandstones	500	207-239			

Table 3.Review of Phanerozoic stratigraphy (completed by Bosák 1988 and 1993 after James and Wynd 1965, Fürst 1970,
Huber 1977).

the salt (Harrison 1930). Recently it seems that the primary origin of some occurrences cannot be excluded (*cf.* Gansser 1960).

Radiometric data of enclosed volcanics give values of 560 to 1,040 Ma (Fürst 1976, p. 190-191) and confirm the Infracambrian age suggested by fragments of trilobites and trace fossils (*cf.* King 1930, 1937; King and Falcon 1961).

Permo-Carboniferous to early Jurassic units

These units are consisting of sequences, which can be regarded as true platform cover since extensive Permian transgression. Carboniferous sandstones (207 to 239 m) is a sequence of lightcolored, often current-bedded sandstones with intercalations of black limestones and shales in the center of the section. Khuff Group (Permo-Carboniferous, 1,000 m) consists of basal clastics and feature-forming carbonate rocks in the area studied. Its lower and upper boundaries are usually sharp, but not well defined. Khaneh Kat Formation (Triassic to Early Jurassic, 365 m) is composed of dark dolostones, often siliceous and featureforming. The upper boundary is sharp. Neyriz Formation (Liassic, 100-350 m) consists of dolostones and limestones with shale interbeds. The upper boundary is conformable, transitional.

Khami Group

The Khami Group (Middle Jurassic to Aptian) is divided into the Lower (Jurassic) and the Upper Khami Subgroup (Lower Cretaceous).

Lower Khami Subgroup

Surmeh Formation (Middle to Upper Jurassic, 450 m) consists of three parts. The lower one is composed of two thick limestones beds separated by marls. The middle part is built of thick dolostones. The upper one consists of thinly bedded organodetrital to oolitic packstone to grainstone, in places dolomitic. In the area of Kuh-e Shu, the upper part is missing, indicating a local unconformity. The lower and upper formation boundaries are conformable at other sites. Hith Anhydrite (Late Jurassic, Portlandian, about 90 m) is the anhydrite-gypsum formation intercalated with dolostones, often oolitic. Both boundaries seem to be conformable.

Upper Khami Group

Fahliyan Formation (topmost Jurassic to Neocomian, 300-350 m) is variable from the point of view of both its lithology and thickness. It is composed mostly of oolitic, in place pisoidal and pelletal grainstones with dolostone interbeds in the lower part. Both formation boundaries are conformable. Gadvan Formation (Barremian to Aptian, 100-150 m) is the sequence of coquinoid packstones, in places dolomitic, interbedded with marls. Both formation boundaries are gradational. Dariyan Formation (Aptian to Albian, 150-250 m) is composed of foraminiferal and rudistid packstone to wackestone, and in places, of porous chalk. The upper part contains some local marl intercalations. The lower formation boundary is conformable, the upper one is marked by a red zone indicating a disconformity.

Bangestan Group

The Group (Albian to Campanian) is newly divided into the Lower and the Upper Bangestan Subgroups. The thickness of the whole group is highly variable from about 150 to more than 800 m.

Lower Bangestan Subgroup

Kazhdumi Formation (Albian to Lower Cenomanian, about 90 m) is built of glauconitic clays to marls and coquinoid packstones alternating with marls and shales. The boundary with the underlying formation is marked by a red oxidized zone with laterites, silty and sandy beds, indicating a disconformity. The upper formation boundary is conformable. Sarvak Formation (Albian to Cenomanian-?Turonian, up to 800 m) is of variable thickness due to the post-Cenomanian erosion and regional changes in lithology. The undivided Sarvak Formation is composed of different types of organodetrital wackestones to packstones, in the lower part with cherts and large-scale cross-bedding. Rudistid limestones prevail in the upper part of the formation (Turonian) in area studied. The topmost horizon is brecciated and oxidized due to hypergenic alteration and vadose freshwater diagenesis during "post-Cenomanian" erosion. The lower formation boundary is conformable. Two members are developed in coastal region: Mauddud and Ahmadi. Mauddud Member (Cenomanian, 60-120 m) is composed of Orbitolina wackestones to packstones. Ahmadi Member (Cenomanian, 0-60 m) is built of shales and limestones. The member dies out to the NE and NW, and the Mauddud Member becomes indistinguishable from the rest of the Sarvak Formation.

Upper Bangestan Subgroup

Surgah Formation (Turonian to early Santonian, 60-90 m) is developed only rudimentarily and in a nontypical development in the area studied as marly-argillaceous sequence of the Gurpi facies. The formation lies with a distinct disconformity on the Sarvak Formation. The disconformity is marked by the weathered horizon, solution potholes and bauxite deposits in places. The upper boundary is also disconformable. Ilam Formation (Turonian to Campanian, about 100 m) is composed of argillaceous wackestone to packstone with thin shale intercalations. The upper part of the Ilam Formation interfingers with the Gurpi facies, in places. The lower formation boundary is disconformable, marked by a horizon of hematite nodules. The upper boundary is conformable. In the area of Kuh-e Shu, the upper part of the formation is missing, probably due to an epeirogenic event.

Senonian to Maastrichtian formations

The deposition in this time span is strongly affected by the early Alpine orogenic phases in the zone of High Zagros, resulting in rearrangement of sedimentary areas and basins.

Tarbur Formation (Upper Campanian to Upper Maastrichtian, max. 500 m) interfingers with the Gurpi Formation toward the S. The formation consists of massive coquinoid packstones, partly with anhydrite. Toward the N, this facies development changes into thick reef boundstones. The boundary with the Gurpi is conformable, in places transitional, in places relatively sharp. The upper boundary is sharp. Gurpi Formation (Campanian-Santonian to Maastrichtian, 150-400 m) onlaps over the Bangestan Group with glauconite-ferruginous basal beds containing iron nodules. The predominant rock type is represented by dark marl and calcareous shale. Argillaceous pelletal wackestone forms subordinate interbeds. This facies interfingers with the Ilam Formation toward the W. In other places, it rests on Bangestan formations with a distinct disconformity. The upper boundary is disconformable and bears marks indicating a hiatus between the topmost Maastrichtian to the Early Paleocene.



Paleocene to Eocene formations

The distribution of the sedimentary facies pattern is rather complicated in this cycle. Sachun Formation (Paleocene to Lower Eocene, max. 1,400 m) has its depocenter in the northern part of the region studied. There are developed gypsum-anhydrite with marlstone and dolostone interbeds. It seals the Tarbur and precedes the Jahrom Formations. Pabdeh Formation (Lower Eocene to Lower Oligocene, 150-1,200 m). The lower part is built of clays with intercalations of nummulitic packstones with cherts, and locally with beds of intrarudites. The middle part consists of dark shales, in places with interbeds of nummulitic packstones with glauconite. The upper part is developed as argillaceous limestones intercalated with marls. The development is sometimes described as Pabdeh-Jahrom facies. The lower formation boundary is marked by a glauconitic and limonitic zone with a coarser clastic terrigeneous component. The upper boundary is conformable, transitional. Jahrom Formations (?Paleocene-Eocene-?Oligocene, max. 600 m) occurs only in a part of the region, on other places it forms rock sequences of the Pabdeh-Jahrom facies. Northwards, the Jahrom dolostone appears as a significant rock unit. This sediment interfingers with underlying Sachun evaporites and is overlain by the Asmari Formation after a short erosion event.

Oligocene to Lower Miocene formations

The Oligocene to Lower Miocene time is represented exclusively by the Asmari Formation, in the studied area. Asmari Formation (Oligocene to Eggenburgian, about 250 m) is the principal oil reservoir in the Khalij-e Fars area. The basal part is built of dolomitic wackestones, in places even of dolostones. This part represents an equivalent of the Kalhur Gypsum Member developed toward the N. The representative of the Ahwaz Sandstone Member is missing here. The lower dolomitic part passes upward into a sequence of argillaceous to chalky wackestones to packstones, often with nummulitic grainstone interbeds. The upper part consists of thick nummulitic grainstones to packstones and fine-grained packstones and grainstones with a distinct cross-bedding. The lower boundary of the formation is conformable, transitional with respect to the Jahrom dolostone. The upper boundary is transitional, with interfingering to the Gachsaran or Razak Formations.

Fars Group

The Fars Group (Lower Miocene to Pliocene) contains three formation sequences. Gachsaran Formation (Eggenburgian, 100-1,000 m) is composed of the evaporitic Chechel Member, the carbonate Champeh Member and the clastic-evaporitic Mol Member. Toward the NE, the formation interfingers with the Razak Formation. Chechel Member (more than 300 m) consists of nodular to crystalline gypsum-anhydrite with marly and limestone intercalations. Salt beds were reported in places. The lower member boundary is conformable, in places interfingering. The upper boundary is transitional with interfingering to the Champeh Member. Champeh Member (100-110 m) is composed of chalky-gypsiferous limestones to dolostones with horizons of marls and nodular to crystalline gypsum. The member lies conformably or with interfingering on the Chechel Member and is overlain by the Mol Member. Toward the SW, it passes gradually into the Mol facies and dies out. Towards the NE, it is overlain by the Razak Formation; the boundary is transitional and interfingering. Mol Member (52 m) is built of sequence of reddish to multicolored gypsiferous marls interbedded with thin layers of gypsiferous limestones and gypsum. The member conformably overlies the Champeh Member, or the Chechel evaporites in places where the Champeh is developed in the Mol facies. Toward the N and NE, it gradually passes into the multicolored clastic-evaporitic Razak Formation. It is conformably overlain by the Mishan Formation with a sharp boundary.

Razak Formation (Oligocene to Lower Miocene, max. 1,000 m) is developed mostly in the N and NW part of the studied region as a relatively thin sequence of multicolored silty marls interbedded with some sandstone, limestone and evaporite. In the area of Jazireh-ye Qeshm, more than 1,000 m of evaporites were reported. The Razak red beds interfinger with evaporites of the Gachsaran Formation toward the S-SE, and with the Asmari Formation toward the N-NE. The area of interfingering coincides with thick development of the Guri Member and with the SW limits of the Tarbur and Sachun Formations.

Mishan Formation (Lower to Middle Miocene, 150 to 3,000 m) consists of the lower Guri and the upper Anguru Members. Guri Member (Lower to early Middle Miocene, 5-650 m) represents mostly sequence 20 to 100 m thick. In the direction to the NW (Kuh-e Genow - Kuh-e Namak - Kuh-e Hamdun, N of Bandar Abbas), the thickness rapidly increases to 650 m of coral reef boundstones. The Guri is developed mostly as a sequence of bedded limestones, often chalky, in the middle part with an argillaceous admixture and terminating with calcarenites. The contact with the Anguru Member is sharp, with traces of submarine erosion, slightly undulating, sometimes gradational. The lower boundary is conformable and sharp. The Anguru Member (Lower to Middle Miocene, max. more than 2,500 m); its basal part is 60 to 70 m thick consisting of organodetrital grainstones, in places with packstone interbeds and thin marly intercalations. This part is highly porous, well bedded and shows a large-scale cross bedding. The thickness and frequency of grainstone beds rapidly decrease from the base upward. The dominant part of the member consists mostly of green marls, in places slightly gypsiferous, with intercalations of coquinoid packstones to grainstones in the lower two-thirds, and with silty sandstone, sandy mudstone and organodetrital sandstone interbeds in the upper third. A cross-bedded, lenticular sequence of mudstones, sandstones and minor sandy grainstones is locally developed in the topmost member section. The contact with the Guri Member is commonly sharp, undulating, with traces of submarine erosion, sometimes gradational. The boundary is marked by cherts and numerous borings. The upper member boundary is obviously conformable, but sharp, slightly undulating with evidences of submarine erosion in places.

Agha Jari Formation (Upper Miocene to Pliocene, 200-3,000 m) consists of an alternation of sandstones, mudstones to shales, sandy siltstones. Fine clastics locally show light green color and contain even abundant glauconite. The basal part is built of marine sediments, mostly. In the direction to Jazireh-ye Qeshm, the upper part changes to Pliocene Lahbari Member. The upper part of the formation, on other places of the region studied, contains numerous interbeds of conglomeratic sandstones to pebbly conglomerates. The amount of psephitic material gradually increases toward the formation top, accompanied by a simultaneous decrease of sandstone to mudstone horizons. Therefore, a precise delineation of the boundary with the overlying Bakhtyari Formation is sometimes difficult in the field. In other areas, distinct angular unconformity divides the Agha Jari and Bakhtyari Formations. The lower boundary is conformable,

sharp. The Lahbari Member (Pliocene) represents the upper part of the Agha Jari Formation on Jazireh-ye Qeshm. It is composed of siltstones, silty marls, interbedded with sandstones and gypsum.

Middle/Upper Pliocene to Quaternary units

The deposition of this megacycle started during the intensive erosional activity resulting from the major late Alpine orogenic uplift of the Zagros.

Bakhtyari Formation (Upper Pliocene to Pleistocene, max. 2,400 m) fills a majority of synclinal valleys and basins. The formation consists of pebble to boulder conglomerate with subordinate cross-bedded sandstones and sandy siltstones. In places, the conglomerates are cemented by pedogenic carbonate cement of the caliche (calcrete) type. The lower boundary is of variable nature. Commonly, a deeply eroded angular unconformity has been reported. But in places, a gradational transition, distinctly conformable, has been observed by Bosák and Václavek (1988). In such case, the Bakhtyari Formation differs from the underlying Agha Jari Formation only by its lower resistance to weathering and by yellowish brown color. Upper part of the formation in the Jazireh-ye Qeshm area is known as Kharg Limestone (Pleistocene). It is developed in the coastal area adjacent to Jazireh-ye Qeshm and directly on it. Conglomerates and sandstones interfinger here with coquinoid limestones to sandstones.

Quaternary Deposits. Younger Quaternary deposits have a large areal distribution. The area covered by Quaternary deposits thicker than 2 to 5 m can be estimated from 30 to 45% in individual regions according to geological maps and satellite images. Quaternary sediments are represented mostly by complex alluvial systems, terraces, deltas, sabkhas, and marine nearshore and backshore deposits. The Quaternary sediments have a highly variable thickness from metes up to first hundreds of metres in the deltas, salty fluvial plains or certain parts of braided fluvial systems in synform structures.

Terraces are developed at three altitudinal levels at least. They are formed by coarse-grained to bouldery conglomerate to gravel, often cross bedded with minor sandy interbeds. Their thickness can be estimated at 2 to 30 m. The gravels and conglomerates contain a higher amount of particles from underlying rocks, incl. pebbles to cobbles of marl, mudstone or shale. The content of pebbles to cobbles of volcanic/magmatic rocks distinctly increases compared with the Bakhtyari Formation; commonly, they contain 5 % of such particles. In places, a higher content of silty-clayey matrix was observed.

Alluvial cones can be distinguished into two categories: (1) alluvial cones under mouths of larger erosional downcuts in anticlines without salt plugs represent extensive thick fan-like forms consisting mostly of cobble to pebble gravel. Such fans are composed of several gradually superimposed fans deposited by braided rivers entering surrounded alluvial plains and river deposits. The content of "exotic" clastic components from salt plugs is very small in this type; and (2) alluvial cones forming rims of active salt plugs. Also these fans are composed of superimposed smaller fans and are resulting from activity of intermittent braided streams coming from salt plugs. They contain high amount of "exotic" blocks derived from dissolved salt of the Hormoz Formation. In satellite images taken in natural and/or nearly natural spectral bands such fans appear as dark areas.

Alluvial-fluvial deposits are developed as river valley fills

composed mostly of poorly lithified gravel, pebbly sand with mudstone interbeds. The grain-size distribution is highly variable, as well as the composition of rock particles. There is, again, a higher proportion of underlying rocks, incl. soft shales to marls, gypsum and anhydrite. The material is derived from Mesozoic to Tertiary limestones, some percentage represents also Miocene-Pliocene sandstones. The amount of pebbles to cobbles of volcanic/ plutonic rocks increased to 5-10 %, locally up to 15 %. Fragments of volcanic/magmatic rocks are derived from alluvial cone rims of salt plugs. Alluvial deposits of rivers coming from areas without salt plugs contain only rare and small pebbles of "exotic" materials, derived probably from the Bakhtyari Formation and/or river terraces. The alluvial-fluvial deposits mostly represent deposition from intermittent braided river systems.

Alluvial plains are developed in broad valleys, synclinal structures and along lower courses of large rivers. Their sediments have a larger amount of fine clastics (silt to clay) with sandy and gravely interbeds. They are often salty. Sometimes are cemented by salt, gypsum or carbonates (saltcrete, gypcrete, calcrete). The deposits represent alluvial sediments of low to high sinusoity river systems with floods during heavy precipitation, forming intermittent lakustrine-fluvial ponds. Toward the shore, alluvial plains pass into deltaic deposits.

Deltaic deposits. Two large deltas are developed in the region studied, i.e. the delta of Rud-e Mehran and the common delta of Rud-e Gowdar and Rud-e Kul. The deltas constitute a flat, gently inclined landscape. Their surface part is built of fine clastic sediments with gravely-sandy river beds. The sediment become more lithified in higher depths. There is probably a higher amount of gravel owing to morphological conditions of adjacent mountain ranges. The sediments are salty due to infiltration of sea water and percolation of salty surface river water. Chemogenic crusts are developed in places. Small eolian dunes can be observed too.

Sabkhas and lakes. Intermittent and stable lakes are present only on two places. Lakes are always situated in synclinal valleys between two anticlinal ridges. The larger one occurs near village of Berkeh Musallam (NW of Bandar-e Lengeh). It has nearly rectangular shape elongated in NE-SW direction. Both shorter sides are distinctly fault/fissure - controlled. The lake is encircled by relatively broad tidal zone (sabkha) with very light gray shade on satellite images indicating development of evaporitic crusts (calcretes, gypcretes, saltcretes). From the W, N and NE, sabkha is invaded by alluvial cones coming from surrounding anticlinal ridges. Two small lakes occur Near village of Kowreh (SW of Razak). The western one is elongated in the SW-NE direction, the eastern one is roughly rectangular and shows broad tidal zone with bands of different gray shades indicating previous water levels in lake. On color composite images, both lakes are characterized by different colors than the large lake in the S. This is caused by lower salt content in water of lakes near Kowreh, because these lakes are situated in closed depression without occurrences of salt plugs in the catchment basin. More, the western lake does not show traces of intensive water level fluctuations (level lowering by evaporation) because it is fed directly by water coming from springs on the SE flank of Kuh-e Bandobast Anticline (?karst springs from Jahrom dolostone).

Tidal deposits are broadly developed, principally between the deltas and Jazireh-ye Qeshm. There is a system of typical tidal marshes, sandy-muddy flat islands separated by shallow tidal channels. Some islands are covered by mangroove-like vegetation. The tidal zone proper is also relatively broad due to the gently sloping shore; it is covered by fine-grained clastic material. In places, short sandy beaches are also present with distinctly developed backshore sand-bars.

4.2.5. Structure (J. Jaroš)

Structures which will be characterized below, deal only with the Phanerozoic platform level. Structural characterization of salt plugs, their position and other features will be mentioned in detail in a separate chapter.

The platform level of the Zagros Fold Belt is characteristic by large anticlinal and synclinal structures. Regional folds are dominant in the structure. The folding encompasses Phanerozoic sedimentary pile as thick as 8 to 10 (12) km (Kamen-Kaye 1970). The pile is separated from the basement of the Arabian Platform along decollement in the level of the Hormoz Salt (Falcon 1967b, Stöcklin 1968a). Besides this basal decollement, inter- and intraformation horizons of partial or local decollement have to be taken into account in the level of extremely plastic members of some formations, like the Hith Anhydrite (Jurassic) or evaporites in the Gachsaran Formation (Miocene).

Regional folds

Regional anticlines are large open structures separated by narrow, often squeezed synclines (Haynes and McQuillan 1974). In the section, folds attain rounded or box-like shape. The folds are mostly unbroken, doubly plunging (Kashfi 1976), and asymmetric (e.g., Stöcklin 1968a) with steeper southern flanks and gentler northern ones (Ilhan 1967). Axial fold planes dip NE at an angle usually exceeding 60° (Falcon 1967b), thereby clearly verging SW toward their foreland (Jaroš 1981), near the coast axial planes are subvertical. The apical angle of 0° is typical for nearly all folds (Falcon 1967b). The fold asymmetry decreases from the north (from the vicinity of Imbricated Zone) toward the coast in the S, where folds are nearly symmetric. The southern flanks are often disturbed by thrust planes or by displacement of anticlines over synclines. Steeper southern slopes of anticlines show gravity collapse tectonics (folds, cascades, rock slides; Harrison and Falcon 1936, etc.). Fold parameters are highly variable, depending on the lithology; they attain the maximum values in thinly bedded rocks (marlstone, claystone). The fold parameters indicate a SW-NE to S-N oriented compression (Falcon 1967b, Stöcklin 1968a), operating as the Arabian Platform was being pushed beneath the Iranian Platform (Jaroš 1981). The style of folding in the Zagros Fold Belt can thus be compared with the bulldozing effect (Vialon, Houchmand-Zadeh and Sabhezi 1972). Zagros folds and thrusts are associated only with a minor deformation of the basement, but with an important decollement along the plastic Infracambrian salt covering the basement on large areas (Lees 1950, Falcon 1967b, Haynes and McQuillan 1974). The decollement occurred at the top or near the top of the Hormoz Salt Formation, as resulting from irregular tectonic style of the Fold Belt (Kamen-Kaye 1970).

The general trend of folds in the Zagros is NW-SE. Folds are more or less non-linear (brachyal, shortened). Their axes trend generally parallel to the Alpine front (Falcon 1967b, Ilhan 1967). Fold axial length varies from several up to hundreds of kilometers (max. 400 km), wave length is in average 12 km (Trusheim 1974) and the fold amplitude 1 to 12 km. In average, mutual distance of anticlines is 21 km near the coast, 14 to 15 km in the center and 13 km in the N of the studied area. The lateral shortening in the fold zone decreases from NE to SW together with the compression rate and fold asymmetry. For the near-surface sediments of the Zagros Fold Belt (Falcon 1967b, 1974a), the associated crustal shortening is about 80 km, i.e. the lateral shortening is equal to 6.5 to 15.5 %, max. 20 %, in average 10 %, which represents an average squeezing of the Phanerozoic in the Zagros Fold Belt and Faulted Zone of about 30 km. Vita-Finzi (1979) calculated annual shortening of the region around Bandar Abbas to 16.6-31.9 mm having the NNE direction.

Two subzones can be distinguished in the fold structure. Subzone of high folds with squeezed folds, broader anticlines are sometimes displaced over narrower synclines, Mesozoic formations are uncovered in anticline cores. In subzone of low folds, the folds are less squeezed, anticlines and synclines have nearly same width, Tertiary formations are uncovered in anticline cores. Relief-forming function of folds is characteristic feature. The relief has primary nature, i.e. anticlines form ridges and synclines depressions and valleys among them.

Folds in the studied region have several specific features as compared with other regions of the Eastern Zagros. Their axes trend from the W to the E, because 55°E latitude in the center of area represents the axis of so-called Laristan arch (Trusheim 1974). Folds of the NW and Central Zagros trending from the NW to the SE bend along the arch into the WNW-ESE, W-E and WSW-ENE directions. The NW-SE trend of folds is attained again in the area close to the Oman line. The development of subzones of high and low folds is not so distinct in other regions, as well as so-called Coastal Flexure. The subzone of low folds, according to criteria stated above, is therefore represented only by several coastal folds (cf. map of Huber 1977). The folds are protruded by salt plugs, larger part of which occurs in the region studied. The anticline cores are bulged just by salt diapirs which leads to the uplift and Mesozoic formations can be uncovered.

Characteristics of regional folds

The general W-E trend of fold axes is locally highly irregular. Conspicuous bends of anticline axes have been known (in places up to 90°). Their sudden plunges cause, that the continuity of individual anticlines and/or their segments is not completely distinct. Plunge and emersion of anticline axes reflect axial elevations and depressions. These transversal axial bends do not continue into neighboring fold structures, in general. This fact proves the high degree of autonomous axial deformation of individual anticlines. Axial depressions of anticlines do not mutually link in the transversal direction (i.e. N-S) elsewhere in the region studied. Direction changes of anticline axes are of double nature: (1) sudden bends, and (2) segmentation by transversal to diagonal, mostly wrench faults, projected most probably from basement structural level. Where salt plugs occur on these direction angles, the decision on the character of the direction change (continuous, discontinuous) is not often possible, i.e. by which mechanism it is caused. Anticlines are sometimes limited by transversal to diagonal faults, often by wrench faults, also in areas of the sudden plunge of anticline axis. Simultaneously with increasing fold asymmetry, the anticline axis shifts from the summit line of centriclinal ridge toward the steeper southern slope.

The interpretation of syncline axes is more complex, in gen-

eral, as the core of synclines is mostly covered by thick Pleistocene to Holocene complexes; only syncline flanks are bare. The exception is represented by synclines formed by younger formations including the Bakhtyari in inversely sculpted relief (synclines owing to mechanic properties of the fill form elevated morphostructures). Compiling the direction of syncline axes hidden below Quaternary sediments, the asymmetry degree of folds derived from the asymmetry of anticlines was taken into account. Syncline structures have more complex non-linear nature in places where fold plunge is caused by fault limit of anticlinal ridge. Such structures were delineated by Fürst (1976) as triangle synclines (Dreieckige S.) where synclinal depressions lie among three plunging anticlinal ridges. Axes of larger synclines in region of anticline plunge have more complex courses.

The relation geometry of anticlines and synclines is determined by the degree of compression and asymmetry of fold structures (decreasing in the N-S direction), and by highly irregular picture of axial direction of the plunge of anticlinal ridges (non-linearity). The relation of anticlines and synclines, besides facts mentioned above, is influenced by the growing intensity of overthrusting of anticlinal ridges over the S synclinal depressions (in the S-N direction), which can lead to the mutual contact of two anticlines. This trend is more distinct in the W part of the region. While this displacement has only local character on the S, i.e. only along short sectors (e.g., displacement of Kuh-e Champeh Anticline over the S coastal anticline), the length of sectors with displacement is gradually growing toward the N (the displacement of Kuh-e Herang and Kuh-e Gavbast Anticlines). Overthrusting is a common feature in the N part of the region (to the north of Kuh-e Siah and Kuh-e Chachal including). On the contrary, the displacement of anticlines over S synclines appears only in the very north in the E third of the region studied (Kuh-e Furgun) in the direct proximity of the Imbricated Zone. This difference in displacement intensity is probably connected with the bend of axial direction of folds from the NW-SE (WNW-ESE) direction to the W of the region studied to approx. W-E direction in the W part (larger portion) and to the WSW-ENE (up to WNW-ESE in the N) direction near the E limit of our region. The most intensive displacement of anticlines to the S should be than connected with this axial bend.

Unconformity at the base of the Bakhtyari Formation

The Bakhtyari Formation occurs only in the synclinal structures except of smaller brachyanticlinal structures in the NW part of the region. It is lying conformably on underlying Agha Jari Formation in open synclines in the S. The unconformity is expressive in more compressed synclines in the N, where the Bakhtyari Formation lies on Agha Jari Formation folded in more detail. Locally, the Bakhtyari Formation lies on older formations, too (Mishan and even older formations). Two folding phases are indicated by the position of the Bakhtyari Formation:

- the older one prior the deposition of the Bakhtyari Formation;
- the younger one after the deposition of the Bakhtyari Formation which completed (compressed) the anticlinal and synclinal structures of the older phase.

The fact, that anticlinal ridges are displaced over the fill of southern synclines including the Bakhtyari Formation, indicates that anticline displacement continued also in the younger folding phase. Vita-Finzi (1979) studying the rate of Holocene folding in the coastal Zagros near Bandar Abbas calculated annual uplift of mountain ridges and synclinal plains to 1.9-7.4 mm, in Gachin and Qeshm about 1.9 mm. It means, that the rate of folding is still high which is reflected in structural patterns of folds.

Local folds

The fold pattern in the Miocene incompetent beds is characterized by the disharmony with competent overlying and underlying rock units (Stöcklin 1968a). The marls and evaporites of the Gachsaran Formation acted to transfer the orogenic pressure over the Asmari substratum; thus, the anticlines formed in the Upper Tertiary clastic units are disharmonic with these of the underlying marine sediments (Dunnington 1967). The disharmony is largely due to regional gliding (decollement) of sediments along plane or planes within the Gachsaran Formation, and due to the flowage of Gachsaran salt and anhydrite from crestal areas of the Asmari anticlines into adjacent synclinal areas. Such structures are preferentially developed on the S to SW flanks of anticlines (Humphrey 1958). The thickness changes of the Gachsaran Formation were caused not only by the tectonic forces, as supposed by O'Brien (1957), but also resulted from the primary asymmetry of the Gachsaran (de Böckh, Lees and Richardson 1929; Lees 1927) which accumulated mostly on SW anticlinal flanks (Humphrey 1958).

Local fold are those developed mostly in the Agha Jari Formation according to the interpretation of satellite images and field observations, although some folding in lower formations of the Fars Group were observed, too, e.g., in the Gachsaran Formation in Khamir, Anguru or Champeh Anticlines. In the S, where regional folds are less compressed, the Agha Jari Formation is bended into regional folds together with other formations: it is parallel with them on the surface and there are no different internal deformations. On the contrary, it is incongruously folded with the respect to the footwall and the overburden (disharmonic folding) in the N, and principally in the western part of the region, especially to the W of Kuh-e Kahneh. Anticlines and synclines with the axial length of tens of kilometers have amplitude of 2 to 3 km. This disharmony is probably caused by great portion of clays in the formation lithology.

Faults

There are prevailing small, short normal faults with low amplitudes. The fold structure is cut by subvertical faults, partly longitudinal, mostly transversal to diagonal, except of probably flat overthrusts (displacements) of anticlines. The rate and direction of mutual movement of blocks could not been derived in a majority of faults. Numerous faults show features of normal faults or wrench faults.

Large fault structures influence the course of fold axes, and, contrary to the small faults, are only hardly distinguishable in the field, but highly expressive on satellite images of different types. They mostly represent projections of basement structures, usually they occur as relatively broad and complex zones, and often reveal higher seismicity (Nowroozi 1971, 1972). Old, N-S basement trends of the Arabian Platform are distinguishable in the Zagros as zones of normal and transcurrent faulting with associated facies changes and anticlinal plunges. Some of these fault projections show distinct earthquake hypocenters in a 50 to 100 km depth (Falcon 1967b). The most important N-S lineament is the Oman line, representing the zone of dextral move-

ment of 120 km (Crawford 1972), affecting Alpine structures of the eastern Iran (Stöcklin 1974, Coleman 1981). Another important manifestation of this trend is the Qatar-Kazerun line, out of region studied, and some other lines with presumably dextral character (Falcon 1967a,b, 1969). In some places, younger Zagros trends are superimposed on the older N-S trends (e.g., Jazireh-ye Lavan, cf. Henson 1951; Mina, Razaghnia and Paran 1967). The effect of the two superimposed trends is typical only for the boundary of the unfolded zone and the folded Zagros Fold Belt (Kamen-Kaye 1970). In the studied area, there are relatively numerous manifestations of SW-NE structures, parallel with trends in the Dasht-e Kevir area (i.e. the trend prevailing in the eastern Elborz). It is clearly visible in the coastal region between Bandar-e Lengeh and Surdo. This trend, roughly perpendicular to the Zagros trend, caused also the bending and plunging of some anticlines.

Numerous salt plugs are associated with large fault structures, and, on the other hand, these fault lines of the basement are important for the origin of salt diapirs (Humphrey 1958). The role of salt for the evolution of thrusts was described by Falcon (1969). Some subordinate thrust faults have developed from simple folds (Kashfi 1976). Small thrust faults could also be associated with the development of large recumbent folds in the Gachsaran Formation.

Fürst (1970, 1976, 1990) distinguished three basic fault trends in the Zagros Fold Belt: (1) NNE-SSW Oman trend dividing the Eastern Zagros into individual blocks, (2) NNW-SSE Lut trend influencing facies boundaries, and (3) NW-SE Zagros trend influencing facies changes since the Jurassic. Four principal directions appear in the trend of fault structures, according to our remote sensing and field phase (Bosák, Jaroš and Rejl 1992): (1) W-E, (2) N-S, (3) NW (NNW to WNW) -SE (SSE to ESE), and (4) NE (NNE to ENE) - SW (SSW to ESE). The orientation of fault structures shows local irregularities distinctly depending on irregularities of fold (anticline) axes. Some normal faults, together with anticline overthrusts, belong to the longitudinal faults (as oriented to fold structures) with approx. W-E trend. Faults without distinguishable rate and nature of movements belong, with some exceptions, to transversal fault category of approx. N-S direction. It can be assumed, that they have a character of tension fissures. Diagonal faults also include faults with not distinguishable movements, numerous normal faults and principally wrench faults.

Remote sensing and photogeology

(J. Jaroš and P. Bosák)

The interpretation of satellite images based on photogeology of air photos shows that the network of photolineations and regional photolineaments is very dense, very close to interpretation of Fürst (1976, 1990). In comparison with Fürst's drawings, lower expression of short lineations is due to technique applied. Fürst used satellite images taken as stereoscopic pairs, which were studied using common stereoscope. This procedure enabled to identify even very small fractures. Our techniques were based on common interpretation of non stereoscopic images. Therefore, only manifestations of possible fault or fissure structures were interpreted, not taking into account short linear forms which can be misinterpreted with bedding facets whatever their form can be influenced by tiny fractures in rocks. Such interpretation lies behind the possibilities of used scale (1:250,000). Photolineations and photolineaments are expressions of geological features in satellite images and air photos.

In the bare relief of the Zagros Fold Belt they indicate, in most cases, existence of fissures, faults and geological boundaries. *Photolineations*, hereafter, are used for short and simple linear features of photos (e.g., fissures, small faults). *Photolineaments* are expressive, regional and more complex structures visible on photos (e.g., expression of major faults).

Several basic trends can be distinguished: (1) NNW-SSE to N-S passing sometimes to NW-SE direction, (2) NNE-SSW, (3) NW-SE, (4) NE-SW and (5) W-E. Where it was possible, dip direction was drawn (normal faults) and direction of relative movement (wrench faults), respectively. The interpretation shows, that some structures have a character of regional photolineaments (especially NNW-SSE and NE-SW trending). Such structures were supposed to be main fault systems of the region. Their composition is not single. Such structures commonly form broad zones of densely packed lineations, more or less continuous. They often have a character of dextral and sinistral strike-slip faults with some normal component. More or less, they represent, at least partly, basement structure projected through the complete pile of the platform cover. When we compare the scheme compiled here (see Fig. 42) with the model of Fürst (1990; Fig. 4) we can observe high similarity, although not identity. The compilation of such models is sometimes highly subjective when delineating main fault system from very dense photolineation network. Our interpretation differs, on some shear zones, in the deduction of the sense of lateral movement. While Fürst interpreted all shear zones as right-lateral Zagros faults, our interpretation can indicate also left-lateral movements along them. Nevertheless, this situation can indicate also more complicated structural dissection of the basement level with not uniform movement and rotation of blocks of various sizes. In spite of this fact, we can generally agree with Fürst (1990) that conjugated shear systems and the orientation of the NE-SW Riedel shear is in the accordance with interpreted strike-slip fault systems whereas the main Zagros thrust system is likely to be related to a master shear of right-lateral movement.

Minor structures are often connected with main photolineaments and photolineations showing pattern of pair system antithetic to main structure. This antithetic structure is mostly composed of several synthetic smaller photolineations. *En echellon* arrangement of photolineations is very common feature indicating torsion forces caused by the rotation of individual structural blocks of variable sizes and orders, a phenomenon connected with strike-slip faults. Photolineations and even photolineaments often pinch out changing into system of tree-like smaller lineations and fissures diminishing so the amplitude of movement. Some photostructures sometimes pass into proved thrust zones, e.g., in the zone between Chahar Birkeh and Champeh plugs.

As photolineations often dissect salt plugs, even those most active and/or with extensive young glaciers, it can be deducted that the tectonic activity of region is also very young, and that fracture-fault zones represent important guide of plug intrusions.

Description of faults

Overthrusts (displacements) represent displacements of anticlines to the south with approx. W-E trends. Their length, detected within our region, varies from several (10) kilometers in the S (the southern slope of the Champeh Anticline) up to nearly 100 km in the N. The amplitude (width) of displacement in their central portions, along which two anticlines are in the contact, reaches the order of the amplitude of covered syncline, i.e. first tens of kilometers.

Longitudinal and transversal to diagonal faults with the respect to fold axis trend can be distinguished in the category of normal faults. The amplitude of normal faults can be deciphered according to field observations and air photos. The relative movement of blocks can be assumed to tens up to first hundreds of metros according to displacement of formation boundaries. Longitudinal normal faults occur in summit parts of anticlines and in upper parts of their flanks. Two types of such faults can be stated. They are represented either by smaller grabens cutting the summit part of anticlines or, on the contrary, by smaller horsts in the same position. Among all anticlinal ridges, Champeh, Namaki, Herang and Bavyiun Anticlines there are the most intensively disturbed by normal faults, i.e. by the system of step faults developed also in the upper part of anticlinal flanks, with the sinking tendency along dip angle of flanks; the structure has a character of complex horst, sometimes of graben. Those structures are dominantly developed in the zone of low folds near the coast of Khalij-e Fars. Fürst (1976) supposed, that longitudinal normal faults represent collapse structures and designed them as linear collapse structures to distinguish them from circular collapse structures (cauldrons). According to our meaning, these structures are not connected with salt diapirism, subrosion and collapse, but with the relaxation after certain phase of very young folding owing to their position only in coastal region (adjacent to Coastal Flexure) and general absence northwards. If connected with salt tectonics, they should occur elsewhere, as salt cushions are supposedly developed in all anticlinal structures.

Transversal to diagonal normal faults segment anticlinal ridges with non systematic sinking tendency of western and eastern blocks. They occur also in places of the plunge of anticlinal ridges, where blocks sink in plunge direction of anticlinal axis (e.g., Genow Anticline). Other normal faults of this category limit cauldrons, in places.

Wrench faults are oriented, with minor exceptions only, in two directions of systems of approx. SSW-SSE and NNE-SSW trends. They are discontinuous, i.e. displacing evidently only one anticlinal ridge, often in the vicinity of salt plugs. Wrench faults of the NNW-SSE system highly prevail (about 80 %) among faults in which the horizontal movement was more or less proved. The statistic evaluation of the movement direction indicate, that NNW- SSE and NNE-SSW systems do not represent pair systems in which the S-N oriented stress perpendicular to fold axes should produce the NNW-SSE system as dextral faults and the NNE-SSW as sinistral faults. Dextral and sinistral faults are in rough equilibrium in each of both systems. More, this fact underlines the autonomous character of wrench faults in individual anticlinal flanks. Cases where two close wrench faults with the same direction have different sense of movement are relatively abundant. It can be stated in general, that together with bends, wrench faults displacing anticline axes represent only other form (cause) of sudden changes in axis direction. The rotation of blocks in the basement is supposed as decisive for such changes (Fürst 1976)(cf. Fig. 4 and Fig. 42). However it seems, that these changes are caused rather by irregular movement of individual segments of anticlines southward, or by their displacement over southern synclines, respectively. Such displacements are also segmented by wrench faults and a number of them does not exhibit the continuation behind wrench faults. Horizontal displacement of block proved on wrench faults represents only hundreds of metros to first kilometers. Movements in a rank of about 10 km can be assumed if possible displacement between some anticlinal ridges is taken into account (e.g., the link-up of Gatech and Shu Anticlines).

Interpretation of geophysical results (*P. Bosák*)

Shallow positive magnetic anomalies in material compiled by Yousefi and Friedberg (1978a-c) are connected rather with increased contents of magnetic minerals. Shallow magnetic bodies of distinctly elongated shape, parallel with the structure of the region occur mostly in coarser-grained clastics (especially in the Agha Jari Formation). Circular or shortly elongated bodies can be connected with higher contents of sedimentary iron ores in upper parts of salt plugs or with iron concentrations in so-called rim synclines. Negative anomalies, e.g., in the surroundings of Puhal or to the NE of Bandar Abbas, have not been interpreted. They can represent areas with non typical rock content in underlying horizons or built of the same material as in surroundings, but sunken.

5. Hydrogeology

(V. Václavek)

Hydrogeological research was focused on: (1) detection of groundwater occurrences in geological structures according to the position of springs; (2) determination of spring yields and measurement of water temperatures by means of simple field methods; (3) water sampling for laboratory determination of hydrochemical properties of groundwater and surface water, and (4) to give a review of hydrochemical type of groundwater and laws of circulation of groundwater in the geological structures concerned.

5.1. Methods

We estimated the yield of springs and/or the discharge of small creeks. In regulated stream beds (e.g., discharge of Genow springs) the discharge profile and the flow velocity was measured, and the water discharge was then determined. The yields of some small springs flowing out of joints were measured, especially in salt plugs and in creeks with small waterfalls using small PVC bags of known volume. The water temperature was determined by duplication of maximum and minimum mercury thermometer, as a rule by repeated measurement.

Further, we studied the presence of H_2S (sensorially), oxidation processes visible on spring outflows and in their vicinity like precipitation of iron and manganese compounds and the formation of salt and gypsum crusts or carbonate speleothems.

To measure the pH value in the field, we applied the WIDE RANGE pH TEST KIT of the HACH Company (USA). For waters showing contents of chlorine (Cl) higher than 50 mg.l⁻¹, the set was not suitable. Waters of the studied area had Cl contents higher by multiples. In the first collection containing 15 samples, we performed the groundwater sampling for chemical analyses from all detected spring outflows. Six samples from the salt plugs could not be processed by the laboratory because of too high electroconductivity (EC>80 000 μ mhos/m) caused by high halite contents. Therefore, during the further field work we did not sampled any water from the salt plugs for analyses.

Chemical analyses of water samples were performed by the Power Ministry - Laboratory of Water at Bandar Abbas. The laboratory performed only determination of main cations and anions Ca, Mg, Na, HCO₃, SO₄ and Cl, as it is equipped only by methods for the determination of hygienic water properties according to Iranian standards. Later we calculated the values of contents of the potassium cation from inequalities of the values of equivalents of cations and anions, knowing that the value calculated subsequently is affected by an error resulting from the existence of other cations, especially Fe and Mn which also combine with the determined anions, but they are not significant as to percentage abundance. As proven by chemical analyses of groundwater from some salt plugs (given by Fürst 1970, 1976, 1990; see Tab. 8), the contents of PO_4 reach up to 460 mg.l⁻¹ (9.7 mval) in some cases. Nevertheless, even this value represents only 0.2 mval % in the percentage abundance of equivalents. In spite of these deficiencies it can be stated that on the basis of the analyses performed, we are able to classify groundwaters according to basic chemical types.

5.2. Aquifers, aquicludes, and aquitards

The determination of hydrophysical characteristics of rock complexes is based on lithofacies descriptions of stratigraphical units, lithological characteristics of the rock types, tectonic exposition, manifestations of weathering as well as on field observations. In this way, we can delimit the basic category of permeability of rocks only, and we are not able to quantify exactly these categories by the transmissivity or permeability coefficients.

5.2.1. Hydrogeological characteristics of the rock types

Psephites (without respect to their genetic type) show high interstitial permeability and constitute aquifers. The permeability can vary from one place to another according to the content of fine-grained fractions and on the lithification/diagenesis degree. In areas with advanced diagenetic lithification, both fracture and fissure permeability also occurs depending on the tectonic exposition. Without tectonic disturbances and with higher consolidation degree they function as aquitards.

Psammites are characterized by low to high permeability depending on the amount of the pelitic component and on the lithification/diagenesis degree. They are noted for both interstitial and fracture (fissure) permeability and form an aquifer rather than an aquitard.

Lutites (incl. marl, marlstone) are noted for low permeability to impermeability and have a function of aquicludes.

Carbonate rocks have variable hydrophysical properties depending on the genesis and tectonic exposition. Biolithic, organodetrital and sandy limestones show good primary interstitial permeability and represent significant aquifers. Chemogenic carbonates are compact with limited primary porosity, but owing to higher rigidity, they are usually fractured; those tectonically affected are well permeable. Locally, they can form an aquifer, an aquitard as well as an aquiclude. Under favorable hydrogeological conditions, especially on circulation paths of infiltrated precipitations and at the drainage basis of groundwater, karst cavities with free flow of water originated.

Evaporites in intact conditions are impermeable and form an aquitard. In zones affected by jointing, permeability increases, and, due to good water solubility, zones of high permeability are formed, often with karst cavities and channels. Locally, they can have high accumulation capacity and create ways of transfer of groundwater. In a high degree, they participate in the origin of the hydrochemical type of groundwater.

Igneous and metamorphic rocks of the salt plugs are not important for the regional hydrogeological conditions of the area.

ЕРОСН	FORMATION MEMBER	LITHOLOGY	THICKNESS (÷ m)	HYDROGEOLOGICAL CHARACTERISTIC	KIND of POROSITY	OCCURRENCE
ZONE OF WI	EATHERING	ELUVIUM RESIDUUM	- 50	AQUIFER locally AQUITARD	INTERSTITIAL FISSURE	ON GROUND SURFACE
QUATERNARY		GRAVEL SAND CLAY	0-50	AQUIFER	INTERSITTIAL	FLUVIAL SEDIMENTS ALLUVIAL CONES DEBRIS
PLIOCENE	BAKHTYARI	CONGLOMERATE SANDSTONE	- 2000 - 200		INTERSTITIAL FISSURE	
	AGHA JARI MISHAN	MUDSTONE MARL	- 2000 - 2000	AQUICLUDE		SYNCLINES WHOLE
MIOCENE	KERMARAN GURI	LIMESTONE	0-100	AQUIFER	INTERSTITIAL FISSURE	REGION
	GACHSARAN	MARL,GYPSUM ANHYDRIDE	- 500	AQUITARD	FISSURE FRACTURES SOLUTION CAVITIES	
OLIGOCENE	ASMARI	LIMESTONE	- 250	AQUIFER	INTERSTITIAL FISSURE FRACTURE	
EOCENE	JAHROM	DOLOSTONE	0-600	AQUITARD	FISSURE FRACTURE	WHOLE REGION
PALEOCENE	РАВДЕН	SHALE MARL	- 680	AQUICLUDE		
CRETACEOUS	GURPI	MARL	- 350		V///////	

 Table 4.
 Hydrogeological characteristics of lithostratigraphic units.

5.2.2. Hydrogeological characteristics of lithostratigraphic units

Hydrogeological characteristics of lithostratigraphic units are based on the stratigraphic classification shown in Table 4. The regional classification of hydrophysical properties of lithological and lithostratigraphic units together with structural-geological pattern allow us to draw conclusions concerning the hydrogeological structures of both local and regional significance. The structures of the salt plugs are evaluated separately on other place. The characteristics are given in Figure 6.

Aquifers of regional significance

Two important aquifers of regional significance exist in the area studied (Fig. 5).

The upper aquifer is situated in coarse clastics of the Bakhtyari Formation and in the upper psephitic-psammitic sequence of the Agha Jari Formation. The thickness of the aquifer reaches more than 2,000 m in places. Bakhtyari conglomerates fill the synclines. The Agha Jari sandstones are mostly denuded in anticlines. In the synclines they underlay the Bakhtyari Formation. The aquifer is an important groundwater reservoir mostly of freshwater (*cf.* Bosák and Václavek 1988).

The lower aquifer is situated in limestones of the Asmari Formation, eventually in dolostones of the Jahrom equivalent that are about 250 m thick. Biogenic limestones (mostly nummulitic) are porous (fossilmoldic porosity). They show both interstitial, and fissure and fracture permeability. In the anticlines the Asmari forms extensive infiltration areas, in the synclines it represents artesian structures.

Both aquifers are separated by mudstone- and marl-bearing aquiclude of the lower part of the Agha Jari Formation, the upper part of the Mishan Formation (Anguru Member), and evaporitic-mudstone sequence of the Gachsaran Formation. Despite of some more permeable layers, this strata generally represent a regional aquiclude. The lower aquifer (Asmari Formation) is underlain by thick strata of low permeable dolostones of the Jahrom Formation and by impermeable marls of the Gurpi Formation.

Aquifers of local significance

Quaternary sediments of streams, alluvial cones and terraces of erosion downcuts in anticlines and salt plugs, and thick debris layers belong to aquifers of the local significance. If they cover the Bakhtyari or Agha Jari Formations, they form an aquifer of an uniform hydraulic regime together with them.

The aquifer in the calcareous Guri Member is relatively unimportant owing to its variable thickness (0-100 m) and limited exposures in anticlines. The Gachsaran Formation is classified as an aquitard. Well soluble evaporites of the Chechel Member at the top of an artesian aquifer of the Asmari Formation can form communication paths of groundwater, especially along corroded faulted zones. Some springs of thermal water bring evidence in this respect (e.g., Anguru, Tarbu, Anveh Anticlines).

Aquifer of the weathering zone

The aquifer of the weathering zone without respect to the stratigraphic pertinence of rocks cannot be neglected. Owing to weathering processes, rocks are disturbed to depths of up to 50 m in places. Infiltrated precipitation wash the interstices and fissures so that conditions for groundwater flow are created. It is typically developed in the area of the salt plugs, in anticlines on the outcrops of rocks without difference in their lithology.

5.3. Groundwater flow

Two main systems of aquifers in different structural-geological positions have different hydraulic systems, i.e. the upper aquifer and the aquifer of the weathering zone of the salt plugs.





B-Bakhtyari Formation, AJ-Agha Jari Formation, M-Anguru Marls, G-Guri Member, Gsr-Gachsaran Formation, As-Asmari Formation, J-P - Jahrom-Pabdeh Formation, Gu-Figure 5. Schematic cross section of an idealized hydrogeological structure. Gurpi Formation.

5.3.1. The upper aquifer

The upper aquifer situated above the sequence of the Anguru Member and the lower portion of the Agha Jari Formation occurs in synclines. Generally, it includes gravitation water, even if conditions of artesian pressure can be created in greater depths locally, where fissure permeability exists. In the consequence of advanced consolidation, porosity decreases, and thus an aquitard or even an aquiclude is formed locally. Pelitic layers in the deeper zones of the Agha Jari Formation can be impermeable. The water flow is gravitational.

Infiltration of atmospheric precipitation occurs in the whole area of the structure. The share of infiltration precipitation will be relatively high due to smaller evaporation in winter months (December to March), low density of vegetation cover and good permeability of weathering zone on the outcrops of sediments, alluvial cones and debris.

Aquifer dewatering in a structure with unexploited groundwater reserves is directed either into creeks or by direct evaporation in areas where the water table lies close to the surface. In littoral synclines it is discharged into the sea. In the sites brought under agricultural cultivation, groundwater of the upper aquifer is used for irrigation. The amount of water utilized for this purpose substitutes natural dewatering. This aquifer has the greatest economic importance for the whole large region. It is a natural reservoir of large, static reserves of groundwater.

5.3.2. Aquifer of the weathering zone of salt plugs

Aquifers of the weathering zone of salt plugs belong to the hydraulic system of the upper aquifer (Fig. 6). This aquifer exists above and at the niveau of local base levels in all rock types of the salt plugs. It takes gravitational groundwater with a streamflow of linear-concentric orientation according to local drainages in valleys of the plugs or rim zone. Permeability is of fracture-type in evaporites, locally even of karst-type. Accumulations of clastic rocks (both fluvial and deluvial) at the base of valleys show interstitial permeability and variable thickness. As a rule, they drain the fracture aquifer with inflow of groundwater from the sides and bottom. The runoff occurs in the direction of inclination of the valley. Where the flow profile in sediments decreases (reduced thickness or width of sediments), there are occurring groundwater outflows and surface streams are created. Surface water in a part of the valley with greater accumulation capacity or greater permeability infiltrates again. This process can be repeated several times along the flow route.

Dewatering of the fracture aquifer occurs often by springs over the base level. This phenomenon can be often observed in evaporites (salt, anhydrite). The communication and drainage of the joint system is washed out in these rocks, up to a stage of initial karstification, in some cases (e.g., Namakdan and Khamir plugs) to karst spaces.

In a series of sites, a thick alluvial cone built of the plugderived material is formed around the salt plug, in which all surface water drained from plugs infiltrates (e.g., Gachin, Puhal, Charak, Bam, and Mesijune plugs). The primary source of the salt plug groundwater is atmospheric precipitation infiltrated from the surface to permeable weathering zone. There exists also a possibility of groundwater fed by condensation of water vapors from the air. It can be admited that hygroscopic salt takes a certain volume of water from air, but without greater influence upon the groundwater regime in the weathering zone. The climatic cycle of the region and retention capacity of porous to karst-type rock environment determine the typical hydrogeological regime of the salt domes. In rainy period (December to February), pores and karst cavities are filled with water, there is a considerable surface runoff.

In the dry period, accumulated reserves gradually discharge with decreasing yield of springs. In structures with small hydrogeological drainage area and small accumulation capacity of the aquifer, the complete dewatering occurs. Only more extensive systems with karst cavities can maintain springs during the whole dry period (*cf.* Namakdan plug).

The plug morphology and its areal extent have a great influence on the hydrogeological regime. In the plug's active stage, the system of joints is little pervious, groundwater circulation paths lead in surface zones, and initial stage of karstification does not create sufficient retention space for infiltrated precipitation. There prevails surface streamflow. Springs appear in the rainy season and shortly after it only and surface streams have short valleys (Fig. 6a).

The medium stage of plug disintegration is hydrogeologically the most active one. There exist washed systems of joints and karst cavities, and surface drainage network of streams with clastic sediments is developed. There is a long-term discharge of groundwater from accumulated reserves. At the plug perimeter there are alluvial cones of plug-derived material several meters thick. Surface waters flowing from plugs infiltrate into the alluvial cones and take part in the circulation of groundwater again.

The stage of plug ruination (e.g., Qalat-e Bala and Zangard plugs) is characterized by low hydrogeological activity. Isolated blocks of sediments have small drainage areas and small capacity of the joint systems. Greater saturation by water could be expected only below the local base levels. Neither springs nor surface streams are visible. During the field reconnaissance we could follow the hydrogeological activity of the domes before the precipitation period (November to mid-December 1992), when most of the plugs remained without evident indications of groundwater, and in the rainy season (mid-December 1992 to mid-January 1993) with numerous springs and surface streams.

5.3.3. The lower aquifer

The aquifer in the Asmari limestones has its infiltration area on the outcrops in the anticlines. In these elevated structures there exists an aquifer with gravitational water up to a level where it is covered by an aquitard of the Gachsaran Formation. In the synclines it submerges below the earth surface of the field and gravitational groundwater enters the artesian regime. The direction of flow is given by the hydraulic inclination towards the place of discharge in the opposite syncline flank (Fig. 5).

The area of interest is markedly arid with rain precipitation concentrated in a period of 2 to 3 months of the year. Springs with high yields of up to hundreds of liters per second are active during the whole year. To know their regime and to evaluate in more details the balance of precipitation as compared with their yield, long-term measurement of yield and temperature would be necessary. In extensive synclinal artesian aquifers, response of springs to precipitation will show considerable delay.

Slow oscillation of yields is given by hydraulic transfer of increased hydrostatic pressure in the area of infiltration. In-



w.l. ground water level (high hydraulic gradient)





Figure 6. Schematic cross section of active (a) and passive (b) salt plug.

creased pressure is partly eliminated by the resistance during water flow through the aquifer so that the resulting effect in the area of discharge can be registered by precise long-term measurement. We observed this phenomenon on the Khamir springs (Khamir plug) before the rainy season (November 10, 1992), at the beginning of the rainy season (December 25, 1992) and after intensive precipitation (January 15, 1993). In all cases, the yield was visually the same. Permanent runoff of groundwater from large springs requires large volume of accumulated water in the aquifer of anticlines. A characteristic feature of an artesian aquifer is the concentration of dewatering into abundant spring groups (Tab. 6).

Yield values reach e.g., in Kuh-e Genow about 170 l.s⁻¹, in Kuh-e Anguru about 150 l.s⁻¹. The intensive yield concentra-

tion of springs indicates a highly permeable faulted drainage system applying in an aquifer of a large area. It is only in this way that permanent high yields can be attained. It is of interest that geologically, the springs are situated prevalently in the lower sequence of the Gachsaran Formation which covers the aquifer. In dislocated and easily soluble evaporites there exist karst cavities and channels along which groundwater arrives to the surface.

5.3.4. Water temperature

When circulating in deeply situated layers, groundwater becomes warm. The temperature of water depends on: (1) heat supply from deeper zones of the Earth's crust due to earth heat flow; (2) heat supply received by the Earth's surface from solar radiation (insolation), and (3) heat transfer between rocks in the collectors and water filling the collector, eventually by exothermic activity of sulfate reducing bacteria. Below the depth of annual temperature oscillation (the so called neutral temperature zone), the water temperature is a function of the geothermal gradient.

Annual temperature oscillation in hot and arid areas propagates up to the depths of 6 to 8 m (Schoeller 1962). The temperature in the neutral temperature zone corresponds to the average annual temperature. According to table 6 we shall consider the value of 27 $^{\circ}$ C.

If we take the value of thermal gradient equal to 0.3 °C.m⁻¹, then it results that e.g., water of the springs of the Anguru Anticline 47 °C warm (sample Nos. 1 and 17) has its circulation paths in a depth of around 700 m, water of the springs of the Tarbu Anticline (Tarbu plug) with temperature of 60 °C must come from a depth of about 1,100 m. The water temperature in infiltration area (cold) and in the dewatering branch (warm water) affects the density of water circulating in the aquifer. These changes of density contribute to the activation of water circulation in the geohydrodynamical system. High temperatures of groundwater in flow openings indicate rush ascent of water from the depth where it is warmed up to the surface.

In the group of springs there occur outflows of different temperatures (e.g., in Anguru Anticline springs with 48, 46.5 and 44 °C). This is caused either by mixing with water from the aquifer of the anticlines or by an independent ascent way with lower flow velocity so that cooling takes place. Basic data concerning the springs are given in Table 6.

5.4. Groundwater hydrochemistry

5.4.1. Upper aquifer

The upper aquifer has got no springs. We sampled the water only in places where it was pumped off. Four water samples are at disposal: (1) Lo-1 - from a well at Lar - Bakhtyari Formation; (2) No. 16 - from a well at Tazian - Bakhtyari Formation; (3) No. 20 - from a well at Sar Chahan - Bakhtyari Formation, and (4) No. 60/1 - from a well at Kuh-e Gahkum - fluvial deposits (*cf.* Fig.8).

The water mineralization ranges from 1,298 mg.l⁻¹ (No 16) to 5,540 mg.l⁻¹ (No. 20, Tab.7) and according to the Davis' s classification it is considered as *brackish water*.

According to the amount of dissolved salts there prevail chlorine (Cl⁻) with 48 to 95 mval% and sulfates (SO₄²⁻) with 22

Sample No	Object	×	Z	Map sheet
1	spring	55°49′30′′	27°16′	7144 I
2	spring	55°49′30′′	27°15′45″	7144 I
3	spring	56°18′	27°27′	7244 I
4	spring	56°18′	27°27′	7244 I
8	spring	55°43′	27°07′	7144 III
9	spring	54°16′30′′	27°26′	6844 I
10	spring	54°16′30′′	27°26′	6844 I
16	well	56°11′	27°18′	7244 I∨
17	spring	55°46′45′′	27°16′30″	7144 I
20	well	55°51′	28o10′	7146 II
21	spring	55°49′	28°13′	7146 II
22	spring	55°42′	27°44′	7145 III
23	spring	55°42′	27°44′	7145 III
24	spring	55°30′	26°56′30″	7143 I∨
25	spring	55°32′30′′	26°58′30″	7143 I∨
15/1	well	54°56′	26°59′	69431
HLO1	well	54°2+051′	27°42′	6845

Table 5. Coordinates of springs and wells documented by chemical analyses (according to topographic maps, scale of 1:50,000).

to 44 mval% in anions, and sodium (Na⁺) with 31 to 42 mval% in cations. Magnesium (Mg²⁺) prevailed in the sample Lo-1 with 38 mval%. Contents of ions (in mval%) is as follows:

Lo-1 M 1,7
$$\frac{Cl 48 SO_4 44 HCO_3 8}{Mg 38 Na 31 Ca 27}$$
No.16 M 1,3
$$\frac{Cl 52 SO_4 35 HCO_3 12}{Na 42 Mg 28 Ca 23}$$
No.20 M 5,5
$$\frac{Cl 74 SO_4 22 HCO_3 3}{Na 39 Ca 25 Mg 24}$$
No.21 M 4.2
$$\frac{Cl 61 So_4 35 HCO_3 3}{Na 37 Ca 33 Mg 20}$$

The source of dominant ions of Na⁺ and Cl⁺ is in salt plugs and salt-bearing formations (e.g., Gachsaran). Intermittent streams coming from salt plugs and having high amounts of dissolved halite (NaCl) infiltrate into the upper aquifer. Low NaCl contents in water occur only where any salt plug or formation is present within the drainage area.

The water sample 15/1 from a well in gypsum in the valley of the Zendan plug belongs also to the upper aquifer. The type of water is completely different here. In the total mineralization of 2,588 mg.l⁻¹, the dominant are Ca²⁺(60 mval%) and Mg²⁺(32 mval%) and SO₄²⁻(78 mval%). Different mineralization is evident from figure 7 and the abundance of ions is:

Sample No.	Location	Stratigraphy	Spring position	Yield estin	nate - 1.s ⁻¹	Water	Other features
				Spring	Spring	temperature	
					group	(⁰ C)	
1	Kuh-e Anguru	Gachsaran-Asmari	fracture	25.0	150.0	47.0	H ₂ S
2	Kuh-e Anguru	Gachsaran-Guri	contact spring	1.5	-	22.0	
3	Kuh-e Genow	Gachsaran	fracture	90.0	170.0	39.5	H ₂ S, pool
4	Kuh-e Genov	Gachsaran	fissure	0.5	-	35.0	H ₂ S
5	Kuh-e Puhal	Gachsaran	contact spring	0.3	1.5	32.0	Fe
6	Kuh-e Puhal	Gachsaran	fissure	-	1.8	33.0	Fe, salts
7	Kuh-e Puhal	Gachsaran	interstitial in debris	0.1	0.8	32.0	Fe, salt sinters
8	Kuh-e Puhal	Mischan-Guri	fissure	0.2	1.5	31.0	
9	Anveh village	Gachsaran-Asmari	fracture	12.0	15.0	38.0	H ₂ S, pool
10	Anveh village	Asmari	stratal spring	2.0	3.0	34.0	spring in basin
11	Kanneh lake	Gachsaran-Razak	?	-	-	31.0	salty plain, inflow to lake in bottom
12	Namakdan plug	salt plug	water level 5 m	-	-	29.0	dolines in salt
			below surface				
13	Gachin plug	zone of weathering	interstitial in debris	0.2	0.4	29.0	salt crusts
16	Tazian village	Bakhtyari	interstitial in debris	-	-	29	
17	Kuh-e Anguru	Gachsaran-Asmari	fracture	50.0	150.0	47.5	H ₂ S, karst forms
18	Hormoz island	salt plug	outflow from drift	0.2	-	24.0	Fe ochre mining salt crusts
19	Namakdan plug	salt plug	karst	0.2	-	27.0	karst drainage in salt
20	Sar Chahan village	Bakhtyari	well	12.0	-	29.5	
21	Kuh-e Gahkum	Quaternary	stratal spring	0.3	-	-	
22	Tarbu plug	Gachsaran	fracture	8.0	30.0	53.0	H_2S , fumaroles
23	Tarbu plug	Gachsaran	fracture	20.0	80.0	60.0	H ₂ S
24	Khamir plug	Gachsaran-Guri	contact spring	0.7	-	31.0	H ₂ S
25	Khamir plug	Gachsaran-Asmari	fracture	2.5	-	41.0	H_2S , pool
26	Kurdeh plug	Asmari ?	fracture	8.0	-	36.0	H_2S , pool

 Table 6.
 Basic characteristics of sampled springs.

No.15/1 M 2,5
$$SO_4 78 Cl 19 HCO_3 3$$

Ca 60 Mg 32 K 7

The water hydrochemistry of salt plugs can be judged only according to analyses presented by Fürst (1970, 1976, 1990, see Tab. 8). According to the Davis's classification they belong to *brines* (TDS>100,000 mg.l⁻¹). The mineralization is formed by Cl with more than 98 mval% and Na⁺ with more than 95 mval%. The water of the sample No. 8 from a small joint spring in the Mishan Formation behind the northern margin of the salt plug No. 11 (Puhal) is close to this water type. With the mineralization of 64 g.l⁻¹ it differs from waters of the lower aquifer, but it does not reach the type brine yet (Fig. 7). It is a fracture aquifer of the salt plug and the Mishan Formation (*s.l.*). Individual ions have the following equivalent % abundances:

No.8 M 64
$$\frac{\text{Cl 97 SO}_4 3}{\text{K 50 Na 41 Ca 5 Mg 3}}$$

We did not note contents of gases (H_2S) sensorically connected with groundwaters of the upper aquifers.

5.4.2. The lower aquifer

For the hydrochemical evaluation of the lower aquifer we collected 11 water analyses. Location of sampled springs is shown on Figure 8, the coordinates are listed in Table 5. The hydrochemical accordance of all the samples is evident from the Durov's diagram (Fig. 7).

Na⁺ and K⁺ prevail with more than 60 % equivalent %. Only in samples Nos. 22 and 23 from the site of Tarbu (in the vicinity of the Tarbu plug) the abundance of Ca^{2+} reached 20 and 22 equival.%, respectively. In other samples, Ca^{2+} has a secondary abundance up to 20 equival.%.

Cl with 59 to 97 equival.% is dominant among cations. SO_4^{2-} with 20, 29 and 39 equivalent % appears in a greater quantity only in waters of the Genow springs (samples Nos. 3 and 4), and Anveh (No. 10 - spring from the Asmari Formation. HCO₃⁻ with low equival.% is quite subordinate.

Total groundwater mineralization ranges from 10 g.1-1 to 44 g.l⁻¹. Mineralization source of the primary importance is halite which penetrates and which is forced into the limestones of the Asmari Formation during diapyrism. The second source of the mineralization is represented by evaporites (mainly gypsum) of the overlying Gachsaran Formation. Similar mineralization of waters accompanies deposits of oil. It is known that the Asmari Formation represents an important reservoir for the accumulations of hydrocarbons in other places of the Zagros Fold Belt. It is interesting that the sampled springs with a lower abundance of NaCl component do not outflow from the Gachsaran Formation. Sources of water samples with a higher mineralization, e.g., Nos. 2 and 3 (Genow) flow out from the Gachsaran Formation and No. 10 (Anveh) from the Asmari Formation, whilst water sample No. 9 with high NaCl contents was sampled about 200 m from No. 10 again from the Gachsaran Formation. This would bring evidence that the dominant proportion of NaCl mineralization is partially primary from the Asmari Formation and partially it is obtained from Gachsaran evaporites. The

	ıval%	96	96	68	59	76	95	78	48	52	95	74	86	91	85	88	19	61
ជ	mval n	628.10	665.70	105.11	100.11	1021.10	310.30	75.80	11.20	9.60	463.00	53.50	128.80	142.15	316.80	400.00	7.50	33.00
	mg.1 ⁻¹	22235	23566	3721	3544	36147	10984	2683	396	340	16390	1894	4559	5032	11214	14160	265	1168
	mval%	3	б	29	39	ŝ	ŝ	20	44	35	4	22	11	7	14	11	78	35
SO_4	mval	18.0	20.0	45.0	65.0	30.0	11.0	20.0	10.2	6.4	20.0	16.0	16.5	11.0	51.8	50.8	31.2	19.0
	mg.l ^{-l}	864	960	2160	3120	1440	528	960	489	307	960	768	792	528	2486	2438	1497	912
	mval%	0.4	0.3	2.0	1.0	0.0	1.0	2.0	8.0	12.0	1.0	3.0	2.0	2.0	1.0	1.0	3.0	3.0
HCO ₃	mval	2.49	1.93	3.34	1.73	0.91	2.68	2.36	1.96	2.29	3.01	2.32	2.16	2.36	1.90	6.30	1.20	1.96
	mg.l ⁻¹	152	117	203	105	55	163	144	119	139	183	141	131	144	116	384	73	119
	mval%	33	35	16	14	50	22	14	4	9	29	6	13	14	33	33	7	6
K	mval	219	242	25	24	533	71	14	1	1	143	7	20	22	122	151	3	5
	mg.l ^{-l}	8562	9462	779	938	20840	2776	547	39	39	5591	273	782	860	4770	5904	117	195
	nval%	55	52	62	65	41	64	62	31	42	55	39	54	56	39	37	0	37
Na	mval	357.0	360.0	95.0	110.0	431.0	209.0	60.0	7.3	7.57	269.3	28.7	79.8	87.2	147.0	169.3	0.0	20.11
	mg.l ^{-l}	8175	8244	2175	2519	9870	4786	1374	167	173	6167	646	1832	1997	3366	3877	0	460
	mval %	2	4	8	7	3	5	10	38	28	5	24	10	10	15	13	32	20
Mg	mval	13.80	27.00	12.00	11.36	33.47	16.42	10.10	8.71	4.89	24.94	17.68	14.05	14.52	58.70	60.00	12.90	11.21
	mg.l ⁻¹	167.7	328.0	145.8	138.0	406.6	199.5	122.7	105.8	59.4	303.0	214.8	170.7	176.4	713.2	729.0	156.7	136.2
	mval%	6	8	13	12	5	8	13	27	23	10	25	22	20	12	16	60	33
Ca	mval	58.70	58.40	20.90	21.39	54.90	27.46	12.77	6.38	3.99	48.38	18.52	32.73	31.13	42.50	76.20	24.00	18.04
	mg.l ⁻¹	1176.3	1170.3	418.0	427.8	1098.0	549.2	255.4	127.6	79.8	967.6	370.4	654.6	622.6	850.0	1524.0	480.0	360.8
T.D.S	mg.l ⁻¹	42108	43331	10798	10398	64157	29399	6110	1719	1298	28697	5539	10891	11583	22944	28194	2588	4217
	Sample	No.1	No.2	No.3	No.4	No.8	No.9	No.10	H Lo 1	No.16	No.17	No.20	No.22	No.23	No.24	No.25	15/1	No.21

 Table 7.
 Chemical analyses of groundwater (Laboratory of Ministry of Power, Bandar Abbas).

Sample		Ca			Mg			Na			К			PO_4			SO₄			ច	
	mg.1 ⁻¹	mval	mval %	mg.1 ⁻¹	mval	mval%	mg.1 ⁻¹	mval	mval%	mg. 1 ⁻¹	mval	mval%	mg.1 ⁻¹	i laval	mval%	ng.1 ⁻¹	mval	nval%	mg.1 ⁻¹	mval	mval%
Kuh-e Namak-Dashti	1330	66.30	1.2	292	24.00	0.4	1E + 05	5214	95.60	5810	148.60	2.7	294.00	6.1	0.1	4340 5	0.40	1.6	2E+05	5355	98.20
Gahkum-spring	1440	71.80	1.3	251	20.60	0.4	1E + 05	5441	98.00	498	12.70	0.2	468.00	9.7	0.2	4430 5	2.30	1.6	2E+05	5440	98.10
Kuh-e Khurgou	1283	64.00	1.2	325	26.70	0.5	1E + 05	5253	95.00	7350	188.00	3.4	0.25	1	1	4795 5	06.6	1.8	2E+05	5420	98.10
Gahkum	340	17.00	0.3	72	6.00	0.1	1E + 05	5581	99.40	350	9.00	0.2	ī	ī	1	1590 3	3.10	0.6	2E+05	5567	99.40
Puhal	1600	79.80	1.5	795	65.40	1.2	1E + 05	5262	96.30	2100	53.70	1.0	0.19	1	1	4030 8	4.00	1.5	2E+05	5367	98.40
		1				1		1	1	1	1	1	1	1	1	1	1	1	1		1

 Table 8.
 Analyses of brines from various salt diapirs (according to Fürst 1970, 1976, 1990).



Genow (samples Nos. 3 and 4) and Khamir (sample No. 25) springs outflow inside an eroded salt plug so that high contents of NaCl are evident.

The groundwater mineralization of the sampled springs is in accordance with mineral abundances of the rocks of the region. Percentage abundances of ions are presented in Table 9. Lower mineralization of sample No. 17 as compared to Nos. 1 and 2 is due to lower contents of NaCl ions. Springs are situat-

Spri	ingsN	lo, loca	ation and hydrochemic	al formula				
Springs of the Anguru an	tidine							
	Nh 1	M421	Cl 96 SO4 3	Geohsaran Formation-				
		101-12-, 1	Na55K33Ca9	- Asmari Formation				
		1422	Cl 96 SC4 3	Geohseren Formation -				
	ND. 2	10143,3	Na52K33Ca8Mg4	- Quri Member				
Springs about 1 km west	ofthep	dug21						
N	b 17	M287	0.95.90,4H00,1	Geohsaran Formation-				
ľ	1 0.17	10120,7	Na 55 K 29 Ca 10 Mg 5	- Asmari Formation				
Springs of Genowplug								
N	b .3	M10.7	0 68 SQ4 29 HOO3 2	Gechearan Formation				
			Na 62 K 16 Ca 12 Mg 8	large springs				
1	Nb. 4	M10.9	Cl 59 SO4 39 HOO3 1	Geohseren Formation				
			Na65K14Ca12Mg7	small spring 0,3 l.s-1				
Springs at Tarbuplug								
	h 22	M10.8	Cl 86 SO4 11 HCO32	debris of Gachsaran				
	0.22	IVI IU,O	Na 54 Ca 22 K 13 Mg 10	formation?				
N	b.23	M11.5	CI 91 SO4 7 HOO3 2	Geobseran Formation				
		,-	Na 56 Ca 20 K 14 Mg 10					
Springs of Khamir Antidine								
	L C .	1400 6	CI 85 SO4 14 HCO3 1-	Gachsaran Formation -				
N	1 0. 24	M22,9	Na 39 K 33 Mg 15 Ca 12 -	Asmari Formation behind plug periphery the plug				
N	b.25	M28.2	Cl 88 SO4 11 HOO3 1	?inside the plup+C9				
			Na 37 K 33 Ca 16 Mg 13					
Springs of Anveh plug								
	Nb 9	M224	0.95.90,3H00,1	Gachsaran Formation				
		,vizz, 1	Na64K22Ca8Mg5	- Asmari Formation				
	No 10	M61	0.7850,20H00,2	Asmai Famation				
		100,1	Na 62 K 14 Ca 13 Mg 10					

Table 9. Percentage abundances of ions.

ed about 2 km westward from the previous ones and further of the Anguru plug.

5.5. Gaseous accompaniment of the springs

Springs belonging to the lower aquifer have a characteristic content of gaseous H_2S which can easily be distinguished sensorially. The rise of H_2S in groundwaters is explained by microbial activity of desulfurising bacteria. The H_2S creation is conditioned by sulfate contents in water, by the presence of organic matter and by the contact of the aeration zone with the reduction zone. The most intensive reduction occurs under temperatures of 45 to 50 °C. All the conditions required are fulfilled on the route before the outlet of water into the spring. Above all, sulfates are reduced by colonies of the species *Vitrio desulfuricans*. In the Anguru springs (sample No. 17), mobile fibriform bacteria of purple and green color are visible; possibly they belong to the family *Thiorhodaceae* and *Antirhodaceae*.

5.6. Analyses of water evaporates

Owing to the limited analytical possibilities of the chemical laboratory, especially from samples with conductivity higher than $80,000 \mu$ mhos, evaporates of water samples were prepared. Evaporates were analyzed in the former MEGA laboratories (Czech Republic) for soluble (Na, K) and insoluble (Ca, Mg, Sr, Ba, Fe) components. The total volume of evaporated water was not obtained, therefore we cannot present the correlation of both analytical methods. Analytical results are listed in Table 10. The sample numbers are the same as in Table 7 and Figure 8.

Sample	Ca	Mg	Sr	Ba	Fe	Na	K
	mg.kg⁻¹						
No. 1	10 010	4 000	31	21	390	430	11 100
No. 2	5 900	410	107	33	550	400	230
No. 3	4 900	400	53	25	280	400	184
No. 4	12 400	830	121	156	3 600	390	122
No. 5	18 000	1 490	189	28	500	380	200
No. 6	5 500	320	44	12,8	250	420	173
No. 7	6 400	250	73	113	1 140	400	210
No. 8	6 200	370	47	260	3 000	400	590
No. 9	4 000	270	31	70	3 700	410	760
No. 21	4 500	300	78	9,10	160		
No. 22	1 113	210			520		
No. 23	1 100	173			168		
No. 24	1 196	171			400		
No. 25	1 158	300			280		
No. 26	1 195	186			112		

Table 10. Analyses of evaporates of groundwater.



Figure 8. Situation of groundwater sampling; scale bar=25 km black circle - spring, black square-well.

6. Salt plugs

(P. Bosák, J. Spudil and J. Jaroš)

About 200 salt plugs (Kent 1970) have been known in the area of the Persian Gulf, from them 150 appear in the Zagros Fold Belt (Kent 1958, Gansser 1960) and 120 close to the coast of the Persian Gulf (Trusheim 1974). They are missing in the central-coastal Fars (Huber 1977). Another salt plug cluster is concentrated, except of some occurrences, along the Qatar-Kazerun line and to the NE of it. In the studied region, plugs are connected with an important structural zone - the Oman line (cf. Humphrey 1958) and parallel zones sometimes with higher seismicity (cf. Gansser 1969). The salt plugs (diapirs, domes) are still morphodynamically active (e.g., Fürst 1970, Talbot and Jarvis 1984). They have different diameters, and a conical shape with clear evidence of mushrooming near the surface (Kent 1958). They contain "exotic blocks" with diameters up to 2 km. Most of the plugs are located on faults or plunges of folds (Kent 1958). Location of salt plugs in the area of interest is on Figure 9 and their detailed description in the Appendix.

Little has been known regarding the intrusive mechanism of the Iranian salt plugs, in spite of presented Symposium Proceeding (1990), but it seems to be similar to the plug origin elsewhere (cf. Jenyon 1986). Competent formations are not affected by the intrusions and primary rim synclines have not yet been recognized (Gansser 1960), except for some Qeshm examples (Kent 1958). The absence of an annular syncline (or zone of subsidence) can be ascribed to the mechanic properties of the host-rocks, which are too strong to sag in a simple form, and also to the influence of lateral development of the plug (Kent 1958). Plugs rise from a great depth under the influence of principally hydrostatic forces (Humphrey 1958, Kent 1958) combined with stress produced by individual orogenic pulses. Salt domes are genetically related to the primary thickness of salt deposits and are little affected by the tectonic features (Gansser 1960). The salt has a lower density than the overlying rocks and this buoyancy enables the salt to migrate upward as narrow cylinders that penetrate the surrounding rocks (Sabins 1981). The relation to igneous activity with the salt intrusion was reported, too (cf. Humphrey 1958, O'Brien 1957, Gansser 1960, Espahbod 1990), but its genetic connections were rejected. The origin of salt plugs is also influenced by the function of the basement (i.e. projected Precambrian) tectonics; this can be stressed by the plugs preferably aligning along the Oman line (Humphrey 1958) or parallel zones (Gansser 1969) and Kazerun line.

6.1. Morphostructure and morphology (J. Spudil and P. Bosák)

Harrison (1930) subdivided salt plugs into four categories, i.e. salt-hills (with subgroup of flat-topped hills), salt glaciers, erosion carries and salt marshes. Hirschi (1944) distinguished salt plug massifs (Salzstockmassive) and salt plug islands (Salzstockinseln). Walther (1972) brought more detailed classification to salt plugs (Salzstock) and salt veins (Salzgang, according to elongation), salt glaciers (plug from which salt flows due to its weight as glacier), salt domes (Salzkuppe, with slightly undulated surface and concentric structure), groups of salt hills (Salzhügelgruppe, often with erosional relief), and ruins of salt plugs (Salzstockruine, with strong erosion and relics of more resistant blocks). Fürst (1970, 1976, 1990) classified salt plugs into inactive, passive and unbreached, i.e. classification which broadly adopted now. Inactive plugs should have negative morphology with blocks of erratic rocks on the surface and salt occurrence only in subsurface. Active plugs should have domal shape with salt outcropping on the surface, exposed to weathering processes. Unbreached type does not occur on the surface, but uplift cover rocks into the domal shape.

The evolution of a salt plug was presented in numerous studies. The succession of Ala (1974), close to our understanding, is divided into four phases: (1) initial phase of diapirism in which rise of salt leads to the development of a bulge in the crestal region of fold, causing an abrupt change in the attitude of the bedding, (2) plug breaks surface with a highly disruptive effect on the fold, (3) development of salt glacier and the dissipation of the salt mass, and (4) removal of salt leaves an amphitheater containing abundant collapse material and exotic blocks.

Numerous genetic and non-genetic criteria for plug classification and description have been adopted in the studied region. Here, we are applying criteria, which can be in agreement with earlier published data, some differ partly, and others are newly appeared elements and views.

Names of plugs given only by numbers can be found in Tables 18 and 19 in the Appendix.

6.1.1. Size and shape of salt plugs

The size of salt plugs usually varies between about 1 and 15 km (along longer axis). The maximum is between 16 and 17 km. In literature, there are mentioned maximum diameters of salt plugs of about 45 km (e.g., Jackson and Talbot 1986). It is very interesting, that in Gulf Coast region (USA) with similar geological situation as in the region studied, plugs with larger diameter than 16 km have not been detected (Bishop 1978). Two size groups of salt plugs were distinguished: (1) small, and (2) large ones.

As to their form on the Earth's surface, salt plugs proper, i.e. without glaciers, can be subdivided into two basic groups: (1) circular, and (2) linear types (Tab. 11). Several subgroups should be distinguished according to some other criteria within these basic groups and between them. As detailed classification should be finished only after study of all plugs of the Zagros Fold Belt and Thrust Zone, we will describe only basic groups without detailed division.

Circular salt plugs

This plug type predominates in the region studied. Plugs are usually encircled by more or less distinct cauldron, striking character of which changes with the activity of diapirism. Classical strictly circular plugs are nevertheless relatively scarce; they are mostly small with diameter up to 3 km. The rest of plugs are usually ovate to elliptical in plan with one longer axis. This shape is rather typical for larger plugs. Their elongation along one axis is influenced by numerous factors, among which


Figure 9. Salt plug distribution; scale bar=25 km; 1-large salt plug, 2-small salt plug, 3-salt vein and combined salt plug.

circular	large	1, 2, 3, 4, 7, 8, 10 13, 14, 17, 22, 23, 32?
	large, structurally influenced	5, 6, 9, 15, 16, 18,
	small	19, 20, 21, 24, 25, 29, 36?, 37, 39, 43, 44, 45, 46
		49, 50, 51, 52, 56, 58, 59, 60, 62, 64, 65
	small, structurally influenced	33, 53, 63, 66?, 68
linear	veins	26, 47, 61, 67,
	thick veins	11, 27, 31, 41, 34, 54
	influence of structure	30, 38, 48
combined		12, 35, 40, 55, 57
unclear		28, 42

Table 11. Review of salt plugs according to their shapes (names of plugs in Tables 18 and 19).

Note: underlined plugs - glacier is developed; structurally influenced plugs - only plugs limited on more sides by fault structures or developed on expressive tectonized zones are list-

Combined salt plugs

The classical example of a combined salt plugs is represented by the Tashkend plug. Its NE-part belongs to the group of circular plugs. It is distinctly younger than the

distinguishable is e.g., position in the structure of the platform structural level. The influence of the lower basement structural level is surely present but poorly detectable. Influence of tectonics to limitation of some plugs (e.g., Band-e Muallem, Champeh and Charak plugs) is clear but plug morphology reflects this phenomenon in a minimum degree.

Figure 9 gives review of the position of large and small plugs. Two different areas can be distinguished. Large plugs, i.e. those having diameter over 4 km, were registered in the southern part of the studied region. Smaller plugs occur to the north. The presence of salt glaciers is not taken into account, as some plugs with extensive glacier flows look larger (e.g., Mesijune plug). The plug position was influenced by the intensity of folding movements and squeeze, distinctly less intensive in the south. Plug linearity is therefore increasing northwards.

Concentric to spiral internal structure is typical for some plugs. This is caused by continuous, long-lasting and slow influx of plug material. Its differentiation was in progress, probably, due to salt dissolution especially in marginal zones during more intensive material supply in the plug center (irregular supply in nearsurface zone).

Linear salt plugs

Linear salt plugs are concentrated into tectonically predisposed and strongly affected zones or structures functioning during diapirism. Typical cauldron is missing around those plugs; only indications of cauldron structures are sometimes present. According to the original structure (overthrust zones, tectonized fissured zones without distinct movement, normal fault zones, sharper bends of plicative structures) or movement during the diapirism and physico-mechanical rock properties into which the Hormoz material intruded, plugs can be further subdivided.

The *first subgroup* is represented by classical veins usually several hundreds of meters thick and several kilometers long. The *second group* is constituted by thick veins with the length of few kilometers and width of 1 to 2 km. So-called veiled veins are represented e.g., by Bam, Shamilu or Deh Kuyeh plugs. The original part of such plug is of vein character passing through tongue-like part into glaciers flow. Combined circular and vein-like plugs are represented e.g., by Nina and Sarmand plugs. The plug proper forming the center of the structure is highly tectonically affected with promontories of classical veins into one or more directions, or veins accompanying the plug in small distances. The distinct elongation of some plugs (e.g., Shu, Ardan and Darmand plugs) can be affected by the position along anticlinal axis.

SW-part having character of ruin which is located along the NW-SE trending structural zone. Other cases are exemplified by the circular plug with vein promontories in one direction (in accordance to general structure) extending in one or both sides from the plug. The Nina plug represents, probably, plug in combination with several veins developed along fault and thrust zones.

Plug of unclear classification

Only two sites belong to this type. The Genow plug ruin can represent a form similar to vein or a relic of small circular structure. According to interpretation of Davoudzadeh (1990), it could represent only local occurrence of the Hormoz material on the surface (owing to the morphological position) at eastern side of large plug hidden in the structure of the Genow Anticline. The Chah Banu plug has a shape of rugby-ball and it represents most probably a broadly opened vein in its center, which is still visible at the northwestern and southeastern plug ends. In this interpretation it is similar to Bam and Shamilu plugs. The other explanation of this structure is also possible, i.e. a combination of plug and vein.

Glaciers of salt plugs

Salt glaciers are one of the most striking phenomenon which has interested geologists since the beginning of plug investigation. First evaluations were given by Lees (1927) who introduced the term salt glacier into the literature. Talbot and Jarvis (1984) proposed the term "namakier" which name is composed of Farsi name for salt -namak- and glacier. We are using here the traditional term salt glacier (glacier flow, glacier tongue). Salt glaciers can be distinguished into (Trusheim 1974): (1) hanging glaciers (on slopes of anticlines, e.g., Genah plug), and (2) tongue-like to areal foothill glaciers intervening synclines (e.g., Siah Tagh and Gach plugs). The distribution of glaciers is on Figure 10.

The conditions of their origin have been truly compared with the origin of classical ice glaciers. Only O'Brien (e.g., 1957) supposed, that the initiation of the diapirism and following glacier origin is caused by magmatic intrusion. This explanation was broadly rejected. Gripp (1958) explained origin of salt glaciers by a salt extrusion below a layer of unconsolidated bottom sediments, which needs a specific unusual conditions to survive as stated by Jenyon (1986). As we will show below, this concept is hardly acceptable in the region studied as more simple



Figure 10. Salt plugs with salt glaciers; scale bar=25 km; 1-large glaciers, 2-small glaciers.

explanation exists and morphological position of glaciers excludes this model.

The occurrence of salt glaciers is influenced by numerous factors, i.e. by the position within the structure of the platform level (axis or flank of anticline, central or marginal position, synclinal position), tectonics of the rock massif, amount of intruding material (the size of region from which salt plug takes its evaporitic and other material in the depth), the character of intruded material, character and location of deeper parts of the plug, surface relief, intensity of the diapirism and probably also its time relations. Temperature gradient took part in broader context, too. Temperature and precipitation on the surface are very important factors widely influencing the viscosity of intruded material.

Ideas (e.g., of Gussow 1968) that diapirism and especially the origin of salt glaciers (e.g., Davoudzadeh 1990) need for their rise temperatures of about 300 °C, eventually more than 200 °C have to be strictly rejected. Such temperature has not been proved in any parts of nearsurface zones. Even organic geochemical characteristic of dark shale of the Hormoz Complex indicate temperatures of burial deeply below 300 °C, probably below 200 °C. Fission track dating of some Hormoz apatites (Vartanian, Märk and Pahl 1976; Hurford, Grunau and Stöcklin 1984) proved, that temperature decreased to 100 °C (petroleum window) before 44±9 or 55.4±2.6 Ma respectively. The position of plug was somewhere in Triassic strata(!) which clearly indicate very low geothermal gradient even in deep structure of the platform cover. Steady cooling took place thereafter due to the continuing uplift salt plugs. Deeply circulating water discharging on the surface as thermal springs in close vicinity of plugs has temperature of only 40-60 °C. The presence of fossil fumarolas and solfataras can indicate somewhat higher temperatures in the past. Moreover, Falcon(1969) registered in Iran salt plugs composed of the Gachsaran evaporites (Masjede Suleyman) with diameter of about 1.6 km, which ascended from shallow depths which are not comparable with the depth from which the Hormoz salt intruded.

Air and rock temperatures in the region are favorable. The water content is important to keep the viscosity of salt intruded on the surface in low temperatures. Jenyon (1986) summarized previous studies on halite saturation of NaCl containing water at atmospheric pressure and room temperature in increased strain. The weakening effect of salt can be caused by minute quantities of brine *inherent* in the salt and starts if only 0.05 vol% of brine is added to the system. The NaCl saturated brine can occur even as inclusions in the salt. Experiments (see Jenyon 1986) proved that the introduction of brine leads to an immediate and large acceleration in creep rate, while the temperature effect acts over much a longer period to produce a comparable increase in the creep rate. The presence or absence of free water is important - perhaps the most important - factor governing the deformation behavior of salt. These results are in a good agreement with the statement of Gansser (1960, p. 1) that "a surprising amount of saltwater under abnormal pressure is generally noted when drilling in salt formation, lubricating the doming salt. This is supported by brine springs observed in some salt domes, in spite of desertic surroundings" in Iranian salt domes (cf. also Chapter 5, Hydrogeology). Water can be added into the system by tiny cracks, along fine discontinuities in salt composition, along exotic blocks and by surface karst forms, eventually in the depths from local and regional aquifers. Direct measurements of Talbot and Rogers (1980) and Talbot and Jarvis (1984) proved great importance of winter rainy season for glacier flow, as well as distinct oscillations of daily temperatures. Talbot and Rogers (1984) reported brief flow during the short winter rainy season as great as 500 mm per day on the Kuh-e Namak (Dashti). It can be concluded, that not high temperature of salt, but normal climatic and hydrological (hydrogeological) conditions on the surface and in nearsurface zone are responsible for increase in creep rate of rock salt and for the origin of salt glaciers. The glacier movement downslopes is governed also by the gravity spreading halokinesis (Jackson and Talbot 1986). Gravity, also dissipates the relief in the top of any salt body that is above its level of neutral buoyancy whether it is above or below the surface. Like any other soft material, salt on the surface can become unstable and flow by gravity spreading down slopes as low as 3°. In Iran, salt is driven above its level of neutral buoyancy, forming extrusive domes that spread sideways under their own weight in subaerial conditions. Such process was named as downslope spreading by Talbot (1990).

Glaciers show the tight connection to small plugs, eventually to combined or linear plugs. Typical feature of such plugs is a narrow vent during which Hormoz material is ascending, which contributed to following disintegration of transported Hormoz Complex. The evolution of salt glacier in small plugs is conditioned not only by enough large areas from which is salt material uplifting from the basement level, but also by other, above mentioned factors supporting the diapirism. More, the proportion of evaporitic material and other lithologies in the vent and in glacier together with the intensity of diapirism and morphology on which glacier transgresses, appeared to be important factors.

The first phase of glacier formation is represented mostly by gravity block breakoff on steep plug slopes along tension cracks, especially in winter rainy season, when the contact of glacier and underlying sedimentary formation is lubricated by infiltrating precipitation accumulated at plug/glacier base, as was observed on the Chachal plug. Material crushing along tension cracks and due to protrusion through a narrow vent contributed to better permeability of all Hormoz lithologies enabling massive precipitation infiltration and gravitation flow of water which became salt saturated through the salt/gypsum mass. Therefore, the effect of brine saturation to increased halite creep is magnified as the crushed area is larger. Although the supply of the Hormoz material is not continuous in most cases, we expect that the formation of large glaciers on slightly inclined surfaces should been relatively uniform and rapid process. Origin of salt glacier on steep slopes is caused especially by the gravity processes enhanced by continuos (more or less) supply of the salt masses.

Areally most extensive glaciers originate on slopes of structurally valleys (synclines, e.g., Mesijune, Siah Tagh and Gach plugs). In place, where slope inclination becomes moderated, the glacier flow decelerates in the marginal glacier zones. The diminished flow of glacier is supported by massive salt dissolution in the tongue causing that positive creep forces of halite making the engine of glacier movement disappear. Therefore, most of glaciers are represented by steep and high front (up to 200 m high) and the internal structure of the glacier tongue shows "scaly" appearance composed of accretional convex zones. Flat depression originated behind the tongue front on the glacier surface, which became filled by other Hormoz lithologies transported here by surface runoff, breakoff and other surface processes. Glaciers are developed also on plugs-veins in which conditions comparable with small plugs act.

It seems, that the narrow vent of ascending plug can cause

the acceleration of uplift flow of salt mass loaded by exotic material, which than result in the origin of extensive salt glaciers. This view is supported by the fact, that large plugs do not show the evolution of aerial large glaciers, because in the same stress conditions produced by tectonism (folding) and by buoyancy of halokinesis, comparable volume of ascending mass appears in wide vents, i.e. on larger areas where salt can be dissolved on the surface and in subsurface more easily than in narrow vents, and by this way the uplift of salt mass can be compensated by dissolution (*cf.* also Talbot and Jarvis 1984).

Plugs appearing in the central (axial) zone of anticlines show usually no or limited evolution of salt glaciers, while glaciers are common in plugs situated on fold plunge or in bends of anticlines. Such position is influenced, most probably, by differing distribution of stress, which is distinctly more intensive in zones affected by strike slips causing bends of anticlines.

Salt glaciers are presently registered only in active salt plugs. This means that intensity of diapirism is recently growing or that we are not able to find criteria to distinguish denuded glaciers originated in the past (e.g., on Ilchen plug) or the denudation is rapid (Gezeh plug), or when old glacier is masked by the renewed intrusion by the cyclic diapirism (Puhal plug).

6.2. Evolution and activity of salt plugs (P. Bosák and J. Spudil)

Salt plugs have been classified with the respect to their present state into active or passive (Trusheim 1974), or active, nonactive and hidden (just originating; Fürst 1976, 1990). Numerous authors, for the last time e.g., Koyi (1990), distinguished presyn- and post-shortening diapirs differing in the shape and the position in fold structure. Pre-shortening diapirs are relatively small and, if affected by later shortening, they are elongated parallel to fold axis and are restricted to synclines. Syn-shortening forms are restricted to anticlines and can be elongated perpendicularly to the fold axes. Post-shortening diapirs are also common in anticlines and can be of the same size as syn-shortening types or larger and circular in the plan. Syn-shortening and post-shortening diapirs can rise through the anticlinal cores due to lateral shortening inducing residual salt at depth to flow up. When reactivated, all the three generations of diapirs may posses different plans than before the reactivation.

The classical evolution of the plug as described by Ala (1974), see above, appear only rarely in the region studied. The features of his first phase can be detected with problems and only according to morphology, however, some interpretation can be speculative. Salt tongue and classical amphitheater occur or originate not regularly. Ala's phases 2-(3)-4 can be subdivided in more detailed manner according to numerous patterns in which morphological elements prevail.

Morphological criteria allow to distinguish three basic groups of salt plugs: active, passive and ruins. Within each group, three subgroups were distinguished. Besides morphological features, also hydrological and petrological criteria were adopted. Presented scheme is not dogmatic, it represents only frame or limits with possible variations. Individual groups and subgroups of salt plugs represent, in general, the evolution succession, in which, nevertheless, all factors cannot be involved. In reality, as usual in the nature, the classification is artificial as both the course of the intrusion and plug destruction are continuous not precisely delimited processes. Unbreached salt plugs the stage of passive plug or plug ruin (subrosion). The recent activity of salt plugs, i.e. morphological uplift was estimated by several authors. Some of them supposed, that the annual uplift rate can reach 2 to 4 inches (3 to 6 cm). Trusheim (1960) reported annual accretion of 1 to 2 mm. The precise study of Talbot and Jarvis (1984) on Kuh-e Namak (Dashti) proved a high rate of salt extrusion caused by Zagros fold pressurization. They showed that even in dry climate with an estimated 280 mm of annual rainfall would be salt dissolved as fast as it rises. Calculations of both authors indicate that presented rainfall can potentially dissolve as much as 470 mm of vertical thickness. In reality 110 mm of 170 mm uplift is removed (resulting from effective and likely viscosity rates) and 60 mm.a⁻¹ of vertical thickness spread sideways and feed glaciers. Salt enters the head of more active northern glacier at an estimated average rate of about 2,000 mm.a-1. Most of this flow rate, which is much greater than the diapiric rate, is dissipated by episodes of rapid extrusive flow during the short winter rainy season. Comparison of air photos of Chahal plug and recent situation in the field, proved the larger extent of glacier flows than visible on 35 years old photos.

6.2.1. Active plugs

The basic characteristic of active plugs is a positive relief and lacking collapse structure, periclinal stream network and dominant role of evaporites. The character of morphological forms, degree of stream network entrenchment, amount of evaporites outcropping on the surface and intensity of karstification were detailed for further subdivision into subgroups. Factors mentioned are influenced both by the extent of the catchment area for which diapirs grew from the basement and, to some degree, also by the morphology of surrounding rocks on the surface, by structural influence and time succession of the diapirism (initial, middle and final phases). Owing to mutual penetration of individual detailed classification into subgroup, diapirism phase should not be expressed. Detailed characteristics for distinguishing of individual subgroups are listed below.

Group	Subgroup		Plug number		
		а	11,19,21,27,34,37,39,43		
active	1	b	24,30,45,46,49,54,58,59,65		
		с	9,36,41,44,47,52,53,56,61,64,68?		
passive		А	4,5,7,13,14,17,26,31,50		
	2	b	2,8,15,16,40,55,57		
		с	6,10,18,23,29,33,35,42,51,60,66,67		
		а	63.38		
ruins	3	b	22,32,48		
		С	3,12,20,25,28,62		

Table 12. Salt plug activity (names of plugs in Tables 18 and
19).

Subgroup 1a

Salt plugs have expressive morphology (copula, dome, whale back), high altitudinal differences of plug foothills and the summit part, extremely steep slopes, often slightly vaulted summit plateau which is sometimes pointed up by central summit, minimal detailed dissection of plug proper, predominance of evaporites, other rock types occur in blocks enclosed by evaporites, large karst forms are practically missing, fissures system is developed, often breakoff planes with collapsed material, which can represents initiations of small glacier flows in suitable places, cauldron is normally missing.

Subgroup 1b

Salt plugs are characterized by distinct morphology with lower total altitudinal differences, mostly with steep slopes, vaulted summit plateau, low dissected plug surface, locally developed areal drainage of summit part, periclinal drainage is initiated at sides which represent the change of integrated plug shape, larger karstic forms are developed sporadically, major parts of plugs is formed by salt, debris of clastic sediments and igneous rock occur on plug margins, glacier flows are locally developed, less distinct cauldron.

Subgroup 1c

Salt plugs have positive morphology, often dissected into several segments with different morphologies, distinctly rugged morphology within some of segments, expressive center in large plugs in which evaporites are largely present on the surface, while at margins blocks of other Hormoz lithologies occur more substantially, large salt glaciers are usually developed on small plugs, common periclinal drainage, sometimes combined with other type (circular, dendritic), expressive karstification of rock salt (karren, solution pipes, dolines, caves).

6.2.2. Passive plugs

The basic feature of passive plugs is represented by only small occurrence of salt on the surface, which amount gradually decreases as plug is degraded. The portion of gypsum relatively increases. In suitable morphological conditions, collapse structure develops in more and more developed stage (variability both of plug morphology and of encircling cauldron). The abundance of karst forms is also variable depending on proportion of evaporites and other rock at nearsurface level and plug morphology. Different types of drainage network can be observed.

Subgroup 2a

Salt plugs are characterized by mostly still distinct morphology (copula, dome), presence of summit plateau or other types of planated (leveled) surfaces, relatively steep slopes, lesser dissection of plug surface, but with deeply entrenched V-shaped valleys (unopposed gradient with large altitudinal differences over a short distance), less distinct cauldron, usual periclinal net of intermittent streams, salt outcrops in marginal parts and at bottom of deep entrenchments, surface covered by other Hormoz lithologies, still slightly developed cauldron, expressive karst in salt.

Subgroup 2b

Salt plugs are typical by preserved copula-like or domal shape but with highly rugged relief both in the plug center and at margins, locally preserved summit plateau or other planated (leveled) surfaces on larger plugs which are commonly destructed on smaller ones, combination of periclinal drainage network and other types (circular and centriclinal when cauldron is developed), karst forms in marginal zones where salt can still occur. Developed cauldron is typical.

Subgroup 2c

This type has following characteristic features: domed shape is preserved only at margins, the central part is highly eroded, summit plateau is missing, other types of planated (leveled) surfaces can occur, soft morphology is developed in some plugs, valleys are predominantly of U-shape type, periclinal net of intermittent streams is not frequent, other types predominate in combinations (dendritic, parallel, circular), karst forms are usually missing, or are destructed, halite is normally lacking, distinct cauldron is usual.

6.2.3. Ruins of salt plugs (J. Spudil and P. Bosák)

The diapirism has ceased long ago. Generally negative morphology is typical if cauldron is developed. Indistinct morphology characterizes plugs without cauldron. Soft morphology of relics of the Hormoz material is built of rounded hills protruding through Recent and subrecent sediments (deluvia, alluvia, marine deposits etc.). Relics of the Hormoz material are often occurring on cauldron slopes as several meters thick layers owing to high alteration and ferruginization. Halite was mostly leached away, its occurrence in deeper parts of plugs cannot be excluded. Karst forms are missing. The dendritic network of intermittent streams prevails in a combination with other drainage types. Centriclinal drainage emptying into linear (parallel) network can occur.

Classification into three subgroups and the transition from passive plugs as well, can resulted in the discussion, because it is based on morphological aspects. Therefore, we are not presenting detailed classification characteristics.

6.2.4. Problems of unbreached salt plugs (J. Spudil and P. Bosák)

Distinct circular, egg-shaped and heart-like structures were identified on several places in the region studied. Most of them have been interpreted (finally Davoudzadeh 1990) as unbreached plugs. Those with the domed shape, can be supposed as active and can appear after some time on the surface. In the case when collapse (morphologically negative) structure occurs as a result of salt subrosion of subsurface intrusion of the plug material, the ceased activity of diapirism can be supposed. All possibilities are listed on Figure 11, where localities are subdivided into: 1 - known: (a) structures which we suppose, similarly to other

authors, as unbreached plugs (i.e. structures marked C, E, and M), (b) structures on which we cannot agree with previous authors, i.e. these structures do not represent unbreached plugs (i.e. A, D, G, H, N, and P), (c) structures



Figure 11. Unbreached salt plugs. For explanation of abbreviation see the text; scale bar=25 km; 1-probable, 2-umprobable, 3-unclear.

which we cannot evaluate both owing to the lack of data and due to the fact that materials are not decisive (i.e. B, F, I, J, K, and L),

2 - newly interpreted (i.e. R, and S).

According to our interpretation, only at sites C and E we can agree with collapse structure and, in the latter case, with initial diapirism. On site M, collapse structure exists, but the Hormoz material has not been identified. On the contrary, on site D there is known plug ruin, but collapse structure represents rather erosional phenomenon. On locations A, G, and P, morphological forms originated by backward erosion of Mesozoic and Tertiary rocks with differing mechanical properties in the anticlinal flanks. The initiation of such form is in runoff groove which changes its shape by successive erosion into egglike, drop-like and heart-like morphological depression. In some cases, leading factors causing the origin of such forms are complex structure and fissure systems, eventually asymmetry of regional folds.

No indications of cauldron structure have been proved at sites H and N. Decisive materials were lacking at sites B, F, I, J, K and L.

Newly introduced unbreached structure occurs on site R, which is in the initial diapirism stage. The existence of ruin on site S (Mehregan Shur-e Zar depression) is proved by interpretations of earlier geophysical data.

6.3. "Collapse structures" (J. Spudil, J. Jaroš and P. Bosák)

Salt plugs are sometimes accompanied by circular structures cauldrons and related features - which can occur also independently, and as linear forms (linear cauldrons of Fürst 1976, 1990). The application of the term *collapse structure* is traditional here, because introduced into literature and broadly used. Nevertheless, we have to warn, that numerous "collapse structures" have nothing to do with rock collapse or block collapse of Phanerozoic units encircling the plug, but they are connected with single process of surface and shallow subsurface evaporite dissolution, remaining walls of original diapir hanging over the present surface of the plug (cf. also Jackson and Talbot 1986, p. 308-309; Talbot 1990). Such forms are caused by surface salt dissolution owing to the higher rainfall of the high Zagros. Exhausted diapirs lose first their sheets and then their domes to end as pipes choked by insoluble debris. This fact is especially pointed up at plugs with cauldron walls covered by relics of the salt diapir or relics of its altered margins. The intrusion of salt diapir is associated with distinct structural changes in the sedimentary cover. Sediments are firstly fractured along basic tectonic lines, which is followed by opening of structures. Original bedding changes into steeper and steeper dips, sometimes are often nearly vertical to overturned. The shape of the structure is again a function of numerous factors, like as original bedding and its dip, amount and character of tectonic features, location within the fold structure, physico-mechanic properties of rocks in surroundings of plugs, diapirism intensity, diameter of diapir intrusion and time, which, together with denudation and dissolution/subrosion of salt, decide on resulting shape.

"Collapse structures" are subdivided hereafter into cauldrons, pseudocauldrons and other structures.

6.3.1. Cauldrons

Cauldrons are circular, elliptical to irregular structures occurring mostly in connection with salt plugs. Cauldrons are simple or complex. Complex cauldrons are double in places, eventually also triple. Their horizontal diameter varies from 2-3 km up to 25 km (along longer axis). Ideal funnel shape, mostly elliptical, less frequently circular in plan, occurs only rarely. Such form originates in zones built of resistant sediments (e.g., Guri and Jahrom carbonates) and in axial zones of well developed anticlines (e.g., Ilchen, Shu, Bonaruyeh plugs). The cauldron in peripheral parts of anticlines (flank, fold plunge) is deformed into lesser (Chahar Birkeh, Khemeshk plugs) or greater (Pashkand, Kurdeh plugs) extent, i.e. asymmetric and/or incomplete. Anticlinal flanks and original structural depressions built of mostly non resistant lithologies represent ideal area for origin of eventual glacier flow (Siah Tagh, Gach plugs). This resulted in semicircular to broken shape in the section. Such and similar shapes originated also where the cauldron limit is influenced by tectonics (faults, structural lines, e.g., Berkeh-ye Suflin, Champeh, Gurdu Siah, Zangard, Pordelavar plugs). Deformation of especially older collapse structures (Khamir, Charak plugs) are caused by denudation and erosion (backward erosion).

Linear cauldrons of Fürst (1976, 1990) appearing in coastal anticlines are clearly the result of folding and salt uplift resulting in graben formation in a tensional regime (for more details see Jenyon (1986).

6.3.2. Other forms

Classical plugs - veins have not developed elliptical or circular to semicircular cauldron (Muran plug). Valley-like forms can appear, however. In all other cases (thick veins, combined shape of plug) certain indications of collapse structure exist (Bam, Bongod-e Ahmadi plugs). Some thick veins are rimmed on one side by distinct linear rim of sediments (e.g., Shamilu plug).

6.3.3. Pseudocauldrons

The interpretation of well developed circular structure can be questionable in some cases. It can be supposed as expressive there, where active salt plug occurs in the distinct collapse structure (Anguru plug). Similar situation can be detected also in double cauldrons (Khamir, Darmandan plugs) or collapse structures interpreted as result of activity of unbreached plug (W of Genah plug). In all cases it is possible that the diapirism was distinctly cyclical, however the cyclicity is poorly identifiable. The most acceptable interpretation of these geological unclear to illogical forms is in the influence of erosional phenomena as commented in subchapter on unbreached plugs. Some salt plugs are encircled by slightly inclined surface in the front of amphitheater (pseudocauldron) slopes (e.g., Mijun plug). Here, slopes of amphitheater are result of slope retreat due to progressive pedimentation.

6.4. Position of salt plugs (J. Spudil, J. Jaroš and P. Bosák)

The location of salt plugs is influenced by numerous structural phenomena. Plug occur mostly in anticlinal structures, at their termination (plunge), in sigmoidal bends of folds axes (circular plugs). This was noted already by Fürst (1976). Location of plugs within anticlines is influenced by more favorable physico-mechanical conditions and by the function of lithostatic pressure. The position within anticlines is mostly located on flanks, not in the axial part, which is caused by structural patterns most probably. Only several salt bodies occur closer to the syncline axis (e.g., plugs Mijun, Do-au, Mesijune plugs). Also salt glaciers moving from plug positions downslope have even synclinal position (e.g., Siah Tagh, Gach plugs). Several plugs have indistinct position, and their appearance in synclines can not be excluded (e.g., Qalat-e Bala, Palangu plugs). Salt plugs partly occur in straight portions of anticlines, but a majority of them is located in places of sudden bends or horizontal displacements of anticline axes. Even if the position in "knots" on anticline axes is not as a rule, as supposed by many authors, nevertheless this link appears to be important for the evaluation of salt diapirism in the Eastern Zagros. The link of salt plugs and unbreached plugs to anticlinal structures suggests the existence of salt "cushions" in the deep cores of anticlines (Fürst 1976) or of discontinuous "cushion" below folded Phanerozoic (Trusheim 1974). Colman-Sadd (1978) stated that salt plugs are unlikely to have been initiated during active buckling folding, except perhaps along major fault zones. The cores of buckle anticlines are not occupied by salt. Pre-existing diapirs have been reactivated by buckle folding in anticlines, but their progress has been halted in synclines except when they already have penetrated through the competent group (in his model Cambrian to Miocene sequences).

Numerous authors have been trying to find preferential direction in arrangement of salt plugs along lines of (deep) faults (cf. Ahmadzadeh Heravi, Houshmandzadeh and Nabavi 1990, Davoudzadeh 1990, Fürst 1990, and others;). The surficial discontinuity of fault structures, the position of salt plugs between them and the occurrence of salt plugs in straight and undisturbed portions of anticline axes do not exclusively support this interpretation. Nevertheless, the presence of continuous deeper ruptures of the basement cannot be excluded. The fact, that salt plugs are connected, in a great extent, with areas of axial bends or transversal and/or diagonal faults displacing anticline axes, is doubtless. In the northern part of the region, salt plugs protrude along displacement (overthrust) planes in the southern limbs of anticlines (linear and combined plug types, e.g., Khain, Darmandan, Muran plugs) and could have a role of tectonic lubricant (Trusheim 1974). The same role has been supposed for the salt in the Imbricated Zone of the Eastern Zagros.

6.4.1. Problem of primary and secondary rim synclines

Owing to the fact that results of deep seismic profiling were not at our disposal, we have to repeat the statements of Gansser (1960) and Motiei (1990), that primary rim synclines have not yet been recognized. Nevertheless, the whole problem of primary and secondary rim synclines can be solved only after interpretation of seismic profiles. In the sense of e.g., Jenyon (1986), *primary* rim syncline is connected with the initial stage of salt bulging, prior the plug pillar is developed. The *secondary* rim syncline is than connected with ascend of the plug, forming funnel-shaped forms in surrounding strata. In any case, overturned sediments formed by extrusion of salt diapir to the surface or by its mushrooming, cannot be called secondary or any form of rim syncline.

Rim zone

External margin of plugs at the contact with surrounding Phanerozoic formations are somewhere marked by very expressive zone which is characterized by strong alteration of rocks. Richardson (1926) and Ladame (1945) used the name Pusht-Tumba Formation to designate altered residual formation of the rim zone. The rim zone is often composed of a tilted mixture of Hormoz rocks (gypsum, fragments of clastic, carbonate or magmatic rocks) and surrounding non plug rocks. The zone is commonly highly tectonized, sometimes up to mylonitized, with abundant slickenside surfaces. The distinct feature is a strong ferruginization (hematitization and limonitization) which reaches high degree and alters the rocks up to hematitic ochres. Strong ferruginization was registered e.g., on plugs Nos. 1, 10, 13, 14, 17, 23, 31, 42, 55, 57. Ochres have been mined in numerous places (e.g., Hormoz Ochre Mine). Rock salt is missing even when is present in plug margins.

The rim zone of numerous plugs is commonly highly tilted with steeply dipping to overturned strata due to plug ascend and mushrooming at the surface. Phanerozoic sediments show usual dips of about 30 to 60°, sometimes 80° (e.g., plugs Nos. 1, 3, 4, 5, 7, 12, 16, 17, 19, 31, 24, 41, 59). Overturned strata were detected e.g., at Bustaneh, Chah Musallem and Gezeh plugs. Tilted are even very young sediments, e.g., on Saadat Abad plug the Bakhtyari conglomerates (30°), on Namakdan, Gachin and Anguru plugs Upper Pleistocene to Lower Holocene alluvia.

6.5. Origin of salt plugs (P. Bosák)

The origin of salt plugs can be connected with folding during the collision of continental and oceanic crust of the Arabian Platform and the Iranian Platform. The Hormoz Complex, as an incompetent rock sequence in general, represents foreign element within competent series of the platform cover. Precambrian Hormoz salt has risen diapirically from depths of 5 to 10 km through an almost continuous Upper Paleozoic and Mesozoic overburden. The Hormoz salt provides a decollement zone for the Zagros folding and thrusting, which began only 15 Ma ago, much later than the Mesozoic diapirism appeared (Jackson and Talbot 1986). Along the coast, the bellows action of Zagros folding reactivates pre-existing salt diapirs, and pumps salt up to and over the surface. Farther inland, the declining ration of extrusion to erosion results initially in decreasing volumes of surviving extrusions and eventually to salt-free cirques or craters in which the former orifices are choked by insoluble debris (Jackson and Talbot 1986). Present-day extrusion is indicated by several lines of evidence, i.e. the necessary maintenance of the extrusive dome against continual erosion and solution, sounds of movement (Kent 1966), the burial of its own insoluble moraine by the namakier (Harrison 1930), and measured flow rates (Talbot and Rogers 1980).

The plug activity and ascend was influenced by movement



Figure 12. Salt plug activity; scale bar=25 km; 1-active salt plug, 2-passive salt plug, 3-ruines of salt plug, 4-trend lines of recent activity.

on faults of basement, as indicated by e.g., Fürst (1990) for plugs in the Zagros Fold belt, or by other authors e.g., for plugs in the northern Germany (Kockel et al. 1990), plugs on the Balearic Rise (Western Mediterranean, Kelling, Maldonado and Stanley 1979), and in general by Jackson and Talbot (1986), and Jenyon (1986). Nevertheless, the effort to connect salt plug by salt plug trends or basement lineaments exclusively (Davoudzadeh 1990) should have detailed explanations and deeper basis. In such region with so intensive diapirism it seems, at the first sight, that diapirs are arranged in some kind of regular pattern and that it is possible to connect plugs by lines in any kind of direction. Fürst (1990) in his interpretation was more restrained. Nevertheless both schemes are highly similar. It seems, that the former author used rather intuitive view, the interpretation of the latter author lacks the time moment. In spite of this moments, a part of interpretation was proved by our investigations. More, Fürst (1990) proved movement mechanism by strike-slip faults of the basement, which are not in connection to genesis of anticline and syncline structures. This group of faults is predominantly syn-orogenic to post-orogenic in time and runs obliquely (SE-SW to NNE-SSW trending) to anticlines and synclines. The understanding of movements is difficult and not completely decisive. We can agree with the author that bend of anticlinal folds appear and that the plug surroundings are highly tectonically disrupted (in places only) representing favorable vents for salt intrusion. The Riedel shear model (Brink 1986, Ziegler 1988) can be adopted to explain movement of projected basement trends. The model of Colman-Sadd (1978) is also very close to our understanding of the problem.

The ascend of plugs can be documented by the fission track studies (Hurford, Grunau and Stöcklin (1984). For example the Hormoz plug (No. 1) reached the level of 100 °C some 55 Ma ago at Paleocene/Eocene boundary. Its position was somewhere at the level of Triassic strata. Since that time, plug has protruded through about 8 to 10 km of platform cover indicating average ascend rate of about 150 to 200 m per one million of years.

Figure 12 gives a review of plug activity. There are visible segments with inactive plugs; a block with large plugs is distinct to the north of Bandar-e Lengeh along trend of plugs Nos. 8-17-16-15-14-13, as well as segment of mostly linear character (dominantly NE-SW trending) with active plugs. The most distinct is the trend of plugs Nos. 9-19-24-34-43 with highly active plugs. Trend of plugs Nos. 11-21-27 and 30-41-47-(39)-61-58 (so-called Muran trend), 1-27-37-58-59, or 65-54-49-43-(30)-(11) are less clearly expressed, as well as combination of active plugs with plugs activity of which ceased not long ago along trend of plugs Nos. 65-54-49-43+(31-14-4). Relatively clearly visible is also trend 6-16-S-23-33-34, which is distinct-ly influenced by tectonic structure appearing also in upper structural levels. We have to admit, that the distribution of plugs to individual trends can be doubtful.

6.6. Age of salt plugs (P. Bosák and J. Spudil)

The origin of salt plug, from the regional point of view, has not been a single process. At numerous sites we can expect an interrupted salt intrusion or variable intensity of plug ascend to the surface. This can be connected with individual pulses of Paleoalpine and especially of Neoalpine folding phases and/or irregular movement intensity on basement faults. This explanation can be documented by periodical appearance of some salt plugs on the surface or in the sea since Paleogene-Miocene times, as presented in numerous references (e.g., Harrison 1930, Krejci 1944, Kent 1958, Gansser 1960, Fürst 1970). Some plugs formed islands in the Miocene seas (Harrison 1930, Gansser 1960), some of them in Paleocene seas (*cf.* Fürst 1970) similarly to the present Hormoz Island in Khalij-e Fars.

The age of the plug intrusions is variable and, according to Kent (1958), there are several phases of the salt invasion: (1) pre-Cretaceous to Lower Cretaceous, (2) Upper Cretaceous, (3) Middle Eocene, (4) Oligo-Miocene, (5) Lower Miocene, (6) Middle Miocene, and (7) Mio-Pliocene. According to Fürst (1970) some of the plugs may be "post-orogenic", which is documented by the recent activity of plugs. Owing to the fact, that the orogeny has been lasting up to now, the term "post-orogenic" can be understand as occurring after the last expressive deformation phase in anticline structures. In fact they are syn-orogenic.

6.6.1. Diapirism cyclicity

The cyclicity or periodical renewal of diapirism is documented by supposed ages of diapirism and was supposed also by Jackson and Talbot (1986, p. 307). The field evidence can be summarized as follows.

At the first sight, the existence of double cauldrons can indicate, that the salt intrusion was not continuous at numerous sites. The problem was discussed above. Some of them can be caused just by the cyclicity. Detailed evidences can be found with problems during applied type of prospection (time limits). This problem needs further detailed investigation and we believe that enough of evidence could be found. Nevertheless, several other indications or evidences exist.

In the Puhal plug, there exists remains of older glacier at the N plug margin. The old, highly ruined, rests are overlain on one place by the rest of young glacier flow. The presence of older material with soft morphology to the SE of Gezeh plug is debatable. Although the plug is highly active and built mostly of halite, here only gypsum occurs covering blocks of clastic sediments and basic magmatites. This gypsum-forming low hills can represent also relic of the Gachsaran Formation forming anticline flank. The Gachsaran Formation is here composed by thick gypsum layers. On the other side of the plug, relics of older glacier flow appear.

6.6.2. Age

The dating of salt plugs is broadly discussed problem since the very beginning of salt investigation. Kent (1958) published table review of salt plug dating based on his observations and literature study. Nevertheless, the application of these data is possible only with extreme care because used stratigraphic nomenclature was too broad (e.g., Fars Group, Tertiary limestones, etc.). The occurrence of surrounding formations (after Bangestan Group) is often taken into account, which can be misleading especially for older units, because their presence is often a function of plug position and character of denudation of surrounding rocks (Takhu plug). Misrepresentation can be caused also by false identification of primary and secondary material, especially in marginal plug zones (rim zone), where rocks of the Hormoz Complex and sedimentary cover are highly "tectonically affected" and occur as breccias.

Plug activity and reduction of primary strata thickness (condensed sequences, as reported e.g., by Fürst 1970) can be used as a certain clue, but they cannot be adopted as unequivocal evidence. Reliable prove is then only the presence of plug-derived material (recycled Hormoz debris, Rahnema 1986) in surrounding sediments which are paleontologically dated. Such localities are relatively scarce when plug-derived material can be macroscopically detected only in coarse clastic sediments (pebbles in sandstones, conglomerates, marls) of nearshore deposits. Fine clastic sediments have to be studied microscopically outside nearshore and surf deposits which was practically impossible.

We can adopt the opinion of Kent (1958), that the oldest plugs appeared in Lower Cretaceous, even when our field studies do not discover plug-derived material in coeval sediments. Diapirism initiation was put into Jurassic to Lower Cretaceous by some authors, others supposed that salt ascend started as soon as in Permian-Triassic times (Ala 1974). Secure evidence of diapir appearance on the surface or in the sea is given by recycled Hormoz debris only in limestones of the Guri Member (e.g., Tarbu plug). Plug-derived material is common in Late Miocene and Pliocene (Agha Jari and Bakhtyari Formations, Lahbari and Kharg Members). Jackson and Talbot (1986) indicate a minimum estimated age of 30 to 300 ka for the start of current extrusion on Kuh-e Namak (Dashti). Samadian (1990) reported even younger movements at 30 to 5 ka time-span.

6.7. Internal structure of plugs (P. Bosák, J. Jaroš and J. Spudil)

Internal structure of salt plugs is very clearly detectable both from satellite images and air photos. Both sources of the information complete each other.

Photolineations from satellite images are commented in Chapter 3 (Geology) and together with the interpretation of air photos are given in description of plugs in the Appendix. It is documented, that salt plugs are dissected not only by large lineations which can be identified with fault structures in the field, but also by minute lines which follow structural scheme in surrounding formations and structures. Prevailing amount of photolineations are cracks without larger movement, projected from underlying sedimentary strata. Nevertheless, some photolineations and photolineaments show distinct movement and displacement of salt plug. This situation can be illustrated e.g., in the Do-au plug, which is displaced along NW-SE trending line in about 500 m (right strike-slip) or in the Ilchen plug which is dissected by normal fault, as well as Darmandan, Muran and Ardan plugs. Other plugs are limited by distinct lines causing straight course of plug contours (e.g., Band-e Muallem, Puhal, Charak, Gavbast, Khurgu plugs). The dissection of plugs by both photolineaments and photolineations proves very young neotectonic activity of detected lines.

The internal arrangement in plugs is also visible on air photos, and to some degree also on satellite images. Especially active plugs with concentric or spiral structure can be interpreted from both sources. Surface morphology, i.e. presence of central vaulted plateau, its degradation, other leveled surfaces were interpreted and drawn in figures attached to the Appendix. The character of salt glaciers and their internal structure (e.g., direction of flow - "flow lines", accretional zones, break of slopes) were detected, sometimes also on satellite images (e.g., Finu, Siah Tagh, Gach, Saadat Abad, Genah, Chachal plugs). Comparison of interpretations of air photos and real present situation showed some changes, e.g., larger extent of salt glaciers in the Chahal plug proving that relatively rapid salt movement on slopes in last 35 years.

6.7.1. Exotic blocks within salt plugs

The content of exotic or erratic blocks within the salt of the Hormoz Complex have been noted since the plug investigation begun. Blocks are nearly exclusively built of lithologies of the Hormoz Complex *s.l.*, including sediments, magmatites and metamorphites of Precambrian to Middle Cambrian age. Nevertheless, blocks of Phanerozoic rocks were noted, too.

Bosák, Jaroš and Rejl (1992) noted, that the internal structure of salt plugs can be distinguished only on more detailed processing products of satellite images, than available. Granular texture of plugs distinct on images and products at the scale of 1:250,000 was supposed to reflect rather the morphology of salt surface than the occurrence of large exotic blocks, owing to the fact that the relief of salt plugs is very rugged with conical to irregularly shaped hills and closed to semi-closed depressions dissected by the valley network, sometimes highly sinuous, especially at plug margins. Exotic blocks were supposed not to be directly detectable from satellite images and products owing to their size, which commonly does not exceed the pixel size on individual types of images. Some kinds of color composite products during the processing procedure showed clusters of pixels with sometimes different color tone, which were supposed to be blocks at the surface of some plugs.

The study of air photos during the field works and reinterpretation of all product of processing of satellite images (blackand-white and composite color photos) during evaluation of results brought some new views on the interpretation of exotic blocks on photos. The more or less detailed knowledge of salt plugs from field trips and helicopter flights was a basic key for this procedure. Nevertheless, the interpretation of blocks even from relatively detailed air photos (at the scale of about 1:60,000) can be problematic as shown in the Chah Banu plug. Extensive blocks, max. 1.5 km long, form expressive part of plug relief. In the southeastern part of the plug, such blocks were observed in the field and contoured in the 1:50,000 maps. Some previous interpretations of air photos assumed the size of 2-4 km (Kent 1979, Fig. 3 on page 122 and the text on page 123). Also Davoudzadeh (1990), clearly based on materials of Kent (1979), noted the existence of Hormoz blocks of unrealistic size of 3 km. Both authors did not take into account that these rafts are composite structures with clearly visible tectonic boundaries between and among individual blocks of Hormoz material which are clearly visible even on Kent's Figure 3, where smaller, elliptical block is composed of two, probably overthrusted parts, and the larger one consists even of five smaller blocks with different strata dips. De Böckh, Lees and Richardson (1929) noted more realistic size of blocks - up to 2 km. The enormous size of blocks was not proved by our field trips and study of air photos, as blocks are composite structures of mutually overthrusted (tectonic slices) smaller blocks separated by plug gypsum (often tectonized). The size of largest block here is about 16 km

6.7.2. Air photos

The study and interpretation of air photos indicate that the resolution of exotic blocks within plugs and their internal structure is a function of the quality of photos. When the photo is contrast and enough sharp, than the contouring of blocks is possible, but not easy. The second limit of such interpretation is in the color of plug salt and gypsum, of different types of crusts covering the surface of the plug and of individual exotic blocks. If phototones are similar for all plug lithologies, than the delineation of blocks is very obscure. Therefore, dark plugs can be interpreted with problems or the interpretation of blocks is impossible (e.g., Shamilu, Bam plugs).

The other limit of interpretation is the activity of plugs. Highly active and active plugs (subgroups 1a to 1b) and plugs with still preserved summit plateau and other planated (leveled) surfaces covered by thick brownish gypcrete cannot be interpreted in general, only very dark colored blocks can be locally distinguished (dark dolostones, basic magmatites), as in the Chiru plug. The best interpretation is for plugs highly eroded to ruined, i.e. for morphologies signed by Walther (1972) as groups of salt hills, with broader valleys and fill of morphological depressions by alluvia and gypsum crusts or marine transgressive sediments. The contrast of light gray and medium gray sediment of infills and relatively darker gray to greet black or whitish gray blocks is the best for the block contouring. The best results of the interpretation were obtained e.g., for Moghuieh, Champeh, Chah Musallem plugs, partly also for the Gachin plug, but we have to mention that similar phototone is typical for light-colored sandstones. Such inhomogeneities were mostly proved as blocks of rhyolitic volcanics and their volcanoclastics. Nevertheless, after field trips, delineation of other blocks was possible, although not for all exotic blocks detected in the field directly, even when we had air photos to our disposal in the field. The promising results were obtained for Band-e Muallem, Bustaneh, Do-au, Qalat-e Bala, Bam, Chah Banu, and Siah Tagh plugs. Blocks in Chiru, Zendan, Chahar Birkeh, and Kurdeh plugs could be interpreted, too. Photogeological map of the Hormoz Island (Wolf 1959, Karami and Eshkevari, not dated) contains contours of blocks as small as 50 m.

The internal structure of some blocks could be detected, too. Strike and dip of strata, fractures and small faults, overthrusting of blocks are visible in large blocks in Bustaneh, Doau, Zendan, Bam, and Chah Banu plugs. Nevertheless, type of lithology could not been directly stated, as to distinguish bedded carbonate sequences and bedded red beds is impossible owing to similar phototones which was proved in the Do-au plug.

6.7.3. Black-and-white satellite products

When the delineation of blocks is possible with problems on air photos, the interpretation of satellite images at the scale of 1:250,000 seemed to be also problematic. Interpretation of all satellite products with our field knowledge and results of air photogeology brought some results, even when objects are relatively small and sometimes with coalesced dark phototones. No results, resp. detected blocks, were obtained from plugs Nos. 5, 11, 21, 19, 29, 30, 34, 37, 39, 43, 46,47, 48, 50, 52, 54, 55, 56, 58, 61, 64, 66.

The Hormoz plug shows light-colored elongated blocks of rhyolites aligned parallel to the circular internal plug structure.

The largest block, 800 m long, occurs on SSW. Dark-colored blocks are distinguishable only protruding from light Quaternary marine sediments. Detectable are blocks even smaller than 1 mm on photo, i.e. about 150 to 200 m in natural size. The Band-e Muallem plug contains blocks which have somewhat darker phototone than background. Blocks are mostly below 750 m in size, but very expressive curved block of layered red beds with total unfolded length of more than 4 km is visible (it was observed in the field, too). The Chiru plug shows dark small blocks on the surface of southern and partly also northern glacier with size of 250 to 750 m. Blocks in the Gachin plug are poorly distinguishable. Blocks are usually smaller than 1 km. Light-colored block is visible only in south-eastern part of the Mijun plug, which is proved by helicopter reconnaissance as rhyolitic rock. Blocks with size up to 1.5 km and alternation of dark and light-colored lithologies are visible in the Do-au plug and proved in the field. The Zendan plug has dark phototone in general. Light-colored spots can represent depression rather than blocks. Single light-colored spots with size of about 250 m in the Champeh plug form similar picture like in the Chah Musallem plug. Here, there are lighter spots composed of poorlycemented sandstones and rhyolitic rocks with size of 200 to 650 m. Light color of some depressions can be misinterpreted as blocks! Although rich in blocks, interpretation of the Charak plug brought very poor results. On the contrary, dark blocks are nicely visible on photo of Ilchen plug, where the contrast with light-colored alluvial sediments enable to distinguish blocks from size of 150 m (max. 750 m). Interpretation of the Chahar Birkeh plug is also problematic. Although rich in numerous blocks, only scarce can be detected with size of 200-800 m. The Gezeh plug is covered by gypcrete which is visible on the image. Block in the Bam plug are poorly distinguishable as the plug background is dark colored. Nevertheless, blocks 250 to 2,000 m long can be detected. Only 4 blocks are visible in the Pordelavar plug in spite of their real abundance (size 250 to 500 m on image). Dark blocks protruding from alluvial sediments in the Ardan plug have size of about 500 m. One lightcolored block (500 m) is visible on dark background in the Tashkend plug. Light-colored blocks up to 650 m in size are scattered in the Shamilu plug. Blocks in the Chah Banu plug are distinctly darker, than general background formed mostly of valley fill (size of blocks varied from 200 to 1,600 m). Glaciers in Siah Tagh and Gach plugs show light-colored fill of depression on the surface only. Only one block was detected in the Palangu plug (650 m in size). The interpretation is not easy in the Kurdeh plug, as color inhomogeneities (200-850 m in size) can represent both blocks and thick gypcrete. One Sarmand block on plug has darker phototone. Dark and light-colored spots visible in the Saadat Abad plug with the size below 250 m cannot represent blocks.

6.7.4. Composite color satellite products

The interpretation of composite colored products was directly compared with interpretation of black-and-white products and was focused on detection of common color inhomogeneities in all satellite products available from the remote sensing phase.

LANDSAT MSS. Plugs expressed in yellowish orange composite color (band PC1-negative green, band PC2-green, band PC3-blue): exotic blocks have generally smeared red color similar to phototone of gypcretes, but sometimes passing to pinkish red tone. Results were obtained only on several plugs. Small blocks in the Chah Banu plug are detectable, the largest ones are not visible at all. Pale red colors in the Kurdeh plug are typical for blocks of the Khami Group, other features are indistinct. Disturbed gypcrete is visible in the Namaki plug.

Plugs expressed in purple composite color (band PC1-negative green, band PC2-red, band PC3-blue): gypcretes covering Do-au, Anguru, Khurgu, and Finu plugs have orange brown, pale red, dark pink and dark orange composite colors. Rhyolite blocks in Gachin and Mijun plug are clearly visible by their light green color. Blocks in the Do-au plug are dark pink and dark bluish purple. In the Ilchen plug, blocks are dark purple to reddish purple and alluvia are green. Color inhomogeneity in Tashkend and Palangu plugs are located in the same place as on black-and-white photo. Some blocks in Tang-e Zagh plug are dark blue. Iron-rich rim zone in Gachin and Tang-e Zagh plugs is pale red.

Plugs expressed in dark green to dark turquoise color (band PC1-red, band PC2-negative green, band PC3-blue): yellow, orange and red spots indicate the presence of rhyolite lithologies in the Gachin plug and similarly we deduce the same lithological composition of identically colored blocks in the Mijun plug (proved by helicopter), Anguru plug and eventually in the Tashkend plug, where located in the same place as on blackand-white photo and image with purple plugs. Small red dots in Khurgu, Khain, and Darmandan plugs are detectable, too. Gypcretes are dark colored (brownish green, dark green) in Do-au, Khurgu and Finu plugs. More blocks, than on black-and-white photo were distinguished in the Palangu plug. They have dark green colors and one block is red (that visible also on blackand-white photos, but its lithology is not rhyolitic, but the block is composed of red shales). As indicated here, the same composite colors can have also different lithologies (rhyolites in the Gachin plug vs. red beds in the Palangu plug), therefore the simple explanation of lithological composition of blocks is not possible without the field evidence.

Plugs expressed in green and blue colors (band PC1-red, band PC2-negative green, band PC3-blue): curved block in the Band-e Muallem plug is very poorly distinguishable but Quaternary transgressive sands to the W of it are pale green. Large amount of salt in plug structure is detectable by deep purple color (e.g., Do-au, Zendan, Champeh, Chah Musallem, Chahar Birkeh, Pordelavar, and Mesijune plugs). Pale green colors in Do-au, Zendan, Siah Tagh, and Gach plugs represent blocks as well as fills of valleys and crust, in Champeh, Chah Musallem, Chahar Birkeh, and Pordelavar plugs than fill of erosional forms. Crusts on the surface of the Genah plug are yellowish green and in the Gezeh plug are dark purple, in the Bam plug even of olive green in color, in Gavbast, Pashkand, Bana Kuh, and Jalalabad plugs light greenish blue in Deh Kuyeh and Namaki plugs crusts are light green in color. Blocks of limestones detected in the field in the Bam plug are olive green. Small blocks in the Chah Banu plug are expressed by dark blue dots, large ones are not distinguishable. Extensive pulverized siltstones in the Mesijune plug are dark purple. Block of presumably Jahrom dolostone on the top of the Deh Kuyeh plug is red. Character of surface in Chiru, Charak, and Kurdeh plugs cannot be interpreted as homogeneous colors occur. Also in this type of color composition shows similar color tones for different features on the plug surface, starting by blocks and ending by salt crust.

LANDSAT TM. Plugs expressed in blue color (band PC1negative red, bad PC2-negative green, band PC3-negative blue): relics of gypcretes are light green on Band-e Muallem plug. The curved block of red bed is not visible at all. Large NE-SW trending block in the center of the Bustaneh plug (limestones, clastic sediments) reaches 2,250 m in length. Light-colored sandstone in the eastern part of this plug have dark brownish gray and pale green colors. Some reddish spots were detected at the southern plug margins. Large rhyolite blocks are red, other blocks are bluish light green to dark brown on Moghuieh plug. In the Zendan plug, blocks of sediments are either pale green or dark brownish gray. The situation in Champeh, Chah Musallem, and Charak plugs is similar to previous plug. Rhyolites are pale red and pale green, other lithologies are brownish gray or light green. Blocks or red beds and carbonate rocks in the SSW corner of the Bam plug are dark green. Blocks in the Pordelavar plug are visible as small greenish dots on dark blue background. Some blocks are in olive green, others are rather red in the western part of the Chah Banu plug.

SPOT XS - in "natural colors" (band 1-blue, band 2-green, band 3-red): plugs on this type of processing are very dark, greenish dark reddish brown with indistinct internal structure. Only blocks of rhyolitic composition in Champeh and Chah Musallem plugs are bluish white. Plugs expressed in yellowish orange color. This type of images, owing to more detailed resolution, are better interpretable than similarly processed LAND-SAT MSS products. In the Berkeh-ye Suflin plug, there is visible pale red iron-rich rim zone and red spots and dots on the surface, which represent, according to topographic maps, crusts and relics of planated surfaces, but blocks, too. Pale red colors in Champeh and Chah Musallem plugs are typical for blocks! Red and reddish colors in Do-au, Zendan, and Bam plugs represent expression of crusts as well as blocks. Blocks cannot be therefore distinguished unequivocally.

SOYUZKARTA KFA 1000 covered only southernmost part of the region along the coast of Khalij-e Fars. Larger blocks of rhyolitic rocks have pinkish white color on Moghuieh and Chah Musallem plugs, smaller ones cannot be distinguished. Owing to darker natural colors of blocks in Chiru and Charak plugs, they coalesce with the background.

Above listed review of textural features of plugs on blackand-white and composite color satellite products indicates, that the delineation of blocks and deciphering of their lithologies is sometimes possible when different products are combined and compared. Nevertheless, without detailed knowledge of the field situation, any indoor interpretation cannot bring satisfactorily precise and detailed results.

7. The Hormoz Complex

(P. Bosák, P. Sulovský and J. Spudil)

Blanford (1872) introduced the name Hormuz Salt Formation for the entire complex of rock salt and associated sedimentary and igneous rocks occurring on Hormoz Island. The name Hormuz Series was proposed by Pilgrim (1908) to designate all rocks brought to the surface by salt diapirism which are stratigraphically related to some degree to the Hormuz salt. Stöcklin (1968) recommended confirmation of the term Hormuz Formation to the salt- and gypsum-bearing rock units excluding the overlying sandstones and Middle Cambrian carbonates based on area between the Zagros thrust and the Lut blocks where sections of unmistakable Hormoz rocks and normal contact with the fossiliferous Cambrian occur. Kent (1979, p. 127) questioned this statement as this definition is broadly acceptable over most of Zagros but it needs two qualifications - firstly that interbedded sediments (whether dolomites, shales, conglomerates or volcanic tuffs) are also properly part of the Hormoz Formation, and secondly that if the upper boundary of the evaporite series crosses the Cambrian stratigraphic boundary - as it maybe near the Iranian coast - the formation then properly ranges into Cambrian. Hurford, Grunau and Stöcklin (1984) supposed, that according to modern stratigraphic nomenclature, the term Hormoz Complex may be more appropriate. In this sense, the term encloses rock salt and all sedimentary and igneous rocks intercalated in salt.

Salt plugs of the Eastern Zagros represent typical tectonic windows. As such they have dragged to the surface a broad palette of rocks of various petrologic character, origin, and age. This assemblage includes rocks of Precambrian basement and rocks of the Hormoz Complex, and younger wallrocks extracted by the diapiric movement of the salt rock. Due to it, the geographic distribution of rocks across the area of salt dome occurrences is a bit disordered or random. Nevertheless, it generally reflects the relative abundance of non-sedimentary rock types in the Hormoz Complex, as they exhibit roughly the same durability. The knowledge of this distribution is strongly affected by many factors, the most important being the degree of ruination of salt domes, i.e. occurrence of non-evaporitic rocks on the surface, their resistance to transport and weathering. The resulting partially random outcropping pattern of the Hormoz Complex rocks is hence given by spatially varying activity of salt diapirs. Although there are several passive domes or ruins in the northern part of the studied area, their abundance generally increases towards the Persian Gulf coast.

The "exotic" blocks vary in size from centimeter size to hundred-meter size. The larger blocks can be found above all in the passive and ruined salt plugs, which ceased to move diapirically, or in which the velocity of diapiric movement is lower than that of salt subrosion.

Due to the multitude of overprinting and overlapping processes to which almost all rocks brought to surface by diapirism were subjected, it is practically impossible to identify indisputably those which date before the deposition of evaporite/ volcanosedimentary sequence named conventionally the Hormoz Complex. The fact that the rocks do not occur on the surface in their original mutual positions makes the assumptions concerning their temporal and genetic relations very difficult, if not impossible.

7.1. Petrology

Rocks comprising the so-called Hormoz Complex - igneous, sedimentary as well as metamorphic - display astonishing variability not only within these three groups, but also within each narrow family of rocks. This is conditioned by a multitude of processes, taking part in the formation of the Hormoz Complex and in the history of subsequent diagenetic changes, hydrothermal alteration, metasomatism, diapirism, and other interaction with solutions of varying origin and composition, weathering etc. Owing to the fact that salt domes represent tectonic windows, the distribution of rocks is a bit disordered or random. The state of our knowledge of this distribution is strongly affected by many factors, the most important being the degree of ruination of salt domes, i.e. occurrence of non-evaporitic rocks (often unjustifiably called "exotic") on the surface, their resistance to transport and weathering. The haphazard outcropping pattern of rocks of the Hormoz Complex, given by spatially variable activity of salt plugs causes different availability and abundance of "exotic" (i.e. non-evaporitic) rocks and doesn't allow to perform regular sampling of individual rock types in the studied area.

7.1.1. Sedimentary rocks (P. Bosák and J. Spudil)

Red beds

Purple, red, brown, locally green, gray and dark-colored siliciclastics are the prevailing constituent of blocks in plugs (Fig. 13). They form classical sequences of red beds with alternation of shales, siltstones and sandstones of variable lithologic types. Interbeds are formed by gypsum, tuffs and tuffites and carbonates. Interbeds of volcanics (acid and intermediate) occur within red beds in places (e.g., Chah Banu plug). Sequences are arranged in rhytmically to cyclically arranged sets of beds, sometimes with upward coarsening or upward fining arrangements. The prevailing color is red, brownish red, brown, purple. Grayish green to greenish gray colors are less common and are rather typical for lithologies with tuffogenic admixture. Large extent of homogeneous, commonly pulverized, gray to purple gray siltstones containing accumulations of hematite is a spectacular feature.

Two kinds of sequences can be distinguished within red bed. The first represents *flyshoid*-like sequences of alternating psammites and pelites originated in less agitated and relatively deeper sedimentary environments. Such sequence is characterized by continuous bedding and alternation of thick and thin layers rhytmically to cyclically arranged. Large-scale lenticular bedding is sometimes present. Cross-bedded sandstones form channel fills with scoured basal bedding plane. Lamination to banding are developed locally in sandstones. Massive texture prevails. On some bedding planes, mostly in fine-grained lithotypes, oscillation ripple marks can occur. Gradational bedding can be observed, too. Locally, intraformation breccias are present.



Figure 13. Dominance of red beds within blocks of the Hormoz Complex; scale bar=25 km.



Figure 14. Distribution of black shales within blocks of the Hormoz Complex; scale bar=25 km.

The second type of sequences rich in typical shallow marine to continental textures can be described as tidalites. Rocks are often laminated, with planar, wavy, flaser and small-scale cross lamination. Very common are different kinds of ripple marks originated both in agitated and in calm environments, including oscillation, linguidal and other forms, similar to features developed in limestones. Flute casts, load casts, traces of escaping gas bubbles, dessication cracks and sandstone dikes, convolute bedding, scour-and-fill structures with cross-laminated fill, small erosional channels and vertical burrows are present in an abundant amount. Some sequences show upward fining arrangement. Imprints or pseudomorphs after gypsum and halite crystals are common especially in hard siltstones, calcareous siltstones and similar lithotypes. Light-colored sandstones often show large-scale cross-bedding and irregular cementation by carbonates in the form of irregular nodules. Such rocks represent beach rock and sand bars. Tidalite sequences in places represent alternation of shallow marine and continental alluvial plain environments.

Basic lithotypes

Shales are dominantly red, purple, sometimes pale green, thinly bedded up to paper appearance Different kinds of lamination (parallel, wavy, flaser) are common. Tuffogenic interbeds are developed in places in the form of argillitized "tonstein" like rocks. Calcareous and dolomitic admixture is relatively common, as well as silty and sandy particles. Muscovite and sericite are very abundant. Some shales show authigenic feldspar growth and different kinds of silicification. Iron-rich to hematitic shales occur in various thicknesses from centimetric to decimetric layers. Content of pyrite is sometimes remarkable.

Dark-colored shales . Their distribution is given in Figure 14. Shales are gray to dark gray, black, sometimes brownish in color. They occur in decimetric to metric sequences. Prevailing amount of dark-colored shales appears as paper shales, laminated to banded. They are often calcareous or dolomitic, sandy admixture is present, too. Sometimes they are silicified. High pyrite content is common. Pyrite occurs as cubic grains, irregular clusters, framboidal grains or replaces ?organic matter. Transitions to limestones were observed. In Namakdan plug, they pass into dolomitic limestones and stromatolitic carbonates. In Chiru plug, Kent (1979) reported trilobites in the intercalation of dark shales (about 10 m thick) in dark thinly bedded silicified dolostones and finely laminated shales. In Khain plug, shales pass into nodular impure limestones. In Palangu and Mesijune plugs, transition to dark gray stromatolitic carbonates was detected. The most spectacular is the presence of thin dark shales overlying horizon of lateritic weathering on sandstones in Bustaneh plug. Dark shales represent deposition in restricted, oxygen-depleted environment as a part of evaporite-carbonate-clastic cycles. In Bustaneh plug, shales represent basal part of ingression horizon in-between two sandstone sequences.

Organic geochemical analysis was performed on sample of very dark, thinly bedded shale from Chah Banu plug. The sample with total weight of about 3 kg was divided into four prevailing lithological types: (A) black thinly bedded shale, (B) black shale with bends of dark purple shale, (C) brownish gray shale with ?detritus of fossil rests, and (D) finely laminated shale. Samples were homogenized and analyzed for: (a) C_{org}/C_{min} , (b) directed pyrolysis, (c) extraction in methanol-acetone-benzene (MAB), (d) separation of hydrocarbons, (e) chromatographic analysis of saturated paraphinic and isoprenoid hydrocarbons.

Common techniques were applied in laboratories of the Czech Geological Institute, Brno. Directed pyrolysis brought no results, as the content of organic matter is very low (Tab. 13).

Sample	wt. %			
	C _{org}	C _{min}		
А	0.00	0.16		
В	0.00	0.02		
С	0.16	0.06		
D	0.00	0.02		

Table 13. Amount of organic and mineral carbon.

The chromatographic analysis was performed only on sample No. C with 0.16 wt.% of C_{org}. The content of n-alkanes and isoprenoid hydrocarbons was very low and was stated in nannograms of hydrocarbons per one gram of sample. Totally 1,046.2 ng/g of n-alkanes was detected in the fraction of n-C₍₁₄₎ to n-C₍₃₆₎ and 56.7 ng/g for two isoprenoids (Tab. 14, Fig. 15). The distribution of n-alkanes is distinctly bimodal, with maxima at n-C₍₂₀₎, and n-C₍₂₉₎ and n-C₍₃₁₎.

Analyzed hydrocarbon		Content
Name	Code	ng/g
n-tetradecan	n-C ₍₁₄₎	<6.0
n-pentadecan	n-C ₍₁₅₎	8.5
n-hexadecan	n-C ₍₁₆₎	24.3
n-heptadecan	n-C ₍₁₇₎	38.7
n-octadecan	n-C ₍₁₈₎	56.4
n-nonadecan	n-C ₍₁₉₎	59.1
n-isosan	n-C ₍₂₀₎	67.5
n-henicosan	n-C ₍₂₁₎	59.5
n-docosan	n-C ₍₂₂₎	60.2
n-tricosan	n-C ₍₂₃₎	59.0
n-tetracosan	n-C ₍₂₄₎	57.8
n-pentacosan	n-C ₍₂₅₎	56.4
n-hexacosan	n-C ₍₂₆₎	57.0
n-heptacosan	n-C ₍₂₇₎	58.2
n-octacosan	n-C ₍₂₈₎	56.3
n-nonacosan	n-C ₍₂₉₎	73.0
n-triacontan	n-C ₍₃₀₎	49.2
n-hentriacontan	n-C ₍₃₁₎	63.2
n-dotriacontan	n-C ₍₃₂₎	36.1
n-tritriacontan	n-C ₍₃₃₎	41.1
n-tertatriacontan	n-C ₍₃₄₎	20.9
n-pentatriacontan	n-C ₍₃₅₎	20.1
n-hexatriacontan	n-C ₍₃₆₎	17.7
pristane	ip-C ₍₁₉₎	21.2
phytane	ip-C ₍₂₀₎	35.5

Table 14. Content of n-alkanes and isoprenoid alkanes.



Figure 15. Distribution of n-alkanes and iso-alkanes in chromatograms of the MAB extract.

The CPI (Carbon Preference Index) was calculated for obtained spectrum of aliphatic hydrocarbons. We used several formulas and results are listed in Table 15. The CPI shows very indistinct predominance of odd n-alkanes in the whole analyzed fraction $n-C_{(36)}$ to $n-C_{(15)}$. The predominance of odd n-alkanes in the fractions $n-C_{(34)}$ to $n-C_{(25)}$ and $n-C_{(31)}$ to $n-C_{(25)}$ is clearly visible when CPI is calculated according to Koons, Jamieson and Ciereszko (1965) and Robinson, Cummings and Dineen (1965) for sets of n-alkanes, or according to Schenck (1965) for individual n-alkanes in fraction above $n-C_{(27)}$. CPI values for odd n-alkanes in heavier fraction are up to 1.44 to 1.48 indicating more distinct predominance of odd hydrocarbons. Even n-alkanes slightly predominate in lighter fraction, below $n-C_{(22)}$ with CPIs for individual n-alkanes from 1.02 to 1.14, which means that the distribution of $n-C_{(n-1)}$ and $n-C_{(n+1)}$ is nearly regular.

Our results correspond to generally published data, that during maturation of organic matter, the content of even n-alkanes increases with decreasing carbon number. Odd predominance could be smoothened in the group up to $n-C_{(20)}$ (e.g., Oró et al. 1965, Bray and Evans 1965). During diagenesis and maturation of organic matter, the odd predominance became less distinct due to the influence of thermal and catalytic alteration by the generation of even hydrocarbons (e.g., Bray and Evans 1961).

Simultaneously with the generation of even alkanes, the total content of organic matter decreases (e.g., Albrecht and Ourisson 1969). According to published data, n-alkane fraction of old Precambrian sediments has normally no odd preference (Van Hoeven, Maxwell and Calvin 1969; Maxwell, Pillinger and Eglington 1971). In such deposits, n-alkanes with C number of 11 to 35 occur having the distribution very similar to young or Recent sediments. The maximum in Soudan Shales (2,700 Ma) is in n-C₍₁₇₎ and 98 % of alkanes is in the fraction with C number of 15 to 20 (Johns et al. 1966). Bimodal distribution in Guntflint Formation (1,900 Ma) with maxima n-C₍₁₈₎ - n-C₍₁₉₎ and n-C₍₂₂₎ were found by Oró et al. (1965). Those hydrocarbons are one of the evidence of life in old sediments (Belsky et al. 1965). Even n-alkanes are preferentially produced in highly

saline carbonate environment, where anaerobic and aerobic bacteria decayed blue algae.

The content	of isopren	ioid hydrocai	rbons is c	listinctly lower

Author	Span of n-alkanes	CPI
Formula of Connan (1972)	Sn-C ₍₃₃₎ - n-C ₍₁₆₎	1.08
	Sn-C ₍₃₆₎ - n-C ₍₁₅₎	1.08
Formula of Koons et al. (1965)	Sn-C ₍₃₄₎ - n-C ₍₂₅₎	1.33
Formula of Robinson et al. (1965)	Sn-C ₍₃₁₎ - n-C ₍₂₅₎	1.26
Formula of Schenck (1965	n-C ₍₁₆₎	1.03
	n-C ₍₁₇₎	1.13
	n-C ₍₁₈₎	1.14
	n-C ₍₁₉₎	1.02
	n-C ₍₂₀₎	0.97
	n-C ₍₂₁₎	0.99
	n-C ₍₂₂₎	0.86
	n-C ₍₂₃₎	0.72
	n-C ₍₂₄₎	0.90
	n-C ₍₂₅₎	0.69
	n-C ₍₂₆₎	0.97
	n-C ₍₂₇₎	0.97
	n-C ₍₂₈₎	0.93
	n-C ₍₂₉₎	1.00
	n-C ₍₃₀₎	0.98
	n-C ₍₃₁₎	1.03
	n-C ₍₃₂₎	1.39
	n-C ₍₃₃₎	1.48
	n-C ₍₃₄₎	1.44
	n-C ₍₃₅₎	1.02

Table 15. Carbon Preference Index (CPI).

than the content of n-alkanes. Similarly to numerous data from the whole World, iso-alkanes pristane and phytane are the most common, showing similar distribution with Precambrian sediments (e.g., Oró et al. 1965). Such acyclic iso-alkanes are formed from phytol chain of chlorophyll.

The character of original organic matter enclosed in studied shales was probably composed of organic matter of algae and lower animals. Detected normal alkanes show smooth to indistinct odd predominance and low concentration. The spectrum is relatively broad. These features indicate somewhat increased degree of transformation and maturation of organic matter, however, relatively rich spectrum of hydrocarbons shows that the metamorphosis of organic matter did not reach higher level (*cf.* Staplin and Evans 1973). It can be stated, that the temperature of maturation did not reach 300 °C. Relatively very high proportion of n-alkanes with higher C number can indicate maximum temperatures of maturation even below 200 °C.

Siltstones form sometimes prevailing part of sequences. Besides normal interbeds in shale to sandstone red beds sequences, siltstones occur in huge amount in some blocks. Such siltstones are greet purple, often homogeneous to pulverized, with prints of halite crystals and small veinlets or clusters of hematite (specularite) (e.g., Nina, Mesijune, Gach, Pordelavar plugs). The rocks are frequently structurless, only locally they show lamination to bedding with different grain-size of layers and coarser clastic admixture. In a prevailing quantity, such rocks contain high amount of tuffogenic admixture.

Sandstones occur in a wide variety of lithotypes from clayeysilty sandstones up to pure quartz sandstones. Prevailing amount of sandstones are purple, brown, sometimes red, often greet green to greenish gray. The grain-size is highly variable, but the content of pebbles is relatively small, in general. Sandstones form layers of centimetric to decimetric thickness and show a variety of internal textures and bedding forms from lenticular channel-like bodies in fine-grained varieties up to thick continuous bodies. Petrographic composition indicates the high percentage of unstable particles. Therefore, prevailing amount of sandstones can be classified as lithic sandstones to greywackes and arcosic sandstones to arcoses. Tuffogenic admixture is very abundant not only in the matrix, but also as tiny clasts of volcanoclastic and volcanic rocks, indicating simultaneous volcanism and red bed deposition. Feldspars in arcosic types are presumably derived mostly from acidic volcanics and volcanoclastics. Some greywackes contain also small fragments of carbonate rock, algal structures, etc. and intraclasts of originally semiconsolidated clastics. Heavy minerals are represented mostly by tourmaline and zircone, sometimes by amphibole. Biotite is present only rarely. Muscovite and sericite are substantial components of many sandstones. Pyrite is sometimes arranged in laminae. Some types contain decomposed rhombs of carbonate minerals (?siderite). Iron cement is of basal to contact type, sometimes may represent replacement of original carbonate matrix

Light-colored sandstones (Fig. 16) are sometimes very distinct feature in the block composition. They are mostly fine to medium-grained, quartz sandstones of beige to ochre color. Sometimes, low level of induration, irregular carbonate cementation and large-scale cross-bedding are typical. Locally (e.g., Chah Banu plug) they contain intercalations of red to hematitic shales and clasts of eroded ferrolites (pisolithic, pseudopisolithic). When silicified, these lithotype forms layers of quartzites, which were found only locally in low amount. Some light-colored sandstone profiles contain interbeds of ferrugineous-gypsiferous-dolomitic crusts.

Conglomerates. The extent of conglomerates is summarized on Figure 17. Conglomerates represent relatively scarce lithotype in the red bed sequences, although some coarse-grained sandstones can contain limited amount of pebbles. In the Bustaneh plug, pebble admixture was detected in shales with tuffitic interbeds. In the Khurgu plug, polymict conglomerates with tuffitic-pelitic matrix occur. In the Shamilu plug, conglomerates to sedimentary breccias contain rounded pebbles of carbonate rocks in multicolored matrix. In Namakdan plug, De Böckh, Lees and Richardson (1929) reported gypsiferous conglomerates within gypsiferous marsltones. Conglomerates in the Chah Musallem plug are composed of well-rounded pebbles up to 6 cm in size composed of quartz (?metamorphic, quartz veins) and decomposed crystalline rocks (kaolinized gneisses, ?migmatites).

Interbeds of carbonate rocks. Two kinds of carbonate rocks occur as intercalations or interbeds within red beds. The first type is represented by limestones and dolostones, presumably of marine origin, forming decimetric layers to sequences several metros or low tens of metros thick. They are often laminated, stromatolitic. In places massive cloudy limestones can represent metasomatic replacement of evaporites (sulfates, e.g., Bam plug). The second type is represented by centimetric to decimetric thin intercalations in shales, siltstones, and less frequently in fine-grained sandstones. They are mostly pink, gray, or greenish in color, fine-grained, often laminated and silicified, resembling lacustrine limestones to pelocarbonates commonly occurring in red beds.

Interbeds of gypsum represent common constituents of many red bed profiles in different plugs and blocks. They are appearing in multiple horizons within shale-siltstone as well as in carbonate sequences. Gypsum layers are mostly laminated, wavy, light-colored with red laminae to bands. Small diapirs occur in places inside thick beds of gypsum (e.g., Chah Banu plug). Intercalations are formed by green tuffogenic layers of silty appearance and by multicolored shales. Gypsum is often overlain by thin layers of banded iron ores. Some gypsum interbeds contain structures similar to products of pedogenesis in their upper part (Hengam and Chahar Birkeh plugs). Gypsum occurs also in shales or siltstones as horizons formed by individual, more or less densely packed, gypsum/anhydrite nodules, sometimes coalescing to thin nodular beds. Interstratal dissolution of gypsum makes lower or upper bed boundaries highly irregular. Some gypsum-containing red bed sequences show trend of increasing gypsum thickness in upward direction forming even the transition into thick gypsum sequence (e.g., Chah Banu plug). Gypsum occurs also as nodules or lense-like bodies in different shale types. Special type of gypsum interbeds is represented by dark, coarse crystalline to columnar fetid gypsum, which occurs in limited maximum thickness of several decimeters. Such gypsum is often associated with dark fetid dolostones.

Interbeds of tuffogenic material form sometimes optically distinct feature in sections. Tuffs to tuffites constitute layers of highly variable thickness and lithology, as well as colour. Greenish color is dominant and centimetric to decimetric thickness of beds prevails, alternating with other red bed lithologies and/or gypsum and carbonates. Sedimentary textures are similar to shales, siltstones or sandstones, according to the depositional environment. Thick tuffogenic sequences often contain interbeds of siliciclastics and/or gypcretes and related lithologies (as presented on several figures below). The most common tex-



Figure 16. Distribution of light-colored sandstones within blocks of the Hormoz Complex; scale bar=25 km.



Figure 17. Distribution of conglomerates within blocks of the Hormoz Complex; scale bar=25 km.

ture is parallel lamination, flaser and small-scale cross-bedding. Convolute horizons are common (slides). Tuffs with volcanic pumice and bombs are often cross-bedded and their character resembles fluxoturbidites. The deposition of thick tuffogenic sequences was often discontinuous, as indicated by irregularly ferruginized horizons resembling pedogenically altered horizons.

Red beds were deposited in the coastal region in alternating shallow marine and continental conditions. Cyclic character of some sequences resulted from ingression-regression regime in the basin. Shallow marine environment varied between subtidal to supratidal zones with common occurrences of evaporitic interbeds, dolostones, fericretes and gypcretes, indicating hypersaline evaporitic environment of supratidal to lagoonal character (tidalite sequences). Flyshoid-like sequences were deposited in shallow shelf conditions and represent product of relatively calm depocenter, partly of submarine delta lobes. Lightcolored, cross-bedded sandstones represent shore facies (beachrock) and sand bars. Part of red beds was deposited under continental conditions on broad and flat coastal alluvial plains encircling marine coast.

Limestones

The occurrence of limestones is given on Figure 18. Large blocks of limestones are uncovered in Do-au, Zendan, and Bam plugs, smaller outcrops were noted in the Pashkand, Deh Kuyeh, Chiru, Berkeh-ye Suflin, and Pordelavar plugs. Limestones form thinly bedded sequences. They are white, light green, gray to dark gray, on the surface they have thin weathering layer of yellow, brown, reddish and white colors. Sedimentary textures are variable. The most common are different types of ripple marks (linguoid, lunate, interference, oscillation) and small-scale cross and flaser lamination. Convolute lamination, load casts, traces of mud movement, as well as small erosional scours made by outflowing water on emerged bedding planes are also abundant. Laminites with parallel thin lamination occur on some places. Stromatolitic limestones (distribution in Fig. 19) with Collenia-type of structures were found in the Deh Kuveh plug. Oncoidal to nodular limestones occur in the Chah Musallem plug. Very spectacular are limestones with pseudomorphs after salt crystals or their imprints on upper or lower bedding planes. Oolitic carbonates are very rare (Bongod-e Ahmadi plug). White hard limestones with cloudy texture sometimes contain pseudomorphs after gypsum/anhydrite nodules or crystals. Limestones with geopetal structures (geodes, flat fenestral textures) are developed in Chah Banu, Pashkand, and Kurdeh plugs, often in association with gypsum layers and/or red beds. Thick greenish limestones commonly contain thin laminae to bands of green marlstones in-between of limestone beds passing into alternation of centimetric layers of marlstones and limestones. The content of clastic admixture is very common as thin laminae to interbeds of calcareous sandstones, ferruginized quartz sandstones, volcanoclastic materials, and occasionally also shales. Thinly bedded to laminated limestones, often dolomitized, contain spectacular crystals of pyrite up to 2 cm in size (e.g., Charak, Chah Banu plug). Cherts occur in places as not continuous layers (Do-au plug, etc.). Some dark-colored limestones are fetid, often associated with gypsum and with dolostone interbeds. Brecciated limestones occur in the connection with brecciated gypsum and gypsum boxworks.

Limestones are recrystallized, mostly sparitic, sometimes microsparitic, with scarcely reserved fine-grained carbonate in clusters and clods or in fine laminae resembling algal structures. Some highly recrystallized types with cloudy ghosts are similar to products of carbonatization of sulfates (gypsum, anhydrite). A lot of admixed clastic quartz is distinctly of volcanogenic origin. Sericite is also common (recrystallized clay admixture). Dolomite occurs as euhedral to subhedral grains dispersed in the calcareous matrix. Pyrite (sulfide) grains are often accumulated in laminae with tuffitic admixture. Primary and secondary vuggy porosity is filled with sulfates or calcite, recrystallization of the matrix around vugs is clearly more developed. Silicification was detected in numerous samples, mostly as diffuse impregnation by microcrystalline to crystalline quartz. Sometimes, silicification by coarse-grained quartz of nodular appearance can have resulted from metasomatism of sulfate nodules in limestones. Presence of authigenic minerals (sericite, muscovite, feldspars) can be mentioned, too.

Variety of sedimentary textures allow to detect the upper and lower bedding planes and therefore also the position of underlying and overlying sequences. In the Do-au plug, some limestone blocks are overlain by ferruginized quartz sandstones, other blocks here are underlain by red beds, and in the Tang-e Zagh plug they are underlain by rhyolite tuffs and red beds. In the Mesijune plug, limestones constitute the terminal part of gypsum-sandstone-tuff cyclic sequence. In the Kurdeh plug, limestones form thick interbeds in red beds. Complex sequence was observed in the Deh Kuyeh plug, where limestones are overlain, from bottom to top, by red siltstones, red shales with tuff interbeds, green shales, limestones and red shales. The alternation of red beds and limestones was observed also on several other blocks. In another outcrop, limestones are overlain by dark green basic volcanics. Intercalations of limestones and black crystalline fetid gypsum are developed in Deh Kuyeh and Chah Banu plugs. Multiple alternation of rhyolite tuffs (Fig. 20), gypsum, black fetid gypsum, dolostone and limestones (often as laminites) is typical for several blocks in the northern part of Chah Banu plug. The thickness of largest blocks (Chah Banu, Do-au, Zendan, and Bam plugs) reaches sometimes more than 100 m.

Structures and textures indicate the deposition took place dominantly in intertidal to lagoonal environment, especially if alternating with gypsum, dolostone and certain red bed lithologies. Nodules after leached, silicified and carbonatized gypsum/ anhydrite indicate inter- to supratidal origin of some layers. Such structures occur mostly in upper parts of some limestone beds (Kurdeh, Pashkand, and Chah Banu plugs). In places, they are associated with solution collapse features resulting from diagenetic leaching of sulfate-halite interbeds in the sequence (Chah Banu plug). The position of limestones in some cyclically arranged sequences indicates, that limestone can represent basal part of transgression-regression cycle deposited in foreshoreoffshore shallow marine environment connected with open shelf conditions. The dolomitization of limestones is connected clearly with their position within the depocenter. Sabkha-evaporation and seepage reflux models of dolomitization (Tucker and Wright 1990) can be adopted here. Thin limestone intercalations in red bed are connected either with limited marine ingressions and/ or with lacustrine precipitation from mineralized lake waters, similarly to other red beds (German Buntsandstein, Permo-Carboniferous of the Bohemian Massif, etc.)

Dolostones

The occurrence of dolostones is given on Figure 21. Dolostones occur mostly as smaller blocks or interbeds in red bedgypsum and red bed-limestone sequences, sometimes also in















gypsum-tuff- carbonate profiles. The most common is the presence of black fetid dolostones, often laminated with white veins of secondary carbonate. Lamination is parallel to wavy, sometimes resembling stromatolitic structures. Cavernous textures (?after leached sulfates) are present in places (e.g., Berkeh-ye Suflin plug). Sandy admixture, laminae of volcanoclastic material are visible locally.

Dolostones are mostly composed of equigranular mosaic of eu- to subhedral grains having only locally zonal character. Very common are dolostones built of polyhedral mosaic of darkened grains. Clastic quartz (partly of volcanogenic origin) is often authigenically overgrown into bipyramidal grains. Mica admixture is present as sericite and muscovite. Authigenic feldspars occur in places. Pyrite as larger euhedral grains or as small framboidal grains is a common admixture. Silicification is abundant diagenetic and/or epigenetic process replacing both dolomite and primary gypsum/anhydrite (veins, nodules, impregnation) content. Silicification is often associated with ferruginization.

As mentioned above, dolostones occur in sequences with other lithotypes. In the Tang-e Zagh plug, dolostones overlay sandstones. In the Chah Banu plug dolostones occur in several horizons. In one block they are constituents of following sequence (from bottom to top): green sandstones, laminated dolostone with sharp lower contact, white rhyolite tuff with sharp contact, dark sandy dolostone with sharp lower contact and laminated to banded dolostone with wavy bedding. In another block, massive dolostone overlies rhyolite tuff. In the northern part of the plug, dark fetid dolostones and laminated dolostones are interbedded in gypsum-volcanic tuff-limestone sequence. Kent (1990) described similar sequences, where dolostone terminated red bed-tuffitic sequences. In the Mesijune plug, dark dolostones form interbed in gypsum-clastic sequence.

The characters of dolostone appearance indicate the connection with evaporite-clastic-carbonate sedimentary cycles as a part of evaporitic sequence of tidal origin. Polyhedral dolomite mosaic is a result of submarine cementation and dolomitization in diagenetic zone of active phreatic environment (Shinn 1975, Longman 1980) of an evaporitic basin. Authigenic quartz crystals are commonly supposed as indicator of highly saline environments (Grimm 1962, Flügel 1978). Silica supply was from decomposed acid volcanic and volcanoclastic rocks.

Gypsum and anhydrite

Gypsum is the second most common evaporitic rocks. Owing to anhydrite instability in near surface conditions, its occurrence is very limited, but not completely excluded (it was detected e.g., in Charak and Pashkand plugs). Gypsum forms usually matrix of "exotic" blocks, although often occurs as intercalations and interbeds in sedimentary and volcanoclastic sequences, especially in red beds. Primary gypsum interbeds were described in individual characteristics of other sequences, as well as various forms of gypcretes and cap rock. Gypsum in-between blocks of rocks is usually multicolored, white, pink, red, purple, green, gray, brown, black, etc. Enrichment in organic matter can be observed locally. It contains fragments of different kinds of rocks. In places it is highly tectonized, thrusted with slickensides and disharmonically folded.

In many plugs, gypsum constitutes the basic evaporitic material in the form of gypsum breccias containing abundant clasts of other lithologies and of very variable size. At plug margins, gypsum is a basic component of hematitized rim zone containing fragment of the Hormoz Complex as well as of surrounded Phanerozoic rocks. Sometimes, different lithologies form thin interbeds in gypsum, indicating that gypsum among blocks partly conserves its primary sedimentary structures. Such intercalations are often boudined into discontinuous layers due to diapiric processes. In the Saadat Abad plug, layered, banded to laminated and disharmonically folded gypsum sequence reaches up to 100 m in thickness, indicating so approximate possible thickness of primary gypsum strata within the Hormoz Complex. The percentage of gypsum in the plug composition increases with the higher degree of plug ruination as the salt is dissolved at the surface. The proportion of gypsum in plugs with similar degree of "passivity" depends on primary content of gypsum beds in cyclic structure of the Hormoz Complex, which resulted from paleogeography of the depocenter. The content of gypsum is clearly higher in the N and NE, while in the SE the halite is present also in highly ruined plugs and gypsum occurs in limited amounts (e.g., Hengam plug). All occurrences of gypsum in plugs forming even breccias among blocks are derived from primary gypsum sequences of the Hormoz Complex, which were deformed, folded and squeezed during diapirism. Anhydrite is occurring not frequently. It is mostly white, hydrated and altered on block surfaces into white to greet gypsum of sandy appearance.

Cap rock and brownish gypcrete

Cap rock is the uppermost part of many salt plugs, especially occurring on the subsurface. Its absence can be ascribed to the fracturing, dissolution and collapse of diapiric summits (Jenyon 1986). Owing to surficial outcropping of plugs in the studied area, sequences which can represent cap rock are only scarce. It is due to dissolution and alteration in shallow subsurface or on the surface. Rests of cap rock were detected in Hengam, Moghuieh, and Gachin plugs. They are composed of layered laminated gypsum with intercalations of iron-rich material and high degree of cementation. Sulfur occurrences in the Hengam plug (Pilgrim 1908) can be ascribed to cap rock, where sulfur usually represents important constituent. As mentioned above, brownish gypcretes of sandy appearance can result from the alteration of cap rock.

The surface of many plugs is covered by brownish gypcrete of variable thickness from about 3 m up to 10 m (Chah Banu plug). It has a sandy appearance and is more or less indurated. The admixture of clastic quartz varies in amount and represents most probably eolian material. In detail, the crust is sometimes laminated by reddish hematite accumulations (e.g., Berkeh-ye Suflin, Bustaneh, Puhal plugs), sometimes it is carbonatized. In the Berkeh-ye Suflin plug, it passes upwards into limonitized beds. In some plugs (e.g., Chahar Birkeh) it contains dark pigment and the structure resembles pedogenic horizons. In the Khurgu plug, the crust contains even gravel material. The crust was detected in more or less areally extensive outcrops in plugs Nos. 1, 3, 4 to 7, 10, 11, 13, 15 to 17, 22 to 24, 27, 31, 33, 34, 37, 42, 43, 46, 49, 51, 53, 52, 54, 60. In active plugs, the gypcrete covers the summit plateaus and flat surfaces originated by the dissection and uplift of original summit flat surfaces. The origin of the brownish sandy gypcrete can be connected with: (1) the stabilization of plug uplift and (2) weathering of plug material where it was formed mostly by the hydratation of anhydrite (Pashkand plug). Sandy eolian admixture and gravel content can prove this explanation. This type of crust can also represent altered (hydrated) anhydrite cap rock. The dissection of such crusts on the recent plug surfaces prove young renewal in diapirism in some plugs. Erosion of less active to inactive plugs damaged the crust into relics.

Salt

Rock salt (halite) is a basic constituent of many plug, mostly active ones. Impurities of non-evaporitic material are expressed in multicolored lamination and banding. Salt is white, greet white to gray, red, purple, brown, green. Without impurities, the color is light green, sometimes orange, yellow, light red. Impurities are represented by finely dispersed mineral and rock particles, or are accumulated in tiny laminae or bands and/or as smaller or larger rock fragments to blocks. Sedimentary rocks and volcanoclastics contained in salt represent, at least partly, broken primary intercalations, for example in the Mesijune plug, salt contains interbeds of layered gypsum with dark dolostones, dark fetid crystalline gypsum with ferrugineous bands, and sandstones, siltstones, tuffitic rocks and carbonates. In some places, accumulations of rock debris resemble fossil scree falling into salt depositional basin or transported by superficial weathering products. The proportion of salt in individual plugs depends on primary content of salt beds in the Hormoz depositional basin, where salt was much more abundant in the south, than in the north in general. Salt is often highly folded up to enterolitic structures due to diapirism and salt ascend. Rock mechanic (halokinetic) properties of salt and salt buoyancy under pressure (overburden, folding stress) caused the upwelling of diapirs. On some places, salt is recrystallized into large, up to decimetric crystals. Such occurrences are light-colored with various tones. The recrystallization is supposed to be young, Recent to subrecent process (e.g., Kent 1979). Except of halite, also other salts were reported in very limited amounts (cf. Fürst 1976). This is also indicated by low K contents in analyzed salt samples. Owing to low K contents in rock salt, the source of potassium for K-metasomatism have to come from other lithologies of the Hormoz Complex.

Gypcretes, dolocretes, calcretes and silcretes

(P. Bosák, J. Spudil and P. Sulovský)

Calcretes, dolocretes, gypcretes and silcretes occur in various lithological compositions and lithostratigraphical positions within numerous salt plugs. Other kinds of gypcretes, which differ in the genesis, are listed under cap rock and brownish gypcretes. The occurrence of crusts was observed within light-colored sandstones, within sequences of acid volcanoclastics, in the connection with red beds, especially at red bed/gypsum interfaces. The most common development of crusts is connected with volcanoclastics. Basic characteristics of the most spectacular occurrences will be listed below.

Multiple sequence of alternating rhyolite tuffs and crusts was observed in the Hormoz plug (Fig. 22). Tuffs are massive and cross-bedded in-between crust horizons. Crusts are represented by dark to multicolored, thinly bedded and laminated shales, sometimes with fine bands enriched in clastic (volcanogenic) quartz and tuffitic material. Shales contain carbonate fraction (dolomite) and ferrugineous admixture. They are underlain by thin horizon of thinly bedded, laminated tuff with large pyrite crystals. When not overlain by tuffs, shales terminate by gypcrete beds. Gypcretes are either earthy, laminated, multicolored, or light-colored, laminated to banded. The thickness of crusts is about 10 to 60 cm.





Figure 22. Profile of crusts within volcanoclastics, the eastern part of the Hormoz plug.

Complex sequence of crusts is developed in western part of the Moghuieh plug (Fig. 23). About 1.5 m thick crust overlays several tens of meters thick complex of rhyolite tuff. At their top, they are highly weathered to argillite and ferruginized in spots. The basal part of the crust consists of thinly bedded shaly sandstones containing tuffogenic admixture and tuff clasts. The crust is composed of alternation of laminated gypcretes containing anhydrite and ferrugineous fragments, ferrugineousgypsiferous dolostones, tuffogenic intercalations. The color is mostly red to brown with light-colored interbeds. The crust terminates by thin layer of ferrugineous dolostone overlain by red lateritic aleurite and clayey-ferrugineous sandstone passing upwards into cross laminated tuffitic sandstone and a sequence of more than 10 m thick, light green, multicolored and whitish dynamically bedded volcanic tuffs with ripple marks and crossbedding. Nearby, similar crusts were observed in blocks fallen into valley. Gypsified laminated rhyolite tuff is overlain by 30 cm thick gray crystalline gypsum with lenticular interbeds of sandy siltstones (small channel fills) and by 20 cm thick layer of brown and ochre limonitized dolostones and fine-grained sandstones, thinly bedded. The sequence is covered by multicolored banded gypsum. Thin crusts occur within light-colored rhyolite tuffs with lamination, cross lamination to cross-bedding also in the eastern part of the Moghuieh salt plug. The intercalation is composed of the layer of light green crystalline gypsum overlain by about 15 cm thick bed composed of mixture of rhyolite clasts, fractured ferrugineous dolostone and gypsum. This bed is overlain by thin pink columnar crystalline gypsum and honey-colored gypsum. Tuff with dynamic lamination and wedge cross-bedding terminated the profile.

The crust in the Gachin plug (Fig. 24) represents one of the most typical crust profiles. It overlies weathered rhyolite. Basal part is composed of three horizons of gypcrete in which uncon-





crust within volcanoclastics, the western part of the Moghu-

sandstone, ferrugineous, tuff clasts, 3-gypcrete, brown, boudined laminae, 4, 6, 7-gypcrete, brown, alternation with tuff bands, 5-tuffite, lithic, ochreous, clasts of volcanic rocks, 8-gypcrete, red, boudined laminae of hematite, 9-dolostone, ferrugineous. gypsiferous, reddish brown, 10-aleurite (lateritic soil), red, 11-sandstone, ferrugineous, brown, laminated, 12sandstone, tuffitic, gray and brown, dynamic lamination, 13-tuff, lithic, grayish white, lami-



Figure 24. Profiles of crusts, Gachin plug.

left profile-south: 1-gypcrete, white laminated, 2-gypcrete, yellow, unconsolidated, clasts of weathered tuffs, 3-gypcrete, pink, clusters of white clay mineral, laminated at the top, 4-shale to dolostone, brown to gray, laminated, 5-shale, multicolored, earthy, 6-shale, gypsiferous, multicolored, earthy, 7-gypcrete, whitish, massive, crystalline, indistinctly banded, 8-soil?, silty, earthy, ochreous, gypsified, laminated, with tuff clasts, 9-gypcrete, whitish, locally brown, banded, 10-shale, sandy, ochreousbrown, gypsified, 12-gypcrete, thickly bedded, 13-gypcrete, banded to laminated; right profile-north: 1-rhyolite and rhyolite tuff, 2-gypcrete, yellow, earthy, with clasts of weathered tuffs, 3-shale to dolostone, brown, laminated, 4shale, gypsiferous, multicolored, earthy, 5-gypcrete, banded to laminated, tuff layer at the top, 6-gypcrete interlaminated by dolostone, 7-gypcrete,

solidated gypcrete with rhyolite clasts alters with dense laminated gypcrete containing small clusters of clay minerals. In the northern part of the profile, this sequence is developed as soft gypcrete. It is overlain by laminated, brown to gray dolostones looking like shales. Dolostones are silicified in thin bands. Silicites are submicrocrystalline, enriched in carbonate and anhydrite/gypsum. They are fractured. Dolostones are overlain by multicolored less cemented dolostones and gypsiferous dolostones. The lower contact is sharp with deep desiccation cracks. The remaining part of the profile is developed as several thick beds of laminated to banded gypsum, crystalline, mostly white to light gray, sometimes with multicolored laminae and bands. Intercalations are composed of clayey gypsiferous, finely laminated soil horizon with rhyolite clasts and white ?gypsum or carbonate pseudomycelia (?rhizocriterions), sandy shale to dolostone, ochre-brown in color. Massive gypsum beds contain also boudined horizon or rhyolite tuff.

Another crust complex occurs also in the Gachin plug (Figs. 25 and 43). Its total thickness is about 5 meters. Crusts are developed in 3 sequences separated by gypsum layers. The complex overlies stratified upward fining rhyolite tuffs. Lower crust horizon is developed as a complex of laminated to banded gypcretes, light ochre, brown to red in color, partly hematitized. Lenticular development of beds and scoured erosional surfaces are visible. The horizon is overlain by 0.8 m thick white crystalline gypsum with multicolored laminae and bands. The middle crust is very complex, 0.9 to 1.2 m, thick composed of alternation of dark brown dolostone and light-colored gypsum or anhydrite. The basal part is represented by gypcrete, sometimes soft, in places coarse-crystalline or laminated. Dolostone horizon contains cherts and silicite bands and passes upwards to gypsum, fenestral with ferruginized laminae and dolostone bands. Fractures are often filled with white crystalline gypsum. The second gypsum layer is 1.1 to 2.0 m thick, composed of banded to laminated, sometimes coarse-crystalline gypsum, at the base with anhydrite band. Lamination and banding occur mostly at the base and at the top of the horizon. The upper crust horizon is 1.4 to 1.7 m thick and consists of laminated and banded gypcretes of various character, light-colored, multicolored, with red, black laminae and bands. Thin ferruginized bands and dolostone laminae to layers form intercalations. The upper gypsum layer is developed only in the western part of the gully. In the eastern part, the crust complex is covered by the cap rock. Similar dolomite-gypsum-ferruginized crusts lying on rhyolite tuffs and overlain by gypsum beds were detected also in other profiles of the Gachin plug. At another profile, this sequence was disturbed, broken, tilted and overturned by salt subrosion, lying mixed with overburden in salt solution pipe.

banded.

The other very typical crusts are developed in three different blocks in the Qalat-e Bala plug. The first profile (Fig. 26, left column) lies on green rhyolite tuff, which is highly weathered and fractured. The basal crust part is composed of fossil weathering horizon to scree of rhyolite tuffs (layer 1A). It is overlain by clayey gypsified sediment, most probably highly dolomitic, brown with green laminae. Interlayer of green greywacke partly fills the structure of clastic dike. Greywacke





Figure 25. Profiles of crusts, Gachin plug. 1, 2 - sequences between crusts; I, II, III - crust horizons; RH - rhyolite.

left profile-east: 1-gypcrete, pink, crystalline, bedded, gray to black laminated, dense, 2-gypcrete, yellow, pink dots, crystalline, porous, soft, 3-gypcrete, pink and green laminated, yellow and soft at the base, 4-gypcrete, pale green and laminate at the base, light greenish brown in the center, white, pink, porous, with eolian quartz in the upper part, ochreous and crystalline at the top, 5-dolocrete to gypcrete, brown, laminated, bands of dark gray cherts, wavy lamination with desiccation cracks, fractures with gypsum fill, 6-gypcrete, pink to beige, whitish laminated, soft and fenestral, 7A-gypcrete, pink, coarse-crystalline, indistinctly banded, 7B-gypcrete, dark gray, grayish green, banded, earthy at the bottom, hard, banded, fine- to medium-crystalline, greenish brown to brownish red in the upper part, 8-gypcrete, large crystals in laminated matrix, multicolored, 9-gypcrete, brown, crystalline, laminated, fine red laminae with hematite crystals, 10-gypcrete, white, porous, soft, with black laminae, 11-gypcrete, multicolored, pale red bands and black laminae, dolomite bands, 12-gypcrete, light greenish brow, soft, hematite in laminae, 13-gypcrete, brown, laminated, 14-gypcrete, white, porous, red and black laminae, 15-gypcrete, brown, purple at the base, multicolored at the top, 16-gypcrete, white, coarse-crystalline;

right profile-west: 1-rhyolite tuff, grayish white, laminated, fractures filled with gypsum, 2-gypcrete, light ochreous, soft, slightly hematitized, 4-gypcrete, dark red, sandy, 5-gypcrete, dark, black laminae, 6-gypcrete, ochreous, lenticular, 7-gypcrete, white, pinky, brownish, crystalline, pink laminae to pale red bands, hematite at the top, 8-anhydrite, whitish, soft, colored lenses, red and beige laminated at the top, 9-gypcrete, yellow, red laminae, 10-dolocrete to gypcrete, alternation of dolomitic brown, gypsum yellowish red to light beige and ferruginized dolostone brownish black bands, fractures with gypsum fill, 11-anhydrite, yellowish green to pink, locally white, 12-gypcrete, light-colored, karstified, red to pink bands, 13-gypcrete, pale red to grayish black, massive, laminate at the top, 14-gypcrete, grayish black, sandy, red laminae, 15-gypcrete, dolostone bands, dark brown, beige, thickly bedded at the base, 16-gypcrete (cap rock).

contains fragments of oolitic and pseudopisolitic iron ores and is cemented by green chlorite (berthierine). The overlying sequence is represented by alternation of thin bands of gypsum, dolostone, ferrolite, siltstone and silty shales with some bands of ferrugineous calcretes. The color is dark gray to brown, sometimes green. Ferrolites contain clasts of pelitomorphic pedogenic-like hematite-limonite rocks. Silicite bands are developed in carbonates. Texture of rocks is laminated with desiccation cracks, small flat pebbles, in places also convolute lamination can be observed. The crust is overlain by laminated to banded gypsum which contains clasts of light-colored volcanics and volcanic bombs! The upper bedding plane is irregular with deep craks. The next layer is composed of earthy gypsified hematitic layer rich in pedogenic structures and chaotic texture. At its top, pebbles of rocks fill small channel. The top of profile is composed of gypsum layer, at the base laminated and lenticular upward passing to banded and massive gypsum. The second profile (Fig. 26, middle column) is very similar to the previous sequence. Weathered rhyolite tuff is overlain by dark sandy ferrugineous shales and porous columnar gypsum. Sequence of brown dolostones, gypsified dolostones with thin beds of dolomitic gypsum contains numerous textures: desiccation cracks, load casts, prints of columnar gypsum and halite crystals, ripple marks and small solution potholes. The sandy admixture is common, as well as bands of cherts and silicites. At the top, desiccation cracks are developed. The crust is overlain by laminated gypsum bed. The third profile (Fig. 26, right column) overlies weathered greenish white rhyolite tuff and about 25 cm thick pedogenic horizon with abundant gypsum filled cracks and still recognizable structures of original tuff. Gypsified iron-



Figure 26. Profiles of crusts, Qalat-e Bala plug.

left profile: 1 -rhyolite tuff, green, weathered, fissured, 2 -layered gypsified sediment, brown, laminated, hard, 3-greywacke, chloritic, greenish gray, 4-ferrolite to gypcrete, brown, laminated, slump structures, 5-gypcrete, reddish brown, with clasts of ferrolite, 6-siltstone, dark gray, 7-siltstone to silty shale, sandy, greenish gray, chaotic, 8-alternation of dolocrete, brown, laminated and shales, gray, and silicite, with gypcrete, 9-gypcrete, at base coarse-crystalline, upwards laminated and massive, enclosed rock clasts (volcanics prevail), 10-chaotic layer, yellowish, ochreous, reddish with vertical veins, pedogenic hematitic layer, 11-gypcrete, layered, lenticular and laminated, clasts of rocks;

middle profile: 1-rhyolite tuff, green, weathered, 2-shale, sandy, tuffitic, ferruginized, dark gray, 3-gypsum, porous, columnar, shale laminae, 4-shales, dolomitic and ferrugineous dolostones, laminated, with bands of cherts, lenses of sandy material, abundant desiccation cracks, load casts, prints of columnar gypsum crystals and pseudomorphs of salt crystals, finely potholed surfaces, ripple marks, 5-gypcrete, banded, folded, arrow indicate the continuation same as on the left profile;

right profile: 1-rhyolite tuf, green, weathered 2 pedogenic horizon, weathered, bleached, with distinct original texture (tuf) and gypsum veinlets, 3-dolocrete, gypsified, iron-rich, brown, with fractures and white veins, 4-gypcrete, white, laminated, with laminae of laminated dark calcrete and laminated dolomitic bands, sometimes silicified, hard laminae are fractured and boudined, 5-gypsum, grayish white, massive, lamination at the base, with small concretions of calrete, 6-gypcrete, earthy, beige, chaotic, ochreous at base, 7-gypcrete, light-colored, with laminae of dark material, laminated to banded, locally homogeneous to chaotic, covered by dark fetid dolostones rich dolostone, laminated and brown to gray, overlies the pedogenic horizon. Silicite bands are common. Dolostones are overlain by white laminated gypsum containing boudined bands of dark dolostone, calcrete and silicites, especially in lower third. The upper part is composed of pulverized, soft gypsum, chaotic, beige in color. The crust is overlain by laminated to banded gypsum layer which is covered by blackish gray fetid laminated dolostones.

The crust in the Chahar Birkeh plug (Fig. 27) lies on calcareous sandstones at the top of red bed sequence. The crust is composed of complex alternation of dolostones, often ferruginized and gypsified, sometimes containing clasts of rocks and showing lamination similar to algal lamination (algal mats), gypsiferous and dolomitic ferrolites, tuffitic sandstones, intraclastic tuffitic carbonate (?dolostone). Ferrolites show common pedogenic textures (glaebulae, etc.). Silicification is abundant. The color of rocks is brown, red and green. Boundaries of beds is often uneven, erosional with scours and desiccation cracks. The sequence is overlain by thick laminated gypsum bed.

Other two examples of crusts are developed in red bed sequences with gypsum interbeds. The profile in the Bam plug (Fig. 28) is developed on purple siltstones and laminated gypsum (lagoonal). Gypsum is covered by banded iron ores, representing partly ferruginized dolostone. Next layer is built of multicolor shales and siltstones, hard, with deep desiccation cracks. The multicolored, probably weathered crust is covered by sandstone-siltstone-shale cycles, most probably continental in origin. Profiles in the Chah Banu plug (Fig. 29) are very similar to the previous one. Banded iron ores and altered tuffitic interbeds cover gypsum intercalations in red and purple shales to siltstones. In the Kurdeh plug, crust of similar evolution as on rhyolite tuffs is developed on gray laminated limestones with prints of columnar gypsum crystals. Limestone contains beds composed of brecciated to boxwork gypsum and is covered by



Figure 27. Profile of crusts on red beds, the western part of the Chahar Birkeh plug.



Figure 28. Profile of gypsum bed and crust within red beds, the southeastern part of the Bam plug.

1-silstone, grayish-purple, 2-gypsum, laminate, 3-siltstone, green, 4-gypsum, laminated, corrosional basis, 5-banded iron ore, 6-shale, multicolored, 7-siltstone, tuffitic, green, 8-shale, multicolored, 9-sandstone, fine-grained, greengray, 10-siltstone, greenish, 11-shale, violet.

spongy and granular gray gypsum. The rest of the crust is ferrugineous-dolomitic-gypsum, laminated to banded with broken bands of gray limestones.

Crusts composed of dolostone, gypsum, limestone, silicite and ferrolites, with some portions of shales, siltstones, sandstones to greywackes, and tuffogenic material to interbeds show very uniform

evolution in the whole region, even when developed in sequences of tuff, sandstones, red beds or on carbonate rocks. Textural features which enable to decipher the depositional environment are relatively abundant, i.e. parallel lamination, ripple marks, scoured surfaces, desiccation crakes, potholed corrosional surfaces, sedimentary boudinage, clastic dikes, etc. The deposition of such crusts is connected with extremely shallow marine depocenters connected with drop of sea level and evolution of shallow lagoonal hypersaline to inter- and supratidal environments. Pedogenic alteration, ferruginization, desiccation and other features indicate periodical emergencies, erosion and weathering not only of underlying complexes (tuffs, limestones), but also of crusts. Crust evolution is connected with the cyclicity of the Hormoz Complex, showing the presence of cycles of the fifth and fourth order. Ferruginization is related both with weathering and supply of iron of volcanogenic origin. Silicification has it silica source from weathering of volcanic products and/or in volcanic sources. Hypersaline conditions of deposition are evidenced by prints of halite and gypsum in dolostones and shales, as well as in the presence of gypsum/anhydrite as intercalations in crusts. The origin of dolostones is connected also with hypersaline conditions. Dolostones are partly primary precipitate and partly they represent replacement of limestone to calcrete horizons by dense Mg-rich brines in sulfaterich environment. The presence and reworked clasts of oolitic to pisolitic iron ores in psammites and ferrolites, and the occurrence of berthierine cement indicate that classical iron ores developed in the shallow inter- to subtidal agitated environment supplied in iron. Gypsum beds are mostly product of lagoonal deposition. Manganese enrichment was detected, too.



Figure 29. Profile of gypsum and crust within red beds, the western part of the Chah Banu plug.

7.1.2. Volcanic rocks (P. Sulovský)

The volcanic rocks of the Hormoz Complex form an essentially bimodal association with distinct predominance of felsic volcanics. The latter are represented mainly by alkali feldspar rhyolite, rhyolite, rhyodacite, ignimbrite, rhyolite tuff and tuffite, and sparse dacite and trachyte. Basic volcanics include fine- or coarse-grained olivine tholeiite, less often quartz tholeiite. Intermediate members of the volcanic suite, andesites, occur in subordinate quantities.

Basic volcanic/igneous rocks

Basic rocks occur in smaller blocks, than felsic volcanics, usually not exceeding meters to tens meters. Blocks of basic rocks have mostly fresh appearance, and fractured, non-abraded surface. Intermediate blocks have sometimes crumbled to hillocks of rock detritus.

The appearance of mafic rocks with volcanic characteristics (amygdaloidal, vesicular, aphanitic/porphyritic texture) found in salt domes is quite varied. Nonetheless, their chemistry (CIPW standard) classifies them only as olivine tholeiite, quartz tholeiite, hypersthene basalt and andesite.

The texture of olivine tholeiite ranges from coarse ophitic to aphanitic, vesicular or amygdaloidal. The normative olivine contents ranges between 12 and 17 %, it has nevertheless not been microscopically observed. Ophitic texture in some samples locally turns to poikiloophitic (larger pyroxene grains enclose smaller plagioclase laths). Many of the studied mafic rocks suffered some secondary alteration, mostly epidotization or zoisitization. In olivine tholeiite this process manifests itself also by a decrease in plagioclase basicity: outer parts of the plagioclase grains have An₃₈₋₄₅, while the centers retain original An₆₅₋₇₀. Alteration afflicted also the mafic minerals. Chlorite, actinolite, and carbonate partly or wholly replace pyroxene.

Quartz tholeiite usually has porphyritic texture. Phenocrysts are formed by plagioclase. The ophitic minute-grained groundmass assemblage is dominated by plagioclase and pigeonite, the latter being partly uralitized. Other alteration processes that



Figure 30. The Zr/TiO₂ vs Nb/Y discrimination diagram for identifying the rock type with plots of mafic rocks (after Winchester and Floyd 1977).

affected the rock were epidotization and chloritization. Normative quartz content does not exceed 3 %. Plagioclase basicity varies between 48 (rim) and 70 % (cores).

Less unequivocal is the dating of dark green fine- to coarsegrained mafic igneous rocks. Authors of previous papers dealing with the petrology of Zagros salt plugs call them usually diabase, suggesting thus their sub-effusive origin, probably coeval with the formation of the Hormoz Complex. This may be in many cases true. They sometimes have coarse-grained ophitic or gabbroic texture, which may indicate hypabyssal or even abyssal origin of these rocks. Samples of such rocks were found e.g., in Do-au, Khurgu, and Finu plugs.

According to the results of their microscopic evaluation, the rocks with gabbroic texture only sporadically contain olivine. Principal components of these rocks have originally been basic plagioclase (usually basic labradorite - An_{60} - An_{65}) and pyroxene, in some instances accompanied by biotite or primary amphibole. The typical signature of these rocks is uralitization of the sometimes only primary mafic mineral - pyroxene. Most of its amount is at present replaced by uralitic amphibole, usually ferroactinolite. In some samples, alkaline amphiboles are the prevailing mafic minerals. They give XRD patterns of crosssite, richterite, riebeckite and magnesioriebeckite. Some of them were reported from low-P/high T environment: crossite is e.g., known from a transitional blueschist/eclogite-facies metabasite in Oman.

Very often are the basic igneous rocks epidotized or albitized. At present they have the mineral composition of uralitized pyroxene gabbro; chemically they correspond to gabbro or gabbronorite. The only sample with textural signatures of igneous origin, which was analyzed for trace elements (gabbro from the Finu plug), has rock type signatures similar to basic effusive rocks in major element chemistry and some trace elements (Fig 30). It is nevertheless different in tectonic setting discriminating trace element ratios. On the Zr/Zr+Y diagram of Pearce and Norry (1979) it plots in MORB field, while the effusive basic rocks plot in the WPD field (Fig. 31b). Similarly, in the Meschede's diagram Meschede (1986) it lies outside the WPB field, occupied by other basic rocks analyzed (Fig. 31a).

The chemical composition of basic effusive rocks in most cases classifies them as olivine tholeiite (Tab. 16), rarely as

quartz tholeiite or hypersthene basalt. Their trace element ratios Zr/TiO_2 and Nb/Y are consistent with the classification, based on major oxides (see Fig. 30).

The trace element chemistry of the basic effusive rocks indicates their within-plate origin. In the Meschede's (1986) tectonic setting discrimination diagram Zr-Nb-Y they fall in the alkaline within-plate field (Fig. 31a). A similar result yields the diagram of Pearce and Norry (1979) (Fig. 31b).

On the Ti-Zr-Y diagram (Fig. 32), the analyzed tholeiites plot close to the triple junction of B, C, and D fields. This could mean they have likely erupted in transitional tectonic settings - either in attenuated continental lithosphere or at VAB/WPB collision zones (Pearce 1996). The sparse data on Th content (determined by gamma spectroscopy) combined with Hf and Ta (calculated from Zr and Nb), correspond to tholeiitic within-plate basalt.

Rock Type	gabbro	hypersthene basalt	olivine tholeiite		quartz tholeiite		
Salt plug	Finu	Shamilu	Puhal	Do-Au	mean (4)	Chah Banu	mean (3)
SiO ₂	49.8	48.15	49.17	47.64	48.9	48.37	46.88
TiO ₂	1.21	0.99	1.14	1.02	1.07	1.99	2.35
Al ₂ O ₃	12.90	14.88	15.71	13.94	14.42	13.42	14.62
MgO	6.14	9.23	8.08	9.83	9.12	6.91	4.48
CaO	10.27	9.39	3.88	6.85	6.27	9.11	8.75
MnO	0.16	0.18	0.56	0.23	0.29	0.20	0.15
Fe _{tot} as FeO					10.06		11.33
Fe ₂ O ₃	2.87	1.08	2.69	2.68		1.78	
FeO (det.'d)	7.92	6.23	6.85	7.42		9.58	
Na ₂ O	4.22	3.77	4.31	3.99	3.69	3.61	1.94
K ₂ O	0.57	0.53	2.75	0.82	1.42	0.47	4.98
P ₂ O ₅	0.12	0.12	0.15	0.21	0.18	0.27	0.16
+H ₂ O	1.13	3.64	3.95	3.9	2.99	2.38	2.38
-H₂O	0.16	0.31	0.23	0.13	0.17	0.00	0.12
S	0.17	0.20	traces	0.04	0.00	1.33	0.00
a	??	0.00	0.35	0.03	0.00	0.12	0
CO ₂	1.99	0.83	0.10	1.62	0.00	traces	0
Cr ₂ O ₃	0.00	0.04	0.00	0.00	0.00	traces	0
total	99.63	99.53	99.92	100.40	98.59	99.54	98.13
Nb	40.7	32.3	32.0	34.0	36.0	46.0	
Sr	188.0	224.0	1117.0	263.0	523.0	2241.0	
Rb	442.0	448.0	376.0	313.0	377.0	644.0	
Ti	6934.0	6365.0	6858.0	5775.0	6522.0	11160.0	
Y	28.4	21.7	19.6	20.0	23.0	37.7	
Zr	54.5	82.0	101.0	68.5	75.0	171.0	

currence of major as well as minor mineral phases indicate that the rock suffered from a complex of alteration process, manifested by amphibolization, albitization, carbonatization, and scapolitization. Most of these is connected with element transport (influx of alkalis, chlorine, mobilization of Fe, Ca, V) which can generally be described as infiltration metasomatism. The nature of this process suggests pronounced activity of seawater (or, rather, hot brines). Chlorine content in kaersutite (up to 4.5 wt%) is very high; together with 7.0% Cl in potassian hastingsite found in quartz tholeiite from the Hormoz Island is probably the highest ever reported in any hornblende species (cf. Morrison 1991)

Intermediate rocks

The uncertainty in datation of gabbroic rocks applies also to intrusive to sub-effusive intermediate rocks of the monzonitequartz monzodiorite-tonalite series (samples found e.g., in Berkeh-ye Suflin, Band-e Muallem, Mohuieh, Do-Au, Champeh, Chah Musallem, Ilchen, Chachar Birkeh, Kurgu, Bam, Gach, Darmadan, Tang-e Zagh, Kurdeh plugs). In several of these rocks (from Do-Au, Champeh, Chah Musallem plugs), the presence of high-Cl hornblende was also observed. Owing to usually more in-

 Table 16. Average chemical compositions of the main types of volcanic rocks in Zagros salt plugs (oxides in wt. %, trace elements in ppm).

Interesting is the occurrence of an albitized gabbro from the Finu plug with several amphibole species, one of them being vanadian Cl-kaersutite. The composition and mode of octensive alterations, it is less easy to derive their original composition. Quartz (monzo)diorite consists of quartz (normative qtz about 10 %), plagioclase ($An_{35.44}$), primary amphibole or py-



Figure 31. Trace element discrimination diagrams for identifying the tectonic setting of basic igneous (point 1) and volcanic (points 2-6) rocks from the Hormoz plug (a-left, b-right).



Figure 32. Zr-Ti-Y discrimination diagrams for identifying the tectonic setting of mafic igneous.

(1 - gabbro, 6 - tonalite) and volcanic (points 2-5) rocks from Hormoz salt plugs. Besides fields defined by Pearce and Cann (1973), a 10%-probability ellipse for VAB/WPB collision zones calculated by Pearce (1996) is drawn.

roxene, sometimes biotite. The assemblage of alteration products includes secondary amphibole (actinolite), carbonates, minerals of the epidote group, chlorite, sericite, and opaque minerals. The abundance of carbonate (calcite or dolomite) in some quartz diorites of quite fresh appearance may have made some authors classify these rocks as carbonatites. They indeed sometimes appear as such in the field, but their actual composition

excludes such classification. Quartz monzodiorites usually contain less carbonate than tonalite. The character of alterations suggests rather the action of hydrothermal solutions than that of metamorphism. This doesn't mean that carbonatites reported e.g., by Watters and Alavi (1973) from the Chah Banu plug do not correspond to real carbonatites.

Felsic volcanic rocks

The most abundant volcanic rocks occurring in the salt diapirs are felsic volcanic rocks (Fig. 33). Their composition ranges from alkali-feldspar rhyolite through rhyolite and rhyodacite to dacite. The average chemical composition of these groups is given in Table 17.

Rhyolites and alkali feldspar rhyolites have mostly porphyritic texture. Phenocrysts are formed by quartz and plagioclase, less often by potassium feldspar. The phenocrysts, especially quartz or plagioclase, are often strongly resorbed. Corroded quartz phenocrysts are indication there had not been an equilibrium between the phenocrysts and cooling magma in the last stage of rock crystallization. Microcline phenocrysts are easily recognizable by fine polysynthetic twinning according to albite and pericline law. Some of them are rather crystal fragments than euhedral grains. Besides the usual phenocrysts, plagioclase and K feldspar sometimes form phenocryst-sized, fan-like aggregates, which have probably formed in the metasomatic stage of rock development, as far they are most abundant in rocks with K_2O content above 8 %. Neo-formed potassium feldspar quite often contains some chlorine. It is debatable, whether it is present as submicroscopic inclusions of halite, or incorporated directly in the feldspar structure.

The groundmass is in most cases aphanitic. Part of the felsic rocks formerly had hyaline matrix, as indicated either by distinct signatures of perlitic parting, or fluidal texture, preserved in recrystallized groundmass. Some spherulitic glass formations have been replaced by coarsely crystalline quartz. These rocks have probably suffered strong silicification. It caused also the formation of quartz vein-like aggregates and streaks; such quartz is free of inclusions, clear, and exhibits undulatory extinction. The groundmass is often partially replaced by younger metasomatic minerals, including above all neoformed quartz, potassium feldspar, albite, gypsum, less often minerals of the epidote-zoisite group.

Several of the sampled felsic blocks can be classified as ignimbrite. Their chemistry ranges from rhyolite to quartz alkali-feldspar trachyte. They contain abundant fragments of glass shards or fragments of rhyolite with distinct fluidal texture. Some of them are even elongated to form the so-called "fiamme", which allows to call such ignimbrites welded.

The most pronounced alteration process can be described as alkali metasomatism. Both albitization and microclinization have affected rocks of the rhyolite clan. The intensity of potassium metasomatism can be documented by the fact, that about a half of the rhyolite samples has K₂O content higher than any other

Rock Type/No. of samples	alkali-feldspar rhyolite (21)	rhyolite (7)	rhyodacite (12)	dacite (5)	tonalite
SiO ₂	71.80 ± 2.35	69.14 + 4.48	71.40 ± 2.36	73.34 ± 3.39	66.91
TiO ₂	0.24 ± 0.06	0.30 + 0.16	0.24 ± 0.13	0.36 ± 0.19	0.50
A_2O_3	10.75±0.64	12.10 + 1.95	12.35 ± 0.95	11.45±1.6	14.13
MgO	1.27 ± 0.89	2.86 + 1.72	1.80 ± 1.06	1.19±0.64	1.52
CaO	1.03 ± 0.59	2.86 + 2.52	1.53 ± 1.22	2.98 ± 1.05	3.13
MnO	0.01 ± 0.01	0.05 ± 0.05	0.02 ± 0.01	0.18±0.24	0.04
Fe _{tot} as FeO	3.36 ± 1.89	3.40 ± 1.77	2.05 ± 0.90	2.71 ± 1.97	3.56
Na ₂ O	0.37 ± 0.23	2.22 ± 2.71	2.47 ± 0.65	6.05±1.12	5.79
K ₂ O	9.02±0.49	5.49 ± 1.57	3.98 ± 0.65	0.95 ± 0.94	0.82
P_2O_5	0.09±0.04	0.12 ± 0.03	0.12 ± 0.07	0.36 ± 0.24	0.12
H₂O⁺	0.63 ± 0.10	1.44 ± 0.83	2.34 ± 1.01	1.18	1.53
H ₂ O	0.19±0.03	0.15 ± 0.06	0.67 ± 0.28	0.23	0.11
Sum	99.4±0.93	99.71 ± 0.51	99.83 ± 0.72	99.61 ± 0.48	99.65
Nb	10.1 + 2.6	12.6 + 1.4	13.4 ± 3.8		19
Sr	123 + 32	228+40	224 ± 85		353
Rb	441 + 77	360 + 92	483±96		271
Ті	1014 + 181	1908 + 326	2180 ± 877		3479
Y	23+6	37 + 7	59±25		32
Zr	150 + 41	111 + 18	147 ± 54		135

 Table 17. Average chemical compositions of the main types of felsic volcanic rocks occurring in Zagros salt plugs (95 % confidence intervals - major oxides in wt. %, trace elements in ppm).


Relative proportion of light-colored acid volcanics and volcanoclastics within blocks of the Hormoz Complex; scale bar=25 km. 1-very abundant, 2-abundant, 3-scarce, 4-rare or absent.

published rhyolite or alkaline rhyolite data (Igneous Rocks Database, maintained by the Subcommission on Databases of IUGS). In the IGBA database, only one rhyolite sample of 360 (lava from Lipari, Washington 1900) is reported to exceed 9.2 % K₂O, i.e. value exceeded by 15 of 29 rhyolites from the Hormoz Complex. The normative K-feldspar value ranges between 43 and 63 % in alkali feldspar rhyolite, and between 25 and 50% in rhyolite; normative quartz is around 30-40%. The rhyolite sub-population has higher normative Ab (up to 25%).

Rhyodacite is typical by phenocrysts of microcline, plagioclase, and less often quartz. Microcline is perthitized, quartz phenocrysts magmatically corroded and ruptured. At the K-feldspar/plagioclase interface, myrmekitic exsolutions of quartz in plagioclase occur. Primary biotite was in all samples completely chloritized. The normative quartz and K-feldspar content is lower than in rhyolites; the opposite applies to normative albite and anorthite. In one case (Puhal plug), rhyodacite was found to be intensively tourmalinized.

In rhyolite tuffs, the ashy groundmass carries fragments of fluidal, felsic rhyolites and abundant crushed quartz phenocrysts. Plagioclase and K-feldspar are met less often. The contact between rhyolite fragments and ashy groundmass is sometimes hemmed with a narrow zone of radiate spherulitic feldspar. Similar overgrowth phenomena are usually explained as indication *of vapour crystallization*.

Rhyolite to rhyodacite tuffites are sometimes heterolithologic mix of tephra and fragments of sedimentary rocks consisting mainly of pyroclastic material. They contain abundant lapilli or bombs of differing lithology (from brick-red alkali feldspar rhyolite to dark gray dacite). The bombs achieve size of up to 30 cm. The rocks making up the bombs often make the impression of a very dense rock, the surface of conchoidal fractures having compact, almost obsidian-like appearance. They are more or less isometric; sometimes containing large central vesicle. Smaller vesicles are often filled with hematite flakes. Their overall complexion seems to suggest they formed of a viscous, volatile poor magma, which deposited in dry, hot environment. Layers composed exclusively of such densely packed tephra sometimes alternate with beds of tuffites containing abundant hyaloclastic material, coming from intrusion of magma into

aquatic environment. It suggests periodic oscillations of the sea level with occasional drainage of the shallow basins.

Generally, the trace element chemistry of felsic effusive rocks is best comparable with the pattern of I-type rhyolites (Fig. 34). There are nevertheless certain differences. At roughly comparable K level, the Hormoz Complex rhyolites are up to five times higher in Rb than average I-type rhyolites (Macdonald, Smith and Thomas 1992) and 2-3 times in Nb. Conversely, they are a bit depleted in Zr.

The Zr depletion is shown on the rock type indicator diagram (Fig. 35) as a shift from the (alkali) rhyolite fields to rhyodacite/dacite field. On the Y versus Nb as well as Rb versus Y + Nb tectonic discriminant plots (Fig. 36 and 37, respectively), the studied rocks fall in the syn-collision granites field, close





to its boundary with volcanic arc granites and within plate granites. There is need to be interpreted with great caution, especially when we take into account the large extent of alkali metasomatism, which had probably introduced high amounts of mobilized Rb. The felsic volcanics from salt plugs of the Southeastern Zagros have conspicuously higher Rb than rhyolites filed in the IGBA database (Fig. 35). The same applies to concomitant potassium (see above).

Light-colored dike rocks compositionally close to granites can usually be described as pegmatite or aplite. They are most common in the salt plug Shamilu. Their composition is sometimes more basic, corresponding to plagiaplites. Fine-grained varieties often exhibit graphic textures. Coarse-grained granitic rocks are rather scarce (Do-Au plug).



Figure 35. Rock type indicator diagram with plotted felsic volcanics of the Hormoz Complex.



Figure 36. The Nb-Y tectonic discrimination diagram for rhyolite-clan rocks from the Hormoz Complex.

Alteration of the Hormoz Complex non-sedimentary rocks

Potassium metasomatism (microclinization), albitization, silicification, carbonatization, epidotization, spilitization-propyllitization, halmyrolysis, to mention a few, influence the major elements content and distribution.

Generally, many igneous rocks of massive texture and fresh appearance contain surprisingly high amounts of chemogenic minerals - gypsum, anhydrite and halite incorporated firmly in the rock fabric. The action of alkali metasomatism (together with the introduction of chlorine in crystal lattice of some secondary minerals) indi**Figure 36.** The Nb-Y tectonic discrimina-

rocks we can find samples intensively albitized as well as microclinized, although the latter is much more common. The dual character of metasomatic alterations (strongly potassic/sodic) can have several causes. According to Lundström and Papunen (1986), the nature of metasomatic exchange of Na, K, and Mg depends above all upon the thermal conditions in the place, composition of HT solutions, and water/rock ratio. At higher temperatures and lower water/ rock ratios, occurring in deeper levels of the volcanic suite, sodium fixation overrides potassium metasomatism, while magnesium and potassium metasomatism are supposed to have occurred in more permeable portions of the volcanic (or, rather, volcanoclastic) pile, characterized by lower temperatures and higher water/rock ratio. Another explanation of preponderant potassic metasomatism applicable to the alteration of the Hormoz Complex rocks (in

fact not only magmatic, but also of volcanoclastic) offers Lagache and Weisbrod (1977). Unmixing of a Na+K chloride solution, buffered by a two alkali feldspar assemblage, can be caused either by a drop in its pressure, or dilution with meteoric water. In order to resume the equilibrium, the fluid must yield potassium to the rock, and gain sodium from it. As a result, the rock undergoes a potassic metasomatism. Metasomatic potassium enrichment is found in a number of different geologic environment.

One type of potassium metasomatism that is often spatially and temporally associated with volcanism and sedimentation is found in ancient closed lacustrine basins. Fedo, Nesbitt and

tion diagram for rhyoliteclan rocks from the Hormoz Complex.cates that hot mineralized solutions were "strong" enough to remobilize many elements. Practically all felsic volcanics sit well within the K-metasomatized field as defined on a $K_2O + Na_2O vs. (K_2O/$ $(Na_{2}O + K_{2}O)) \ge 100$ (Fig. 38, after Hughes 1973). Felsic volcanic and volcanoclastic rocks show potassium enrichment by a factor of two or more

Within the volcanic suites of the Hormoz Complex, rocks affected by intensive metasomatic, probably synvolcanic or early post-volcanic hydrothermal alterations are very abundant. In these alteration processes, highly saline seawater or brines played an important role. Among the rhyolite



brines played an important **Figure 37.** The Rb *vs.* Nb+Y tectonic discrimination diagram for rhyolite-clan rocks from the Horrole. Among the rhyolite moz Complex.



A1kali discrimination plot (after Hughes 1973) for felsic volcanics from the Hormoz Com-

Young (1995) proposed that metasomatising fluids may be plumes driven by instabilities inherent in evaporation-induced density stratification found beneath saline lakes.

In felsic rocks, depending on temperature, growth of hydrothermal K-feldspar or albite accompany seawater devitrification processes (Munhá, Fyfe and Hynes 1980), such that K and Na contents vary in volcanics that have sustained seawater metasomatism (Hughes 1973); this is also true for Mg and Fe contents. Relatively high Mg contents in felsic volcanic rocks (mean MgO content in seven rhyolite samples being 2.86 %, and 1.27 % in 21 samples of alkali-feldspar rhyolite) may indicate they deposited in submarine rather subaerial environment (Ewart 1979).

Appreciable amounts of silica have been leached during devitrification processes associated with seawater alteration. Hydrothermal alteration had such effect, too. In advanced stages of HT alteration and metasomatism, mobile elements such as K, Na, Ca, Mg, Fe, Rb, Sr and SiO, are not reliable indicators of primary magma composition.

Conclusions

An interbedded sequence of effusive rocks and pyroclastics, associated with bedded volcanoclastic sediments (tuffites) is the main feature of the Hormoz Complex, outcropping in salt plugs of the Eastern Zagros. Volcanic rocks in the Hormoz Complex are dominantly felsic, generally with less than one third of mafic volcanics. The felsic suite is represented by alkali-feldspar rhyolite, rhyolite, rhyodacite, their tuffs and ignimbrites. The mineral characteristics and textural features of these rocks indicate they emplaced in shallow submarine to subaerial environment, probably during periodic oscillations of the sea level with occasional drainage of the shallow basins.

Mafic rocks are clearly tholeiitic in character. Overall major and trace elemental chemistry, namely the LIL (especially K, Rb, and Sr) and HFS (esp. Y, Nb) elements enrichment is characteristic for within-plate environment to transitional volcanic arc/within-plate collision zone. Syn-collisional setting can be inferred from trace element patterns of the felsic volcanics, implying a common source for the bimodal volcanism. The bimodal nature of the volcanic suite suggests it formed in an intracontinental rift setting.

Hydrothermal alterations of the volcanic rocks are common and widespread. The intensity of alteration processes was very high, leading to unique chemistry of altered rocks. A large part of the felsic volcanic and concomitant volcanoclastics were subject to strong potassic metasomatism, resulting in the formation of rhyolites with highest K₂O contents ever reported. Common occurrence of minerals that adopted large amounts of chlorine in their structure (Cl-kaersutite, potassian chlorian hastigsite and other alkali amphiboles, scapolite, even neo-formed microcline) suggest highly saline fluids (evaporitic brines?) took important part in the metasomatic process.

7.1.3. Metamorphic rocks (P. Sulovský)

The frequently occurring porcellanite, found e.g., in Hormoz, Do-Au, Charak, Gurdu Siah, Chah Banu, Siah Tagh plugs are representants of metamorphic rocks. The presence of pseudomorphs after halite crystals in such rocks specifies the timing of contact metamorphism, i.e. dike intrusion, as posterior to the sedimentation of volcanosedimentary rocks of the Hormoz Complex.

7.2. Stratigraphy and correlations (P. Bosák)

7.2.1. Finds of fossils

The dating of the Hormoz Complex is not easy. Finds of fossils are limited as well as numerical dating results. The dating given by some authors in first stages of plug exploration varied from pre-Cretaceous up to pre-Miocene (cf. Blanford 1872, Richardson 1926, Krejci 1927, De Böckh, Lees and Richardson 1929). The view on dating changed only in late twenties of the 20th Century.

De Böckh, Lees and Richardson (1929) found trilobites of the Cambrian age in sandy dolomitic shales in the Band-e Muallem plug and in greenish shales in the Bustaneh plug. According to all morphological features, trilobites can be compared to family Ptychoparia of Middle to Upper Cambrian age. Except of trilobites, annelid were found, too. Similar finds are reported by Kent (1970) from the Hormoz Island. King (1930) described these fossils, including Billingsella sp., Anomocare spp., Chuangia sp., ? Coosia sp. and Ptychoparia sp. The material was compared with finds of De Böckh, Lees and Richardson (1929). Hirschi (1944) noted fossils (trilobites, Billingsella sp., etc.) most probably as commentary to previous finds. McGugan, Warman and Kent (Kent 1958, 1979) found about 30 pieces of trilobites in about 10 m thick dark gray to brown shales appearing as intercalation in dark, thinly bedded silicified dolostones and in finely laminated shales in the Chiru plug. According to Stubblefield (in Kent 1970), trilobites represent new forms of the Middle Cambrian aspect. The more detailed identification was not possible due to the lack of comparative material and to the fact, that finds were "unfortunately subsequently lost" (Kent 1979, p. 126). Crimes (1968) and Stöcklin (1968) noted traces of trilobite activity on bedding planes.

Relatively common were finds of algal structures, which were summarized by Kent (1979). Collenia type of algae is reported from some plugs, as well as of other stromatolitic structures. Conophyton was found in Gach, Aliabad, and Chah Banu plugs within the studied area and in Kamarij plug (Kazerun region) and in one of Oman's plugs outside our sector. Cryptozoon and Solenopora structures accompany above mentioned finds, in the Chah Banu they occur in bedded dolostones. Thin algal discs allied to Spriggina were found in the Gach plug in black platy dolostones and in the Vanak plug in High Zagros. They are comparable with Precambrian of South West Africa.

Search for fossils, although very intensive, was not successful in our exploration program. The presence of finely laminated stromatolitic structures are very common in limestones to dark dolostones on many plug visited, some of them resemble fine algal discs. They are silicified often (e.g., in Sarmand plug) making thick homogeneous multicolored silicite beds. Other stromatolitic structures were found on Gach plug. Indistinct relics of bioclasts were discovered in one sample from Mesijune plug, where cores of small lamellibranch-like fragments, silicified ?trilobite carapaces and relics of bryozoa-like structures, as well as other bioclasts with unclear classification (spheres, algal structures) were detected.

7.2.2. Numerical dating

Numerical (radiometric) dating was performed by Player (1969, in Samani 1988b), Crawford and Compton (1970), Fürst (1976), and others especially outside region studied (central Iran, Oman, etc.). Player dated volcanic rocks to 1,040-560 Ma (i.e. Upper Proterozoic {Riphean} to Lower Cambrian). Fürst (p. 190-191) noted 1,050-430 Ma data (i.e. Upper Proterozoic {Riphean} to Ordovician), ages from 800 to 600 Ma prevail. Berberian and King (1981) dated acid volcanics on Arabian-Nubian Shield to 663-555 Ma and Husseini (1988) suggest the granite emplacement in Arabia during 620 to 580 Ma.

7.3. Lithostratigraphic correlations - volcanic activity (*P. Bosák*)

First attempt to correlate the Hormoz lihtologies with equivalents outside the Zagros Fold Belt was made by Stöcklin (1971). Non-evaporitic or slightly evaporitic equivalents are believed to be present in the Infracambrian Group of northern and central Iran, particularly the Soltanieh Dolomite, the Barut Formation, and the Rizu Series, and in Member 1 of Mila Formation (Middle Cambrian), which contains salt pseudomorphs. Slightly gypsiferous limestones and dolostones from South Arabia have equally been compared with the Hormuz Formation. The Hormoz Salt Formation is further believed to correlate with the Punjab Saline Series of the Salt Range (Pakistan), the "Salt Pseudomorph Stage" of the Salt Range may in turn correspond to higher levels of the Hormoz Salt, to the Kalshaneh Formation and to Mila Member 1 of Iran.

Berberian and King (1981) ascribed late Precambrian to Cambrian post-orogenic volcanics to extrusive equivalents of the Doran granite (Stöcklin 1968b) composed mainly of alkali rhyolite, rhyolitic tuff, and quartz porphyry, sometimes accompanied by basaltic volcanics of alkali affinity, noting that although alkali basalt is a typical member of the rifting magmatism, extensional tectonics in the continental crust also permits rapid rise of rhyolites and acid plutons. The volcanic phase is associated with the formation of the epicontinental platform from Arabia to Elburz. Succession of alkali acid volcanism with some basic volcanism to basic volcanism (e.g., in the Soltanieh Dolomite Formation) is typical for normal faulting and stretching of the continental crust. Thick ignimbritic sequence overlies Late Precambrian Gorgan schists, and is underlain by the Cambrian Lalun sandstone in the Gorgan area (northern Elburz). Similar post-orogenic rhyolitic pyroclastic rocks, lavas, and subordinate basaltic volcanics of alkali affinity were developed on the Arabian-Nubian Shield during 663 to 555 Ma. Volcanics of the Hormoz Complex are comparable with the Takhnar Formation (Kashmar region, northeastern Iran) and with the Gharadash Formation (northwestern Iran).

Hurford, Grunau and Stöcklin (1984) compared volcanics composed predominantly, but not exclusively, of an acid (quartz porphyry or rhyolitic) composition in the Hormoz Complex with similar rocks interbedded in Gharadash Formation (northwestern Iran) and Rizu Series (Yazd-Kerman area), commented that they are related to widespread family of petrographically similar subvolcanic granites, which usually penetrate only deeper levels of the Infracambrian sediments. As none of these magmatic rocks ascends as high as the Cambrian Lalun Sandstone or younger beds, their age is stated. Basic volcanics in plug they attributed to the Infracambrian and not to a Paleozoic volcanism.

Davoudzadeh, Lensch and Weber-Diefenbach (1986) also compared post- orogenic volcanics to the extrusive equivalent of the Doran granite. They suggest, that to this succession, following formations belong: Gharadash Formation (alkali rhyolite, rhyolite tuff, quartz porphyry, northwestern Iran, Stöcklin 1972), Takhnar Formation (Kashmar region, northeastern Iran), Rizu-Desu Series (Kerman area), and the rhyolite in the Hormoz Formation in the Zagros area.

Husseini (1988) connected volcanic activity with random intrusions of granite diapirs in Arabia (between 620 and 580 Ma) and correlated it with the emplacement of post-orogenic Doran granite in Iran.

7.4. Lithostratigraphic correlations - sedimentary sequences (*P. Bosák*)

Wolfart (1972) compared the Hormoz Complex with Lalun and Desu Formations of the northeastern Iran.

Kent (1979) supposed, that dark dolostones of the Hormoz Complex are an equivalent of Soltanieh Dolomite (Elburz area), and color shales and light-colored cherty quartzites were compared with the Lalun Formation of Lower Cambrian age. He concluded, that there is, indeed, clear evidence that the Hormoz Complex extends downwards below the Cambrian date. In the High Zagros mountain belt the Middle Cambrian dolostones and marls overlying Lower Cambrian sandstones (Lalun) are extensively exposed, and Hormoz rocks appear alongside, in plugs mainly intruded from lower levels along fault slices. Clearly the Hormoz dolostones cannot be Middle Cambrian since they have come from much deeper zones.

Berberian and King (1981) made first continental correlations of Precambrian and lowermost Paleozoic sequences. Upper Proterozoic Soltanieh Stromatolite Dolomite of central Iran are coeval non-evaporitic equivalents of the Hormoz Complex, comparable with Jubaylah Group in Arabia. Those units can be found from Arabia (Huqf Group) to Elburz Mountain, to central Afghanistan (Lower Bedak Dolomite), and Pakistan (Punjab Saline Series). This and Lower Cambrian shallow sea deposits of the Zaigun-Lalun red arcosic sandstone-shale Formation in Zagros, Central Iran, and Elburz and its (possibly time transgressive) equivalents, the Saq Sandstone in Arabia, Quwiera Sandstone in Jordan, Sadan, Kaplaner, Cardak Yalu-Calaktepe in southeastern Turkey, Tor Petaw Sandstone in Zargaran (central Afghanistan), and the Purple Sandstone and Shale in Pakistan, suggest that at least from the late Precambrian to Late Paleozoic times, Iran was a part of Gondwanaland.

Hurford, Grunau and Stöcklin (1984) compared the Hormoz Complex with underlying and overlying complexes of the Lalun Formation in the Kerman-Tabas region. All essential Hormoz lithologies reappear in this area also in thick undisturbed, layered sequences of alternating sedimentary and volcanic rocks. Two evaporite groups can be distinguished here, i.e. below and above the Lalun Formation. The lower evaporite group corresponds to the widespread "Infracambrian" sedimentary group of the Iranian Plateau (Stöcklin 1972). In its non-evaporitic development, this group consists of thick cherty and stromatolitic dolostones (Soltanieh Dolomite) and of associated dark fetid limestones, red sandstones and red and green silty shales (Stöcklin 1974). Rhyolitic volcanics appear interbedded with these sediments in northwestern Iran (Gharadash Formation) and in the Yazd-Kerman area (Rizu Series). A change from dolostone to gypsum and rock salt by lateral interfingering is observed north of Yazd and north of Kerman, and is described as the Ravar Formation and the Desu Series. The Upper Proterozoic age of the lower evaporite group is confirmed by the position of the Soltanieh Dolomite 1,000 m below the oldest datable strata containing late Lower Cambrian trilobites (Ano*mocare*) in beds immediately overlying the Lalun Formation in the Kerman area, and trilobite footprints attributable to the Early Cambrian Redlichia zone in the upper part of the Lalun Formation itself. The abundant Collenia-type stromatolites in the Soltanieh Dolomite resemble Riphean forms, but they are undiagnostic. The black shale marker of Chapoghlu Shale in the lower part of the Soltanieh Dolomite was found to be full of Chuaria circularis (Fermoria) a characteristic fossil of the latest Proterozoic-Vendian. Similar black shale horizon in the Rizu Series has yielded remains comparable to *Spriggina*, *Charnia*, *Rangea* and other forms of the Ediacaran fauna-type dated by Huckriede, Kürsten and Venzlaff (1962) between 760 and 595 Ma

The upper evaporite group, above the Lalun Formation, was found north of Tabas and was named the Kalshaneh Formation. It is composed of the Hormoz-type of strata (gypsum, dark dolostone, fetid limestone, red shale, dolerites). Stratigraphic position above the Lalun Formation and below the paleontologically dated Middle to Late Cambrian Derenjal Formation indicate its Early to early Middle Cambrian age. The horizon can be thus correlated with the dolomitic Member 1 of Cambrian Mila Formation (northern Iran) and with the Anomocarebearing beds near Kerman. Discussed authors than concluded that the Hormoz plugs are apparently represented by the lower group of the Upper Proterozoic age as indicated by the abundant rhyolitic material and by the general Upper Proterozoic habitat of sedimentary lithotypes. The occurrence of Collenia and Spriggina-like organic remains (Kent 1979) strongly supports this correlation. Many of the classical Hormoz plugs are likely to be composites of both evaporitic groups.

Husseini (1988) in his structural study compared the Hormoz Complex with Ara evaporites (Oman), Zaigun, Barut and Soltanieh Formations (Iran), Huqf Group (Oman), Jubaylah Group (Arabia) and Punjab Saline Series (Pakistan). All formations are of presumably Upper Proterozoic age, as the Zaigun Formation is overlain by the Lalun Formation. In the study from 1989, Husseini supposed Upper Proterozoic to early Lower Cambrian age of the Hormoz Complex and its equivalents: Hajiz and Khufai Formations (Ghaba-Huqf Mountains, Oman), Shabb Formation (Ghaban, western Arabia), Badayi Formation (540±20 Ma, Mashhad, western Arabia) and Lower Dolomite (Derenjel and Elburz, Iran).

Davoudzadeh (1990) concluded that much of the Hormoz Complex must be older than Lalun Sandstone of Lower Cambrian age and can be correlated stratigraphically with the Desu Series of the Kerman area, the Kalshaneh Formation of eastern Iran and the Soltanieh Formation of central and northern Iran. Lateral changes from Soltanieh Dolomite into evaporite facies is well developed in the eastern Ardekan.

Ahmadzadeh-Heravi, Houshmandzadeh and Nabavi (1990) subdivided the Hormoz Complex into four specified units, in which unit 1 (salt) can be concerned to Lower to Middle Cambrian, and units 2 (marl, anhydrite, ironstone, acid volcanics), unit 3 (fetid black algal carbonates) and unit 4 (alternation of sandstone, marl, shale, acid and basic volcanics) are Middle Cambrian to Ordovician, not bringing any evidence of the stated ages.

7.5. Age (P. Bosák)

It seems that postulations of Harrison (1930) that the Hormoz Complex extends both slightly higher and considerably lower than Middle Cambrian is still valid. However, later authors connected the Hormoz Complex mostly with the Upper Proterozoic (Infracambrian) and broadly discussed the possibility of presence of Cambrian elements within the Hormoz sequence.

Radiometric dating of the Hormoz material varies from 1,050 to 430 Ma, i.e. from Upper Proterozoic or boundary Middle/Upper Proterozoic up to Ordovician (Player 1969, Fürst 1976). It cannot be excluded, that datum below about 800 Ma (the start of complete tectonic cycle of cratonization of the Arabian Platform, cf. Husseini 1988) can include the age of the basement rocks brought by salt diapirs. This statement can be indicated by the note of Fürst (1976), that a major datings fall within 800 and 600 Ma. Dating in supposed non-evaporitic equivalents shows 540±20 Ma (Badayi Formation) and 654 Ma (Huqf Group, Husseini 1989), 760-595 Ma (Huckriede, Kürsten and Venzlaff 1962), i.e. time span from Upper Proterozoic to Lower Cambrian. Magmatic activity connected with extensional phase of post-orogenic crust evolution when the Hormoz Complex and its equivalents were deposited are dated to 663-555 Ma (Berberian and King 1981) and 620-580 Ma (Husseini 1988), i.e. Upper Proterozoic to lowermost Cambrian. Numerical dating thus indicate, that at least partly, the Hormoz Complex is of Cambrian age.

According to our opinion, the crucial fact in the dating of the Hormoz Complex is the find of trilobites of Middle Cambrian affinities noted by Kent (1979) and Middle to Upper Cambrian trilobites described by King (1930). These paleontological materials indicate, that a part of sedimentary sequence broken and brought up by salt diapirs, can evidently be of Lower to Middle Cambrian age. Limited amounts of finds, concentrated to coastal plugs (Band-e Muallem, Bustaneh, Chiru) also indicate that such marine Cambrian strata had a limited areal extent in the upper parts of the Hormoz Complex, caused by small surviving depositional basins with marine regime surrounded by coastal alluvial and terrestrial clastic sequences in other places, which are generally non-fossiliferous. Subsidiary evidence or support for the termination of evaporitic regime (?the end of Hormoz Complex deposition) during Middle Cambrian can be seen in facts, that first fully marine carbonates were deposited in Middle Cambrian, and that the salt pseudomorphs disappeared in the same time from sequences in Iran (Berberian and King 1981).

To conclude this subchapter, we assume taking into account all above mentioned data and criteria, that the Hormoz Complex is of Upper Proterozoic (Riphean-Vendian) to Middle Cambrian in age.

7.6. Stratigraphic subdivision (P. Bosák)

Several attempts to compile internal stratigraphy of the Hormoz Complex have been made. Richardson (1926, *cf.* also in Ladame 1945) introduced Pusht-Tumba Series for ancient residual series lying on the Hormoz salt, eruptive series and ancient sedimentary series (Middle to Upper Cambrian) to describe the contents of plugs. Krejci (1927), clearly based on Richardson's earlier publications, distinguished: (1) pre-Miocene to post-Oligocene Upper Hormuz-Group, (2) Middle Hormuz-Group, and (3) Lower Hormuz-Group, and he introduced new (4) pre-Cretaceous Khamir-Group, composed of crystalline schists, dark blue limestones, black and white crystalline limestones, fetid limestones, etc.

Richardson (1928, maybe also 1926, 1924) described (1) the upper Hormoz Group (gypsum, hardened rock - in German Erstarrungsgesteine-führende, tuffs, agglomerates, fetid limestones and, at upper group boundary, sandstones dated to Cambrian), (2) middle group (dolomitic-anhydritic), and (3)lower group (layered salt).

First detailed stratigraphic subdivision was made by De Böckh, Lees and Richardson (1929), who subdivided the Hormuz Series into four parts, from top to bottom: (4) purple sandstones, grits, and shales, (3) volcanic tuffs and agglomerates, generally gypsiferous, (2) dolomitic limestones and shales, with flints, and (1) rock salt. In later descriptions of salt plugs, the same units appeared, but with partial change of the succession. Salt remained as the oldest stratigraphic member in all interpretations, even the recent ones. The stratigraphic subdivision was later based on observation of large "exotic" blocks within plugs.

Fürst (1970, 1976, 1990) summarized such view, describing the Lower Hormuz Members (whitish to pink, crystal clear laminated rocks salt, gray and red colored salt is found at localities of the mainland) and the Upper Hormuz Member (in which to present a complete profile is however difficult). The Lower Hormuz Member is characterized by decreasing amount of rock salt towards the top, whereas the number of gypsum beds increases. The Upper Hormuz Member is typical by alternation of clastic sediments, gypsum and volcanic rocks.

The last published stratigraphic subdivision came from Ahmadzadeh Heravi, Houshmandzadeh and Nabavi (1990), who introduced four units, from top to bottom: (4) H4 - alternation of tuffs, sandstones, marls with some intercalations of anhydrite and black algal limestones, (3) H3 - laminated black fetid algal limestones, (2) H2 - alternation of marls, anhydrites, tuffs, ignimbrites, ironstones with some intercalations of fine laminated algal limestones, and (1) H1 - salt beds with fine intercalations of tuff, marls, limestone, iron oxide and sulfides. Stratigraphic subdivision mentioned in some unpublished reports of Iranian companies are sometimes very close to above mentioned divisions, supposing that poorly cemented sandstones are at the top of the sequence with underlying dark dolostones and limestones. The metamorphics were supposed to be the oldest rocks of the sequence.

Nevertheless it seems, that salt and other evaporitic sediments do not form only one uniform level, but they are constituting originally multicyclic, dominantly evaporitic sequence (Trusheim 1974, Ala 1974, Kent 1979, Davoudzadeh 1990), similarly to stratigraphically comparable sequences to the SE of Agda and NE of Ardekan (central Iran) representing multicyclic evaporites (Davoudzadeh 1990). Kent (1979) supposed, that several very thick salt units alternated with dolomitic and clastic beds, like in the European Zechstein.

However, it can seems that the compilation of the lithostratigraphic sequence of the Hormoz Complex could be finished, field observations proved rapid lateral and horizontal facies changes and discontinuity of rock sequences in individual blocks, plugs and geographical regions. Therefore, to decide the proper stratigraphic succession is highly problematic and highly speculative. Only detailed sedimentological, lithostratigraphical and biostratigraphical investigations can bring more light to this problem in the future.

7.7. An outline of paleogeography (*P. Bosák*)

Late Precambrian formations were deposited in basins on the presumably peneplanated Arabian basement (Berberian and King 1981, Davoudzadeh, Lensch and Weber-Diefenbach 1986) with thick weathering crusts developed in places. Deep faults, especially of Oman-Lut trend and Main Zagros Thrust appear to have acted as facies dividers separating evaporitic basins from coeval non-evaporitic facies (Stöcklin 1968, Berberian and King 1981, Husseini 1988, 1989). All features indicate the evolution in an extensional phase. The Hormoz salt and related sediments were deposited in an isolated, NW-trending, rectangular basin which was developed during right-lateral displacement along the Zagros fault. it was geometrically bounded to the E by the Zagros fault, to the S by the Dibba fault (Oman line) and finally by the Hawasina fault as a transform fault (Husseini 1988).

The deposition of the Hormoz Complex is multicyclic in nature. According to our observations, especially clastic red beds often pass upwards into gypsum sequences in numerous plugs, which supports multicyclic evaporite theory. The deposition took place in an extensive evaporitic basin, as indicated by facies and cyclic nature of the Hormoz Complex. The explanation of salt precipitation from volcanogenic source as presented e.g., by Momenzadeh and Heidari (1990) is completely improbable. The distribution of individual facies can be deciphered from regional distribution of plugs and the content of evaporites and non-evaporitic lithologies. Predominance of gypsum in plugs in the northern and the NE part of the studied region together with occurrences of rock salt even in highly ruined plugs in the south indicate the primary distribution of evaporitic facies. It can be supposed, that the center of Hormoz sedimentary basin contained much larger proportion of salt, maybe in more continuos sequences interrupted by sequences of non-evaporitic and gypsum/anhydrite lithologies. The percentage and thickness of salt horizons decreased to the basin margins, where gypsum and non-evaporitic rocks deposited in a greater extent and





thickness. This model fits all the known models of evaporitecarbonate-clastic basins. Cyclicity was influenced by repeating sea-level oscillations resulting in transgressions or ingressions of the sea and establishment of open and restricted shelf depocenters, extensive lagoons and broad flat tidal zones.

The cyclicity of the Hormoz Complex can belong to different orders. The composition of blocks show internal metric to decimetric cyclic character (cycles of the fifth and fourth orders) arranged in cycles of the higher order (the third order?) with thickness of tens to first hundreds of meters. Such feature is especially expressed in Bam, Chah Banu, Kurdeh, and Deh Kuyeh plugs. The thickness of non-evaporite portions of individual cycles of the higher order are expressed by the total thickness of individual blocks of the Hormoz Complex in plugs, because evaporitic portion is either leached (salt) or squeezed (sulfates). The general character of sedimentary strata shows carbonate-clastic-evaporite nature of individual micro, meso and megacycles of the transgression-regression nature, most probably upward shallowing in nature. Cyclicity of the sequence is caused both by the combination of relatively short-termed eustatic and by long-termed tectonic controls (cf. e.g., Tucker and Wright 1990). The evidence of eustatic control of the cyclicity cannot be discussed in detail as the existence of natural outcrops in not tilted or disturbed position is excluded. Tectonic control of the sedimentary basin is clearly proved, therefore the influence of tectonism on the structure and composition of sedimentary sequences can be assumed. The whole depositional region was in relatively unstable conditions of the terminal part of pan-African Orogeny, when individual deep faults and related structures had a possibility to be expressed in the internal structure of the Hormoz Complex, as well as in its cyclic character

Maps of extension of found different lithotypes (Figs. 13 to 21) show some interesting relationships, however incomplete, but with the same systematic and methodical error resulting from applied methodology of field work and final evaluation. Map showing the presence of limestones (Fig. 18) indicates low content or absence of limestone blocks and sequences in the eastern part of the region with pinching out in southeastern and probably also southern directions. Also the northwestern corner of the region is deficient in limestones (but here the absence is the function of very low level of our reconnaissance). The substantial content of limestone blocks is bound to strip of the NE-SW direction from plugs of Gahkum-Saadat Abad-Tange Zagh to Chiru plug. Owing to the fact, that nearly all limestone outcrops show shallow marine origin, this zone can indicate presence of repeating deposition in structurally controlled shallow shelf gulf within predominant siliciclastic depocenter. Tidal flat progradational foreshore-offshore depositional model in carbonate lagoons seems to be the most convenient. The extent of limestone depositional environment was most probably limited by the N-S to NNE-SSW trending divider, parallel with the Oman trend and the carbonate depocenter was ruled by NE-SW subsiding zone oblique to both the Zagros and the Oman trends (shear zone).

The extent of dolostone facies (Fig. 21) indicates some sim-

ilarities with the extent of limestones. Dolostones are common in the north of the region and in its western part. The southeastern part contains dolostones, sometimes in substantial proportion, too. The continuation of dolostone outcrops in northern and southern directions can indicate the connection with coeval sedimentary basins with dolomite deposition (Soltanieh and Barut Formations, Iran) in the N and Jubaylah Group (Khufai and Buah Formations) in the S (Oman, Arabia). Khufai and Buah Formations are two dolostone levels separated by the Shuran clastics (*cf.* Husseini 1988, 1989). It seems that the depositional zone of dolostones was governed by N-S to NNW-SSE and NE-SW trends, similarly to limestones. The increased presence of limestones and dolostones in the same plugs can, more, indicate the presence of carbonate-evaporite cycles resulting from sea-level oscillations (marine ingressions).

The presence of conglomerates (Fig. 17) is bound to the N-S trending zone in the center of the region studied. The distribution pattern can indicate the transport of coarse clastic material from the north and from the south, i.e. from exposed zones of Iranian and Arabian Plates, which is proved by the finds of conglomerates containing highly weathered crystalline rocks in the Chah Musallem plug.

The distribution patterns of dark shales (Fig. 14) is highly irregular, but in general, they occupy the NE-SW trending broad zone, interrupted by the NW-SE trending zone, where dark shales are absent. The influence of N-S trending lines is also detectable, but not distinct. Dark shales represent deposition in starved lagoonal basins with reduction regime at the bottom, and, in some places (Chah Musallem plug), they appear as the lowest bed of the transgressive sequence on lateritically weathered surface of sandstones to greywackes.

Facies distribution of individual lithofacies types was clearly governed by the structural scheme and evolution of the Hormoz depositional basin which developed in tension zone limited by deep (crustal) fault zones. The projection of N-S (NNE-SSW to NNW-SSE) trends in the combination with the NE-SW trending zones and in a lesser extent also NW-SE directions influenced basically facies boundaries and extent of uplifted or subsiding zones (Fig. 39).

The material of red beds was derived from deeply weathered horizons having character of red weathering products to laterites. The lateritization was simultaneous with the deposition of the Hormoz Complex, as indicated by the occurrence of thin lateritically weathered sandstones in the Bustaneh plug. Intensive weathering destructed also volcanic products supplying unstable components to the depocenter. The kaolinitic portion of destructed weathering crusts is not preserved owing to limited stability of kaolinite which recrystallized to sericite.

The participation of light-colored volcanoclastic deposits in the composition of blocks in plugs is presented in Figure 33. There is expressed continuous decrease of such lithotypes from the SE to the NW, proving the most intensive volcanic activity close to the Oman line. The volcanism was bounded to deep crustal fault lines (e.g., Espahbod 1990) and it appeared on the surface, without any doubts, in several volcanic centers, as indicated by lava flows within blocks in different plugs. Pillow lavas indicate also submarine effusions (e.g., Gansser 1960).

8. Contributions to economic geology

(J. Spudil and P. Sulovský)

The low abundance of basement rocks at the surface of salt plugs makes them unimportant with respect to ore mineralization. It is therefore of no sense to devote special interest in this structural level.

Much more important position within the area studied is held, from the ore survey point of view, the upper structural level (platform cover). Of it, most interesting are early platform stage and real platform stage, which can serve both as potential source and as hosts to ore mineralization.

8.1. General characteristics of structural levels of interest

8.1.1. Early platform stage

Already the stratigraphic position of the rocks of the Hormoz Complex (possibly also of their basement) to some extent predetermines the possible nature of the mineralization. This follows from a number of studies on rocks of Precambrian or Early Paleozoic age in the whole world. Typical features of mostly volcano-sedimentary series (so called riftogenic complexes, consisting of alternating clastics, carbonate rocks, evaporites and volcanogenic rocks of very variable composition) is the presence of banded iron formations of the SVOP (shallow-volcanic-platform) or SOPS (sandy, oolite-poor shallow-sea) type in the sense of Kimberley's (1989) nomenclature. The occurrences of minerals of Cu, Co, Ba, U, Fe and carbonates, but also of Ti, Pb, Zn, Mo, P (apatite), Au, Ag, possibly even Pt and Pd are connected with strong, extensive alterations like silicification, hematitization, carbonatization, chloritization and alkaline metasomatism or with typical hydrothermal solutions (Bell 1989). According to Samani (1990), the Hormoz Complex as well as other rocks of Precambrian to Cambrian age in Iran (above all in its central part) are not only of the same age, but display also similar petrological, structural, and minerogenetical characteristics.

The overview of ore deposits or notes on their occurrences are given in a number of older papers (e.g., Pilgrim 1908, Ladame 1945, Hirschi 1944, Walther 1960). Short, but quite comprehensive overview of the metallogenesis of Precambrian (in our meaning of basement and rocks of early platform stage) was lastly published by Samani (1988). Deposits of industrial minerals bounded to rocks of this age were off the focus of ore geologists. The existence of sulfur deposits, evaporites, building and other materials was considered as natural, therefore much less attention was paid to them, than to ore occurrences.

8.1.2. Real platform stage

The second type of mineralization, known for many years, is connected with the so called cap rock. The ore occurrences connected with cap rock include sulfur, iron sulfides and base metals, sulfates (e.g., barite); uranium occurs in it less often. During all stages of salt dome evolution we can meet a whole number of geochemical reactions, modified above all by hydrogeological conditions. The mineralization processes are very complex and up to now difficult to explain. Most processes leading to accumulation of minerals in the cap rock of the salt diapir are influenced above all by interaction of salt with solutions of various origin. The basic transport medium is meteoric and marine water of shallow circulation, most often in the brecciated marginal zone of the salt plug and in the fissure system of the plug. Both types of structures greatly influence the circulation of water solutions as well as the configuration of the salt dome, its thermal regime and other characteristics. Both salt movement due to diapirism and its dissolution cause formation of local depressions in the domes, in which various, mostly porous types of rocks subsequently deposit. During interaction of underground water mineralized with hydrocarbonates and CO₂, these layers may become calcitized; subsequent metasomatic replacement of Ca by divalent metals is common, especially dolomitization.

8.2. Deposits and their indices

Deposits were not subdivided according to individual structural levels, as they can be mixed by the redeposition. Nevertheless, genetically different deposits are connected with salt plugs. Metallic and non-metallic deposits occur, as well as caustobioliths. Single genetic type of deposit can be utilized for different purposes, therefore it can be classified as metallic and nonmetallic raw material.

8.2.1. Metallic raw materials

Different types of iron ores are typical for the Hormoz Complex and the close plug surroundings. Walther (1960) describes three generations of hematite mineralization in the Hormoz Complex and overlying younger sedimentary rim. Six genetic types were divided (iron rich plug rim, hematite ochres with small crystals, hematite veins of metasomatic origin, limonite ores of Tertiary sediments, Recent to subrecent placers, evaporite crusts enriched in Fe³⁺ minerals). Hematite rich zones have been reported by Diehl (1944) and Ladame (1945) from Hormoz, Larak, Hengam, Bustaneh, Gachin, Puhal, Champeh, Chah Musallem, Charak, and Kurdeh plugs. Earthy hematite ochres (primary mineralization of banded iron ore type) have been explored, up to now, as a mineral dye. They occur usually in marginal plug zones in situ (several meters to tens of meters in thickness) or reworked and redeposited near plugs. Hematite from ore bunches or veins (secondary hematitization by metasomatosis) was utilized most probably also as iron ore. Well crystalline apatite occurs close to ochre deposit in Hormoz Island. Similar paragenesis was discovered e.g., by Huckriede, Kürsten and Venzlaff (1962) in Kerman-Baqf region in rhyolites and other volcanogenic rocks (Desu and Ricu Formations). The enrichment in iron minerals is typical also for some younger sediments, e.g., in Agha Jari Formation (cf. shallow magnetic bodies of Yousefi and Fridberg 1978a-c).

Copper mineralization is connected with some basic magmatites, mostly in the form of malachite. Archeological finds proved the existence of prehistoric copper smelting works near Chahal plug (Kent 1979). Copper mineralization occurs also in red shales with gypsum interbeds of the Hormoz Complex (Meggen depositional type), e.g., in the Chah Banu plug.

Molybdene mineralization is petrogenetically connected with acid eruptive rocks. Mo mineralization (uranium molybdenate - umohoite, calcium molybdenate - powellite) was detected in larger extent in some geochemical samples from the Gachin plug.

8.2.2. Non-metallic raw materials

Rock salt (halite) has been exploited in numerous sites, e.g., in Hormoz and Namakdan plugs. Clastic sedimentary rocks are utilized for ballast and for production of asphalt mixtures in road construction. Acid tuffogenic rocks and sometimes also basic eruptive rocks represent popular building stones for easy treatment and favorable isolation properties. Partly decomposed blocks and boulder occurring in riverbeds are especially utilized. Larger cobbles and pebbles are exploited, too.

Tertiary and Mesozoic carbonate rocks and marshones are utilized for the production of building materials, cement and lime (e.g., Guri, Jahrom, Pabdeh-Gurpi and other formations). Gypsum serves for the production of plaster of Paris (Gachsaran Formation being the most common source). Sulfur was mined in Khamir and Bustaneh plugs (*cf.* Jenkins 1837, Pilgrim 1908) from cap rock and sulfur-impregnated hydrothermally altered rocks. Bricks have been produced from Recent to subrecent eolian accumulations or from claystones or marlstones (e.g., Mishan Formation). Fluvial and alluvial deposits are exploited as building stones.

8.2.3. Caustobioliths

Hydrocarbon deposits in exploitable amounts have not bee discovered in the region studied. Nevertheless, indices of them are present. Borehole He E1 (Hengam) proved crude occurrence in the boundary of Ilam and Sarvak Formations during offshore drilling by the SOFIRAN. Gaseous occurrences are known from numerous sites, e.g., from Qeshm Island (Pilgrim 1908) or at Sarkhun North of Bandar Abbas (Motiei 1990). Indices of heavy oils or asphalts were registered by previous geological mapping in Kuh-e Gavbast, Kuh-e Shu, Kuh-e Khamir, Kuh-e Anguru, Kuh-e Genow, Kush Kuh. Sulfur springs were supposed in the past as indications of hydrocarbons, too.

9. Conclusions

(P. Bosák)

Regional reconnaissance study of salt plugs covered the area of about 50,000 square kilometers (coordinates 53°50' to 56°30' E and 26°30' to 28°15'N). Altogether 68 salt plugs were characterized from the viewpoint of their position in the structure of area, morphological and evolution stages, rock content and mineralization.

Salt plugs are emplaced within the Fold Belt of the Zagros Mts. composed of huge and elongated anticlines with the dominant NW-SE trends. The intensity of overfolding of anticlines over synclines simultaneously increases generally northwards due to the transition of the Fold Belt into the Imbricated Zone of Zagros. The Fold Belt is subdivided into southern coastal subzone of "low" folds and into the northern subzone of "high" folds.

Two structural levels are distinguished in the studied region: (1) basement level and (2) platform cover. The basement is of Proterozoic age representing epi-Pan African Platform which is an integral part of the Arabian Shield. It is supposed, that platform cover started with the deposition of the Hormoz Complex over peneplanated basement. Platform cover is represented by over 10,000 m thick sedimentary pile. Several evolutionary stages can be stated in the platform cover: (1) early stage, mostly evaporitic (evaporite-clastic-carbonate megacycle of the Hormoz Complex and correlative formations; late Precambrian to Middle? Cambrian), (2) transitional stage (complex periods characterized by numerous breaks and sometimes by weak metamorphism ending by the extensive Permian transgression), and (3) real platform stage (since Permian, stable platform conditions prevailed with platform carbonates, passing in Cenozoic to evaporite-clastic and evaporite-carbonate units and terminating by clastic late Cenozoic to Quaternary deposits).

Relics of *basement rocks* are included in salt plugs, which represent typical tectonic windows. Coarse-grained rocks with gabbroid texture, pegmatites, aplites or coarse-grained granitoids are common within igneous rocks. Regionally metamorphosed rocks are represented by mica schists and metadiabases, belonging to the greenschist facies (biotite zone), possibly also to metamorphically higher almandine zone of the epidoteamphibolite facies (gneisses), and zoisite-hornfelses and similar rocks with abundant occurrences of blue fibrous alkaline amphibole (magnesioriebeckite). Contact metamorphosed rocks - the most common garnetiferous calc-silicate rocks - show a remarkable spread of values of the isotopic composition of carbonate carbon, indicating locally very variable temperature of contact metamorphism and/or input of carbon from the magmatic rock.

The *basement structure* can be deciphered from the structural plan of the platform cover. It is supposed, that most of large fault systems dissecting the platform sedimentary cover are projections of basement structures. Old, N-S basement trends of the Arabian Platform are distinguishable in Zagros Mts. as zones of normal and transcurrent faulting with associated facies changes and anticlinal plunges. In some places, younger Zagros trends are superimposed on the older, N-S trends. In the studied area, there are relatively numerous manifestations of the SW-NE trending structures. They are clearly visible in the coastal region and from the delineation of some salt plugs. This trend, roughly perpendicular to the Zagros trend, caused also the bending and plunging of some anticlines. Geophysical data indicate that the top of basement ascends from the S to the N in general, i.e. from the axis of Khalij-e Fars where lies at the depth of 12,000 m b.s.l. in direction to the Main Zagros Thrust where occurs at about only 4,000 to 5,000 m b.s.l. Behind the Main Thrust, basement abruptly rises to about 0 m.

Seven large sedimentary megacycles separated by more or less distinct disconformities and unconformities compose the real platform stage: (1) Permian (Permo-Carboniferous) to Triassic, (2) Lower Jurassic to Lower Cretaceous; (3) Lower to Upper Cretaceous; (4) Upper Cretaceous; (5) Upper Cretaceous to Eocene; (6) Eocene to Middle Pliocene, and (7) middle Upper Pliocene to Quaternary. On an average, each megacycle is 600 to 1,500 m thick. Several new lithostratigraphic units were newly distinguished within this stage. The Bangestan Group wass newly subdivided into Lower Bangestan Subgroup (Kazhdumi and Sarvak Formations) and into the Upper Bangestan Subgroup (Surgah and Ilam Formations). Both Subgroups are separated by an important tectono-erosional so-called "post-Cenomanian" event of orogenic nature accompanied by subaerial erosion, paleokarstification and even bauxite formation. The Lower Bangestan Subgroup represents the top of the second megacycle, the Upper Bangestan Subgroup forms the lower part of the third megacycle. The Mishan Formation has been subdivided earlier (James and Wynd 1965 and others) into the Guri Limestone Member and undivided Mishan Formation. Because this state does not represent the real situation in the region studied, the Formation was subdivided by Bosák and Václavek (1988) into: (1) lower part, i.e. the Guri Member (limestones), and (2) upper part, the Kermaran Member (mostly marls). The name Kermaran Member, although reflecting real geological situation and geographical position, is not proper from the priority point of view, because James (1961) used term Anguru Marl. Therefore, we are returning to this older name. Upper marly sequence of the Mishan Formation is named here as the Anguru Member.

The *platform cover* of the Zagros Fold Belt is characteristic by large anticlinal and synclinal structures. Regional folds are dominant in the structure. The folding encompasses Phanerozoic sedimentary pile as thick as 8 to 10 km. The pile is separated from the basement of the Arabian Platform along decollement in the level of the Hormoz Salt. Besides this basal decollement, inter- and intraformation horizons of partial or local decollement have to be taken into account in the level of extremely plastic members of some formations, like the Hith Anhydrite (Jurassic) or evaporites in the Gachsaran Formation (Miocene).

Regional *anticlines* are large open structures separated by narrow, often squeezed synclines. In the section, folds attain rounded or box-like shape. The folds are mostly unbroken, doubly plunging, and asymmetric with steeper southern flanks and gentler northern ones. Axial fold planes dip NE at an angle usually exceeding 60°, thereby clearly verging SW toward their foreland, near the coast axial planes are subvertical. The apical angle of 0° is typical for nearly all folds. The fold asymmetry decreases from the N toward the coast in the S, where folds are nearly symmetric. The southern flanks are often disturbed by thrust planes or by displacement of anticlines over synclines. Steeper southern slopes of anticlines show gravity collapse tectonics (folds, cascades, rock slides). Fold parameters are highly variable, depending on the lithology; they attain the maximum values in thinly bedded rocks (marlstone, claystone). The fold parameters indicate a SW-NE to S-N oriented compression.

The *unconformity* at the base of the Bakhtyari Formation was newly detected by the study of satellite images. It is expressive in more compressed synclines in the N, where the Bakhtyari Formation lies on Agha Jari Formation folded in more detail. Locally, the Bakhtyari Formation lies on older formations, too. Two folding phases are indicated by the position of the Bakhtyari Formation: (1) the older one prior the deposition of the Bakhtyari Formation, and (2) the younger one after the deposition of the Bakhtyari Formation which completed (compressed) the anticlinal and synclinal structures of the older phase.

Fault structures within the platform cover are characterized prevailingly by small, short normal faults with low amplitudes. The fold structure is cut by subvertical faults, partly longitudinal, mostly transversal to diagonal, except of probably flat overthrusts (displacements) of anticlines. Numerous faults show features of normal faults or wrench faults. Large fault structures influence the course of fold axes, and, contrary to the small faults, are only hardly distinguishable in the field, but highly expressive on satellite images of different types. They mostly represent projections of basement structures, usually they occur as relatively broad and complex zones, and often reveal higher seismicity. In the studied area, there are relatively numerous manifestations of SW-NE structures, parallel with trends in the Dasht-e Kevir area, clearly visible in the coastal region. This trend, roughly perpendicular to the Zagros trend, caused also the bending and plunging of some anticlines. The orientation of fault structures shows local irregularities distinctly depending on irregularities of fold (anticline) axes.

The interpretation of satellite images shows that the network of photolineations and regional photolineaments is very dense. Several basic trends can be distinguished: (1) NNW-SSE to N-S passing sometimes to NW-SE direction, (2) NNE-SSW, (3) NW-SE, (4) NE-SW and (5) W-E. The interpretation shows, that some structures have a character of regional photolineaments (especially NNW-SSE and NE-SW trending). Such structures were supposed to be main fault systems of the region. Their composition is not single. Such structures commonly form broad zones of densely packed lineations, more or less continuous. They often have a character of dextral and sinistral strikeslip faults with some normal component. It appeared that the proportion of left-lateral faults is haigher tha supposed ealier. Minor structures are often connected with main photolineaments and photolineations showing pattern of pair system antithetic to main structure. En echellon arrangement of photolineations is very common feature indicating torsion forces caused by the rotation of individual structural blocks of variable sizes and orders, a phenomenon connected with strike-slip faults.

Hydrogeological works proved the existence of regional and local aquifers. Upper regional aquifers are situated in the Bakhtyari Formation filling most of synclines, the lower is connected with Paleogene limestone units. Both aquifers are separated by the aquiclude of Agha Jari and Mishan formations. The weathered zone of salt plugs shows its own hydrogeological regime and aquifers. Groundwater show usually increased temperatures up to 60 °C indicating very deep groundwater circulation to depth up to 1,100 m below the surface. Some springs close each to other show different temperatures caused either by mixing with water from the aquifer of the anticlines or by an independent ascent way with lower flow velocity so that cooling takes place. The water temperature in infiltration area (cold) and in the dewatering branch (warm water) affects the density of water circulating in the aquifer. These changes of density contribute to the activation of water circulation in the geohydrodynamic system. High temperatures of groundwater in flow openings indicate rush ascent of water from the depth where it is warmed up to the surface. Groundwater is usually highly mineralized. Waters of the upper aquifer with the mineralization 1,298 mg.l⁻¹ to 5,540 mg.l⁻¹ can be classified as brackish water. Waters from the lower aquifer have a total mineralization from 10 g.l⁻¹ to 44 g.l⁻¹ and can be calssified mostly as brines. Springs belonging to the lower aquifer have a characteristic content of gaseous H₂S coming from the microbial activity of desulfurising bacteria.

Salt plugs were classified into three structural-morphological groups (circular, linear and combined). Circular plugs are usually encircled by more or less distinct cauldron. They are commonly small with diameter up to 3 km. Concentric to spiral internal structure is typical for some plugs. This is caused by continuous, long-lasting and slow influx of plug material. Its differentiation was in progress, probably, due to salt dissolution especially in marginal zones during more intensive material supply in the plug center (irregular supply in nearsurface zone). Linear salt plugs are concentrated into tectonically predisposed and strongly affected zones or structures functioning during diapirism. Typical cauldron is missing around those plugs. Two types can be distinguished within the linear plugs: (1) classical veins usually several hundreds of meters thick and several kilometers long, and (2) veins with the length of few kilometers and width of 1 to 2 km (veiled veins with the original part of such plug is of vein character passing through tonguelike part into glaciers flow; combined circular and vein-like plugs with highly tectonized plug proper in the center of the structure and with promontories of classical veins into one or more directions, or veins accompanying the plug in small distances).

The size of salt plugs usually varies between about 1 and 15 km (along longer axis). The maximum is between 16 and 17 km. According to size, plugs are distinguished as *small* (below 4 km in diameter) and *large*. Large plugs were registered in the southern part of the studied region. Smaller plugs occur to the north. The plug position was influenced by the intensity of folding movements and squeeze, distinctly less intensive in the south. Plug linearity is therefore increasing northwards.

Salt *glaciers* originated in surficial conditions by increased creep caused by the hydratation of salts. Movement of glaciers can be very fast if supplied by salt from plug vent. No anomalously increased temperature is needed to start the glacier flow.

Activity of plugs was divided into three traditional groups, i.e. active, passive and ruins, each of groups being subdivided into three subgroups. Completely new criteria were adopted to estimate the activity in the most objective manner. The basic characteristic of *active* plugs is a positive relief and lacking collapse structure, periclinal stream network and dominant role of evaporites. *Passive* plugs contain only small surface occurrence of salt, which amount gradually decreases as plug is degraded. The portion of gypsum relatively increases. In suitable morphological conditions, collapse structure develops in more and more evolved stage. The abundance of karst forms is also variable depending on proportion of evaporites and other rock at nearsurface level and plug morphology. Different types of drainage network can be observed. *Ruins* of salt plugs are typical where the diapirism has ceased long ago. Generally negative morphology is typical if cauldron is developed. Indistinct morphology characterizes plugs without cauldron. Soft morphology of relics of the Hormoz material is built of rounded hills protruding through Recent and subrecent sediments (deluvia, alluvia, marine deposits etc.). Relics of the Hormoz material are often occurring on cauldron slopes as several meters thick layers owing to high alteration and ferruginization. Halite was mostly leached away, its occurrence in deeper parts of plugs cannot be excluded. Karst forms are missing. Dendritic network of intermittent streams prevails in a combination with other drainage types. Centriclinal drainage emptying into linear (parallel) network can occur. Unbreached salt plugs are represented by a distinct circular, egg-shaped and heart-like structures on the surface. Their occurrence is highly limited. Some of earlier distinguished unbreached plugs represent rather a combination tectonic features than a indication of salt plug.

It is shown, that "collapse structures" are connected rather with other processes than solution collapse after leached salt. They are subdivided into: cauldrons, pseudocauldrons and other structures. *Cauldrons* are circular, elliptical to irregular structures occurring mostly in connection with salt plugs. They are simple or complex. Complex cauldrons are double in places, eventually also triple. Their horizontal diameter varies from 2-3 km up to 25 km (along longer axis). Ideal funnel shape, mostly elliptical, less frequently circular in plan, occurs only rarely. Tectonic effects, erosion and pedimentation took part substantially in the formation of cauldrons. Linear cauldrons are connected with tension regime in the apical zone of anticlines. *Other forms* and *pseudocauldrons* result mostly from erosional processes.

Prevailing amount of plugs lies in the flanks of anticline folds and is bounded to fold plunges and sigmoidal bends, where the most favorable conditions are established for the salt plug intrusion. The position of plug is strongly influenced and/or predisposed by basement tectonics. Primary and secondary rim synclines have not been yet detected.

The origin of salt plugs was a multicyclical process intensively active at least since Paleogene and it is connected with folding during the collision of continental and oceanic crust of the Arabian Platform and the Iranian Platform. Precambrian Hormoz salt has risen diapirically from depths of 5 to 10 km through the whole Phanerozoic sedimentary pile. The plug activity and ascend was influenced by movement on faults of basement. The average ascend rate of about 150 to 200 m per one million of years can be stated.

The Hormoz Complex consists of rock salt and associated sedimentary, igneous and metamorphic rocks displaying astonishing variability within rock groups, but also within each narrow family of rocks. This is conditioned by a multitude of processes, taking part in the formation of the Hormoz Complex and in the history of subsequent diagenetic changes, hydrothermal alteration, metasomatism, diapirism, and other interaction with solutions of varying origin and composition, weathering etc. Sedimentary rocks are represented dominantly by lithologically variable red beds (shales to conglomerates). The study of organic matter in dark shales indicate its origin from algae and lower animals. Detected normal alkanes show smooth to indistinct odd predominance and low concentration. It can be stated, that the temperature of maturation did not reach 300 °C. Relatively very high proportion of n-alkanes with higher C number can indicate maximum temperatures of maturation even below 200 °C. Red beds were deposited in the coastal region in alternating shallow marine and continental conditions. Cyclic character of some sequences resulted from ingression-regression regime in the basin. Shallow marine environment varied between subtidal to supratidal zones. Flyshoid-like sequences were deposited in shallow shelf conditions and represent product of relatively calm depocenter, partly of submarine delta lobes. Light-colored, cross-bedded sandstones represent shore facies (beachrock) and sand bars. Part of red beds was deposited under continental conditions on broad and flat coastal alluvial plains encircling marine coast. Thin limestone intercalations in red bed are connected either with limited marine ingressions and/or with lacustrine precipitation from mineralized lake waters, similarly to other red beds. Limestones are less common. They were deposited dominantly in intertidal to lagoonal environment, especially if alternating with gypsum, dolostone and certain red bed lithologies. Nodules after leached, silicified and carbonatized gypsum/anhydrite indicate inter- to supratidal origin of some layers. Limestones can represent basal part of transgression-regression cycle deposited on foreshore-offshore shallow marine environment connected with open shelf conditions. The dolomitization of limestones is connected clearly with their position within the depocenter. Sabkha-evaporation and seepage reflux models of dolomitization can be adopted here. Dolostones are represented mostly of dark fetid lithotypes. The character of dolostone appearance indicate the connection with evaporite-clastic-carbonate sedimentary cycles as a part of evaporitic sequence of tidal origin. Authigenic quartz crystals are commonly supposed as indicator of highly saline environments. Silica supply was from decomposed acid volcanic and volcanoclastic rocks. Gypsum is very common evaporitic rock within salt plugs with a thickness up to 100 m. The content of gypsum is clearly higher in the N and NE, while in the SE the halite is present also in highly ruined plugs and gypsum occur in limited amounts. Rock salt (halite) is a basic constituent of many plug, mostly active ones. In places, salt contains interbeds of layered gypsum with dark dolostones, dark fetid crystalline gypsum with ferrugineous bands, and sandstones, siltstones, tuffitic rocks and carbonates, and even accumulations of rock debris resembling fossil scree falling into salt depositional basin or transported by superficial weathering products. The proportion of salt in individual plugs depends on primary content of salt beds in the Hormoz depositional basin. Cap rock is the uppermost part of many salt plugs, especially occurring on the subsurface. Its absence can be ascribed to the fracturing, dissolution and collapse of diapiric summits. Brownish gypcrete of variable thickness from about 3 m up to 10 m covers the surface of many plugs. In active plugs, the gypcrete covers the summit plateaus and flat surfaces originated by the dissection and uplift of original summit flat surfaces. The origin of the brownish sandy gypcrete can be connected with the stabilization of plug uplift and weathering of plug material where formed mostly by the hydratation of anhydrite This type of crust can also represent altered (hydrated) anhydrite cap rock. Calcretes, dolocretes, gypcretes and silcretes occur in various lithological compositions and lithostratigraphical positions within numerous salt plugs. The occurrence of crusts was observed within light-colored sandstones, inside sequences of acid volcanoclastics, in the connection with red beds, especially at red bed/gypsum interfaces. The most common development of crusts is connected with volcanoclastics. Crusts show very uniform evolution in the whole region, even when developed in sequences of different lithologies. The deposition of such crusts is connected with extremely shallow marine depocenters connected with drop of sea level and evolution of shallow lagoonal hypersaline to inter- and supratidal environments. Pedogenic alteration, ferruginization, desiccation and other features indicate periodical emergencies, erosion and weathering not only of underlying complexes, but also of crusts. Crust evolution is connected with the cyclicity of the Hormoz Complex, showing the presence of cycles of the fifth and fourth order. Hypersaline conditions of deposition are evidenced by prints of halite and gypsum in dolostones and shales, as well as in the presence of gypsum/anhydrite as intercalations in crusts. Dolostones are partly primary precipitate and partly they represent replacement of limestone to calcrete horizons by dense Mg-rich brines in sulfate-rich environment. The presence and reworked clasts of oolitic to pisolitic iron ores in psammites and ferrolites, and the occurrence of berthierine cement indicate that classical iron ores developed in the shallow inter- to subtidal agitated environment supplied in iron. Gypsum crusts are mostly product of lagoonal deposition.

Volcanic rocks of the Hormoz Complex form an essentially bimodal association with distinct predominance of felsic volcanics. Basic volcanics include fine- or coarse-grained olivine tholeiite, less often quartz tholeiite. The trace element chemistry of the basic effusive rocks is characteristic for within-plate environment to transitional volcanic arc/within-plate collision zone. Syn-collisional setting can be inferred from trace element patterns of the felsic volcanics, implying a common source for the bimodal volcanism. The bimodal nature of the volcanic suite suggests it formed in an intracontinental rift setting. Intermediate members of the volcanic suite, andesites, occur in subordinate quantities. The most abundant volcanic rocks occurring in the salt diapirs are *felsic volcanic rocks* ranging from alkalifeldspar rhyolite through rhyolite and rhyodacite to dacite. They are accompanied by tuffs, tuffites and ignimbrites. The most pronounced alteration process can be described as alkali metasomatism. Both albitization and microclinization have affected rocks of the rhyolite clan. The intensity of potassium metasomatism can be documented by the fact, that about a half of the rhyolite samples has K₂O content higher than any other published rhyolite or alkaline rhyolite data. The trace element geochemistry of felsic effusive rocks is best comparable with the pattern of I-type rhyolites. At roughly comparable K level, the Hormoz Complex rhyolites are up to five times higher in Rb than average I-type rhyolites and 2-3 times in Nb. Conversely, they are a bit depleted in Zr. The mineral characteristics and textural features of these rocks indicate they emplaced in shallow submarine to subaerial environment, probably during periodic oscillations of the sea level with occasional drainage of the shallow basins. Hydrothermal alterations of the volcanic rocks are common and widespread. The intensity of alteration processes was very high, leading to unique chemistry of altered rocks. A large part of the felsic volcanic and concomitant volcanoclastics were subject to strong potassic metasomatism. Common occurrence of minerals that adopted large amounts of chlorine in their structure (Cl-kaersutite, potassian chlorian hastigsite and other alkali amphiboles, scapolite, even neo-formed microcline) suggest highly saline fluids (evaporitic brines?) took important part in the metasomatic process.

The soliferous Hormoz Complex was deposited in Upper Precambrian (Riphean-Vendian) to Middle Cambrian on rifted continental margins of Arabian Plate in a rectangular basin limited by deep (crustal) faults. New fossils have not been found. The Hormoz Complex represents product of deposition in evaporitic basin with multicyclic nature and repeating horizons of salts and other evaporites within carbonate-clastic-volcanosedimentary accumulations. The percentage and thickness of gypsum and especially of salt decreased from the center of the basin towards its margins. Predominance of acid volcanics and volcanoclastics is bound to the southeastern part of the region close to the Oman line. Distribution of individual lithofacies types was clearly governed by the structural scheme and evolution of the Hormoz depositional basin The projection of N-S (NNE-SSW to NNW-SSE) trends in the combination with the NE-SW zones and in a lesser extent also NW-SE directions influenced basically facies boundaries and extent of uplifted or subsiding zones.

Explanations to Figures 40 to 42





Figure 40. Structural scheme of disconformities, faults, overthrusts, folds, salt plugs and cauldrons (compiled by Jaroš 1992, reinterpreted by Bosák 1993).





Figure 41. Photolineaments and photolineations deduced from satellite images (interpreted by Jaroš 1992) and air photos (interpreted by Bosák 1992/1993).





Figure 42. Scheme of main faults as interpreted from satellite images and air photos (compiled by Bosák 1993).





Figure 43. Profiles of gypcretes in volcanoclastics and acid volcanic rocks in the Gachin plug.



Explanations to Figure 43

STRUC	TURES	LITHOLOGY		
			very fine-grained tuff homogeneous	
	BEDDING		very fine-grained tuff, laminated	
			very fine-grained tuff, banded	
777	crossbedding		very fine-grained tuff, crossbedded	
	LAMINATION		gycrete, laminate	
	narallol	0°0°0	fine-grained tuff with lapilli	
	paraller		fine-grained tuff, laminated	
\approx	wavy		fine-grained ash tuff	
¥ =	flaser	(fine-grained ash tuff, laminated	
\\\\.			fine-grained ash tuff, thinly bedded	
	cross		altered, pedogenic horizon	
\sim	ripple marks	\	fine-grained sand tuff	
	convolute		sand tuff, crossbedded	
	convolute		sand tuff	
	scours with crosslamination		sand tuff, thinly bedded	
	BOUNDARIES OF LAYERS	6.00	sand tuff with volcanic bombs	
		660	tuff with abundant volcanic bombs	
	transitional	0.0	conglomerate composed of bombs	
	sharp	(SOS	conglomerate composed of bombs	
\sim	erosional		boulder conglomerate	
C	ciosionai		massive tuffs to rhyolites, altered	
~~~~	smooth	$( \  \  \  \  \  \  \  \  \  \  \  \  \ $	massive tuffs to rhyolite	
			rhyolite	
			ferruginous gypcrete to ferrolite	

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## Appendix

#### Characteristics of salt plugs

The Appendix represents the compilation of all available data concerning individual 68 salt plugs in the studied region obtained from field observations and from the literature. Characteristics of salt plugs are represented by: morphological characteristics (i.e. coordinates, location, size, activity, morphology and geomorphology), hydrological characteristics (i.e. springs, streams, chemistry, yield), regional geological position, petrological characteristics of the Hormoz Complex, and references concerning the respective plug (see references above). Most of salt plugs are illustrated by the plug drawing (sketches) expressing only the most important features (plug contour, photolineations where available from air photos, morphological features, salt glaciers, planation surfaces, cauldrons etc.). Topographic features are not included owing to poor quality of available copies of 1:50,000 maps. For regional position of plugs see Figure 40.

For the better orientation and owing to the fact that some plugs were unnamed or they were mentioned under several names (Tab. A1), in the studied region, the plugs were numbered from 1 to 68, i.e. from E to W and from S to N. Previous number of salt plugs presented by de Böckh, Lees and Richardson (1929), completed by Harrison (1930), and used by Kent (1958; column 1 in Tab. 19) was not adopted during field operations for several reasons: (1) previous authors did not mention all plugs in the region; (2) number order was a bit chaotic as plugs were numbered gradually in order of individual, subsequently following trips, and (3) our exploration did not cover some islands in the Khalij-e Fars (Persian Gulf).

#### Table A1. List of salt plugs

No.	Name	Synonym
1	Hormoz	Ormuz (Tietze 1879, Cornu 1907)
		Hormuz (Harrison 1930)
		Hormouz (Ladame 1945)
		Hurmuz
2	Larak	Larrak (Tietze 1879)
		Larek (Whitelock 1838, Stahl 1911)
3	Hengam	Anjar ( <i>Whitelock 1838</i> )
		Hanjam (Blanford 1872)
		Henjam (Pilgrim 1908, Krejci 1927, Harrison
		1930, Hirschi 1944)
4	Namakdan	Kischm ( <i>Tietze 1879</i> )
		Quishm (Lees 1927, Harrison 1930, Heim 1958)
5	Berkeh-ye Suflin	Homeiran
		Hamairan (Krejci 1927, de Böckh et al. 1929,
		Hirshi 1944, Trusheim 1974,
		Davoudzadeh 1990)
6	Band-e Muallem	Band-e Mu´allem (James 1961)
		Al Busa (Hirshi 1994, Trusheim 1974)
		Al Buza (Krejci 1927, de Böckh et al. 1929)
		Buza (Davoudzadeh 1990)

No.	Name	Synonym
7	Bustaneh	Bustanou (de Böckh et al. 1929, Richardson 1928)
		Bostaneh (de Böckh et al. 1929, Ladame 1945)
		Jabel Bustaneh ( <i>Diehl 1944</i> )
8	Moghuieh	Ras Yarid ( <i>de Böckh et al. 1929</i> ) Mughoyeh
9	Chiru	Gurzeh (de Böckh et al. 1929) Kalat (Kent 1979, Davoudzadeh 1990)
10	Gachin	Bostanah ( <i>Tietze 18</i> 79) Bostanuh ( <i>Walther 1</i> 972) Gätschin ( <i>Heim 1956</i> ) Khanet Surkh ( <i>Kent 195</i> 8)
11	Puhal	Pohal Pojal Pujal ( <i>Heim 1958</i> )
12	Khamir	Cummeer ( <i>Jenkins 1837</i> ) Kuh-i-Pul-i-Khamir ( <i>Wilson 1908</i> ) Kiamir ( <i>Stahl 1911</i> )
13	Mijun	
14	Do-Au	Do-Aby
15	Zendan	Zandan
16	Champeh	Kuh-i-Champh (Walther 1960)
17	Chah Musallem	Chah-i-Musallam ( <i>de Böckh et al. 1929</i> ) Kuh-i-Schah-i-Mussalam ( <i>Diehl 1944</i> ) Kuh-i-Cha-i-Mussalim ( <i>Walther 1960</i> )
18	Charak	Deh Nau ( <i>de Böckh et al. 1929, Diehl 1944</i> ) Dehnow ( <i>Ladame 1945</i> ) Deh-i-Nau ( <i>Walther 1960</i> )
19	Genah	Jebel Turanjeh ( <i>de Böckh et al.</i> 1929) Darbast ( <i>Kent 1958</i> ) Janna ( <i>Davoudzadeh 1990</i> ) Jenah
20	Qalat-e Bala	Tehru ( <i>de Böckh et al.</i> 1929) Kalat ( <i>Kent</i> 1958) Kalat-Bala ( <i>Walther</i> 1972) Qualat-e Bala ( <i>Samani</i> 1988) Ghalat-e Bala Khalat-e Bala
21	Anguru	Kuh-i-Namak-i-Anguru ( <i>Wilson 1908</i> ) Anguran
22	llchen	Kuh-i-Irche (Harrison 1930)
23	Chahar Birkeh	Mehran (de Böckh et al. 1929)
24	Gezeh	Fariab ( <i>de Böckh et al. 1929</i> ) Geze

No.	Name	Synonym
25	Khemeskh	Kuh War? ( <i>de Böckh et al. 1929</i> ) Khemishk ( <i>Kent 1958</i> )
26	Takhu	Tang-i-Bouharegh ( <i>de Böckh et al. 1929</i> ) Khushk Kuh E. ( <i>Harrison 1930</i> ) Kuh-i-Khushk ( <i>Walther 1</i> 972) Khush Kuh
27	Khurgu	Khorgu Kuh-i-Namak (Lees 1927, de Böckh et al. 1929, Fürst 1976)
28	Genow	Ginao ( <i>de Böckh et al. 1929</i> ) Ginau
29	Gurdu Siah	Kuh-i-Girdu Siahl also Gurdu Siah ( <i>Harrison 1930</i> ) Girgu Siah also Guniz ( <i>Kent 1958</i> )
30	Shu	Sho Kuh-e Shoor ( <i>Ala 1</i> 974)
31	Bam	Tudiran ( <i>de Böckh et al. 1929</i> ) Tang-e Bam Kuh-i-Bam also Kuh-i-Abad ( <i>Trusheim 1974</i> )
32	Zangard	Zangur (Harrison 1930)
33	Pordelavar	Bastak E (de Böckh et al. 1929)
34	Gavbast	Bastak NE (de Böckh et al. 1929) Bastak (Diehl 1944, Walther 1960)
35	Bongod-e Ahmadi	Bongold-e Ahmadi Sipah Pir-Alan-Sabz ( <i>Harrison 1930, Walther 1972</i> )
36	Kajagh	Ahram also Kuh-i-Qaeh-i-Dukhtar ( <i>de Böckh</i> <i>et al. 1929</i> ) Tang-i-Namak ( <i>Harrison 1930</i> )
37	Finu	
38	Ardan	Kuh-i-Hardun (Harrison 1930)
39	Tarbu	Baz (Walther 1972)
40	Tashkend	
41	Shamilu	Kuh-i-Shamilo ( <i>Harrison 1930</i> ) Kuh-i-Shamil ( <i>Heim 1958</i> ) Chamilo ( <i>Trusheim 1974</i> )
42	Chah Banu	Chah Benu ( <i>Harrison 1930</i> ) Chahbenow ( <i>Samani 1988</i> )
43	Chachal	Kuh-i-Shur ( <i>Harrison 1930</i> ) Kuh-e Namak
44	Siah Tagh	Kuh-i-Siah Taq also Kuh-i-Siah Girashi ( <i>Harrison 1930</i> ) Burkh ( <i>Davoudzadeh 1990</i> )
45	Gach	
46	Pashkand	Anveh (de Böckh et al. 1929)

No.	Name	Synonym
47	Khain	
48	Darmandan	Kuh-i-Darmadan (Harrison 1930)
49	Aliabad	Tang-i-Nisf-i-Rah ( <i>Harrison 1930</i> ) Aliabadad SW
50	Tang-e Zagh	Tang-i-Zagh ( <i>Harrison 1930</i> ) Tang-e Zaghi
51	Palangu	Tang-i-Surkh-i-Palangu ( <i>Harrison 1930</i> )
52	Mesijune	Kuh-i-Namak (N of Shah Ghaib) ( <i>Harrison</i> <i>1930</i> ) Meseyjun
		Mesejune
53	Kurdeh	
54	Deh Kuyeh	Dah Kuh ( <i>Harrison 1930</i> )
55	Nina	Kuh-i-Kaana South ( <i>Harrison 1930</i> ) Danz
56	Namaki	Kuh-i-Kaana ( <i>Harrison 1930</i> )
57	Sarmand	Sirmand Simand
58	Gahkum-East	Kuh-i-Gakum East ( <i>Harrison 1930</i> ) Gakun E Gachkum E
59	Saadat Abad	Kuh-i-Gakum W ( <i>Harrison 1930</i> ) Gakun W Gachkum SW ( <i>Fürst 1976</i> ) Gakun SE ( <i>Walther 1972</i> ) Gahkum SE ( <i>Davoudzadech 1990</i> ) Tarum ( <i>Hirshi 1944</i> )
60	Gahkum	Kuh-i-Gakum West ( <i>Harrison 1930</i> ) Gakun W Gachkum W ( <i>Fürst 1</i> 976)
61	Muran	Kuh-i-Muran West (Harrison 1930)
62	Qaleh Shur	
63	Goru	Kuh-i-Qaleh Shur also Tang-i-Goru ( <i>Harrison 1930</i> )
64	Bana Kuh	Kuh-i-Gachi (Harrison 1930)
65	Bonaruyeh	Plug 10 miles NE of Binaru (Harrison 1930)
66	Jalalabad	Tul-i-Siah (Harrison 1930)
67	Kush Kuh West	Khushk Kuh West ( <i>Harrison 1930</i> ) Kush Kuh ( <i>Heim 1958</i> )
68	Darbast	

*Note*: Synonyms without references are taken from official topographic maps at the scale of 1:250,000 and 1:50,000, geological maps of different origin and age (see references), and from information of personnel of the Ministry of Plan and Budget

Table A2 gives the review of all salt plugs occurring in the studied region and characterizes the type of plug study, i.e. by helicopter, car, boat, combined by foot trips. Only several plugs were not personally visited or observed from helicopter (column 6).

Table A2. The review of salt plugs and their visits

No.	Name	1	2	3	4	5	6
1	Hormoz	10	у		у		
2	Larak	11					n
3	Hengam	15	У	у		у	
4	Namakdan	16	У	у		у	
5	Berkeh-ye Suflin	36	У			у	
6	Band-e Muallem	37	У			У	
7	Bustaneh	38	У		у		
8	Moghuieh	39	У	у	у	У	
9	Chiru	-	У			у	
10	Gachin	12	У			у	
11	Puhal	13	У			У	
12	Khamir	14	У			у	
13	Mijun	-		у		У	
14	Do-Au	-	У			У	
15	Zendan	-	У			У	
16	Champeh	40	У			У	
17	Chah Musallem	41	У			У	
18	Charak	42	У			у	
19	Genah	49	У			у	
20	Qalat-e Bala	8	У			у	
21	Anguru	9		у		у	
22	lichen	64	У	у		У	
23	Chanar Birken	43	У			У	
24	Gezen	48	У			У	
20	Knemesnk	-					n
20	Takhu	13	.,			у	
21	Conow	0	у			У	
20	Gurdu Siah	י די	у	v		у	
20	Suluu Siali	65		у		у	
31	Bom	45	V			у	
30	Zangard	40 66	у			у	
32 32	Pordelavar	11	y V			y V	
3/	Gavbast	44 17	y V			у	
35	Bongod-e Ahmadi	47 87	y V			y V	
36	Kaianh	88	y			y	n
37	Finu	86	v			v	
38	Ardan	75	J			v	
39	Tarbu	84	v			y V	
40	Tashkend	83	y V			v	
41	Shamilu	76	J	v		v	
42	Chah Banu	71	v	J		v	
43	Chahal	67	v			v	
44	Siah Tagh	46	v			v	
45	Gach	68	v			v	
46	Pashkand	51	ý			y	
-			,			,	

No.	Name	1	2	3	4	5	6
47	Khain	82		у		у	
48	Darmandan	81		у		у	
49	Aliabad	69	у			у	
50	Tang-e Zagh	4	у			у	
51	Palangu	3	у			у	
52	Mesijune	80	у			у	
53	Kurdeh	70	у			у	
54	Deh Kuyeh	79	у			у	
55	Nina	98	у			у	
56	Namaki	97		у		у	
57	Sarmand	89	у				
58	Gahkum-East	90					n
59	Saadat Abad	2	у			у	
60	Gahkum	1	у				
61	Muran	85				у	
62	Qaleh Shur	78					n
63	Goru	77				у	
64	Bana Kuh	96				у	
65	Bonaruyeh	100				у	
66	Jalalabad	99				у	
67	Kush Kuh-West	74				у	
68	Darbast	5					n

Explanations:

1 numbers according to de Böckh, Lees and Richardson (1929), and Harrison (1930)

2 visited by car and foot trips

3 visited by helicopter landing and foot trips

4 visited by boat and car/foot trips

5 observed from helicopter

6 not visited or observed from helicopter

Explanations to drawings of plugs

	plug contour
	contact line of salt plug and salt glacier
	breakoff planes and their slopes
	summit plateau
	other plateaus
	flow line
	karstification (dolines, swallow holes, etc.)
	photolineations
	inner cauldron
	outer cauldron
/////	terrace at +20 m a.s.l.
<i>\       </i> ,	terrace at about +100 m a.s.l.

## 1. HORMOZ



Figure A1. Sketch of the Hormoz plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°04' N 56°28' E, Shape: elliptical (W-E trending longer axis), Max. length: 7 km, Max. width: 6 km, Activity: 1c (for the review of the character of plug activity *cf*. Chap. 6.2 and Fig. 12)(Fig. A1)

The plug with nearly circular shape has concentric to spiral structure. Since the time the plug activity finished, the original cupola has been differentiated by denudation, abrasion and differential salt solution (incl. subrosion) into two morphologically different parts, i.e. the central part with the diameter of about 2.5 km, maximum elevations of 160 to 180 a.s.l. and relatively rugged relief, and the outer rim.

The foreland of the central part is represented by two morphologically differing regions. Slightly inclined abrasion terrace in the N has an elevation of about 20 m a.s.l. Plug relics occur on it as low hills. The terrace is mostly covered by younger Quaternary deluvia and marine deposits. Distinct flat region with elevations of 60 to 100 m a.s.l. (mostly 80 to 100 m) lies to the S of the central part. It represents abrasion surface covered by ingression Pleistocene(?) sands 5 to 10 m thick. Sharp cliffs in the south are built of Tertiary sediments.

Karst forms are distinct feature of the surface morphology (elongated to irregular solution- and collapse dolines).

#### Hydrological characteristics:

The spring region drained by the combination of circular and periclinal network of short intermittent streams (W-E direction prevails). The drainage is direct on the surface and/or indirect by the system of karst caves into the Tangeh-e Hormoz. Surface streams flow even in a dry season with documented discharge of about 3 l.s⁻¹ in one stream. Springs and streams are covered, partly or nearly completely, by salt crusts. Reddish color of water is typical for the vicinity of hematite occurrences. The outflow of mine waters in the ochre mine was about 0.2 l.s⁻¹.

#### Regional geological position:

The relation to anticlinal or synclinal axes is unclear. The plug lies, maybe, in the eastern continuation of plunged Hollor Anticline of the Qeshm Island built mostly of Miocene Agha Jari Formation containing plug derived material (Gansser 1960), and Mishan Formation. Their strata dip in the southern part of the island (60 to 80°) proves high plug activity with probable pulsation nature, as indicated by marine terraces. Tertiary sediments and Hormoz material are covered by Recent to Subrecent deluvia and marine sediments (terraces), locally by eolian dunes.

#### Petrological characteristics:

The rock spectrum is relatively rich, but changing with the location within the plug. Different kinds of varicolored evaporitic sediments prevail in the central (more active?) part of the island. Finely stratified salt (white, translucent, greet, reddish, alternating in bands) is dominant and contains laminae and interbeds of non-evaporitic material. Gypsum often forms brownish crust several meters thick. Iron compounds usually form variable admixture. Sedimentary (reddish aleuropelites prevail) and volcanogenic rocks (light-colored rhyolite and its tuffs) are in minority. Greenish tuffogenic layers, as well as red claystones, appear as interbeds even in salt.

Clastic sedimentary and magmatic rocks prevail in the marginal part over evaporites, which are usually represented by gypsum. The most common are acidic to intermediate volcanogenic rocks - white, greenish, yellowish and pink rhyolites, and gray rocks with bipyramidal quartz phenocrysts. Sometimes they belong rather to ignimbrites with recrystallized glass groundmass. They are accompanied by tuffs (ash, agglomerate and crystalline varieties) or light varicolored tuffites (white, yellowish, greenish), often altered (sericitization, kaolinization, silicification, etc.) and later pyritized (pentagonal dodecahedrons up to 2 cm in size). Volcanogenic sequences contain, in places, red to brownish red, locally laminated crusts composed of alternating gypsum- and Fe-oxides/hydroxides layers. Light varicolored porcellanite fragments were found, too, proving caustic metamorphism of older material by volcanics (Kent 1979 reported even intrusion of diabases into salt). Basic magmatites - dark green pyroxene gabbros, diorites with ophitic structure, andesite - occur less often. Unstable mafic minerals (pyroxenes) are decomposed (uralitization and epidotization prevails, some zoisitization). Albitization of basic magmatic rocks occurs, too. Sedimentary rocks are represented usually by grayish aleuropelites to fine-grained lithic sandstones with gypsum. Dark pyritized dolostones and dolomitic limestones locally contain cherts or jasperoids. Red hematite shales with distinct stratification and gradational bedding occur in the S. In the southernmost part of the island they pass up to hematite ores (average 75 % of Fe₂O₂). The presence of hematite as specularite on fissures and vugs after leached minerals (siderite?) is a distinct feature. Hematite forms often secondary cements. Specularite in the form of crystal aggregates (iron roses) occur in numerous sites. Crystals of greenish apatite occur in reddish residual sediments in the southern part of the island.

Extensive hematitization accompanies rocks in outer plug zone with ironstones several meters thick and with dip up to 80°. Ferrugineous layers, composed mainly of iron hydroxyoxides, quartz and lathy hematite crystals, intercalated with gypsum layers originated in weathering zone (lateritic weathering profiles?)
*References:* Blanford 1872; de Böckh at al. 1929; Diehl 1944; Fürst 1970; Gansser 1960; Harrison 1930; Heim 1958; Hirschi 1944; Hurford et al. 1984; Kent 1979; Kre-

# 2. LARAK



Figure A2. Sketch of the Larak plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 26°52' N, 56°22', Shape: elliptical (WSW to ENE trending longer axis), Max. length: 7 km, Max. width: 4 km, Activity: 2b (Fig. A2)

The plug core of elliptical shape is situated eccentrically on the island. The highest present elevations are situated on the NE (up to 142 m a.s.l.). Similar morphology is also on the SW, but broader depressions are more common. Enormous amount of karst forms was reported, especially of corrosional and collapsed dolines of elongated or irregular shapes, some of them more than 20 m deep. The original plug morphology can be assumed as copula-shaped to domed. High denudation, effects of marine ingressions and solution of evaporitic rocks lowered the plug after activity was finished. Distinct NW-SE trending morphological depression originated. Increased number of fractures and fissures in it can indicate its tectonic nature.

Plug surroundings lie at 20 m a.s.l. (abrasion terrace), but in the S and in the depression between the northeastern and southwestern part of the island at 50 to 60 m a.s.l. (relic of a damaged terrace at 80 to 100 m a.s.l. with number of relic hills).

The eastern and southern plug rims are composed of Pliocene sediments (Lahbari Member?). The highest elevations

are 60 m, some levels were influenced by marine abrasion (terraces at 20 m and 80 to 100 m a.s.l.).

jci 1927; Ladame 1945; Pilgrim 1908; Samani 1988; Stahl

1911; Tietze 1879; Trusheim 1974; Vartanian et al. 1976;

#### Hydrological characteristics:

Walther 1960; Wolf 1959.

The periclinal network of short intermittent streams drains the spring region directly (on surface) or indirectly (through karst systems) into Tang-e Hormoz.

#### Regional geological position:

The regional geological position is unclear. The elongated island shape can indicate uplifted anticline crest parallel to anticlines of the Qeshm Island. Except of Holocene and Pleistocene sediments, Pliocene limestones with lamellibranchians (Kharg Member) occur. Their base is conglomeratic containing blocks of rhyolite tuffs and fragments of specularite. Older are limestones of the Lahbari Member (Agha Jari Formation) containing again hematite of most probably older origin (Diehl 1944). Gansser (1960) reported Miocene marls (Mishan to Agha Jari Formations) with strata dips up to 60° in the southern part of the island.

#### Petrological characteristics:

Rocky salt and gypsum represent evaporitic sediments. Owing to salt solution, the salt can be registered only in valleys or other more distinct downcuts. It is covered by gypsum (often red hematitized) and blocks of clastic sediments and magmatites (O'Brien 1957). In the central western part of the island this author reported e.g., clastic sediments, represented often by pink sandstone, of volcanics then abundant rhyolites and their tuffs. Small body composed mostly of alkaline feldspar intruded into the block consisting of rocks mentioned above. Dark green basic rocks are more abundant together with three blocks of actinolitites containing beryl crystals. In the center of the island, large blocks consist of fresh grayish pyroxene-biotite granitoids and large amount of feldspar porphyry. Blocks of red hematite ore are also abundant. Walther (1972) described lenses of hematite ochres up to 6 m thick and 100 m long from marginal zone.

*References:* de Böckh et al. 1929; Diehl 1944; Gansser 1960; Harrison 1930; Heim 1958; Hirschi 1944; Kent 1979; Krejci 1927; Ladame 1945; O'Brien 1957; Stahl 1911; Samani 1988; Tietze 1879; Walther 1960,1972.

# 3. HENGAM



Figure A3. Sketch of the Hengam plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 26°39' N, 55°53' E, Shape: nearly circular, Max. length: 4 km, Max. width: 4 km, Activity: 3c (Fig. A3)

The ruin of salt plug of nearly circular shape is a relic of originally domed structure. Due to the salt solution, and marine abrasion, large uvala-like depression originated. The highest elevations occur in the northern to northwestern areas (about 105 m a.s.l.) and are situated on highly eroded Miocene Agha Jari sediments. The summits of plug are at 80 m a.s.l. Neogene to Quaternary filled depression with the surface at about 50 m a.s.l. proves the activity extinction to the end of Miocene, at least. Collapse karst dolines are filled by young sediments.

Inclined abrasion surfaces on Tertiary-Quaternary sediments constitute the island periphery. Tertiary sediments are cut by abrasion and discordantly covered by Quaternary deposits. Distinct are elevations of +20 m a.s.l. especially in the northeastern and southwestern parts of the island, +40 m a.s.l. in the south and +60 m a.s.l. Relics of plug cauldron are somewhat higher than 60 m a.s.l., still distinctly recognizable in the E and in the N.

## Hydrological characteristics:

The depression is drained by circular network of short intermittent streams (dominantly W-E trending) into Khalij-e Dayrestan in the west, and to Khalij-e Fars in the E. No spring were found.

#### Regional geological position:

The southwestern continuation and plunge of the Suza Anticline (NE-SW) from the Qeshm Island. The separation of the Suza and Hengam Anticlines is caused by local undulation of the anticline axis or by its dissection by regional fissure-fault systems.

The island is built mostly of the Agha Jari Formation and its Lahbari Member, transgressively overlying salt plug. The transgression plane is uneven, often made of oyster lumachellas and pebbles to cobbles of plug material. Carbonate cemented breccias occur in the position of ancient cliffs. Fine-grained oyster marls and laminated tidalites show calm conditions of transgression. Neogene sediments are slightly folded due to the subrosion and collapse of underlying plug evaporites. Plug material below the transgression plane is decomposed, leached, forming horizon of cap rock of the "gossan" nature. Anticlinal parts of the island are often abraded and covered by Subrecent marine terraces up to the elevation of 50 m a.s.l.

At the western and eastern plug margins, the Mishan Formation also occurs. Strata dips are generally low, but in places highly inclined (up to 70°).

#### Petrological characteristics:

The Hormoz Complex outcrops on several places below Late Tertiary sediments. Red shales intercalated with purple and green tuffogenic layers are dominant. In places, shales pass into highly hematitic varieties.

Greenish intermediate volcanites (rhyodacite, andesite) are highly altered (epidotization, chloritization, etc.) and silicified. They were discovered in the SW of the island. Greenish gray basic volcanites, also altered, are less abundant. Specularite occupies the vugs after leached mafic minerals in these rocks. White to whitish purple, highly altered (sericitization, kaolinization, etc.) rhyolites as well as their tuffs (ash and crystal tuffs), sometimes silicified were considered to be rather rare by previous authors. According to our observations, rhyolite and rhyodacite and their tuffs occur in volcanosedimentary complexes quite often. Pyroxenic gabbro was reported by Gansser (1960) in the SE. Here, block of slightly metamorphosed pyroxene granite to granosyenite (granitogneiss without micas) with distinct undulatory extinction observed in quartz grains were found. Diffusional transitions into aplitoid rocks and aplite veins were identified. Pilgrim (1908) described hornstones with cellular texture and vugs partly filled with decomposed material of volcanic rocks with light blue mineral. Breccia composed of effusive rocks (Proterozoic) with carbonate cement (Tertiary) occurs in places.

Rests of reddish banded rock salt were detected only rarely (karst collapses). Gypsum is relatively common, often hematitized, forming gypsum breccias and dominant brownish surface crusts. Pilgrim (1908) noted finds of sulfur. In some sites, gypsum forms material similar to gypcretes and interlayers in tuffitic siltstones. Gypcrete up to 2 m thick contains interbeds of varicolored tuffites and tuffs, and even gray clays. The profile resembles fossil soil horizon.

*References:* Blanford 1872; de Böckh et al. 1929; Gansser 1960; Harrison 1930; Heim 1958; Hirschi 1944; Kent 1958, 1979; Krejci 1927; Ladame 1945; Pilgrim 1908; Samani 1988; Whitelock 1838.



Figure A4. Sketch of the Namakdan plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 26°37' N, 55°29' E, Shape: circular, Max. length: 6 km, Max. width: 6 km, Activity: 2a (Fig. A4)

The foothills of inactive salt plug with distinct circular structure (most probably originally cupola shaped) lies at differentiated elevations. The seashore on the S is at 20 m a.s.l. The foothills on the N and W are at 100 to 120 m a.s.l. The highest summit of 237 m a.s.l. is situated in the mid-western part of the circular structure. The total height difference reaches about 220 m. The surface of plug margins is morphologically distinctly diversified. Rests of leveled surface occur in the central part with elevations of 150 m a.s.l. The surface is open to the S and can represent combination of terrace abrasion surface, relic of summit plateau decreased by intensive salt solution, or reaction to tectonic movements. Depressions are often filled with Quaternary deluvia.

The maximum elevation of sedimentary plug rim with steep to overturned beds is 304 m a.s.l. Abrasion platform at 20 m a.s.l. with distinct abrasion cliff in salt occurs in the southwestern plug edge. Accumulation marine terrace occurs in the SE of the plug in the same position, i.e. fossil beach deposits and Suza Sandstone (Samadian 1990). The same author reported slightly tilted younger alluvium (Dullab Alluvium, 6 to 30 ka BP) and steeply turned older beach deposits (Gheshm Limestone, 30 to 40 ka BP), indicating plug activity ceased in the Lower Holocene times. Karst forms are very abundant. Surface features are represented by solution and collapse dolines up to uvalas with the maximum depth of 43 m. Some of them are filled with highly salty water. Swallow holes are situated at the plug margins draining depressions on the surface. Abundant are caves and cave systems with salt speleothems. The larger cave lies in the southeastern part of the plug with entrance 10 m wide and 12 m high and length over several tens of meters. The system (at least in 2-3 levels) drains the surface of plug.

#### Hydrological characteristics:

The spring region is drained by combined periclinal and circular network of intermittent streams leading especially to the N into Khoran Bostanu and to the S into Khalij-e Fars. Hydrologic and hydrogeologic situation is highly influenced by salt karstification. Karst springs situated in above mentioned caves yielding about 0.2 l.s⁻¹ in dry season are surrounded by expressive salt crusts and sinters with salt crystals.

#### Regional geological position:

The W part of relatively flat, the SW-NE trending anticline crest between so called Basa'idu and Salakh Anticlines. The anticline is built of Mishan and Agha Jari Formations. The plug is encircled by "an almost complete and overturned rim syncline" (Samadian 1990) with dips of about 80°. The plug and its surrounding is cut by numerous faults and fissures. In the plug foothills, there are Quaternary deposits represented by e.g. Gheshm (Kharg) limestone Member (Pliocene to Pleistocene), beach deposits or deluvia. Eolian sands are also common. Relic of the Mishan Formation was registered in the vicinity of the plug, too.

#### Petrological characteristics:

The plug is composed mostly of chemogenic sediments with abundant varicolored halite with folded laminae to bands (about 65%), and less common gypsum and anhydrite. The prevailing area of the plug surface is covered by Subrecent brownish crust, up to 5 m thick, built of gypsum with some fine-grained sand admixture, most probably of eolian origin, at least partly.

Sedimentary rocks of the Hormoz Complex are represented by abundant grayish, less reddish wacke shales and clayey to quartz sandstones (probably silicified), silicites, black graphitic shales are locally present. Banded iron ores are rare. Dark shales are calcareous in places passing into dolomitic limestones and even stromatolitic carbonates. Conglomerates with gypsum and gypsiferous marl interbeds can be commonly found (de Böckh, Lees and Richardson 1929).

Volcanic rocks are subordinate, represented by rhyolites and andesites. They were originally intensely altered (chloritization, epidotization, sericitization) and later silicified and hematitized. Fine-crystalline (serpentinite?) to massive varieties are rare. Mostly greenish, less varicolored, schliered, exceptionally beige, laminated and altered more acidic rocks of tuffogenic nature (tuffs and tuffites) contain in many cases sulfide crystals (pyrite, chalcopyrite?) which are often limonitized. Sulfides occur also in more basic tuffogenic rocks (without quartz) of green color. Increased limonitization can be observed in marginal parts of the plug.

References: Blanford 1872; de Böckh et al. 1929; Fürst 1970; Harrison 1930, 1956; Heim 1958; Hirschi 1944; Kent 1958, 1979; Krejci 1927; Ladame 1945; Lees 1927; Pilgrim 1908; Richardson 1926; Samadian 1990; Stahl 1911; Tietze 1879.

# 5. BERKEH-YE SUFLIN



Figure A5. Sketch of the Berkeh-ye Suflin plug; scale bar = 1 km.

### Morphological characteristics:

Coordinates: 26°44' N, 55°06' E, Shape: elliptical (NW-SE trending longer axis), Max. length: 6 km, Max. width: 5 km, Activity: 2a (Fig. A5)

Nearly circular plug of cupola-shaped character with already ceased activity. Southern slopes are relatively steep, ending at 20 m a.s.l. Similarly to islands in the Persian Gulf, expressive leveled surface occurs in the southern foothills (most probably relics of marine terrace). The highest summits lie in the central and northern parts (up to 396 m a.s.l.). All features of copula shaped form are still preserved. The denudation value is low at the northern margin. Less distinct leveled surface occurs here at 300 to 320 m a.s.l. Backward erosion extensively damaged the southern part of the plug after the plug activity ceased. Gradients of short streams are not poised. Total height difference is high (nearly 380 m) over short distances (about 2 km). The maximum elevation of 444 m a.s.l. lies on the rim of overturned Tertiary rocks (about 80°) in the N. Southwestern plug margins are rimmed by the system of alluvial fans. Plug activity can be dated by the plug material in the Guri Member. Karst depressions were registered at the eastern plug margin.

#### Hydrological characteristics:

The spring region is drained by the combination of circular and periclinal stream network leading directly to Khalij-e Fars in the S, W and E. The northward drainage follows the plug along its rim and then also to the sea. The occurrence of groundwater was not detected.

#### Regional geological position:

The plug is situated in the southern flank of the central part of short coastal W-E trending anticline. The anticline is built of the Mishan Formation and its Guri Limestone Member with steep dips in northern and eastern part especially. The rim of sediments at the north-western side of the plug although composed mostly of soft Mishan deposits is relatively expressive. Guri limestones (biolithomicrosparites) contain abundant clasts of the Hormoz Complex, in places.

#### Petrological characteristics:

Due to the fact that plug activity finished, varicolored, often laminated to banded halite occurs only in places, in lower positions in the plug. Blocks of green holocrystalline halite form expressive component of valley deposits and green to reddish salt occurs in valley walls. Gypsum is more abundant, except of the S, whitish to gray, sometimes of sandstone appearance, less frequently pink or reddish with hematite laminae, in places also black. Gypsum forms purple gray cement of breccias, occasionally red matrix in the plug rim. In the central part several meters thick reddish brown crust passes up to limonitized beds.

Sediments are represented by several rock types. The complex of blocks of grayish red aleuropelites to clayey sandstones, sometimes with interlayers of grayish green tuffites(?), often with ripple marks is very expressive. It is completed in brecciated (postsedimentary?) beds of gypsum with fragments of volcanosedimentary rocks, sometimes with nodular gypsum as thin lenselike beds. Light-colored, yellowish to greenish (tuffitic?) sandstones and black organogenic shales are less abundant. Conglomerates with poor grain wear are rare. Dark dolostones to dolomitic limestones, sometimes vuggy, with some gypsum interbeds were detected in places as well as nodular limestones.

Smaller blocks of whitish, reddish brown spotted (Fe hydroxides) and highly fractured acidic volcanics (rhyolites? with bypiramidal quartz) rarely occur along south-eastern and western plug margins. Green, most probably intermediate tuffs to agglomerates with brownish intercalations were identified in salt blocks. The presence of intermediate to basic volcanites is not too common. Both rhyolite, rhyolite tuff and andesite had previously glassy groundmass, now devitrified. Dark green rocks of diabase to ultrabasic character occur in places. Volcanic rocks with tabular feldspar phenocrysts and low quartz content (porphyritic andesite?) are very rare. Richardson (1929) noted nicely crystalline grossular from the contact of magmatites with limestones.

Originally unstable minerals are altered (illitization, sericitization, chloritization, epidotization, etc.) and rocks are silicified. Silicification can be traced in the field by positive rock morphology of different silicified rocks (carbonate rocks and breccias). Gypsum crusts are probably also silicified and sometimes pyritized. Silicified basic rocks contain still numerous dark minerals (?zoisite, amphibole, pyroxene, epidote, chlorite). Greenish white silicified erlane with olive-green garnet occurs as blocks. Quartz druses cover fissures in diabases. The manifestations of contact metamorphism and metasomatism (occurrence of tremolite and talc) are quite abundant.

The rim zone of the plug is constructed by breccias of the Hormoz Complex, sometimes mixed with adjacent Tertiary sediments. Guri limestones contain clasts of greenish volcanosedimentary rocks. The rim zone is more distinctly hematitized and limonitized.

*References:* de Böckh et al. 1929; Fürst 1970; Harrison 1930; Hirschi 1944; Kent 1979; Krejci 1927; Nili et al. 1979a; Pilgrim 1908; Trusheim 1974.

## 6. BAND-e MUALLEM



Figure A6. Sketch of the Band-e Muallem plug; scale bar = 1 km.

#### Morphological characteristics:

Coordinates: 26°40' N, 54°57' E, Shape: trapezoidal (WNW-ESE trending longitudinal axis), Max. length: 12 km, Max. width: 4 km (W) - 7 km (E), Activity: 2c (Fig. A6)

Extensive, for a longer time span inactive salt plug. Its shape is probably influenced by tectonics of NW-SE direction. It belongs to the category of veins s.l. The maximum elevation is 335 m a.s.l. The elevation of foothills increases from 20 m at the seashore in the S to 100 m a.s.l. in the N. The average elevation in the S is about 100 m, in the N up to 170 m a.s.l. The total height differences exceed 300 m. Soft morphological forms and broad depressions (about 80 to 100 m a.s.l.) are typical for the southwestern part of the plug. In other places, relatively high altitudinal differences in a short distance occur. Morphology rejuvenation is due to the young backward erosion. The general trend of elevation decreasing from the N to the S is directly dependent of hydrologic conditions (character of river network and marine ingressions). The highest summits of the Upper Tertiary rim are at about 300 meters a.s.l.

The presence of broad depressions at about 100 m a.s.l. is influenced by both tectonic/lithologic factors and effects of marine ingressions. Some depressions are filled with yellow to beige, burrowed, fine-grained sands with large-scale cross-bedding evidently of marine origin. Intercalations are composed of eolian sands and deluvial debris derived from the plug. Deposits of the same character form the rim of the plug from the western side. These deposits can be correlated with similar sediments of islands in the Persian Gulf. Cemented cross-bedded sandstones are situated to the S of the plug. Quaternary alluvial and marine deposits of low terraces (5, 10, 15 m a.s.l.) are composed of sandy gravels to pebbly sands, cross-bedded sands up to 5 m thick with variable cementation degree and form common constituent of the landscape. In both cases, sediments of this nature and high degree of plug erosion prove that plug activity finished prior the Pleistocene (Pliocene?).

#### Hydrological characteristics:

The spring region to spring depression drained by dendritic to parallel network of short intermittent streams to Khalij-e Fars in the S and E and by parallel short streams into depression of Mehregan Shur-e Zar. The occurrence of groundwater was not detected.

### Regional geological position:

In the S flank of the central part of short coastal anticline (W-E trending). The sedimentary rim is composed of the Bakhtyari Formation in the W, by the Agha Jari Formation on the NW and by the Mishan Formation (incl. Guri Member) in the NE. In some places (especially in the NW and NE), strata dips are steep to vertical, sometimes overturned.

#### Petrological characteristics:

The most common are blocks of flyshoid sedimentary and volcanosedimentary rocks. Reddish to gravish shales, sandy shales and brownish gray, rarely white to pink, fine-grained sandstones prevail. Ripple marks are common. Feldspar blasts can indicate slight metamorphism. These sediments form interesting curved to spiral block near the south-western plug margin. The block is excellently recognizable on air photos, with problems also on black-and-white and composite color satellite images. Similar sediments of greenish gray colors with content of volcanogenic material (e.g., on the NW) are also relatively common, as well as of alternating red and gray colored which are folded in places. The only find of metamorphosed breccia with prevailing elongated material of probably magmatic origin (clasts of ultrabasics, basics, volcanogenic rocks with matrix built of quartz, feldspars, mafic minerals). De Böckh, Lees and Richardson (1929) described even intrusion of acidic to intermediate magmatites into such conglomerates. Dark dolostones and calcareous sediments, quartzites and banded iron ores are subordinate. Marginal plug areas are distinctly hematitized. De Böckh, Lees and Richardson (1929) noted fossils of the Cambrian age from sandy dolomitic shales. Proterozoic to Lower Paleozoic rock, similarly to other plugs, are locally intensively folded and highly tectonized (small tectonics prevails).

Magmatites of acidic to intermediate compositions are substantially present. Rocks close to rhyolite, rhyodacite and andesite (pink, greenish to yellowish or light gray colored) are often observed, especially in the southern part of the plug. Their tuffs (different greenish to bluish colors) are present, too. Aplite-like rocks are rare. They locally contain feldspar phenocrysts, as well as traces of limonitization and pyritization (pyritohedrons). Basic rocks (diabases) are less common, mostly of green colors, massive, porphyritic and coarse-crystalline, too.

Unstable minerals of all rock types are altered, at least partly (sericitization, illitization, chloritization, epidotization). Secondary hematitization, silicification, sideritization and limonitization is local. Rhyolite and rhyodacite sometimes possess features indicating vapor crystallization. Secondary albitization was also extensive process in volcanic rocks.

Gypsum of different color represent abundant constituents of plug, including dark varieties enriched in organic matter. It forms interbeds in sediments or occur on the surface of different rock types as a weathering product (less cemented, locally sandy). Varicolored gypsum breccias with rock fragments and variable presence of organic and iron pigments are relatively abundant. Light-colored gypsum crusts occur in numerous surface locations at the northern plug rim due to lesser degree of denudation. Salt was not discovered owing to long-lasting solution.

# 7. BUSTANEH



Figure A7. Sketch of the Bustaneh plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 26°33' N, 54°42' E, Shape: elliptical (W-E trending longer axis), Max. length: 7 km, Max. width: 6 km, Activity: 2a (Fig. A7)

The copula shape of the plug is relatively well preserved. The highest elevations occur in its center (537 m a.s.l.). The summit plateau is missing (lowered by denudation and salt solution). Indistinct leveled surfaces occur at about 450, 350 and 300 m a.s.l. The total difference of elevations reaches about 440 m. The character of denudation phenomena (e.g., sharp Vshaped valleys) indicate short time-span after the plug activity finished. Plug foothills are at 80 to 100 m a.s.l. in the S and up to 200 m in other places. Young transgressive sediments with cross-bedding and interbeds of plug-derived material occur along the western foothills at 100 to 120 m a.s.l. and are covered by young alluvial cones. Marine interbeds were discovered in gravel pit in the S at about 50 to 60 m a.s.l. proving above mentioned statement concerning plug activity.

Almost the whole foot of plug is rimed by telescoping alluvial fans of relatively great thicknesses with variable cementation and individual thin marine intercalations. Slightly inclined abrasion surface at about 20 m a.s.l. partly cuts older fans.

### Hydrological characteristics:

The spring region of intermittent streams with the periclinal (radial to circular) arrangement is drained directly to Khalije Fars in the S and to Mehregan Sur-e Zar depression in the N. Tectonized zones are followed by streams in places. The occurrence of groundwater was not detected.

## *References:* de Böckh et al. 1929; Harrison 1930; Hirschi 1944; James 1961; Krejci 1927; Kent 1958; Nili et al. 1979; Pilgrim 1908; Trusheim 1974.

#### Regional geological position:

In the axial zone of short coastal Bustaneh Anticline of WSW to ESE direction continuing as unnamed coastal anticline toward Band/e Muallem plug. Sedimentary cover, except of the southeastern plug margin, is built of Neogene formations. The Agha Jari Formation with admixture of plug-derived material (nearshore to beach facies) forms direct plug rim in the W. The Mishan Formation occurs along the northeastern plug periphery. Strata are tilted by diapirism. In anticline flanks, dips are up to 10°. Along the plug, dips increase commonly to 40 up 70°. In the N, strata are overturned (78° to the N). The plug is dissected by NW-SE and N-S trending fissures/faults (photolinea-ments).

#### Petrological characteristics:

The presence of distinct large blocks of the Hormoz Complex is typical here. Different types of red, brownish red, greenish gray aleuropelites are dominant, locally calcareous, with sandstone interbeds, with tuffitic admixture to intercalations in places. From the textural point of view, two kinds of paleofacies occur here within this sequence: (1) flyshoid rhythmic deposits, and (2) tidalites with broad variety of textures (ripple marks, cross-bedding of different scales, etc.). Strata dips are mostly about 75°. Varieties of sandstones are relatively abundant from lithic types, sometimes conglomeratic, with shale and tuff interbeds up to beige fine-grained quartz sandstones with irregular nodular calcareous cementation (fossil beach-rock) and cross-bedding. Light-colored to white, mostly fine-grained, locally laminated and poorly cemented sandstones occur in the north-eastern part of the plug. Fossil weathering profiles of laterite type are rarely developed on gray to green sandstones and lithic sandstones. They are overlain by transgressive dark to black shales and sandstones with laterite derived pigment. Dark gray limestones and calcareous shales are rare. On their fissures, calcite crystallized. Dark dolostones with conchoidal fracture are somewhat more abundant. Carbonates are often pyritized. De Böckh, Lees and Richardson (1929) noted that "Cambrian trilobites were found in greenish shales". Also Hirschi (1944) reported fossils (trilobites, Billingsella sp., etc.). More frequently, as compared with other plugs, clastic dikes and tectonization occur accompanied by hydrothermal alteration and mineralization (e.g., by copper - malachite).

Magmatic rocks are subordinate to rare. Dark up to coarsecrystalline types (gabbro?) with alterations (epidotization, hematitization, etc.) were registered, as well as greenish gray rocks resembling melaphyres with amygdales (vesicles filled with calcite and hematite). Hirschi (1944) described agglomerates and silicified tuffs and syenitic rocks. Blocks of biotitic gneisses and diorites with hematitic crusts were found already by Pilgrim (1908), and by our group, too. Sporadic occurrences of rhyolitic volcanics can be mentioned, too. The plug periphery is relatively rich in salt (varicolored, laminated to banded, locally with small karst forms as caves and dolines). Gypsum occurs on the surface most commonly as gypsum breccias, it forms intercalations in sedimentary rocks, frequently in dolostones and limestones. Expressive light color of the plug surface in its eastern part is caused by low eroded gypsum crust 4 m thick in average, more colored in detailed sections, and by yellowish weathered shales with gypsum intercalation on the E. The plug rim on the NE is highly hematitized. Hematite was later oxided to ochreous limonites. Limonitization of the surrounding Mishan Formation is also distinct. Hematite occurs as larger crystal aggregates.

*References:* de Böckh et al. 1929; Diehl 1944; Harrison 1930; Hirschi 1944; Ladame 1945; Nili et al. 1979; Pilgrim 1908; Richardson 1928; Tietze 1879; Walther 1960, 1972.

# 8. MOGHUIEH



Figure A8. Sketch of the Moghuieh plug; scale bar=1 km.

## Morphological characteristics:

Coordinates: 26°37' N, 54°27' E, Shape: elliptical (NW-SE trending longer axis), Max. length: 10 km, Max. width: 7 km, Activity: 2b (Fig. A8)

Plug foothills occur at 60 to 100 m a.s.l. Maximum elevations of about 390 m a.s.l. are situated in the mid-western part of the plug. The plug morphology, after the activity finished, was influenced especially by erosion, backward erosion and marine ingressions. Valley slopes in the central part are mostly gentle, in the marginal zone of the plug rather steep, but Ushaped. The longer plug axis is followed by distinct plateau at about 300 m a.s.l. representing one of the most important leveled surfaces. The plateau shows promontories to the S or N. Morphological forms are relatively gentle here, without more distinct influence of backward erosion. Relics of plateau at about 200 m a.s.l. are less expressive and with smaller extent. The marginal zone of the plug is characterized by high altitudinal differences over a short distance. Karstification (dolines) occurs in the SW.

The plug is rimmed by young terrace deposits on the SW and NW. Marine terrace complexes inter-bedded with plug-derived debris are on the S at about 15 to 20 m a.s.l.. In the west at 100 to 120 m a.s.l., there are fossil cemented cross-bedded sand dunes, like as around the Bustaneh plug, partly covered by younger alluvial fans which form surrounding of the plug in other places.

### Hydrological characteristics:

The spring region is drained by periclinal radial network of intermittent streams into Khalij-e Fars in the SW and to depression of Mehregan Shur-e Zar in the NE. Two fissure spring were registered even in dry season on the southern plug margin (yield of 2 to 4  $1.s^{-1}$ , temperature of 33 °C).

#### Regional geological position:

Position of the plug is unclear. Plug lies on very gentle short coastal anticline. Its position is highly tectonically influenced. The plug is partly surrounded by two levels of Quaternary transgressive sediments and by complex of relatively thick and often telescoping alluvial fans. Fans pass northward and northeastward into sabkha environment of salt plain of Mehregan Shure Zar which is covered by some eolian dunes. Facies alternation is rapid. In direction to the Bustaneh plug, there are another complexes of cemented Quaternary beach-like deposits (+20 to 45 m a.s.l.).

#### Petrological characteristics:

The rock spectrum of the Hormoz Complex is relatively rich. Sediments are the most common (about 70 %), i.e. purple, brown, grayish and reddish shales, sandy shales, sometimes calcareous, clayey sandstones (mostly fine-grained). Interbeds of volcanic material are gray to green. Quartz sandstones are rare. Alternation of thin bedded sandstones, tuffitic sandstones, arcoses, tuffs and tuffites, calcareous sandstones with intercalations of limonite- or hematite-laminated crusts and granular ("sandy") gypsum are also present in places.

Volcanic rocks range from acidic (rhyolite, ignimbrite) to intermediate (andesite). Their light-colored (whitish, beige, greenish, green, yellowish) block sometimes exhibit transitions to tuffs and tuffites. They are often strongly altered, carbonatization and albitization being the most pronounced alteration processes. The presence of altered ignimbritic rocks were detected, too. Complex tuff to tuffite sequences can contain banded to laminated gypsum-dolomite-ferrugineous crusts. Acidic volcanic products are registered more often in the marginal plug zone than in the center, but they can be mistaken for light-colored sandstones during air survey as well as on aerial photos. In some places, whitish blocks of erlane (composed of calcite, K-feldspar, quartz, abundant green hydrogrossular) indicate the existence of contact metamorphism during formation of the Hormoz Complex. Green basic rocks with chloritization and epidotization are represented mostly by diabases (pyroxene diorite with ophitic structure). In some places they cover thick sequence of reddish clastics with grayish green interbeds overlying directly acidic tuffs to rhyolites.

Bedded varicolored salt occurs in marginal parts. Gray earthy gypsum and purple gypsum breccias are common. Abundant

specularite and red to brown iron compounds form hematite ochres, at places. Gypsum crust was registered in numerous sites. It is mostly brownish and reddish laminated by hematite.

*References:* de Böckh et al. 1929; Bosák et al. 1992; Harrison 1960; Nili et al. 1979; Richardson 1928.

# 9. CHIRU



Figure A9. Sketch of the Chiru plug; scale bar=1 km.

## Morphological characteristics:

Coordinates: 26°47' N, 53°55' E, Shape: bulb-like (longer axis: NNW-SSE, longer base in the S), Max. length: 13 km, Max. width: 5-10 km, Activity: 1c (Fig. A9)

The plug at the end of its activity. Although situated along complicated fault knot, it cannot be classified as vein. The classification proper is complicated by numerous breaking off planes, glacier evolution along nearly whole perimeter with its bulge along longer plug axis.

The highest summit (712 m a.s.l.) lies in the central part built of 6 km long vaulted summit plateau (680 to 700 m a.s.l.). The surface is covered by gypcrete (cap rock). Other parts, situated to the S and N, are represented by salt glacier (flow) with average elevation of 450 m a.s.l. The transition of plug center to glacier is gradational, the transition to margins then rapid. The plug foot lies at 100 to 140 m a.s.l. in the N and at 20 to 70 m a.s.l. in the SE. Similarly to other plugs situated near the seashore, there are terraces developed at about 20 and 100 m a.s.l. The total height difference in the plug is nearly 700 m. Alluvial fans make rim of the plug in the N (75 to 100 m a.s.l.) descending to large elongated depression with lowest points at 37 m below s.l. Such depressions can indicate subrosion of buried salt or unbreached masses followed by sinking of overburden. Alluvial fans occur also in the S foreland of the plug, covering marine terraces.

Karst features can be observed on the majority of plug surface, more commonly at margins of the plug proper, less frequently on the summit plateauhowever, they are small to be expressed on Figure A9.

Tertiary sediments of surrounding anticlines reach 749 m a.s.l. in the W and 595 m a.s.l. in the E, respectively.

#### Hydrological characteristics:

The spring area is drained into Khalij-e Fars by the periclinal network of intermittent streams, partly influenced by karst forms. Drainage in the S is directly to Khalij-e Fars. Drainage from the NE is directed through Rud-e Tange Khur to sea embayment near Bandar-e Charak, and from the NW by river to the sea near Bandar-e Nakhilu. During the wet period (January), runoff can be observed.

#### Regional geological position:

The plug and its glacier is situated between anticlines of Kuh-e Chiru on the W and Kuh-e Charak on the E in the position where the plunge of axial plane causes the sigmoidal bend (one anticline influenced by tension movements). The Agha Jari sediments form anticline flanks, the Mishan Formation outcrops in the anticline cores. Flanks are partly covered by Bakhtyari coarse clastics filling synclines.

### Petrological characteristics:

Owing to the fact, that the plug was visited only from the N and for a short visit, the best review of the composition of the Hormoz Complex lithologies can be obtained from alluvial fans. The material is variable.

Sediments are represented by common massive poorly bedded gray to grayish brown limestones, black dolostones sometimes thinly laminated and varicolored (dominantly gray) thickly bedded carbonate rocks. Large blocks (up to 600 m long) are built of folded, reddish brown to purple shales passing into grayish red sandstones and sandy siltstones in the flyshoid development. Pseudomorphs after halite are present locally. Intercalation of green rocks probably enriched in volcanogenic materials are developed in them. Kent (1958) reported finds of trilobites in a layer of dark gray to brown shales, about 10 m thick, forming interbed in dark thinly bedded silicified dolostones and finely laminated shales.

Gypsum in broad morphological varieties is common: gypcretes several meters thick (air survey), and fragments of white and pink original sediments. Grayish weathering products having character of gypsiferous sandstones and gypsum breccias are frequent. Their color depends on the content of clastic constituents. Bedded and laminated crystalline gypsum with rock fragments forms plug mass in visited sites. Fissure pseudokarst caverns are developed in gypsum along tension cracks parallel to steep valley walls. The salt was not detected directly on the surface in the northern part of plug. Its presence is documented again by Kent (1958) as red, yellow and gray folded layers with sediment interbeds from central plug zone. At the southern margin, salt appears in blocks.

Rhyolites, rhyodacite and their tuffs (agglomerates), of-

10. GACHIN



Figure A10. Sketch of the Gachin plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°06' N, 55°56' E, Shape: circular, Max. length: 9 km, Max. width: 9 km, Activity: 2c (Fig. A10)

Nearly circular plug with finished activity. Original cupola shape and internal concentric structure with the center in the northwestern part of the plug are still visible. Maximum elevations up to 280 m a.s.l. are situated in the northeastern section. The interpretation of the plug structure near the coastal line is rather difficult. There occurs a distinct depression with maximum elevations not exceeding 120 m a.s.l. The planation influence of marine ingression at 80 to 100 m a.s.l., easily identifiable e.g., at Hormoz and Larak Islands and in some plugs around salt plain of Mehregan Shur-e Zar, cannot be excluded as well as differential activity of individual plug segments in more cycles or combination of all respective factors. Similar "depression" was interpreted also along the NW plug rim of Upper Miocene sediments. The low relief is a result of river erosion connected here with older abrasion terrace.

The foothills in the S lie at 10 to 15 m a.s.l. and in the NW at about 20 m a.s.l. The youngest river terrace system of inter-

ten weathered and altered (kaolinization, sericitization, epidotization) are mostly light-colored to reddish. Light leucocratic rhyodacites with plagioclase contain quartz (rock crystal) and specularite on fissures. Rocks mentioned occur mostly in the plug center. Dark green rocks of melaphyre (amygdaloid texture) to diabase appearance, sometimes with pillow texture (submarine extrusion) represent relatively common basic rocks (volcanic to subvolcanic types - paleobasalts) and occur rather in marginal plug zones. Kent (1979) reported basic intrusions into dolostones. Massive light green to gray andesites occur in places. Gray porous pumice lava of rhyolitic composition is rare.

*References:* de Böckh et al. 1929; Kent 1958, 1979; O'Brien 1957.

mittent streams inside the plug is linked to this level. Destruction of older terrace system is a result of lowering of the base level. The tilting of these sediments along small faults in some places indicates the continuous movement in the region. Movements could be of different nature. Nevertheless the influence of diapirism will probably be minimal. It was more intensive during older periods (Pliocene to Pleistocene). The tilting of young sediments is more probably caused by the combination of tectonism and salt subrosion.

Maximum elevation difference of positions inside the plug and of marginal sedimentary rim (max. 420 m a.s.l. in the NE) indicate the plug activity finished long ago. Intensive salt solution can be supposed. Salt is preserved on the surface in many sites, especially at plug periphery, with numerous karst phenomena (solution and collapse dolines, small caves and shafts, with diameters more than 15 m, karren to pinnacles, vertical columns, etc.).

#### Hydrological characteristics:

The spring area to spring depression is drained by the combination of circular and radial types of periclinal network of short intermittent streams. Drainage in the S and SW (periclinal type) leads directly to Khoran Bostanu, in the N to Rud-e Kul around plug margins (circular type). River beds and streams are often covered with salt crusts and sinters locally colored red by iron compounds. At the end of dry period (November) the stream discharge in the southern parts of the plug was very low. Here, two small spring flowing out from deluvial deposits yielded 0.1 and 0.2 l.s⁻¹, respectively. Hidden springs yielded about 0.4 l.s⁻¹. Water temperature was 30 °C. At plug margins, where salt sinters are colored to red by ferric compounds in places, water infiltrates to fluvial clastics.

#### Regional geological position:

The plug is situated in the sigmoidal bend between the Latidun Anticline (the eastern plunge, the southern limb) and Khaleh Surkh Anticline (the western plunge, the axial part). The plug rim is composed of young Tertiary Mishan, Agha Jari and Bakhtyari Formations in which plug derived material was reported. Rocks in the eastern plug margin are highly mylonitized.

## Petrological characteristics:

Halite occurs in limited amount as banded and laminated, varicolored and reddish relics in marginal plug parts and in limited extent at locations within the plug. Different genetic types of both gypsum and anhydrite are common. Original bedded crystalline yellowish or reddish (different iron compounds) evaporites are present only rarely. More frequently they occur as individual thicker layers (interbeds in sediments mostly) or as weathering and diapirism products. They are represented usually by gray sandy gypsum and gypsum breccias with various colors (depending on amount and color of admixed sedimentary and magmatogenic clasts). Gypcretes, most probably of variable age are also relatively common. Recent to Subrecent crusts are several meters thick, dominantly brown (stained with ferric hydroxyoxides) layers overlying different rock types. Older ones can be registered, e.g., as intercalations in tuffogenic and sedimentary rocks.

Igneous rocks are represented frequently by acidic, intermediate and basic rock types. Rhyolitic rocks, their tuffs and related tuffogenic rocks, are the most common acidic magmatic rocks. They are whitish to yellowish, frequently also green, sometimes bluish (tuffitic varieties). When limonitized or hematitized, red to reddish brown color prevails, especially in tectonized zones. Acidic tuffogenic rocks show broad variety of sedimentary structures and textures indicating deposition in shallow marine conditions with decreasing environment energy from base to top. Volcanic bombs, lapilli etc. are common. Basic to intermediate rocks are mostly dark green and gray, coarse crystalline (gabbros) and massive (subvolcanic to volcanic types) with different structures (e.g., vesicular).

Sedimentary to slightly metamorphosed rocks are represented especially by red, reddish or purple shales, siltstones and fine-grained sandstone varieties arranged in flyshoid rhythmic sequences. Volcanogenic admixture is common in interbeds, laminae or dispersed in sediments. Color of such horizons is rather green, greenish or gray. Banded iron ores alternate with red, hematite enriched shales or siltstones. Limestones, dolostones and other carbonate rocks in different shades of gray were registered in subordinate quantities.

The majority of blocks at plug margins has brecciated structure. They are strikingly hematitized and limonitized, sometimes containing blocks of rock of the Mishan Formation.

*References:* de Böckh et al. 1929; Fürst 1976; Heim 1958; Kent 1958; Krejci 1927; Ladame 1945; Movahed et al. 1981; Nili et al. 1979; Poosty et al. 1981, 1985; Samadian 1990; Samani 1988b; Walther 1960, 1972.

# 11. PUHAL



Figure A11. Sketch of the Puhal plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°05' N, 55°43', Shape: kidney-shaped (N-S trending long axis), Max. length: 7 km, Max. width: 3 km, Activity: 1a (Fig. A11)

Active plug of the domed shape and vein character is located along complicated structural knot with dominant N-S trending fault zone. The summit at 725 m a.s.l. lies in the central plug segment. The total height difference in the plug reaches about 700 m. The vaulted plateau at 550 to 620 m a.s.l. is developed along plug longer axis in the S. Karst depressions are developed here. An expressive plateau at 640 to 700 m a.s.l. is located on the N. Both leveled surfaces are limited by steep break off planes.

The plug is narrower in the central part. Therefore it is possible to consider it is a double plug or one plug with two parts of different activities. Several conspicuous photolineaments, evidently tectonic, influenced the structure in the northern sector of the plug especially. Broader summit plateau is probably differentiated into more blocks. Sunken or slowly elevating segments can be detected with problems owing to young backward erosion.

Plug slopes are steep with height difference of 400 m over 1 km distance. Plug foothills lie at 20 m a.s.l. on the S and at about 80 m a.s.l. on the N. The former level represents the lowest marine terrace and river terrace of Rud-e Kul, the latter one is the highest portions of alluvial fans covering terraces. Fans are markedly developed on the N, E and S. On the northeastern and southeastern side, fans are eroded by river.

Plug activity is probably polycyclic, taking into account not only two plug segments of different activities. The relics of older salt flow were registered on the northern side of the plug. In one site, they are covered by the Recent salt glacier. Harrison (1930) described 3 m high elevation of Hormoz material to the S of plug in alluvial plain of Rud-e Kul. Plug derived material was reported by Harrison (1930) in conglomerates of younger Miocene and Pliocene (Agha Jari Formation?). Recent salt glaciers start to form also in the southern plug end.

#### Hydrological characteristics:

The spring area is drained by the periclinal stream net into the N, S and E into rivers of Rud-e Kul and Rud-e Gowdar, and directly to Khoran Bostanu. In dry season, numerous springs occur here, but in wet periods the water regime is activized and changed.

Three groups of salty springs appearing from fissure system in the Gachsaran Formation were registered in dry period (November) at southeastern plug border. The southern spring group (I) yields from two nearby springs about 1.2 l.s⁻¹ with temperature of 32 °C. The central group (II) consists of three fissure springs with total discharge of 0.7 l.s⁻¹ and temperature of 33 °C. Spring group III (northern) is composed of six small springs in different elevations. The total yield is about 0.8 l.s⁻¹. Water temperature reaches 32 °C. After short flow, water infiltrates into fluvial clastics. Spring areas are covered by varicolored gypsum sinters and crusts (pigmented by iron compounds) and salt crystals and crusts.

In the northern part of the plug, i.e. in its glacier, numerous small springs were registered with yields in 0.X 1.s⁻¹ and flow through inaccessible fracture discharging about 1 1.s⁻¹ without surface outflow. Marginal Recent sediments contain numerous small springs appearing from deluvia covering Mishan Formation with water temperature of 31 °C.

#### Regional geological position:

The plug is located at the E end of the Puhal Anticline in its axial part, in places where cut by marked N-S trending tectonic zone. The anticline is built from flanks to its center by following formations: Bakhtyari, Agha Jari, Mishan (incl. Guri Member) and Jahrom.

#### Petrological characteristics:

The plug is dominantly built of gray, red (hematite), greenish, bedded and banded to laminated salt. Whitish gypsum is present in a lesser extent forming both layers and breccias. Summit plateaus are covered by brownish gypcrete, sometimes laminated (hematite) on the section, often karstified (karren). Sediments are represented by abundant red shales to siltstones passing even to banded hematite ores. Purple tuffitic sandstones occur rarely. Those rock types are metamorphosed in places into chlorite-amphibole schists to migmatites. Hematite ochres often occur in marginal plug zones. Common are also dark limestones, often pyritized, dark calcareous shales, light laminated and crystalline sandy limestones. Quartzites were registered, too. Fine quartz veinlets sometimes occur in sediments, more abundant are calcite veinlets.

Broad variety of magmatites and their tuffs was registered. Blocks of light-colored volcanogenic rocks (rhyolites to rhyolite tuffs) with quartz phenocrysts and altered (sericitized) feldspars are more frequent in the N. Epidotization and chloritization of mafic minerals is very common. Occurrence of myrmekitic intergrowths of quartz and K-feldspars may indicate that these rocks originated by vapor crystallization. They are accompanied by blocks of coarse-crystalline greenish magmatites with quartz (quartz diorites to granodiorites?). More basic rocks are represented by dark gray pyroxene andesite or paleobasalts, green diabases, but also diorites and actinolitites, and volcanogenic rocks of pillow structure. Alteration of dark minerals (chloritization, epidotization, uralitization), as well as hematitization and pyritization are common. Silicification occurs in the form of tiny quartz veinlets. Metamorphic rocks, mentioned already by previous authors, are represented by amphibole gneiss and mica schists.

## **12. KHAMIR**



Figure A12. Sketch of the Khamir plug; scale bar=1 km.

### Morphological characteristics:

Coordinates: 26°58' N, 55°32', Shape: irregular elongated, Max. length: 3 km, Max. width: 2 km, Activity: 3c (Fig. A12)

The ruin of the plug is represented on several places by material of the Hormoz Complex. Relics of plug occur in the bottom of indistinct, to the S open cauldron as rounded to conical hills protruding from alluvial fans in the E and in the central part of the plug, or making outcrops at the foot of Khamir Anticline in the W. Original plug shape was probably elliptical combined with vein-like appendices along tectonic zones dissecting southern flanks of both Khamir and Puhal Anticlines.

Alluvial fans cover, most probably, marine deposits of ingression which took part also in the ruination of the plug during Quaternary. Although completely ruined, relatively abundant surface and underground karst forms occur (swallow holes, collapsed and solution dolines, caves, karren, pinnacles, etc., Bosák 1993). Plug foothills are at 40 m a.s.l., the summit is at 120 m a.s.l. The summit of the internal cauldron lies at about 300 m a.s.l. and that of sedimentary amphitheater lies at about 450 m a.s.l. Strata dips in surroundings of the plug are up to 50°.

#### Hydrological characteristics:

The central zone represents the spring region. The marginal

parts are drained by parallel to dendritic net of intermittent streams, appearing on anticline slopes, directly to Khoran Bostanu in the E and to delta of Rud-e Mehran in the W. Swallow holes in salt can drain precipitations from extensive regions of central part of amphitheater in eroded junction of Khamir and Puhal Anticlines.

The presence of springs is characteristics both in the plug itself and along W-E trending tectonic line. Water of all springs infiltrates after several tens of meters of flow into deluvial and alluvial clastics. The smell of hydrogen sulfide is a characteristics feature of all springs.

Two spring groups occur within the cauldron of the ruined plug. The northern one has main outflow of 2.5 l.s⁻¹ into the spa pool with temperature of 41 °C. The southern group (in distance of about 300 m) is composed of 3 springs with total yield of about 1 l.s⁻¹ and water temperature of 38 °C. Beyond the western end of the plug, spring appears in sediments of Gachsaran Formation, most probably connected with a tectonic line. Its yield is about 0.7 l.s⁻¹ and temperature in spa pool reaches 31 °C. Warm springs are connected with warm, hydrogen sulfide rich groundwater encountered in vicinity of the plug during the exploration drilling for cement raw materials (Bosák and Václavek 1988).

Past activity of thermal waters along approx. N-S trending line is documented by conical, fumarola-like forms composed of rhyolite fragments cemented by gypsum and, in places, also by native sulfur occurring on western side of the amphitheater (*cf.* Bosák and Václavek 1988, Bosák 1993).

#### Regional geological position:

The plug is situated at the junction of two anticlines, i.e. of the Khamir Anticline in the W (the eastern end, the southern flank) and the Puhal Anticline in the E (western end, the axial part). It cannot be excluded, that the Khamir Anticline plunges to the SE and continues as the transverse anticline on the Qeshm Island, although some authors consider the Khamir and Puhal Anticlines as one anticlinal structure with the sigmoidal bend near Bandar-e Khamir (in region where the plug is located). Anticlines are built of Eocene formations (Pabdeh-Gurpi and Jahrom) and by Cretaceous Bangestan Group in the core. The zone represents also complicated knot of intersecting tectonic lines (photolineaments) of different directions.

*References:* de Böckh et al. 1929; Fürst 1990; Harrison 1930; Heim 1958; Hirschi 1944; Kent 1958; Krejci 1927; Nili et al. 1979; Richardson 1928.

## Petrological characteristics:

Chemogenic sediments are represented by common salt, mostly gray, laminated and banded up to varicolored. Gypsum or anhydrite of variable genetic nature often form breccias of grayish color. Hematite pigmented layers are usually red, rare rock crystals (quartz) occur on fractures, sometimes accompanied by siderite rhombs. Finds of sulfur impregnating hydrothermally altered rhyolites are interesting.

Among acidic magmatites, varicolored rhyolites (light gray, white, greenish, reddish spotted) with different fabrics (usually massive to porous structure, medium to coarse crystalline, porphyritic to pegmatitic texture) were observed. They appear together with gray, varicolored schliered tuffogenic rocks, sometimes of agglomerate nature, rarely calcareous, bedded. Andesitic rocks of gray color contain fine plagioclase phenocrysts.

## Dark green mafic magmatites of the diabase type are present, too. All rocks were strongly affected with hydrothermal solutions - altered to some degree (kaolinization, chloritization, sericitization, epidotization). Very interesting find represents the occurrence of dark gray biotite schist (already described by Richardson 1928 as siliceous gneiss). Sedimentary rocks are registered mostly as reddish aleuropelites, laminated limestones, calcareous sandstones or calcareous rocks of brecciated structure. Ironstones (originally sandstone?) with specularite filled voids are frequent. Pyritization is a common type of alteration.

*References:* de Böckh et al. 1929; Bosák 1993; Bosák-Václavek 1988; Harrison 1930; Hirschi 1944; Jenkins 1837; Krejci 1927; Ladame 1945; Nili et al. 1979; Pilgrim 1908; Richardson 1928; Stahl 1911; Tietze 1879; Whitelock 1838.

# 13. MIJUN



Figure A13. Sketch of the Mijun plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°04' N, 55°18' E, Shape: irregular (NNW-SSE trending longer axis), Max. length: 7 km, Max. width: 5 km, Activity: 2a (Fig. A13)

The plug itself is nearly circular and shows concentric structure, with diameter of about 5 km. It lies in distinct cauldron open to the S. The rest of the plug has nature rather of a glacier, although lacking distinct structural features. The plug summit is at 744 m a.s.l., margins lie at about 420 m a.s.l. The total height difference is than 320 m. Marginal cauldron zones are situated at 960 to 1,160 m a.s.l.

The character and elevations of the cauldron and morphological features within the plug prove generally low activity during diapirism and after its end. Erosion is an important element in morphology formation. It was caused by region uplift by continuing folding and by the poising of river beds. Water streams deeply downcut into older sediments, i.e. Tertiary or Subrecent alluvial fans at the western plug margin. Cauldron is distinctly of erosion-planation nature originating by pedimentation(?) from the plug to external zones.

#### Hydrological characteristics:

The spring region is drained by the circular net of intermittent streams to the S, in general, into river basin of Rud-e Mehran. Surface run-off and underground drainage are activated during wet seasons and shortly after. Accumulations of fluvial and deluvial sediments in valleys keep water for the longest time as fissure aquifer of plug primary rocks is drained into them. Groundwater outflows in places infiltrate after a short distance.

### Regional geological position:

The sigmoidal bend between the eastern end of the Baviun Anticline and the western end of the Khamir Anticline. The plug is located in the southern anticline flanks in relatively complex structural knot. Photolineations of NNW-SSE and NE-SW directions intersect there. Sediments of the Mishan Formation and Guri Member are exposed in the southern margins of anticlines, a majority of folds is composed of Gachsaran and Asmari-Jahrom Formations. These formations are limonitized or hematitized (distinctly red to reddish brown staining) at the NW plug margin.

#### Petrological characteristics:

Blocks of sedimentary rocks dominate. Reddish gray and gray shales and siltstones occur in the W. Brownish gray, rarely also purple and green silty sandstones, laminated and thinly bedded, sometimes cross-bedded were detected, together with some dark dolostones, in the E.

Magmatites form minor constituent. The most common are grayish green tuffogenic rocks, less frequent are green basic varieties (fine grained diabases). Light-colored volcanogenic rocks of rhyolitic character occur in the summit part.

# 14. DO-AU



Figure A14. Sketch of the Do-Au plug; scale bar=1 km.

### Morphological characteristics:

Coordinates: 27°01' N, 55°07' E, Shape: ovate (NE-SW trending longer axis), Max. length: 11 km, Max. width: 6 km, Activity: 2a (Fig. A14)

The dome shaped plug appearing as wheelback on broad depression. The plug foothills increase from about 260 m a.s.l in the S (local base level of Rud-e Mehran) to 480 m a.s.l. in the N. The summit part is at 700 to 825 m a.s.l. The total height difference reaches up to 560 m. Relatively high activity and its finish in the near past is documented by the low effect of backward erosion and the presence of the summit plateau above 650 m a.s.l. The plateau is morphologically diversified, forming flat, low-lying portions among morphologically positive large blocks of the Hormoz Complex. The plug is rimmed, practically continuously, by young alluvial fans, often telescoping, in a zone about 3 km wide. Valleys of intermittent streams cut down older alluvial fans commonly to the depth of about 10 m, in the S also up to 20 m. The downcut is connected with distinctly developed terrace system of Rud-e Mehran, especially with lower terraces at +10, +20 and +40 m. Higher terrace systems occur at +40, +60-70, +90, +120, +140 and between +180 and +250 m above the present level of Rud-e Mehran.

## Hydrological characteristics:

The spring region with dominant periclinal drainage of dendritic to parallel type into river basin of Rud-e Mehran. The circular type of drainage appears structurally and lithologically Red coloring of rocks of the marginal zone is caused by iron compounds (hematite and Fe hydroxyoxides) not only in the Hormoz Complex, but also in Tertiary formations.

Below exotic blocks, salt occurs (varicolored, banded) and in marginal parts also gypsum and anhydrite are visible. Gypsum breccias and crusts are less common.

influenced. Streams utilize less resistant plug lithologies surrounding blocks of the Hormoz Complex, especially around isometric blocks. No springs were discovered inside the plug in dry period. Small springs occur at base levels, as in the northern part of the plug.

#### Regional geological position:

The plug position is not completely clear. Probable it is positioned in the westward plunged part of the Mijun Anticline (in Agha Jari Formation) continuing to the W into the Gach Anticline (the eastern plunge behind the Zendan plug). The second possibility, supported by presence of Guri limestones and Mishan marls on the N and interpreted as disturbed southern flank of the Baviun Anticline, is the position in axial part of syncline. Low elevations of only about 500 m a.s.l., as compared with other surrounding plugs, can be explained by this interpretation. The plug is cut by two very distinct photolineaments of NE-SW and NW-SE directions. The NW-SE lineation has a character of right slip fault.

#### Petrological characteristics:

Chemogenic sediments (salt, gypsum) are exposed on the surface only in subordinate amount. Gypsum is more common than halite, but it occurs mostly at plug margins as varicolored gypsum breccias. Gypsum frequently contains siderite rhombohedrons, often limonitized. Light-colored gypcrete covers summit plateaus.

The plug contains abundant and relatively large blocks of different Hormoz lithologies, sometimes arranged as tiled slices separated by thrusts and gypsum. Very abundant blocks of reddish brown to purple shales, siltstones and sandstones contain horizons of greenish gray and brown purple clayey sandstones and green intercalations of tuffogenic material. Intraformational conglomerates, ferrugineous to quartz sandstones with irregular carbonate cementations occur occasionally. Complexes have nature of shallow marine red beds with a variety of characteristics textures (common ripple marks, load casts etc.). Large and thick blocks of carbonate rocks built of thinly bedded greenish and beige limestones alternating with marly intercalations, sometimes with cherts, full of shallow marine textures (ripple marks, skeletal and cubic pseudomorphoses after halite etc.) are steeply inclined (strata dip up to 80°). Dark dolostones and silicites are subordinate. Sandstones and conglomerates are often ferruginized (hematite, limonite). One block of biotite gneiss was found, too.

Igneous rocks are represented mostly by intermediary to basic types - diorite, carbonatized diorite (tonalite), olivine-free gabbro and melaphyres with massive, amygdaloidal, porphyritic or coarse ophitic textures. Acid igneous rocks occur in the north-eastern part as elongated blocks of aplitic granite, showing signs of pressure metamorphism (grain elongation). Porcellanites of white, yellow, green and red colors prove contact metamorphism of shales and calcareous sediments by effusion of volcanic rocks. Directly observed was the contact of greenish thermally altered rocks overlain by green basic rocks (diabases) in the northeastern part of the plug. Light-colored (whitish, greenish to pink) acid volcanic rocks - rhyolites, rhyodacites and their tuffs - were discovered only in the southeastern part. Alteration processes are common, i.e. chloritization and epidotization of mafic minerals and sericitization and illitization of light unstable components. Some parts are silicified (small quartz on fissures, white quartz-chalcedony - as penetration in carbonates). Sedimentary silicites composed originally of chalcedony are of the most part recrystallized. Hematitization and subsequent limonitization are frequent along plug margins. The usual rim zone of Tertiary sediments is practically missing. Horizons of compact iron ores (ironstones) capping the sequence of Hormoz sediments in the central plug area are usually covered with weathered gypsum layer. Weathered gypsum is in places washed down into adjacent depressions and redeposited there, giving rise to bright spots on aerial photos. The profile is often eroded, building thus breccia-like accumulations in morphological depressions or highly hematitized layers. Gypsum blocks are sometimes impregnated with crystalline halite. Efflorecences of native sulfur occur in the northern part.

References: Nili et al. 1981a,b.



Figure A15. Sketch of the Zendan plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 26°55' N, 54°53' E, Shape: rectangular (NNE-SSW trending longer axis), Max. length: 12 km, Max. width: 6 km, Activity: 2b (Fig. A15)

The distinct dome structure was probably influenced (elongated) by tectonic zone of the NNE-SSW direction. Plug foothills on the eastern and northern sides lie at 400 to 500 m a.s.l., in average about 440 m a.s.l. The summit at 893 m a.s.l. is situated in the plug center. The total height difference from the E and N margins represents about 450 m. The presence of leveled surface at 600 to 700 m a.s.l. forms important morphological feature. Low ridges and hillocks protrude from the plateau (single blocks of the Hormoz Complex). The western plug limit is built up of step-like surface connecting the plug and Tertiary Agha Jari and Mishan Formations in which the summit at 1,043 m a.s.l. occurs above a small rest of leveled surface at 900 to 1,030 m a.s.l. It cannot be excluded, that leveled surfaces at 1,043 m a.s.l. on Tertiary sediments and at 600 to 700 m a.s.l. on the plug represent originally uniformly leveled surface differentiated along structural lines and by salt solution.

The plug is highly damaged by backward erosion connected with low terrace systems of Rud-e Mehran (see also description of the Do-au plug) indicating end of activity. U-shaped valleys are distinct feature in the morphology. The eastern plug foothills are composed of thick deposits of alluvial fans, sometimes highly cemented. Fans are dissected by young erosion gullies to the depth of some 15 m.

#### Hydrological characteristics:

The spring region with not explicitly defined drainage network. Drainage types (circular, radial, dendritic and parallel) depend on the character of plug segments (lithology, content of Hormoz blocks, tectonization). The western and southern parts are drained along plug rim, i.e. towards the N and E into basin of Rud-e Mehran. Other parts are drained to Rud-e Mehran directly, i.e. toward the E and NE. Backward erosion propagated far westward beyond the longitudinal plug axis constituted favorable conditions for piracy of drainage along plug margins. Fissure springs with yield of 0.1 l.s⁻¹ were located at the northern plug margins. Water well in one of large valleys in the SE of the plug had groundwater level at -15 m below the local base level in dry period.

#### Regional geological position:

The northern segment of the plug is situated along the eastern plunge of the Gach Anticline built of Mishan Formation. Here, the plug core with circular to elliptical structure (diameter of 1.5 km) occurs. The southern part lies in (on?) indistinct synclines built of Agha Jari sediments.

# 15. ZENDAN

The photolineation pattern on air photos is somewhat different from a net on satellite images. On air photos, the plug is dissected by N-S, NNW-SSE, NNE-SSW and about N-E trending lineations. On satellite images there are distinct NNW-SSE, NW-SE, N-S and WSW-ENE trends.

### Petrological characteristics:

Blocks of the Hormoz Complex are dominantly built of folded and faulted brownish red shales and siltstones with sandstone interbeds. Three lithological sequences can be distinguished: (1) flyshoid rhythmic alternation of shales, siltstones and abundant sandstones, grayish red to purple colored, where beds are continuos in horizontal level and in thickness, and specific textures are rare (scours, lenticular bedding), (2) alternation of red shales and siltstones with greenish sandstones and volcanogenic material and abundant textures indicating shallow marine to tidalite depositional environment, and (3) alternation of red and green shales to sandstones, probably transition of both previous types. Dark shales, calcareous shales and dolostones occur only in the NW. Light-colored (beige, yellow, locally slightly greenish) rhythmic limestones and marly interlayers with dynamic textures occur in the SE.

Gypsum and gypsum breccias are frequent in the marginal zone. Color depends on enclosed material. Leveled surfaces are covered with rests of light gypcretes. The presence of dolines and caves detected from air can indicate the existence of salt in lower positions along the western side.

Light-colored volcanic rocks (rhyolites to andesites) occur only near the plug summit in the southern segment of the plug. Basic igneous rocks are subordinate. Find of rhyodacite which carried along piece of igneous rock of the basement (amphibole diorite) documents the stratigraphy of magmatic rocks.

References: Walther 1960.

# 16. CHAMPEH



Figure A16. Sketch of the Champeh plug; scale bar=1 km.

### Morphological characteristics:

Coordinates:  $26^{\circ}51'$  N ,  $54^{\circ}43'$  E, Shape: equilateral triangle, Max. length: flank 5 km, Max. width: flank 5 km, Activity: 2b (Fig. A16)

The negative plug with southwestern flank located along an important tectonic line (NW-SE). Distinct cauldron in the SE is open to the SW, i.e. toward the tectonic zone. The concentric structure can be detected in the southeastern segment.

Plug foothills on the S are at about 120 m a.s.l. on the surface of large alluvial fan declined to Mehregan Shur-e Zar. Summit at 520 m a.s.l. is rimmed by elevations of 400 to 450 m a.s.l. The total height difference is then 400 m. The southern segment can represent small glacier flow. Karst features as well as collapses and folding of Quaternary sediments due to salt subrosion were observed.

The height of sedimentary rim varies from 500 to 650 m a.s.l. in the E and W up to 1,000 m a.s.l. in the N. The morpho-

logical situation with substantial height differences of plug and sedimentary rim as well as influence of denudation (backward erosion especially) indicate that plug activity has already finished.

### Hydrological characteristics:

The plug and cauldron represent the spring region drained by combined type of intermittent streams. Cauldron slopes show centriclinal network, margins of plug than circular net, tectonized zone is drained by parallel network and the southern part of the plug by dendritic network. The general drainage is directed toward Mehregan Shur-e Zar.

Relative high frequency of springs is influenced by the morphological and tectonic position. Some springs smelling after hydrogen sulfide (sulfur impregnations) are active all over the year with yields up to 2.5 1.s⁻¹ and temperature between 31 and 34 °C. Clastic sediments in valleys are permanently water bearing with numerous short infiltrating streams accompanied by halite sinters.

#### Regional geological position:

The western part of the Band-e Lengeh Anticline at the sigmoidal bend of the Kuh-e Chah Musallem Anticline, in the southwestern flank. The sigmoidal bend is caused by important thrust to strike-slip fault line. Anticlines are composed of Mishan Formation, Guri Member, Gachsaran and Pabdeh-Gurpi Formations. De Böckh, Lees and Richardson (1929) noted plugderived material in *Globigerina* Eocene marls.

The plug is dissected by abundant photolineations on air photos (NNW-SSE, NE-SW, WNW-ESE trending) cutting also plug cauldron. On satellite images, NNE-SSW, WSW-ENE and NNW-SSE trending lines are visible, as well as large left strikeslip in the southwestern part of the plug.

#### Petrological characteristics:

Sedimentary rocks prevail in the northern part of the plug, i.e. grayish red to brownish purple shales to siltstones, often with mud cracks, and fine-grained sandstones alternate with greenish lithologies, probably with tuffitic admixture. Fragments of grayish black thinly laminated shales with organic matter can locally be found. Green igneous rocks, (e.g., diorite), are usually altered - carbonatized, epidotized. Light-colored (white, yellowish, greenish) acidic to intermediate volcanogenic rocks (rhyolites-andesites) and their tuffs (ashy, sandy) and tuffites occur as substantial component in the central and southern segments as intercalations in sediments or as individual blocks. They also suffered intensive alterations (sericitization, uralitization, chloritization).

Sedimentary and volcanic blocks are underlain by dominantly gray halite with karst forms. Gypsum occurs in marginal zones. Brownish gypcretes up to 3 m thick are frequent. Gypsum breccias are common, mostly gray colored according to the content of rock fragments.

The rim zone of the plug is developed nearly along the whole plug contour. Hematitization is characteristics (reddish rock staining). Hematite is subsequently limonitized (yellowish and reddish brown staining). The rim material is composed of gypsum, tectonically affected with sliced plug lithologies. Coarse crystalline aggregates of metallic gray hematite are abundant.

References: de Böckh et al. 1929; Harrison 1930; Hirschi 1944; 1928; Walther 1960.

Kent 1958, 1979; Krejci 1927; Nili et al. 1979; Richardson

# **17. CHAH MUSALLEM**



Figure A17. Sketch of the Chah Musallem plug; scale bar = 1km.

#### Morphological characteristics:

Coordinates: 26°47' N, 54°35' E, Shape: elliptical (WSW-ENE trending longer axis), Max. length: 8 km, Max. width: 7 km, Activity: 2a (Fig. A17)

The negative plug with preserved copula shape and with concentric structure along margins. Marginal slopes are relatively steep with high altitudinal difference (250 to 300 m) over a short distance (0.5 to 1 km). Plug foothills are at 120 m a.s.l., the summit at 574 m a.s.l. Total height difference than represents about 450 m. Relics of summit plateau are still preserved in the northern part, where backward erosion is slight. Karst depressions (collapse dolines, etc.) were registered in places.

The plug is surrounded by distinct, often telescoping system of alluvial fans descending from 120 m a.s.l. down to 20 m a.s.l. in Mehregan Shur-e Zar. In places, they are covered by eolian sediments (loess-like deposits). Marginal plug rim built of Tertiary sediments ascends in the E to 490 m a.s.l. The plug evolution was long-lasting as indicated by fossil alluvial cones of plug-derived material in the Agha Jari Formation surrounding the plug mostly from the N. Bakhtyari clastics are tilted with gradual transition to young alluvial cones together with descending strata dips.

#### Hydrological characteristics:

The spring region is drained by the periclinal (radial) net of intermittent streams into all directions. Only along cauldron margin in the E, there is drainage basin with circular net. The majority of region is drained directly to Mehregan Shur-e Zar, the northern part into Khalij-e Fars near Bandar-e Charak.

Springs were not detected inside the plug. Clastic sediments of riverbeds are locally water-bearing. Small springs with yield up to 0.7 l.s⁻¹ outflow from Mishan/Agha Jari rocks in a valley at the northwestern periphery of the plug. Temperature of water was 22 °C. Karst collapses can drain surface waters at plug margins.

#### Regional geological position:

The W end of short anticline of Kuh-e Chah Musallem (axial part), eventually continuation of the Band-e Lengeh Anticline after its bend along tectonic zone at Champeh plug to the WSW. The plug rim is formed by the Agha Jari and Bakhtyari Formations in anticline flanks, and the Mishan Formation with Guri Member in the central part. Strata dip at the northern plug margin increase continuously from 65° to 90°. Overturned strata were registered, too (80°). The plug is dissected by photolineaments of close to the N-S and NW-SE directions.

#### Petrological characteristics:

The concentric structure is reflected also in petrographic composition of plug segments. The central part is built mostly of blocks of reddish and gravish shales and somewhat lighter siltstones and light-colored (gray to white) fine-grained sandstones. They are, in places, intercalated by greenish beds of differing thicknesses, containing probably volcanogenic material. Blocks are, in numerous places, covered by gypcrete. Carbonate rocks are less frequent, i.e. dolostones to dolomitic limestones, varicolored, locally with algal onkoid-like textures.

The outer zone contains more variable lithologies. Except mentioned sediments with volcanogenic admixture and dynamic textures, coarse-grained sandstones with contact cement up to conglomerates composed of well cemented and well rounded pebbles of kaolinized crystalline rocks and quartz occur. Blocks of massive, sandy to silicified hard limestones of brown color are conspicuous. Igneous rocks are quite abundant. The spectrum of magmatic rocks ranges from light-colored (greenish, yellowish, white) intermediate and acidic effusive rocks as rhyolites, andesites through basic volcanites (diabase, basalt) to various igneous rocks (carbonatized diorite, aplite).

The alteration is characteristics feature of magmatites. Mafic minerals are epidotized, chloritized and light unstable minerals are sericitized, illitized or kaolinized. Silicification and hematitization of rocks is common. Coarse-crystalline aggregates and druses of hematite are frequent. Pyroclastic rocks - rhyolite and andesite tuffs and tuffites - are frequent, too.

# **18. CHARAK**



Figure A18. Sketch of the Charak plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 26°49' N, 54°22' E, Shape: elliptical (NW-SE longitudinal axis), Max. length: 8 km, Max. width: 7 km, Activity: 2c (Fig. A18)

The plug has been inactive for a longer time. Its western limit is predisposed by tectonic lines (NW-SE). Maximum elevations reach up 240 m a.s.l. The total height difference is about 150 m. Although in first stages of the ruination, the original shape is still visible. The planation level at about 150 m a.s.l. forms the majority of the plug surface. Similar level at 90 to 120 m a.s.l. occurs in the SE, corresponding to abrasional surfaces and terraces in the coastal zone and on islands in Khalije Fars. Broad, shallow U-shaped valley is filled here by finegrained fluvial and alluvial deposits with cross-bedding indicating low energy of streams emptying into the sea embayment filling the Mehregan Shur-e Zar depression. The karstification is not abundant.

Plug foothills lie at 60 to 80 m a.s.l., gently descending by alluvial fans to Mehregan Shur-e Zar at 10 to 35 m a.s.l.; on the N to valleys of tributaries of Rud-e Tang-e Khur.

The marginal plug rim built of Tertiary sediments is pre-

Original chemogenic sediments were registered underlying exotic blocks in places. Varicolored salt is usually rich in rock fragments. The salt content decreases due to intensive solution. Gypsum occurs more frequently, where salt is missing. Gypsum forms relic blocks, gypsum breccias (sedimentary and diapiric) and brownish gypcrete on summit plateaus.

The marginal plug zone is hematitized/limonitized. Hematite ochres occur in places. Salt with karst collapses and short caves is present, in places.

*References:* de Böckh et al. 1929; Diehl 1944; Harrison 1930; Nili et al. 1979; Richardson 1928; Walther 1960.

served on the N and W, there with highest summits at 230 m a.s.l., i.e. similar as in the plug itself.

#### Hydrological characteristics:

The drainage by radial centripetal network of intermittent streams. The northern part is drained into river basin of Rud-e Tang-e Khur ending in Khalij-e Fars near Bandar-e Charak. The southern part is directly drained into Khalij-e Fars or through Mehregan Shur-e Zar depression. Springs were not registered.

### Regional geological position:

The plug is located in an axial part of the eastern end of the Charak Anticline. The anticline is built of young Tertiary deposits (Agha Jari and Bakhtyari Formations). Nearly linear W limit is fault affected by broad tectonized zone of NW-SE direction.

The network of photolineations consists of NNE-SSW, NNW-SSE, NW-SE (prevail) lines belonging to two main systems. The western plug limit is elongated along distinct NNW-SSE photolineament.

#### Petrological characteristics:

Blocks of folded sediments prevail in the W, i.e. reddish and brownish shales, siltstones, sandstones and calcareous sandstones, with interbeds of greenish gray, probably volcanogenic material. Poorly cemented light gray sandstones occur in the E. Calcareous shale, light and thinly bedded and gray laminated limestones with iron compounds on bedding planes and calcareous sandstones are present locally. Textures in sediments indicate shallow marine origin. Banded hematite ores, and dark and pink dolostone are rare. Veinlets and aggregates of coarsely crystalline hematite occur in sandstones at the northern plug margins.

Green basic magmatites occur occasionally. Their textures indicate igneous (gabbro, diorite) and volcanic origin (andesite, melaphyre). They are highly altered (epidotized and chloritized) mostly. Acidic volcanic rocks (rhyolites) are more abundant in the E part. They are accompanied by tuffs or tuffites of greenish color with high alteration degree (sericitization, illitization, kaolinization?). Hematitized or limonitized volcanoclastics are rather reddish brown or yellowish. Silicification is local. Aplite-like light beige massive rock was registered in several places. Fragments of porcelanite with limonitized siderite were found in deluvia, proving the caustic alteration of sediments by volcanic rocks. Percentage of varicolored gypsum increases from west to east due to plug ruination (solution of salts). Gypsum forms sandy gypsum relics and gypcretes. Fragments of karstified nodular white to brown gypsum are not exceptional. Gypsum in the plug rim is stained with iron compounds. De Böckh, Lees and Richardson (1929) described salt.

# 19. GENAH



Figure A19. Sketch of the Genah plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 26°57' N, 54°07' E, Shape: amoeba-like, Max. length: 6 km, Max. width: 4 km, Activity: 1a (Fig. A19)

The active salt plug of nearly circular shape and diameter of 3.5 km (central part) with numerous shorter glacier flows. Plug foothills are at 1,000 to 1,100 m a.s.l., the summit lies at 1,480 m a.s.l. The total height difference represents nearly 500 m. Salt glaciers move from the plug center in all directions, more distinctly to the N and to the S. Three tongues in the N have their bases at 500 m (western), 460 m (central) and 420 to 480 m a.s.l. (eastern one). The southern flow ends at 400 m a.s.l. The summit elevation (vaulted plateau) is developed at 1,400 to 1,480 m a.s.l. forming distinct morphological element.

The marginal plug rim, composed of Tertiary sediments,

*References:* de Böckh et al. 1929; Diehl 1944; Harrison 1930; Kent 1958; Ladame 1945; Richardson 1928.

reaches elevations of max. 1,190 m a.s.l. Conspicuous feature is represented by the series of rocky triangles (facetes) of the Jahrom Formation encircled by salt glaciers in the N described already by Kent (1958). The cauldron is missing. The morphological form resembling a cauldron in the S formed by erosion influenced by physico-mechanical properties of rocks and tectonics. The pseudocauldron is older than the southern salt glacier filling its morphological depression. The northern limit is encircled by very complex system of thick alluvial fans deeply entrenched by young erosion. Surface portions of high fans are cemented by carbonate with the transition up to calcretes.

#### Hydrological characteristics:

The spring region with areal outflow to all directions due to the morphology. The initiation of the periclinal drainage network in salt flows with drainage northward to Rud-e Mehran and in the S toward Rud-e Tang-e Khur. Springs were not registered.

### Regional geological position:

The N flank of anticline named Kuh-e Namaki in the E and Kuh-e Lavarestan in the W. Axial zones are built of Pabdeh-Gurpi and Jahrom Formations. The northern flank is composed of Guri Member and Mishan Formation. Sediments of anticline structure occur in places on the surface of the plug. Strata dips in anticline flanks reach up to 80°, strata being sometimes overturned.

The NNW-SSE trending photolineations on satellite images are completed by NNE-SSW lines on air photos.

#### Petrological characteristics:

The whole plug, similarly to other active plugs, is composed of salt with enclosed some smaller exotic blocks. Among them dark dolostones, reddish aleuropelites to fine-grained sandstones and clayey sandstone prevail. They are thinly bedded and contain beige (tuffogenic) interlayers, in places. Light gray limestones are rare. Gypsum is a common constituent of the plug as original grayish layers, grayish weathering products and brownish gypcretes several meters thick. De Böckh, Lees and Richardson (1929) described also basic magmatic rocks.

References: de Böckh et al. 1929; Kent 1958; Richardson 1928.

# 20. QALAT-e BALA



Figure A20. Sketch of the Qalat-e Bala plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°19' N, 56°04' E, Shape: circular, Max. length: 4 (7) km, Max. width: 4 km, Activity: 3c (Fig. A20)

The highly ruined plug with rests of concentric structure and 4 km in diameter is composed of numerous relic hills surrounded by Quaternary deposits. The rim zone and encircling Tertiary or other older sediments are missing. According to the occurrence of plug relics to the W of the main body, original presence of larger diameter of 7 km can be expected. Structural position of relics outside internal circle can be explained, however, in other ways, though highly speculative in nature (e.g., vein, relic of dissolved salt flow, etc.). The summit of the plug lies at 144 m a.s.l. The foothills decline from the NE (80 m a.s.l.) southeastward (50 m a.s.l.). The total difference of elevations does not exceed 100 m.

#### Hydrological characteristics:

The W part is drained directly by Rud-e Kul. Morphological depressions among hilly relics filled with Quaternary deposits represent important accumulation region of groundwater and infiltration zone of intermittent streams having springs in southern slopes of the Genow Anticline. The Bakhtyari Formation represents here important freshwater aquifer. No springs were located.

## Regional geological position:

The junction of Khalate and Tarzian Synclines near the eastern end of the Anguru Anticline (plunged anticline axis?) covered by complexes of Pliocene and Quaternary sediments. The youngest sediments of the Bakhtyari and Agha Jari Formations, at anticline slope also of the Mishan Formation, are presently covered by complex system of often telescoping alluvial fans making rims of anticline flanks and by fluvial sediments of low terraces along Rud-e Kul (+10 to +20 m).

No distinct photolineations can be photogeologically interpreted. The NE-SW line separates both pats of the plug (center in the E and promontory in the W).

#### Petrological characteristics:

Morphological elevations are most frequently built of lightcolored (whitish, yellowish, pink, greenish) acidic volcanic rocks with porphyritic texture (rhyolites to rhyodacites), their tuffs (ash, sandy and lapilli-bearing varieties), and ignimbrites. They are usually strongly altered (sericitized, illitized?, saussuritized, epidotized). Three of the macroscopically most altered rhyolites were examined by X-ray diffractography to determine the nature of their alteration. Only illite presence is possible within the group of clay minerals (illite lines are almost identical with those of muscovite, i.e. sericite). Rocks are sometimes highly fractured and can contain limonitized cubic crystals and pentagonal dodecahedrons (pyrite), limonitized, hematitized and silicified portions. Green basic magmatites without phenocrysts and with epidotization and hematitization of fissures are common but subordinate.

Grayish purple to reddish brown to brown thinly bedded shales to siltstones with conchoidal fracture are only occasionally inter-bedded by fine-grained sandstones. Carbonate, especially limestones, dolomitic limestones and dolostones of light colors to dark gray, are not abundant.

Chemogenic sediments are represented by frequent brown, beige non-structural or laminated calcretes or gypcretes, sometimes of pedogenic nature, overlying blocks of effusives. They consist of alternating thin layers of quartz, calcite, siderite, hematite and gypsum, with vein-like accumulations of Mn oxides. Whitish gypsum of original diapiric layers as well as weathering products (sandy gypsum or gypsum breccia, sometimes with karstification) are common. Red fossil weathering crusts resembling laterites are interesting elements in morphology.

*References:* Gansser 1960; Kent 1979; Nili et al. 1979; Poosty et al. 1981, 1985; Samani 1988b; Walther 1960, 1972.

# 21. ANGURU



Figure A21. Sketch of the Anguru plug; scale bar=1 km.

### Morphological characteristics:

Coordinates: 27°17' N, 55°51' E, Shape: oblique-angled parallelogram (N-S trending longer axis), Max. length: 5 km, Max. width: 4 km, Activity: 1a (Fig. A21)

The core of highly active plug lies in its northern segment with maximum elevation of 1,050 m a.s.l. The plug proper is fan-shaped, open to the S. The lowest part in the S is built of glacier at 150 m a.s.l. Glacier movements induce noise effects (quakes). The total height difference is about 600 m. Slightly vaulted summit plateau lies at 900 to 1,000 m a.s.l. continuously passing into leveled surface on Tertiary sediments in the NE. Numerous karst depressions were observed.

The marginal plug rim reaches about 1,600 m a.s.l. and has extremely large diameter (nearly 15 km). Owing to the cauldron size and plug activity, the diapirism activity in more phases can be supposed although evidence of polycyclicity has been still missing. We cannot exclude, that cauldron existence represents here incidental morphological element (pseudocauldron) originated by interaction of erosion (pedimentation) in favorable geological structure with suitable mechanical rock properties. Peaks of limestone scarps protrude from the salt flow.

#### Hydrological characteristics:

The spring region. The summit plateau is areally drained. Plug margins and glaciers show initiation of periclinal network of intermittent streams. Cauldron walls are drained by centriclinal network. Drainage basin between the plug *s.l.* and the cauldron has a circular character. General southward drainage empties to Rud-e Kul. No springs were detected inside the plug or cauldron. Relatively large springs are situated nearby in the southern anticline flanks (contact of Asmari and Gachsaran Formations).

#### Regional geological position:

The more steep southern flank of the Anguru Anticline, its central zone. Nearly complete stratigraphic sequence starting in the Khami Group and ending by the Bakhtyari Formation is present. Photolineations of the NNW-SSE, NNE-SSW and NE-SW direction dissect in the plug and in its surroundings, forming complicated knot.

#### Petrological characteristics:

The plug is built mostly by evaporitic sediments. Greenish halite dominates over gypsum. Blocks of sediments and magmatites are enclosed in them. Sediments (slightly metamorphosed) are represented mostly by reddish brown shales and siltstones, less frequently by dark gray to black slightly graphitic shales. Gray to greenish intermediary igneous and volcanic rocks usually contain low quartz amounts (dacite to andesite, quartz diorite to diorite) and dark green to blackish green basic rocks are relatively common. Hydrothermal alterations are quite frequent (epidotization, chloritization and hematitization). Pebble material of intermittent streams contains subordinate lighter colored (greenish, gray) acidic volcanics (tuffs, tuffites, rhyolite).

*References:* de Böckh et al. 1929; Harrison 1956; Heim 1958; Hirschi 1944; Lees 1929; Nili et al.1979; Samadian 1990; Walther 1972; Wilson 1908.

# 22. ILCHEN



Figure A22. Sketch of the Ilchen plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°12' N, 55°13' E, Shape: elliptical (W-E trending longer axis), Max. length: 6 km, Max. width: 4 km, Activity: 3b (Fig. A22)

The plug ruin inside distinct cauldron. The cauldron bottom, partly filled with Quaternary deluvia, is situated at 500 to 530 m a.s.l. Relics of the Hormoz Complex protrude as rounded hills with maximum elevation of 714 m a.s.l. The total height difference is about 200 m. Plug material appears, place to place, hanging on cauldron walls in cemented relics up to 5 m thick. The southern part is highly disturbed. Plug material and its alteration products occur also outside the lowered cauldron rim in the NNE, indicating past presence of a short, recently dissolved, salt flow.

Cauldron elevations are variable, higher on the E (1,012 m a.s.l.) and on the W (1,345 m a.s.l.) and lower on the S and N (700 to 750 m a.s.l.). Cauldron walls are nearly vertical in the W and E, in other places steep. Guri limestones, constituting the dominant part of the cauldron (except of subordinate Gach-

saran Formation), contains thin intercalations of calcareous conglomerates with plug-derived material (Harrison 1930). Middle Miocene diapirism is therefore evident. Relic nature of plug indicates that activity ceased long ago.

### Hydrological characteristics:

The spring depression is drained by dendritic network of intermittent streams to the N through the lowered cauldron rim into Rud-e Rasul (Gowdar). No springs were observed.

#### Regional geological position:

The central part of the Ilchen Anticline in its axial part with abnormal thicknesses of the Guri Member (limestones). The plug is cut by NW-SE normal strike-slip fault and some other photolineations (NE-SW trending).

#### Petrological characteristics:

Grayish shales and siltstones with irregular color changes to red, purple, green or olive green in vertical and horizontal directions as well as horizons parallel to bedding form common blocks. Sometimes, transition to pale red hematite-rich shales was observed. Another substantial constituent, often lying above shales, is represented by brownish gray to grayish brow sandstones with variable grain-size and cross-bedding to calcareous sandstones, rarely by fetid dark dolostones and sandy dolostones. Occurrences of greenish polymict conglomerates with probable tuffogenic admixture in the matrix are worth mentioning. Altered basic magmatites of dark green color are less frequent.

Chemogenic deposits are represented only by gypsum of various colors. Red gypsum with hematite is abundant as relics after salt solution. Gypsum breccias have purple gray pigmentation, mostly. Gypcretes were registered only in the northern plug segment. Some rocks, especially of tuffogenic character, are silicified. Distinct hematitization is bound to rim zones of the plug.

References: Harrison 1930, 1956; Kent 1958.

# 23. CHAHAR BIRKEH



Figure A23. Sketch of the Chahar Birkeh plug; scale bar = 1 km.

#### Morphological characteristics:

Coordinates: 27°02' N, 54°35' E, Shape: elliptical, Max. length: 7 km, Max. width: 6 km, Activity: 3a (Fig. A23)

The plug in high degree of ruination is located inside distinct cauldron open to the N into Rud-e Gowdar valley. Presence both of plug and of salt glacier is unusual rarity among plug ruins. The cauldron bottom in the southern part lies at 460 to 480 m a.s.l., the highest summits at about 540 m a.s.l. The maximum height difference is only 80 m. The baseline of the glacier front in the N is at 300 m a.s.l., glacier summits at 500 m a.s.l. Larger extent of the glacier in the past cannot be excluded, but it had to be dissolved by the river.

The cauldron as well as plug evaporites are covered with Recent to Subrecent deposits, in many places. Content of evaporitic materials grows northward as drainage is entrenched. The cauldron rim composed mostly of Miocene formations is at 986 m a.s.l. on the W, 730 m a.s.l. on the S and 885 to 973 m a.s.l on the E.

#### Hydrological characteristics:

The spring depression is drained by combined centriclinal (cauldron slopes) and circular (cauldron perimeter) network of intermittent streams. Drainage empties generally to the N into Rud-e Mehran. Recent clastic alluvial sediments in the lower part of the salt glacier are water-bearing with several small springs infiltrating after short distances. Permanent outflow occurs only from clastics (deluvia, proluvia, alluvia) at the glacier front in lower positions above local base level of Rud-e Mehran.

#### Regional geological position:

The sigmoidal bend between the Heran Anticline (the eastern end, the northern flank) and Gach Anticline (the western end, the northern flank) is influenced by distinct fault zone which follows up to the southwestern margins of the Champeh plug. The zone of right stike-slip fault is expressed on air photos and satellite images. Fault influences the western side of the plug.

#### Petrological characteristics:

The prevailing amount of blocks is built of varicolored (red, purple, green, blue, brown) shales and brownish gray finegrained sandstone. Altered tuffogenic admixture (silicification, argillitization or carbonatization) is common. Ripple marks belong to abundant textures. Rosy to gray limestones and dark dolostones and dolomitic limestones are less frequent. White quartzites are rare. Gypsum represent evaporites at the surface. Halite may occur in deeper parts.

Magmatite blocks in the plug are represented by pink to purple relatively fresh rhyolite (locally hematitized), white massive partly altered rhyolites (?), light rhyolite tuffs (sometimes carbonatized) and grayish green tuffites, and grayish acidic volcanics (ignimbrites?) with feldspar and quartz phenocrysts and abundant limonitized siderite (rhombic pseudomorphoses up to 3 cm). All those rocks are irregularly altered (kaolinization, sericitization, epidotization, etc.) and subsequently silicified or sideritized.

The majority of glacier mass is composed of gypsum, gypsum breccias or calcareous sandstone of brownish gray color. Basic igneous rocks occur only sporadically as dark green to grayish black rocks with quartz crystals on fissure walls. The presence of up to 4 m thick Subrecent gypcretes sometimes dark pigmented by organogenic material (character of pedogenic horizons) or iron compounds is quite conspicuous feature of the plug.

References: de Böckh et al. 1929; Kent 1979; Richardson 1928.

# 24. GEZEH



Figure A24. Sketch of the Gezeh plug; scale bar=1 km.

## Morphological characteristics:

Coordinates: 27°04' N, 54°13' E, Shape: egg-shaped (NNE-SSW longer axis), Max. length: 5 km, Max. width: 3 km, Activity: 1b (Fig. A24)

The classical active plug of elliptical to egg-like shape with salt flow in the S, without the cauldron. The elongation can be influenced by tectonics. The plug summit at 1,019 m a.s.l. is surrounded by the summit plateau with the base at about 900 m a.s.l. Slopes, including glacier front, are very steep. Basis of glacier flow is at 400 to 440 m a.s.l., plug foothills are at about 500 m a.s.l. Total height difference is 600 m. Karstification was registered in the southern part (dominantly karren).

The northern plug margin is in direct contact with Lower Tertiary sediments. In other positions, these sediments form only relics. Rims of alluvial fans prevail there, descending to 300 m a.s.l. where they pass into alluvial deposits and fluvial sediments of broader alluvial salty plain of Rud-e Mehran. Marginal rock scarps of sedimentary rim lie at 760 to 790 m a.s.l. in the E and the W.

Zone of the glacier segregation from the plug is well traceable according to strata strike of thin Guri Member. Distinct island built of gypsum is separated from the plug body by deluvia. The interpretation of this structure is not unequivocal as two possibilities exist: (1) gypsum is a part of the Gachsaran Formation combined with gypcretes containing plug-derived material. Photogeological features on air photos indicate similarity of internal structure of this relic with internal structure of Gachsaran evaporites in the southern limb of the Gezeh Anticline. The gypcrete then can represent solution residuum of older, more extensive salt flow and/or gypsified older level of alluvial fans, or (2) the whole structure represents damaged part of an older salt glacier. Although the second possibility is less probable, both explanations assume polyphase plug activity.

### Hydrological characteristics:

The spring area with initiation of the periclinal network of intermittent streams draining the southern part into Rud-e Mehran directly and the northern part to the left bank tributary of Rud-e Mehran.

### Regional geological position:

The eastern margin of Kuh-e Gezeh Anticline, its southern flanks. The stratigraphic sequence from Pabdeh-Gurpi up to Mishan Formations is present. The Mishan Formation and its Guri Member are in flanks partly covered by deluvial-proluvial and fluvial deposits. The influence of diapirism can easily be traced on strata dips. While farther from plug dips are about 30° to the S, in the southern anticline flank (at places of glacier segregation), close to plug dips reach 50 to 80° to the S, but also 50 to 80° to the N. The plug and its surrounding are dissected by numerous approx. N-S trending photolineations, which are expressions of broad tectonic zone.

#### Petrological characteristics:

The plug is composed dominantly of salt, gypsum is less frequent. Gypsum represents basic constituent of brownish crust covering the summit plateau in thickness of 5 m in average. Carbonates are abundant there, too. The gypcrete is broken to a number of smaller blocks towards plug margins.

Shales of brownish red color, locally highly enriched in hematite, prevail among sedimentary exotic blocks. With increasing contents of silty and sandy fractions (siltstones and fine-grained sandstones with altered siderite rhombs), gypsum cement and gypsum intercalations or tuffogenic admixture, the color changes from grayish brown to brownish gray and green.

Subvolcanic type dominates among magmatites, i.e. dark green basic rocks with variable texture (e.g., actinolite hornfels with dispersed sulfides, diabase).

References: de Böckh et al. 1929; Kent 1958; Richardson 1928.

# 25. KHEMESHK



Figure A25. Sketch of the Khemeshk plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°05' N, 53°54' E, Shape: elliptical (NW-SE longer axis), Max. length: 4 km, Max. width: 3 km, Activity: 3c (Fig. A25)

The ruin of plug with individual relics of the Hormoz material in a distinct cauldron. Kent (1958) described it as empty crater. Plug relics protrude from flat depression in the center, as well as from Quaternary deluvia of marginal rim between the cauldron and depression.

#### Hydrological characteristics:

The spring depression with the centriclinal to dendritic network of intermittent streams drained generally to the SE into Rud-e Mehran. Thermal spring to the S of the plug are probably connected with the Gachsaran Formation.

#### Regional geological position:

The eastern plunge of the Dehnow Anticline, its axial part. Gachsaran Formation crops out in the axial part and Guri limestone in anticline flanks. Guri sediments contain well rounded pebbles of plug-derived dark dolostones and hematitized shales. The plug is cut by distinct NNW-SSE and N-S trending photolineations (on air photos).

#### Petrological characteristics:

The dominant part of the Hormoz material occurs in deluvial sediments outside the cauldron. In conical hills inside the cauldron, blocks of dark locally thinly bedded fetid dolostones are intercalated with greenish aluropelites. Green magmatites of basic composition are common. Warman in Kent (1958) described the intrusive contact with dolostones.

References: de Böckh et al. 1929; Kent 1958, 1979.

# **26. TAKHU**

### Morphological characteristics:

Coordinates: 27°37' N, 56°43' E, Shape: vein, Max. length: 7 km, Max. width: O,1 km, Activity: 2?

The linear plug most probably with finished activity. Typical vein composed of several separated parts (boudinage). The elevation generally decreases from the SW to the NE from 1,400 to about 500 m a.s.l.

#### Hydrological characteristics:

Intermittent streams from Kush Kuh Anticline flow through the plug and drain it generally to the W into Rud-e Jamas (known also as Jalabi or Basan-Langi).

#### Regional geological position:

Thrust zone of the Kush Kuh Anticline which is built of Khami Group to Mishan Formation. De Böckh, Lees and Richardson (1929) and Lees (1929) reported the presence of Hormoz material already in Asmari-Jahrom Formation, noting that older sediments are eroded in vein surroundings. They misinterpreted the vein as intercalation in Eocene sequences, assuming the Eocene age of Hormoz salt and that the plug activity ceased long ago. The plug and its vicinity is dissected by distinct photolineaments of various direction (about N-S trending lines prevail).

### Petrological characteristics:

The helicopter survey identified the presence of reddish shales and siltstones, reddish (gypsum?) breccias and pale red hematitic shales. Some dark dolostones were registered, too. De Böckh, Lees and Richardson (1929) described serpentinites. Light-colored (acidic) volcanics and tuffs also occur. Salt is missing, gypsum is present.

*References:* de Böckh et al. 1929; Gansser 1960; Harrison 1930; Heim 1958; Kent 1979; Lees 1929; Trusheim 1974; Walther 1972.

# 27. KHURGU



Figure A26. Sketch of the Khurgu plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°33' N, 56°17' E, Shape: kidney-shaped (NW-SE longer axis), Max. length: 7 km, Max. width: 2 km, Activity: 1a (Fig. A26)

The active plug. Character of thick vein. The shape is influenced by complex structural zone of the NW-SE direction. Plug foothills occur at 380 m a.s.l, the summit at 1,084 m a.s.l. The total height difference is 700 m. The summit plateau lies above 900 m a.s.l. Another surface at 800 m a.s.l. is linked up with the northwestern part of the summit plateau, representing probably some lower-leveled surface or tectonically sunkened higher plateau. At the northwestern and southeastern plug segments, salt glacier starts to form, overwhelming triangle facetes of Guri limestone and covering even rocky river terrace in the NW. Tension and break-off planes were registered at plug margin on other locations. Karst forms occur (karren, dolines, collapses, caves) especially on summit plateau(s) and in the salt flow.

The summit plateau of the axial part of the anticline on the E reaches about 1,300 m a.s.l. On the N it quickly plunges under Quaternary fluvial sediments.

#### Hydrological characteristics:

The spring area, where summit part is drained areally. Periclinal network of intermittent streams is based on plug slopes draining the region through Rud-e Khurjal into Khalij-e Fars. Three spring with low yields  $(0.05 \ l.s^{-1})$  and temperature of 30 °C outflow from alluvial fan and fissures of the Mishan Formation.

## Regional geological position:

The southwestern end of the Kuh-e Khurgu (Kuh-e Namak) Anticline at places dissected with a broad tectonic zone (NW-SE) displacing down the western end of anticline which quickly plunges. Guri Member and Razak Formation compose anticline to the E of plug (highly tectonized with reddish staining by iron compound). Guri Member and Mishan Formation constitute anticline nose to the W of plug. Recent to Subrecent alluvial fans cover older formations. Interpretation of satellite photolineations indicate the plug's position on a basic structural line of the NW-SE direction and on about N-S trending lines.

#### Petrological characteristics:

The plug is dominantly built of rhythmically bedded and varicolored salt. Some parts of coarse-crystalline to ball-like salt aggregates are authigenic forms. Gypsum occurs in marginal zones. The most common is brownish gypsum crust, which is present also on summit plateaus. Gypsum sediments are reddish (dispersed hematite) or greenish to yellowish (bands of tuffitic admixture). The content of blocks of sediments or magmatites is not high, but lithologically variable.

Sediments are represented by common red shales with transitions to siltstones or fine-grained sandstones. Rocks contain high hematite admixture in places, which was mined as hematite ochres in the eastern plug margins. Dark wacke shales occur in the W. Containing organic admixture, they pass up into azoogenic graphitic shales, locally slightly silicified. Grayish to purple gray tuffogenic aleuropelites occur more often. Dark dolostones with cherts are less abundant.

Magmatogenic rocks are represented by green basic rocks (massive, fine and coarse-crystalline - gabbro), and grayish green medium-crystalline intermediary rocks sometimes with porphyritic texture (e.g., diorite). Light grayish green, sometimes white and yellow (altered) effusive rocks (andesite, rhyolite) are less abundant, occurring especially at summit part and in eastern plug margins. Alteration of rocks is usual (epidotization, sericitization, chloritization). Rocks are often hematitized, tuff sometimes silicified (veinlets) and pyritized. Sporadic occurrence of blue asbestos amphibole (magnesioriebeckite) was observed in the southern plug margin.

*References:* de Böckh et al. 1929; Fürst 1970, 1976, 1990; Ganser 1960; Heim 1958; Lees 1929; Nili et al. 1979; Trusheim 1974; Walther 1972.

# **28. GENOW**

#### Morphological characteristics:

Coordinates: 27°27' N, 56°18' E, Shape: curved (W-E elongated), Max. length: 2 km, Max. width: 0,5 km, Activity: 3c

The plug ruin in highly tectonically affected region with not completely clear position. Plug foothills are at max. 160 m a.s.l. Maximum height difference reaches about 60 m. Single relics appear in structural valley mostly as positive morphological forms rimmed by slope deposits.

Davoodzadeh (1990) misinterpreted circular structure with diameter about 10 km to the W of the plug as unbreached salt plug. The structure represents combination of dense tectonic network of dissecting lines and lithological properties.

#### Hydrological characteristics:

The spring depression drained generally northeastward into Rud-e Khurjal. At the western margins of spring depression, a group of springs appears. Pools are constructed on them. The total yield is 170 l.s⁻¹. Water temperature is 39.5 °C. Two smaller springs were surveyed in the close vicinity of main outflows. They yielded 0.3 l.s⁻¹ of water 35 °C warm. The smell of hydrogen sulfide is distinct at springs.

#### Regional geological position:

The eastern end of the Kuh-e Genow Anticline, in the broader N flanks. Pabdeh-Gurpi to Guri sediments are present. The eastern promontory of the anticline is displaced down by a system of parallel faults appearing also as photolineations both on air photos and on satellite images as a complex structural knot. Pebbles of plug-derived material of conglomerate intercalations in Asmari-Jahrom and Guri carbonates (Richardson 1926) indicate ancient plug activity.

#### Petrological characteristics:

Plug relics are composed dominantly by gypsum, representing partially also residuum after salt dissolution. Gypsum is varicolored, often pigmented by iron compounds to shades of red. It occurs also as gypcretes enclosing fragments of rocks. Salt is exposed at the surface in some places, its occurrences being conspicuous by the presence of karst forms (solution and collapse dolines). Sediments are represented by reddish shales and aleuropelites in the E. Fragments of green acidic and intermediate volcanics and agglomerates are reported near spas in the W. They occur as breccias also in the E. Dark dolostones and silicites (lydites) can be found in places.

Depressions are filled with Subrecent deposits, mostly by deluvia. When overlying the Hormoz Complex, deluvia are cemented with gypsum, with transitions to gypcretes in places. Gypsum cemented terrace sediments (cross-bedded sands to gravels) were noted, too. Their thicknesses are up to first meters.

*References:* de Böckh et al. 1929; Hirschi 1944; Kent 1958; Nili et al. 1979; Richardson 1926; Walther 1972.

# 29. GURDU SIAH



Figure A27. Sketch of the Gurdu Siah plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°30' N, 55°37' E, Shape: square-shaped to rectangular, Max. length: 2,5 km, Max. width: 2,5 km, Activity: 2c (Fig. A27)

The inactive and small plug, activity of which has ceased long ago, is situated in continuously uplifting anticline and poorly defined and diversified cauldron. While the plug shape is nearly square-like to rectangular (N-S longer axis), the cauldron is elliptical with longer axis of the NW-SE direction. The lowest point lies in the N at about 800 m a.s.l., where the character of relic plug material indicates short transport (glacier?). The highest summit is at 1,218 m a.s.l. in the southern segment. The total height difference is about 400 m. The cauldron rim elevations vary from 1,171 to 1,625 m a.s.l., being decreased in the NNW and S.

#### Hydrological characteristics:

The spring depression with dendritic network of intermittent streams is drained northward into Rud-e Kul. Springs were not detected. Groundwater table lies low beneath the surface of streambeds (well).

### Regional geological position:

The central part of the Kuh-e Guniz Anticline, its axial zone, composed of the Jahrom Formation. Important N-S tectonic line

The highest percentage is represented by sedimentary rocks

- reddish purple to brownish shales and siltstones, brownish

gray laminated sandy siltstones and silty sandstones. Occasion-

al are quartzites of cementation type, structureless limestones,

conglomerates and black shales with organic pigment. Mag-

matogenic rocks are common - green basic rocks, according to

textures probably of subvolcanic origin and more acidic effu-

sives - white altered disintegrating rhyolites and their tuffs, sometimes silicified. Grayish gypsum breccias are frequent. Gypsum

cuts the eastern margins of the plug (strike-slip fault, oblique fault), being distinct also in the morphology of the northern anticline flank, on air photos and satellite images. Sediments around the plug are intensively folded with steep dips. Depressions in highly ruined plug are filled with cemented deluvia constituting terrace levels at +10, +15 and +20 m and proving cyclic anticlinal uplift. Plug derived material appears in the Guri Member indicating Miocene plug activity.

#### Petrological characteristics:

The rock spectrum is relatively rich as documented by pebbles of plug-derived material in cemented deluvia and proluvia along larger streams.

30. SHU



Figure A28. Sketch of the Shu plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°25' N, 55°11' E, Shape: elliptical (W-E longer axis), Max. length: 4 km, Max. width: 2 km, Activity: 1b (Fig. A28)

The active plug of domed character uplifting in distinct, but highly morphologically diversified and probably double cauldron. The cauldron morphology can be influenced not only by solution collapsing, but also by lithology, mechanical rock properties of Upper Mesozoic and Tertiary formations and erosion. Plug foots are at 1,200 m a.s.l. in the S and up to 1,800 m a.s.l. in the N. The summit lies at 2,043 m a.s.l. in the northern segment. Indications of the summit plateau can be traced at about 2,000 m level. The total height difference is nearly 850 m. The rim of "inclined" cauldron which is open to the SW overtops the marginal plug zone by 200 to 300 m in average.

#### Hydrological characteristics:

References: Harrison 1930; Kent 1958.

occurs, too.

The spring region is drained by the combination of the periclinal (plug) and circular (cauldron) network of intermittent streams southwards into Rud-e Rasul (Gowdar).

#### Regional geological position:

The distinct sigmoidal bend of an anticlinal structure influenced by horizontal movements in greater depths expressed by complex knot of fault zone on the surface. In the detail, the plug is situated in the junction point of axial zones of the southeastern end of the Shu Anticline, the southwestern end of the Avin Syncline and the northwestern end of the Kishi Anticline. Anticlines are built of rocks belonging to Khami Group to Jahrom Formation. Photolineations of the NW-SE, N-S and NE-SW direction intersect in the plug surroundings.

#### Petrological characteristics:

The plug is built mostly of salt. Reddish colored salt forms up to 250 m high walls (Fürst 1970). Gypsum is common, forming layers and intercalations in clastics. Sediments are represented by varicolored (gray, brown, red, purple and greenish) aleuropelites and some sandstones, probably containing tuffogenic admixture. Harrison (1930) reported dark limestones in pebbles of valley and terrace sediments. Dark green basic magmatites occur in the central and western plug segments, most probably subvolcanic rock types. More acidic rocks (rhyolites) occur only at the eastern margin. Gypsum crusts preserved in morphologically diversified relief indicate certain cyclic character of the plug activity. Hematitization and limonitization of rocks can be encountered at plug margins.

References: Ala 1974; Fürst 1970; Harrison 1930.

## 31. BAM



Figure A29. Sketch of the Bam plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°17' N, 54°45' E, Shape: trapezoidal, Max. length: 16-9 km, Max. width: 9 km, Activity: 2a (Fig. A29)

The plug of trapezoidal to triangular shape, probably already inactive. The plug core is situated in the northern segment which is elongated in the W-E to WNW-ESE direction, most probably along a structural zone. Relics of vaulted summit plateau occur in many places here at 1,000 to 1,200 m a.s.l. Altitudinal differences of individual relics can be also tectonically influenced. Low ridges and hills protrude from plateau with summits at about 1,250 m a.s.l., with maximum of 1,370 m a.s.l. The plug margin in the S lies close to Rud-e Rasul (Gowdar) River at about 420 m a.s.l., continuously elevating northwards to 600 m a.s.l. (rim of alluvial fans). The northern foothills are situated at about 700 m a.s.l. The total height difference is nearly 900 m.

The plug morphology is highly diversified at the western, southern and eastern margins with height differences up to 500 m over short distances of about 1 km. This plug segment can be classified as areal salt flow ("prolapse"), although it encloses relatively large blocks. The position is clear at the southern margin, where the plug material is overlain by Upper Miocene deposits nearly horizontally with maximum dip of 10°. The plug/ salt flow boundary is not completely clear neither from maps and air photos nor from helicopter survey. Harrison (1930) supposed, that the material was transported southwards over about 4 miles. Karstic phenomena are developed especially at the eastern margins.

The sedimentary plug rim built up by Tertiary sediments is linear on the N (W-E trending) with maximum elevation of 1,430 m a.s.l. Longer plug activity is indicated not only by its extent and structure, but also by evident presence of well rounded plugderived material in shore facies of the Agha Jari Formation at the southern and northern plug limits. The plug activity can be considered finished owing to general plug morphology.

#### Hydrological characteristics:

The spring area is drained by combination of periclinal and dendritic network of intermittent streams into Rud-e Rasul directly in the S and into its left-bank tributaries in the N. Influence of tectonics on river network is distinct in some plug segments (linearity of streams). Several small springs occur at the southern plug margins owing to the inclination of plug foots. Their yields are up to 3 l.s.⁻¹. Similar springs were observed also in the eastern part of the plug. Long canyon-like valleys contain water-bearing proluvia with numerous sites of water outflow. Water infiltrates back after short distances.

#### Regional geological position:

The central part of the Kuh-e Abad Anticline, its southeastern flank. The anticline consists of Bakhtyari to Jahrom Formation (from flanks to center). Condensed profiles of Agha Jari and Mishan Formations prove plug activity already during Middle Miocene. Strata dips, owing to diapirism, are nearly vertical around the plug. Plug is dissected by broad zone of the NW-SE trending photolineations and by some NE-SW and nearly W-E lines.

#### Petrological characteristics:

Petrographic composition of plug is variable with occurrence of chemogenic, clastic sedimentary and magmatogenic rock types.

Sedimentary clastics are represented mostly by red, purplered and grayish red shales to siltstones, and grayish to reddish sandstones (mostly fine-grained, silty, arcosic to lithic). Intercalations of green to grayish beige tuffogenic rocks are common in places. Red bed sequences are sometimes covered by limestones, siliceous limestones and dolostones. These sequences build large blocks, often also in salt glacier. Color changes both in vertical and in horizontal directions is common, partly caused by variable tuffogenic admixture to presence of tuff to tuffite interbeds. Dark gray shales are subordinate. The presence of great limestone blocks is distinct feature of the plug (comparable with Do-au and Zendan plugs) especially in the S. Limestones are of two kinds. Massive, thickly bedded forms have white to beige color, contain siliceous admixture (sandy or authigenic quartz) and are crystalline, with cloud-like structure. More common are thinly bedded limestones of light gray to green color with beige to whitish weathering zone, sometimes sandy or dolomitic with abundant shallow-water textures on bedding planes and pseudomorphoses of halite crystals. Limestones are highly tectonized to phylonites, in places. Fetid dark dolomites with cherts were registered, too. Some lightcolored massive quartzite are also present. Tectonized rocks contain quartz crystals (rocky and smoky quartz) on fissures.

Magmatogenic rocks are represented mostly by intermediary to basic types, i.e. greenish, crystalline (massive, porphyritic to coarse-grained equicrystalline) igneous rocks (gabbro, diorite, quartz diorite), indicating their formation in different conditions. Distinct igneous rock type, occurring as large gray blocks of fresh appearance in the northern plug segment is classified as carbonatized tonalite. The most abundant magmatic rocks are volcanic to subvolcanic rocks with composition corresponding to andesite, less often to basalt (types with amygdaloidal structures). They are usually altered - propyllitized. Acid effusives, represented by hematitized rhyolite are rather rare. Whitish compact aplitic rock occur in places, but they are highly altered - epidotized. Other effusive as well as intrusive rocks suffered hydrothermal alterations (calcification and limonitization causing brownish coloring), too. Abundantly occurring tuffaceous rocks are usually light green and microscopic observations showed the presence of glassy matter in them, indicative of rapid cooling. Their composition classifies them as andesite tuffs. Magmatogenic conglomerates to agglomerates are present as well as tectonic melange of magmatites. Originally greenish, grayish, yellowish to white rocks are distinctly stained to red or reddish spotted when hematitized in tectonized zones, where quartz crystals occur.

Salt was registered at the northern plug margin in deeply entrenched valleys. Salt is grayish brown (fragments of shales and sandstones) or red (hematite). Gypsum is common as layers (whitish, coarse-crystalline, but also black and folded) and interbeds in sediments (white to gray and varicolored, massive to laminated horizons, sometimes folded and inter-bedded with different rock types). Gypsum as weathering products is abundant. Brownish crusts occur on plateaus. Products after solution at plug margins are grayish, non-coherent, impure. After short transport mixed with other rocks, gypsum breccia forms mostly fillings among blocks. White gypsum in a great amount covers terrace sediments at eastern plug margins. Weathering products inside the plug are frequent, especially limonitized and hematitized rocks ate plug margins, represented mostly by red shales of ochre nature, sandstones and siltstones, and rocks of Tertiary age. Accumulations of organic pigment occur there.

References: Harrison 1930; Kent 1979; Trusheim 1974.

# 32. ZANGARD

Morphological characteristics:

Activity: 3b (Fig. A30)

Walls of depression are morphologically distinct, with summits elevating from the NW (630 m a.s.l.) and SW (910 m a.s.l.) toward SSW (1.409 m a.s.l.). The elliptical shape of the depression is interrupted in the SSE by outcrops of Tertiary sediments at the bottom. The western side of the depression is fault-affected (somewhat eroded fault slope) along lines of the NE-SW direction. Rests of the Hormoz material usually covering the walls as well as sudden dip change typical for diapiric structures are missing here. It cannot be excluded, that original cauldron was substantially smaller (around present outcrops of plug), because only here, substantial changes of strata dips were measured. The depression is open to the NNE.

## Hydrological characteristics:

The depression is drained by nearly parallel, fault affected network of intermittent streams toward the NNE into Rud-e Rasul. After entering broad alluvial plain, drainage patterns change to dendritic. Springs were not observed even in wet season.

#### Regional geological position:

The central part of the Kuh-e Nakh Anticline, its northern flank. The depression is composed of Guri, Gachsaran and Jahrom units (from the S to N). Between the depression and river, relics of Mishan and Agha Jari Formation occur in alluvial plain. The NNW-SSE to NW-SE trending photolineation transsect the region of plug.

#### Petrological characteristics:

Grayish green, green, whitish and gray shales to siltstones and fine-grained sandstones contain abundant tuffitic admixture. Harrison (1930) reported also dark carbonates. Plug rocks are covered with a gypsum crust, often with high amount of iron compounds. Gypsum occurs, in places, also as relics after salt dissolution, and occasionally as gypsum breccia. Dark green basic magmatic rocks were detected subordinately. Subrecent to Recent deluvia can cover other Hormoz rocks, including hematitized marginal zone.

References: Harrison 1930.



Coordinates: 27°05' N, 54°35' E, Shape: elliptical (N-zS

The ruin of plug occurring as numerous rounded hills at the

trending longer axis), Max. length: 7 km, Max. width: 5 km,

south-eastern margin of distinct morphological depression resem-

bling a cauldron. Plug hills protrude through thick deluvial se-

quences. The hill summits lie at 570 to 585 m a.s.l. Foothills are at about 460 m a.s.l. The height difference reaches then some

100 m. The elevation of alluvial fans decreases from the N (800

m a.s.l.) to the S towards Rud-e Rasul (440 to 380 m a.s.l.).

# 33. PORDELAVAR



Figure A31. Sketch of the Pordelavar plug; scale bar=1 km.

### Morphological characteristics:

Coordinates: 27°12' N, 54°28' E, Shape: rhomboidal (N-S trending longer axis), Max. length: 4 km, Max. width: 3 km, Activity: 2c (Fig. A31)

The inactive plug is tectonically controlled on the W side developed along the NNW-SSE trending fault. The lowest point of the plug occurs at the NW (840 m a.s.l.). The highest summits lie below 1,200 m a.s.l. The total height difference is 350 m. The northern plug segment has soft morphology and numerous karst forms (solution and collapse dolines, karren to pinnacles, bends of rocks due to subrosion). Morphology of the southern segment is rugged with great height differences over short distances.

The maximum elevation of sedimentary rim of Upper Cretaceous rocks is at 1,600 m a.s.l. in the W and 1,825 m a.s.l. in the E. The plug is not encircled by forms of typical cauldron, as its W limits are represented by fault scarp. Tectonics influences the presence of linear elements in the plug and cauldron morphology. Young backward erosion caught also the southern plug segment causing more pronounced morphological differences. The presence of distinct terrace levels (+15 and +10 m) in the front of the N slopes of mountains, to the N of plug, indicate the telescoping of alluvial fans due to intensive and cyclic regional uplift.

#### Hydrological characteristics:

The spring region is drained by the dendritic to irregularly circular network of intermittent streams to the N and to S. Streams lead directly to Rud-e Mehran in the S and to its tributary in the N. The tectonic zone influenced also hydrological situation by water piracy from the S. No springs were registered in dry season.

## Regional geological position:

The western end of the Ku-e Nakh Anticline, its axial zone, near the sigmoidal bend and thrust over Kuh-e Gavbast Anticline. The plug rim consists of Bangestan to Pabdeh-Gurpi sediments, anticline flanks contain also Jahrom and Gachsaran Formations. The plug is located in a complicated structural knot of intersecting NNW-SSE (dominating system) to NW-SE, NE-SW and ENE-WSW photolineations.

#### Petrological characteristics:

Blocks of rocks are represented mostly by red to purple shales with siltstones and intercalations of sandstones. Interbeds of whitish agrillitized (tuffitic) sediments are common. In places, interbeds of weathered brown limestones, cross-bedded brown quartz sandstones and gypsum (varicolored laminated gypcretes) were detected in profiles. Light gray homogeneous tuffitic(?) siltstone contain dispersed hematite or specularite concentrated along on tectonic lines often occur. Blocks of gray laminated limestone with dynamic structures occur on the top of some red beds. Dark dolostones and dark green basic magmatic rocks are rare.

Salt was detected at the western plug margins in highly corroded state (collapses, pinnacles, karren). Salt is green to varicolored, often very coarse-grained. Salt subrosion causes bending and breaking of sedimentary blocks. Gypsum occurs more frequently as weathering products (brownish crusts, purple gypsum deluvia) or relics after salt dissolution (breccias).

References: de Böckh et al. 1929.

## 34. GAVBAST



Figure A32. Sketch of the Gavbast plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°17' N, 54°26' E, Shape: rectangle (N-S trending longer axis), Max. length: 5 km, Max. width: 2 km, Activity: 1a (Fig. A32)

The active plug, thick vein, with initiations of glacier flows on the S and N, based on distinct tectonic zone of N-S direction. Plug foothills on both sides are at 640 m a.s.l. on the top of alluvial fans. The summit lies at 1,312 m. Total height difference reaches up to 700 m. The summit is encircled by the summit plateau, elongated in the N-S direction, with the base at 1,150 m a.s.l.

Triangular facets of Tertiary sediments protrude from salt on the N. The highest peaks of Tertiary rim lie at 1,378 m a.s.l. in the E and 1,430 m a.s.l. in the W, so the plug does not disrupt the anticlinal ridge in which it occurs. The classical cauldron is missing. Alluvial fans descend relatively steeply to alluvial plains at about 400 m a.s.l. Telescoping alluvial fans indicate differentiated plug activity and timing of the anticlinal uplift.

## Hydrological characteristics:

The spring regions. The summit plateau is drained areally. Plug slopes are drained by the dendritic network of intermittent streams, in the N directly to the capture area of Rud-e Rasul (Gowdar), the southern branch to basin of Rud-e Mehran. The fissure spring from salt yielding 0.02 l.s⁻¹ was registered in the northern part of the plug even during dry season.

#### Regional geological position:

The eastern end of the Kuh-e Gavbast Anticline dissected by the N-S trending tectonic zone (distinct on air and satellite photos), along which plug intruded without distinct disturbation of the anticline. The whole plug rim is composed of Jahrom Formation. Glacier flows utilized morphological depressions in soft Gachsaran Formation in anticline flanks, ending in the front of triangular facets of Guri limestones. Diapirism caused higher strata dips up to 70°, but beds are not overturned.

#### Petrological characteristics:

Petrographic spectrum is rather uniform. The plug is mostly composed of halite, gypsum is the subordinate component (brownish, several meters thick crusts covering the summit plateau and as broken blocks sliding on glaciers, and gypsum breccias).

Red aleuropelites prevail in the eastern segment. They pass, sometimes, to fine-grained psammites. Fragments of light-colored silicites and dark dolostones were registered occasionally. Greenish and grayish tuffogenic aleuropelites and dark green basic magmatic rocks occur in subordinate amounts. The rock spectrum of the western segment is different. Greenish tuffogenic rocks prevail and dark green basic magmatic rocks play only subordinate role. Reddish shales and magmatites are abundant in the central segment. Hematite ochres occur at the N margins, in a small highly weathered block.

*References:* de Böckh et al. 1929; Diehl 1944; Kent 1958; Walther 1960.

# 35. BONGOD-e AHMADI





#### Morphological characteristics:

Coordinates: E -  $28^{\circ}00'$  N, W -  $28^{\circ}00'$  N, E -  $56^{\circ}41'$  E, W -  $56^{\circ}37'$  E, Shape: elliptical and vein (W-E elongated), Max. length: E - 0.5 km, W - 2 km, Max. width: E - 0.5 km, W - 1 km, Activity: 2c (Fig. A33)

The small inactive plug to ruin composed of two parts, the plug center in the W and vein following the anticline axis in the E.

The western part with maximum elevation of 1,322 m a.s.l. occurs partly in pseudocauldron open to the N (after salt dissolution?) and partly in valley sink (elongated in the W-E direction) with the base at 1,100 to 1,160 m a.s.l. Plug relics are surrounded to covered by deluvial sediments, which form 50 m high NW-SE trending ridge in the N. Maximum elevations of Tertiary rim are between 1,532 and 1,709 m a.s.l.

The eastern part - relics of vein? - is located in deeply entrenched anticlinal valley, 700 m wide and with ENE-WSW trending axis. The lowest elevations are descending from 1,400 m a.s.l. in the E to about 1,040 m a.s.l. in the W. Ruins cover several thousands of square meters at 1,100 to 1,180 m a.s.l. Maximum elevations of Tertiary rim are between 1,600 and 1,700 m a.s.l.

#### Hydrological characteristics:

The western part of the plug represents spring depression with the centriclinal network of intermittent streams and continuing linear eastward drainage. The eastern part is drained by the semi-dendritic network (only right bank tributaries exist) of intermittent streams to the WSW. The drainage is a part of Rude Cill basin (capture region of Rud-e Shaghar - Hasan Langi). No springs were discovered.

### Regional geological position:

The position of the plug is still unclear - either in the northeastern promontory of the Kuh-e Furghun Anticline, or in the axial part of individual anticline structure (Kuh-e Pur) at the contact with Colored Melange. Intensive tectonic disturbance by fault structures of the W-E and NW-SE directions is evident (also from air photos). Guri Member occurs in anomalous thickness in anticline flanks and red beds of the Razak Formation are uncovered in the axial zone of anticline.

#### Petrological characteristics:

The western part. Weathered (sericitized) rhyolite occurs in many places. A typical feature of both rhyolite and acidic tuffs (of various colors) is the presence of devitrified glass in their groundmass. In some cases they can rather be called ignimbrite. Dark ash tuffs to agglomerates of basic composition were discovered, too. Brownish siltstones, often weathered to white color, pass into lithic sandstones, shales and gypsiferous ironstones with ripple marks on bedding planes. Relics of the Hormoz Complex are covered by gypsum-hematite crusts of the gossan type. Relics of banded salt occur in the central part. Distinct collapsed dolines and swallow holes are present there. Brown weathered oolitic limestones were registered above salt in thickness of 15 m. Blocks of dark dolostones in reddish, shortly transported weathered plug materials (gossan) are common.

The eastern part. Three outcrops of dark, often limonitized dolostones can be considered as plug relics. Brownish red aleuropelites rimmed and intercalated by weathered red and dark gray weathered gypsum as well as several centimeters thick light gray barite sill accompany these relics from the east. Barite sill's direction  $(340^{\circ}/70^{\circ})$  corresponds well to basic structural features of the region. Shales contain also yellowish, pinkish and purple layers of rhyolite tuffs (sand tuffs) and tuffites up to 1 m thick. Fragments of dark green, highly altered (epidotized, chloritized) basic magmatic rocks were found only scarcely. Reddish and greenish shales with gypsum occur low above local base level, but these rocks belong, most probably, to the Razak red beds.

References: Harrison 1930; Walther 1972.

# 36. KAJAGH



Figure A34. Sketch of the Kajagh plug; scale bar=1 km.

### Morphological characteristics:

Coordinates: 28°05' N, 56°42' E, Shape: elliptical (NNE-

SSW trending longer axis), Max. length: 4 km, Max. width: 3 km, Activity: 1c (Fig. A34)

Small plug with features of concentric structure rimmed with morphological form resembling cauldron open to the SSW. Size interpretation allows several possibilities: basic one, with the smallest area of nearly circular shape, larger one adjoining promontory to the N, and last variant assuming that the southern part of plug is buried under Recent deluvial deposits. Plug foothills lie at about 1,280 m a.s.l. in the S. The summit is at 1,630 m a.s.l. The total height difference is 350 m. Cauldron summits are at about 1,700 m a.s.l.

### Hydrological characteristics:

The spring area is drained by irregular dendritic network of intermittent streams with circular drainage along plug margins. The general drainage direction to the S leads into Rud-e Hasan Langi.

## Regional geological position:

The plug is clearly connected with broad marginal tectonic zone of the Zagros Main Thrust and Colored Melange. The plug is situated in the axial part of a syncline built of the Agha Jari and younger formations.

#### Petrological characteristics:

The petrological characteristics cannot be presented as the plug was not visited.

References: Harrison 1930.



Figure A35. Sketch of the Finu plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°49' N, 56°15' E, Shape: elliptical, Max. length: 5 km, Max. width: 4 km, Activity: 1a (Fig. A35)

The active plug of a circular shape (4 km in diameter) with a short glacier. Concentric to spiral structure is well developed. About 1.5 km wide central elevation marks the plug center. Foothills raise from 800 m a.s.l. in the S up to 1,000 m a.s.l. in the NNW. The summit lies at 1,422 m a.s.l. The total height difference is more than 600 m. The summit nearly in the plug center is rimmed by the top plateau with the diameter of about 1 km and elevation of about 1,380 m a.s.l. The second plateau, slightly declined toward plug margins, spirally ascends from 1,100 m a.s.l. in the W up to 1,200 m a.s.l. in the E. Plug slopes are almost vertical, about 200 m high in average, with exception of the southeastern segment with developing glacier flow. The separation of flow from the plug center occurs on scarps of Tertiary sediments having ESE-WNW direction and elevation of about 1,088 m a.s.l. Karst depression were registered in the northern part of the plug.

Large alluvial fans surround the plug in the S and in the E. Fans, up to 8 km long, descend from the N (1,140 m a.s.l.) to the S (740 m a.s.l.). Valleys deeply entrenched into Subrecent fans indicate plug uplift combined with backward erosion due to lowered regional base level. Cauldron around the plug is missing. Anticlinal structure in the W is situated at 1,400 m a.s.l. and in the N even over 3,000 m a.s.l.

### Hydrological characteristics:

The spring area with periclinal areal drainage into dendritic network of intermittent streams along plug margins. The drainage pattern of plug itself is in initial stage. Springs were not observed in dry season.

#### Regional geological position:

The eastern end of the Kuh-e Finu Anticline, its axial part. The anticline consists of Jahrom Formation in the center, Gachsaran Formation (morphological depressions) and Guri Member on flanks. Synclines in the S are filled with Mishan Formation covered by partly cemented material of telescoping alluvial fans. Northern anticlinal structure (Kuh-e Furghun) is overthrusted on Mishan sediments. The plug is cut by the NW-SE trending photolineations on air photos. On satellite images, nearly N-S trending system of photolineaments limits the plug from the W and E.

#### Petrological characteristics:

The basic components of the plug is halite, often banded, slightly folded. Light-colored gypsum is less frequent, in top parts constituting brownish gypcrete several meters thick. Sulfur efflorescences were found, in places. Blocks of sedimentary rocks and magmatites are present in subordinate amount in equal proportions.

Sediments are represented most commonly by slightly metamorphosed shales, siltstones, and some sandstones. Their color is variable, often reddish brown to brown, less frequently grayish green (tuffogenic admixture?), dark gray to black (organic pigment) or red (hematite ochres).

Dark green basic igneous rocks (gabbro, actinolite-rock, diorite with ophitic texture) are more common than silicic volcanic rocks. The mineral composition and characteristic features of alterations indicate the former suffered acidification (albitization, scapolitization etc.), which can be sometimes described as alkali metasomatism. Intermediary to acidic volcanic rocks of light grayish green colors or varicolored (hematitization, limonitization) belong to rhyodacite, rhyolite and ignimbrite. They are also altered to a variable degree (sericitized, epidotized, kaolinized?). White massive aplite is rare. Ash and crystal tuffs (altered ignimbrites) and tuffites of different compositions were detected, too.

References: Harrison 1930; Walther 1972.

# **38. ARDAN**



Figure A36. Sketch of the Ardan plug; scale bar=1 km.

### Morphological characteristics:

Coordinates: 27⁰41' N, 56⁰06' E, Shape: flat elliptical (W-E trending longer axis), Max. length: 6 km, Max. width: 2 km, Activity: 3a (Fig. A36)

The ruin of plug in W-E elongated and distinct double cauldron. Marked plug linearity indicates that original plug morphology was influenced by structures of the anticline in the combination with lithology of sedimentary cover. We cannot exclude, that the plug represents a vein-like structure. The Hormoz Complex is registered now in several morphologically positive relics at the cauldron bottom and on walls of the internal cauldron. The summit lies at the top of a distinct conical hill in the eastern plug segment (1,365 m a.s.l.). The lowest part is in the S, lying at 800 m a.s.l. inside the internal cauldron and at 650 m a.s.l. in the external cauldron, where the plug is drained. This position represents the base level of the plug and is tectonically affected by fault zones of NNE-SSW direction. The height difference in the plug is 560 to 700 m.

The internal cauldron is not broad. The external one is situated especially to the S and E of the plug. The summits of internal cauldron are at about 1,600 m a.s.l. and tops of the external one are at 1,825 m a.s.l. on the E and 1,882 m a.s.l. in the W. The total height difference is 1,200 m. Typically developed but less distinct is only the internal one. External rim, similarly to other forms of the area studied, formed by denudation and erosion of morphologically, structurally, lithologically and mechanically suitable portions of the anticline. Its N and also probably W limits are common with internal cauldron.

### Hydrological characteristics:

The spring depression is drained by combination of the dendritic and centriclinal network of intermittent streams to the S and to the W into Rud-e Shur (Kul).

### Regional geological position:

The central part of the Kuh-e Ardan Anticline, its axial zone. The anticline is built of Jahrom and Razak Formations, and Guri Member. The plug is situated in structurally complicated knot of intersecting about N-S and NW-SE trending photolineations. NNE-SSW trending lines displace the eastern (sunken) and western parts of the plug.

#### Petrological characteristics:

In morphological elevations, grayish purple to purple shales to siltstones passing to brownish red up to hematitized shales were observed. The highest hill is composed of sandstone, but it cannot be excluded that the rock represent sunken block of Tertiary deposits because in the axial part of the anticline Razak Formation occurs. The plug material covers area probably larger than outcrops on Recent surface, buried under Pliocene(?) and Quaternary, poorly-sorted deluvia of a great thickness.

References: Harrison 1930.
# **39. TARBU**



Figure A37. Sketch of the Tarbu plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°45' N, 55°45' E, Shape: circular, Max. length: 1 km, Max. width: 1 km, Activity: 1a (Fig. A37)

Highly active small plug, probably in the initial stage of diapirism, with typical domed morphology (vaulted summit plateau) and even small glacier flows. Recent diapirism is evidenced by salt flows overwhelming Subrecent morphology. The summit lies at 942 m a.s.l. and foothills are situated at about 600 m a.s.l. The total height difference is 350 m. The cauldron is indistinct and imperfectly developed (influenced by tectonics?).

#### Hydrological characteristics:

The spring region with areal periclinal drainage and initial circular drainage along plug margins is drained by one valley southward into Rud-e Shur (Kul). No springs occur in the plug.

Two groups of springs are connected with tectonic lines in

the southwestern foreland of the plug. The upper spring group outflowing from boulder scree yields about 30  $1.s^{-1}$  with water temperature of 53 °C. Springs are encircled by fumarolas composed of small gypsum cones covered by sulfur impregnations. The lower group outflows from fissures in the Gachsaran Formation. The yield of three springs is about 50  $1.s^{-1}$  and water temperature is about 60 °C. Hydrogen sulfide exhalations accompany the spring district. Small spring was found at the base of young alluvial fan (gravels to boulders) cutting Mishan clays/ marls. It yielded about 0.1  $1.s^{-1}$  of fresh water.

#### Regional geological position:

The central part of the Kuh-e Baz Anticline, its southwestern flank. Anticline flanks are built of Guri, Razak and Jahrom sediments. The depression to the S is developed on Mishan clays to marls are cut by a system of alluvial cones developed in more generations and altitudinal positions connected with terrace system of Rud-e Shur (+10 and +20 m frequently). The position of plug on the NW-SE trending tectonic lines cannot be excluded. These lines are distinct also to the W in the tectonically affected valley of Rud-e Kul. Diapir use for its ascend probably also the plasticity of sediments of the Razak Formation. Photolineations of NNW directions dissect in the broader zone around the plug.

#### Petrological characteristics:

The plug consists mostly of halite. Gypsum occurs less frequently, mostly as brownish crusts. Material of young alluvial deposits contains dark green basic rocks (coarser-grained gabbroids), some purple shales, brownish red fine to medium grained quartzites, dark colored shales and numerous fragments of reddish brown, medium-grained clayey sandstones which can represent also material of the Razak Formation. Pebbles of laminated gneisses with sulfide mineralization and hematite (fragments, concretions) and hematitic shales occur occasionally there, too. The marginal plug zone is highly hematitized in the southern part of the plug. Helicopter reconnaissance proved the presence of one block of highly altered and disintegrated lightcolored volcanic rock (rhyolite ?).

References: Harrison 1930; Walther 1972.

# 40. TASHKEND



Figure A38. Sketch of the Tashkend plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°41' N, 55°39' E, Shape: irregular (amoebalike), Max. length: 6 km, Max. width: 3 km, Activity: 2b (in average) (Fig. A38)

The form of the plug body is irregular and very difficult to describe. It occurs in an important fault knot. The plug activity and morphology are most probably influenced by subordinate faults of NNE-SSW direction and distinct NW-SE trending lines. The plug consists of two, or rather three parts in which diapirism was active in different periods with differing intensity.

The most active (1c) is the northeastern segment of the elliptical shape. Domed character (about 2.5 to 3 km) is apparent. Summits are at 832 to 872 m a.s.l. On the E, blocks break off, making initial stages of glacier flows. Here, the plug is surrounded by a system of alluvial fans descending from 440 m a.s.l. toward Rud-e Kul (Shur). The ridge of sedimentary rocks with an elevation up to 1,390 m a.s.l. and NE-SW trends encircle the plug on the W.

Rhombohedral segment is linked to the former in the S. This segment can be classified as inactive (2b). According to morphology and block content, this part is probably older. Although the plug top is situated here at 1,030 m a.s.l., distinct depressions occur at the southern margins (about only 700 m a.s.l.) and probable relics of short glacier flow are preserved here. The sedimentary rim of the plug reaches the elevation of 935 m a.s.l.

The oldest segment occurs in the northwestern part of the plug. It has character of a ruin (3a-b) constituted only of several relics having character of narrow promontory (about 800 m a.s.l.) from the southern part of the plug northwestward. Relics are situated in a morphological form similar to cauldron and on its walls. The cauldron has elliptical shape with the NW-SE trending longer axis, open to the S. As the cauldron is based mostly on tectonic line dissecting the center of the anticline, it can be classified as pseudocauldron. The highest elevations in cauldron ascend from the SE (937 m a.s.l.) to the NW (1,357 m a.s.l.).

#### Hydrological characteristics:

The spring region is drained by the centripetal network of

intermittent streams on the NE segment and further along the margins into Rud-e Shur (Kul). The dendritic network prevails in the southern segment, combined with the centriclinal drainage type in the NW, drained southward into Rud-e Kul basin. Intermittent springs rimmed with salt sinters occur at eastern margins of the north-eastern segment with yields of 1 to 2 l.s⁻¹.

#### Regional geological position:

The western margin of the Ku-e Baz Anticline in the sigmoidal bend from the NW-SE direction to the NE-SW direction. The axial part is built of the Guri Member, eventually Gachsaran (Razak) Formation, flanks are composed of the Mishan and Agha Jari Formations. From the N, W and SE, the plug is limited by distinct photolineations (by photolineament in the N). The plug is cut by the left-lateral strike-slip photolineament of the NNE-SSW direction.

#### Petrological characteristics:

The northeastern segment of the plug is build mostly by evaporites (dominating in lower levels), the upper part is composed of layers of light-colored tuffogenic rocks and gypsum, or light-colored dolomitic rocks. Blocks of reddish shales and green altered basic magmatites occur at the eastern margin. Only one block of greenish rhyodacite, altered to different degrees, was observed there. Such rocks constitute pebbles and cobbles in alluvial fans. Among the material of fans, large fragments of pinkish brown hornfelse with druses and veinlets of actinolite and blue amphibole asbestos are quite common.

The southern segment of the plug is characteristics by the presence of blocks with variable petrologies. Typical are shales and siltstones of purple brown color, sometimes with green intercalations, on which distinct calcareous sinters form along streams. Gray to black dolostones, layers of acidic dolostones, layers of acidic tuffs and tuffites (varicolored - pale green, bluish green, pinkish), inter-bedded with laminated reddish brown crusts occur, too. The bed-shaped formation of pale-green tuffs is very conspicuous, positioned mostly just below Recent surface. Dark green basic igneous rocks with variable textures (predominantly of subvolcanic rock types) or intermediary rocks (fine-grained diorite) are relatively abundant. Acidic effusive rocks (rhyolite, rhyodacite, ignimbrite) and their tuffs occurring in this segment are to some extent altered (albitized). The same applies for intermediary rocks. Evaporites are represented mostly by varicolored gypsum (most common as relic material of weathering) and gypsum breccias. Several meters thick gypsum-ferrugineous crusts are distinct.

At a first sight, the northwestern segment of the plug has a gossan character. All relics of plug material are highly hematitized and/or limonitized. It is very difficult to distinguish intensely altered Hormoz Complex and similarly altered Razak red beds. Also younger Miocene and Pliocene sediments at the southwestern plug margins are highly limonitized along the NW-SE trending tectonic line. We cannot exclude, that the denudation of glacier took place here.

### 41. SHAMILU



**Figure A39.** Sketch of the Shamilu plug; scale bar=1 km.

### Morphological characteristics:

Coordinates: 27°36' N, 55°24' E, Shape: triangle, Max. length: 8 km (SV), Max. width: 4 km, Activity: 1c (Fig. A39)

The plug, probably at the end of its activity or with low level of activity as indicated by its hydrological character. The plug core of linear to lense-like shape occurs at the northeastern plug margin. It is probably elongated along tectonic line of the NW-SE direction. Summits (over 1,100 m a.s.l.) are constituents of inclined summit plateau up to 1 km broad with the base at 950 to 1,100 m a.s.l., inclined to the SE. Plug foothills descend from 820 m a.s.l. in the W to 500 m a.s.l. Plug is surrounded by a system of alluvial fans, which are separated from the river (427 m a.s.l.) by an expressive ridge of Pliocene and Miocene sediments. The ridge and river terraces are overwhelmed by glacier flow on the S, whose extent can be larger than drawn on figures. Glacier is eroded by river in places. Karstification is characteristics for the W glacier margins.

The northeastern plug margins are encircled by nearly vertically tilted beds of Tertiary sediments, with pseudocauldron summits at 1,100 to 1,258 m a.s.l.

### Hydrological characteristics:

The spring region with irregularly developed (partly peri-

clinal, parallel, dendritic) network of intermittent streams. The plug is drained mostly southward, streams directed to the N are sporadic. The plug is a part of Rud-e Shur basin.

#### Regional geological position:

The eastern part of the Kuh-e Shamilu Anticline, its southeastern flank in indistinct sigmoidal bend on junction with unnamed anticline on the E. Guri Member forms the anticline center, Mishan (Kermaran) sediments constitute its flanks. Photolineations of the NW-SE direction limit the northeastern plug margins. The plug is dissected by the NNW-SSE trending photolineament and by NNE-SSW and NE-SW photolineations.

#### Petrological characteristics:

The central part of the plug is composed mostly of evaporites and blocks of sedimentary and magmatic rocks. Evaporites are represented by halite and gypsum, the latter as basic material of brownish crust. Evaporites started to prevail toward the eastern plug margins. Dark gypsum and gypsum breccias are common with blocks of reddish shales and siltstones, locally also of fine-grained sandstones. Gray to black shales with organogenic admixture occur subordinately. Conglomerates to breccias with poorly rounded pebbles of dolostones and limestones and greenish, gravish brown and reddish pelitic matrix were observed, as well as quartzites. The occurrence of columnar to acicular hornblende crystals and blue fibrous amphibole asbestos on fissure walls and cavity fillings in shales, often enclosed in calcite and quartz is very distinct phenomenon. Druses of rocky quartz of distinctly blue color (caused by admixture of blue asbestos) are another interesting feature of plug petrology. Dark green magmatites (altered olivine gabbro) were registered in places. Those rocks are usually highly altered - epidotized.

White to light green, sometimes pink effusive rocks resembling aplitic rocks were often observed. Their composition corresponds to carbonatized rhyodacite. They contain several mm to several cm large carbonate rhombohedrons with thin limonitized rims. They sometimes overlay brownish fine-grained sandstone with probably gypsum cement in the western plug margins. Interbeds of green tuffogenic rocks are distinct in blocks of reddish shales which pass locally up to sandy siltstones. Dark dolostones with veins of white to pink color are sporadic.

References: Gansser 1960; Harrison 1930; Heim 1958; Kent 1979; Trusheim 1974.

### 42. CHAH BANU



Figure A40. Sketch of the Chah Banu plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°36' N, 55°02' E, Shape: rhomboidal (SE-NW trending longer axis), Max. length: 17 km, Max. width: 9 km, Activity: 2c (Fig. A40)

The inactive plug resembling the rugby ball. The longer plug axis is probably influenced by a tectonic line. The glacier is not developed, only some indications exist at the north-western margins, although vein-like promontory with soft morphologies after salt dissolution is more acceptable. The highest points of plug lie in a strip from the SE to N (870 to 955 m a.s.l.). Maximum height difference of 400 m is still great, but highly damaged by denudation. Relatively broad U-shaped valleys to valley sinks occur, especially in the NE part of the plug, build of rounded hills (730 m a.s.l., in the SE 650 to 700 m a.s.l.) protruding from a depression. Morphological depression elongated from the WSW to ENE with elevations of about 700 m a.s.l. is another distinct relief element.

Valleys and depression are filled with deluvial sediments around protruding hills and along ridges. Fluvial sediments prevail in their axial zones. Material is not well-sorted, but fragment wear is relatively high. Owing to the continuous but cyclic area uplift, indications of terrace systems occur.

Cauldron remnants can be detected especially along the southwestern plug margins. They are built of steeply dipping Guri Limestones and some Gachsaran sediments. On other places, the rim is composed of less resistant Mishan Formation. Local outcrops of Agha Jari, on the NW also of Bakhtyari Formations contain plug-derived material. Harrison (1930) and Kent (1970) noted intraformation breccias of plug-derived material in Middle Miocene clastic sediments or limestones (Guri Member). Miocene diapirism should be proved by up to 100 m thick reef in the Mishan Formation (Guri ?).

Alluvial plain with surface declining from 750 to 550 m a.s.l. is composed of deluvial to fluvial deposits beyond plug margins. Relics of the plug protrude from them on the E and NW. Plug margins are encircled, in places, by plug-derived material transported for a short distance and cemented by gyp-sum.

#### Hydrological characteristics:

The spring area with dendritic network of intermittent streams leading to Rud-e Shur in the E, and to Rud-e Rasul (Gowdar) in the S. No springs were detected in dry period. In alluvial deposits, occasional slightly mineralized groundwater infiltrates after a short distance again. A spring occurs in fluvial sediments off the northeastern plug margin. The yield is about 6 l.s⁻¹.

#### Regional geological position:

The eastern part of the Kuh-e Chachal Anticline, its southeastern flank, in bended junction with Kuh-e Shamilu. The axial zone is composed mostly of Guri Member and Gachsaran Formation, sometimes also of Agha Jari Formation to Bakhtyari-filled syncline outcrops. The plug is limited by NW-SE photolineation on the NE and SW, and by the NNW-SSE line on the E. The N-S and NE-SW trending photolineations occur in the western half of the plug.

#### Petrological characteristics:

Highly variable Hormoz Complex is present. Extensive blocks, max. 1.5 km long, form distinct part of plug relief. Davoodzadech (1990), based on materials of Kent (1979) noted the existence of Hormoz blocks of unrealistic size of 3 km, concluding that "nonturbulent flow of the salt in diapirs" occurred. De Böckh, Lees and Richardson (1929) noted more realistic size of blocks - up to 2 km. The enormous size of blocks was not proved by our field trips, or by the study of air photos. Those expected megablocks are composite structures of mutually overthrusted (tectonic slices) smaller blocks separated by often tectonized plug gypsum. The blocks are dominantly composed of flyshoid to tidalite-like rhythmic sequences of red, purple and brown shales to siltstones often with dynamic structures and banded gypsum intercalations. Gypsum forms several meters thick layers of laminated internal structure with bands of banded iron ores and green tuffitic rocks. Small microdiapirs occur in gypsum, in places. Shales are locally highly ferrugineous and sometimes pass laterally into gravish green tuffitic interbeds. Gravish brown dolomitic sandstones to dolostones occur above shales. In upper parts of some sections, purple gray trough cross-bedded sandstones form intercalations at top of profiles. Shales sometimes transgressively overlay basic volcanic horizons. Gray to black organic-rich shales are less frequent. The whole complex is covered, in numerous places, by brownish dolostones of variable thickness. Stromatolithic limestones are common. Finds of algae (Collenia, Cryptozoon and Solenopora types of algae) were reported (Kent 1979) not only here, but also in other plugs (e.g., Gach, Aliabad). Some blocks are composed of sandstone sequences of iron-rich unsorted and medium-grained lithotypes containing intercalations of green shales to hematitic shales (altered iron ores?), which are overlain by coarse-grained sandstones with clasts of iron ores (pisolithic, pseudopisolithic, clastic) and rocks (metamorphic quartz, green tuffs) and terminating by beige cross-bedded coarse-grained sandstones. Complex sequences of alternating gypsum, limestone, dolostone and acidic tuffogenic rocks occur in the N (generally in profiles up to 50 m thick). Carbonate rocks, originally white to gray, are often stained yellow by weathering. Dolostones are sometimes black. Lamination of sequences is common, locally up to laminites. Thin intercalations of gypsified and iron-rich paper shales occur in some limestone horizons (up to 30 cm thick). Limestones at the top of profiles often

contain cubic crystals of pyrite. Gypsum horizons are crystalline, mostly light-colored, sometimes laminated to thickly bedded. Dark fetid columnar gypsum with laminae of gypsum and iron-rich shales occurs rarely. Tuffogenic intercalations are acidic, light-colored, sometimes gypsified with thin veins of gypsum+calcite+quartz. Green, fine-grained sandstones occur as subordinate layers.

Dark magmatites of basic composition are relatively abundant in the western part of the plug, making also thick interlayers (up to 18 m) in gypsum-shale sequences (a kind of lava flows). Such rocks are altered by fossil weathering at the top of sequence and by hydrothermal processes (quartz-calcite veins with crystals). Ophitic texture is developed only in central parts of the flow. Acidic volcanic rocks and derived volcanoclastics occur more often in the north-eastern part of the plug. They are light-colored (white, greenish, grayish, pink) rhyolites, rhyolite tuffs and tuffites, often with reddish limonitized interbeds. More basic volcanic rocks - andesites (propyllitized) - are also common. Watters and Alavi (1973) described even carbonatites with apatite and rare earth minerals. We have found aplite composed of quartz and plagioclase with some actinolite.

Varicolored plug gypsum was registered among original evaporites. It occurs in numerous varieties, mostly as interbeds in clastics, as gypsum breccias containing blocks of different rocks, and sandy gypsum or breccias representing weathering products and products of a short transport. Up to 10 m thick brownish gypsum crust covers summits of morphologically positive elevations in the southeastern part of the plug. Halite could be present in deeper structural levels of the plug, as water-bearing alluvia contain only freshwater and karst forms are missing.

Limonitization and hematitization of plug margins are common feature. In the SW, limonitized Guri Member was observed, in the N (in general) iron-rich margins are composed mostly of highly tectonically disturbed hematitic shales.

# 43. CHAHAL



Figure A41. Sketch of the Chahal plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°32' N, 54°43' E, Shape: amoeba-like (N-S trending longer axis), Max. length: 6 km, Max. width: 4 km, Activity: 1a (Fig. A41)

The plug itself is young and highly active now. It has elliptical shape (3 to 4 km) with longer axis in the NNE-SSW direction. On the western side, it is completed with short glacier flows, whereas on the northern and southern sides glacier flows are longer, sometimes overwhelming narrow triangular facets of more resistant lithologies and filling young valleys. The plug summit lies at 2,023 m a.s.l. and it is surrounded by vaulted summit plateau above 1,950 m a.s.l. Plug foothills occur at 1,300 to 1,400 m a.s.l. The total height difference exceeds 700 m. Triangular facets of Tertiary sediments (Guri Member and Gachsaran Formation) occur at 1,300 to 1,656 m a.s.l. over which glacier flows descend to 1,100 m a.s.l. Flow of salt is proved by blocks separating from the glacier front and falling into deep gorges (glacier calving). Numerous karst forms (dolines, collapsed dolines, keyhole-like small caves in several levels, karst spring outflowing from caves) were registered in glaciers. The indications of cauldron appear to the E of plug in the Tertiary rim.

#### Hydrological characteristics:

The spring region, in which the summit part is drained periclinally (areally). Plug slopes show initiation of periclinal network of short intermittent streams with collecting circular network along margins. Prevailing area of the plug is drained to the N, smaller portion then to the SE, in general to Rud-e Shur basin. Intensive runoff was registered in wet season completed by outflows of highly mineralized waters from numerous fissures and from cavities at plug/glacier bottom.

#### Regional geological position:

The western end of the Kuh-e Chachal Anticline in its axial part at the junction with Kuh-e Burkh Anticline (sigmoidal bend?/tectonically affected). Guri Limestone and Gachsaran sediments occur in anticline flanks. The plug is encircled by Lower Tertiary and Upper Cretaceous formations (Jahrom-Asmari, Sachun, Pabdeh-Gurpi and Bangestan). Sediments of rim with dips of 60 to 70° indicate high plug activity.

The system of alluvial fans overlies soft lithologies of Mis-

*References:* Davoudzadeh 1990; Harrison 1930; Kent 1958, 1979; Nili et al. 1981; Samani 1988b; Trusheim 1974; Walther 1960.

han (Anguru) clays and marls behind marginal facets of Guri Limestones. The system is developed in several levels, often showing telescoping structure. The thickness of individual "levels" is tens of meters. Fan/Mishan contact is flat, apparently declining from the plug. Fan material is poorly sorted and poorly rounded with numerous blocks. The top of older fans is cemented by carbonates, forming classical calcrete horizons (up to 1 m thick). The cementation by gypsum is also common. Fan telescoping proves cyclic area uplift. Fans pass after about 3 km into better sorted alluvial plain filling the syncline.

The NNW-SSE trending photolineaments cut the plug on satellite images. On the contrary, on air photos, NNE-SSW trends are only distinguishable within the plug, but NW-SE ones occur to the E of it, too.

#### Petrological characteristics:

44. SIAH TAGH

The plug consists mostly of evaporitic rocks. Dark colored, layered, banded or laminated halite prevails. The summit pla-

Figure A42. Sketch of the Siah Tagh plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°31' N, 54°34' E, Shape: egg-like to elongated trapezoid (N-S trending longer axis), Max. length: 7 km, Max. width: 2-4 km, Activity: 1c (Fig. A42)

The plug center occurs in the S part of the whole structure having size of 2 to 3 km. The summit lies at 1,345 m a.s.l. Plug teau is covered by brownish gypsum crust. Rim zone is enriched in characteristics blocks of red hematitic shales with gypsum enclosed in bedded, varicolored gypsum.

Purple gray and gray, sporadically dark shales to siltstones are common block constituents. Fine-grained, locally quartz or clayey, thinly bedded sandstones sometimes occur. Tuffogenic admixture is indicated by green color, in places. Silicites are rare and yellowish weathered dolostones only sporadic.

Basic magmatites form blocks in salt and represent common constituent of deluvia. They are mostly epidotized with different textures (actinolite-rocks, diabases with epidote amygdales, less frequently gabbros). Black basaltoid rocks (with secondary quartz?) occur rarely, as well as gray rhyolites and rhyolite tuffs, carbonatized quartzites and altered granitoids (granodiorite?) and melaphyroid breccias.

References: Harrison 1930; Kent 1979.

foothills are at about 900 m a.s.l. The total height difference is about 350 m. Northward inclined plateau occurs in the summit part (1,200 to 1,300 m a.s.l.). The eastern and western sides are represented by semicircular break-off walls.

The northern part is built of distinct glacier flow utilizing broad valley in syncline. Glacier front has its base at 720 m a.s.l. The height of glacier front and sides reaches 150 m. The glacier surface is relatively flat, increasing from 850 m a.s.l. in the N up to 1,100 m a.s.l. in the S. Initial karstification forms occur on the surface. The plug erosion is also in an initial stage, but it cannot be excluded that the arrangement of slice-shaped blocks prevented more rapid denudation. Glacier foothills rise continuously from the N to S up to 800-900 m a.s.l. The glacier is surrounded by distinct system of alluvial fans, descending to alluvial plain in the valley center in the N.

The plug center is surrounded by distinct cauldron, whose eastern and western sides are tectonically limited. The cauldron is broadly open northward. Its summits reach up to 1,800 m a.s.1.

#### Hydrological characteristics:

The ceasing plug activity is indicated by initial stages of irregular network of intermittent streams in the plug itself and in the glacier flow. The catchment area at the southeastern and southwestern margins of the plug is contributed by waters flowing down from anticline axis. Three fissure springs were detected in the lower part of glacier. Springs yields were from 0.1 to 10. 1.s⁻¹ (during wet season). Springs were accompanied by salt and gypsum sinters colored orange and brown by iron compounds.

#### Regional geological position:

The northern flank of the Kuh-e Burkh Anticline at its eastern end and joining with Gateh Anticline. Jahrom Formation forms major part of the anticline. On satellite images, the plug contours seem to be limited by the NNW-SSE to NNE-SSW lineaments on both longer sides and by nearly W-E trending line on the N. Photogeology of air photos proved this indica-



tions, but showed more complicated fracture (lineation) structure, with dominant NNE-SSW lines, accompanied by the NNW-SSE to NW-SE trends which dissect the plug glacier.

#### Petrological characteristics:

The plug proper (plug core) contains a sequence of grayish red to purple or brownish shales and siltstones, less frequently sandstones (maybe forming one large block). Dark dolostones occur at plug margins, sometimes accompanied by dark green basic, often epidotized subvolcanic rocks with massive texture (diabases), or volcanic rocks with amygdaloidal structure (altered andesite). Pebble material of alluvial deposits contains about 90% of fragments of aleuropelites.

Glacier contains, except of rocks mentioned, also grayish

# 45. GACH



Figure A43. Sketch of the Gach plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°34' N, 54°28' E, Shape: pear-shaped (NNE-SSW trending longer axis), Max. length: 8 km, Max. width: 4 -6 km, Activity: 1b (Fig. A43)

The plug center proper is situated to the N and it is beanshaped with the diameter of 3 to 4 km and the W-E trending longer axis. The summit lies at 1,437 m a.s.l. Plug foothills are at about 960 m a.s.l. The distinct summit plateau elongated along plug core axis has its base at 1,300 m a.s.l. Semicircular breakoff planes are developed at the eastern and western slopes, the western one being completed with a small glacier flow. green tuffogenic siltstones to fine-grained sandstones laterally passing to purple gray shales. Blocks lie on salt. Due to salt dissolution, varicolored gypsum occurs on the surface (grayish, at margins reddish, often white and coarse-crystalline, black with white veins). Brownish gypsum crust cover some more leveled glacier parts. White carbonatized or green andesite tuffs form subordinate small blocks. Laminated light-colored limestones and darker dolomitic carbonates with ripple marks are present, too, as well as red siliceous rocks (jaspilites) and light-colored rhyolite tuffs to rhyolites in the frontal part of glacier.

*References:* de Böckh et al. 1929; Harrison 1930; Nili et al. 1981a.

The remaining, larger, part of the plug represents a conspicuous glacier flow descending to the S into 760 m a.s.l. in synclinal valley. The glacier consists of two morphologically different parts. The glacier front in the SE is characterized by distinct height difference of up to 150 m over a short distance. The second segment represents area between the glacier front and the plug core with low and soft morphologies.

The plug is encircled from the N by poorly distinguishable cauldron which is built of upper Mesozoic sediments. The cauldron summits lie at 1,300 to 1,500 m a.s.l. In other parts, the plug is surrounded by deluvia forming composite alluvial fans which pass into proluvial-fluvial deposits in the S. The morphology of the plug core, presence of break-off planes, small glacier flow and possible indications of double cauldron can support idea of diapyrism cyclicity.

#### Hydrological characteristics:

The summit part of the plug core is drained areally by the periclinal drainage. The periclinal net of intermittent streams is initiated on plug slopes and directed to the S, in general. The glacier flow shows totally different patterns. Intermittent streams are nearly parallel and follow accretional zones in the flow elongated generally in the W-E direction (with bend). Shallow valleys in alluvial fans are linked, on both sides, to streams in the glacier. During wet seasons, springs occur nearly in all valleys at the glacier front. They yielded max. only of  $2 \text{ l.s}^{-1}$ . Fissure springs were detected in the plug core with yields up to only  $0.05 \text{ l.s}^{-1}$ .

#### Regional geological position:

The plug is situated in a structurally complicated zone built of central parts of the Kuh-e Gach Anticline in the N, of the eastern end of the Kuh-e Bunaskatu (Siah) Anticline in the central part, and of plunged anticline of Kuh-e Bavush in the S. Double cauldron is formed by Mesozoic (Jurassic to Cretaceous) Khami and Bangestan Groups, and Pabdeh-Gurpi Formation. Alluvial fans cover younger, Tertiary formations (Asmari-Jahrom, Gachsaran, Mishan and Agha Jari).

The foreland of the glacier flow is built of carbonate cemented Bakhtyari Formation with surprisingly low content of plug-derived material. Relatively young, but intensive plug activity is documented also by its movement over Subrecent unconsolidated terrace material of local stream. The plug is dissected by the NW-SE trending photolineation, accompanied by some NNE-SSW trends on satellite images. On air photos, the lineation structure is more complicated, with dominating NNW-SSE and NNE-SSW trends, completed in the southern part of the glacier by NE-SW lineations to lineaments.

#### Petrological characteristics:

The glacier front contains blocks of reddish and purple shales and less frequent dark green basic magmatites (diabase, hornblendite, massive basaltoids) enclosed in varicolored and often laminated gypsum. Acidic magmatic rocks - granitoids or highly altered rocks of rhyolite type to rhyolite tuff composition with siderite rhombs and limonitic pseudomorphoses after them - occur sporadically. Silicified magmatic rocks are rare.

Gypsum with blocks of greenish, fine-crystalline to massive basic rocks prevail in higher parts of the glacier. Red shales and dark dolostones are less frequent. The presence of fragments of quartz veins, pink calcite and light-colored limestones (Jahrom) is a distinct feature of this plug part.

The plug core is composed of evaporites, in lower parts by halite, above it with blocks of grayish, highly pulverized siltstone with frequent vugs filled with hematite, and dominantly by gypsum breccia and gypcrete. The crust is whitish to grayish brown, in average 3 m thick and contains fragments of fine-grained, often laminated (white, red, and pink) sandstones, graphitic and calcareous shales, mostly red siltstones or impure black dolostones and green magmatic rock of basic composition. Relatively abundant blocks of stromatolitic limestone were observed in the western slope. Kent (1979) described here concentric disk of *Conophyton* algae (Middle Cambrian?) from dark bedded dolostones.

*References:* Ala 1974; Gansser 1960; Harrison 1930; Kent 1979; Nili et al. 1981a.

### 46. PASHKAND



Figure A44. Sketch of the Pashkand plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°25' N, 54°09' E, Shape: elliptical, Max. length: 2,5 km, Max. width: 1,5 km, Activity: 1b (Fig. A44)

The small plug with features of the concentric structure and the summit at 1,030 m a.s.l. Plug foothills are at 800 m a.s.l. in the S and 680 m a.s.l. in the N. Total height difference is 350 m. In the N, the plug is encircled by triangular scarps (facets) of Guri Member and by a system of alluvial fans descending to slightly inclined structural plateau of the Dasti depression.

The cauldron in the S, built of Lower Miocene formations, is indistinct with distinct enlargement by pedimentation. Cauldron summits lie below the highest point of the plug, i.e. 835 m a.s.l. on the E and 935 m a.s.l. on the S.

#### Hydrological characteristics:

The drainage by the combination of the periclinal and circular network of intermittent streams from the spring area to the N into depression of Dashti or to drainage basin of Rud-e Alamarudasht. Streams from the southern plug part belong to Rud-e Rasul (Gowdar) basin. No spring was discovered.

#### Regional geological position:

The plug is located on sigmoidal bend between the eastern end of the Pashkand Anticline and the western end of the Kuhe Burkh Anticline, along tectonic zone. Jahrom, Gachsaran, Guri and Mishan (Kermaran) units compose the structure. The plug activity dates back to Miocene, because organodetrital sandy carbonates contain plug-derived clasts up to 15 cm in size (basic magmatites, dark dolostones, limonitized hematite nodules). Hematitized rim of the plug (gypsum, tectonized) is thrusted over carbonate-marly-gypsum formation which can belong to Gachsaran Formation. Continuous but slow diapirism is indicated by plug morphology and absence of salt on the surface.

The plug lies in the quadrangle limited by distinct the NW-SE and NE-SW trending photolineation, accompanied by NNW-SSE trends on satellite images. Air photos show intersection of the NNW-SSE, NNE-SSW and NE-SW trending photolineations.

#### Petrological characteristics:

The plug is covered with thick brownish gypsum crust. The presence of halite in deeper structural levels cannot be excluded. Gypsum to anhydrite of various colors (white, grayish, reddish) occur on numerous sites as blocks. Gypsum is common also in the marginal plug zone. There it occurs in the form of hematitized gypsum layers and gypsum breccia enclosing fragments of sedimentary rocks and igneous rocks of the Hormoz Complex. Grayish sandy to silty gypsum represents a product of weathering or of a short transport. White crystalline anhydrite forms blocks covered with white and gray hydrated gypsum crust which falls down.

Blocks of the Hormoz Complex are mostly built of sedimentary rocks. Carbonates prevail: dark dolostones, indistinctly bedded, brecciated with thin veins, and gray limestones, bedded, with numerous nodules (geods) and brownish laminated, thinly bedded, yellowish weathered, if fresh than greenish limestones are the most common lithologies. Brown clastics are less frequent, compared with other plugs. Ferrugineous sandstones to fine-grained sandstones, bedded, brown to ochre with secondary ferruginization are more abundant than fine-grained lithologies in this plug. Dark basic igneous rocks form large blocks in the eastern and northern parts of the plug. They are mostly of subvolcanic origin, but also porous volcanics occur, in places. Diabase type rocks prevail, mostly green to dark green, epidotized, sometimes amygdaloidal to variolitic (ferrugineous fillings). Pebble composition of Recent valley fill is lithologically uniform, but with differing percentages of individual rock types, according to lithologies of blocks in drainage area, and varies from 50 % of dark carbonate, 30 % of basic igneous rocks, 15 % of light-colored carbonate and 5 % of other rocks (ferrugineous sandstones, sandstones) up to 55 % of basic igneous rocks, 20 % of dark dolostones, 20 % of light-colored carbonate and 10 % of sandstones, incl. ferrugineous ones.

References: de Böckh et al. 1929.

# 47. KHAIN



Figure A45. Sketch of the Khain plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°47' N, 55°37' E, Shape: vein (NE-SW elongated), Max. length: 4 km, Max. width: 0,5 km, Activity: 1c (Fig. A45)

Low active plug of flat lenticular shape connected with thrust plane of NE-SW direction. The lowest point lies at 840 m a.s.l. in the S and the summit is situated at 1,100 m a.s.l. in the N. Small dolines often occur. The plug is encircled probably by double cauldron. Traces of internal cauldron have their summits only little above the plug summit (1,130 to 1,214 m a.s.l.). Outer cauldron reaches 1,413 to 1,719 m a.s.l. Polycyclic diapirism can be indicated by the morphology of cauldrons (pseudocauldrons).

#### Hydrological characteristics:

The spring region is drained by the dendritic network of intermittent streams southwestward. Only a small part of the plug is drained northeastward. The region belongs to Rud-e Kul basin. Spring were not discovered.

#### Regional geological position:

The eastern end of the Kuh-e Darmandan Anticline (southeastern flank) reduced by a thrust line. The plug is encircled by Upper Cretaceous Bangestan Group on the NW. Behind the thrust in the SE, younger formations occur, i.e. Upper Tertiary Agha Jari, Mishan and Guri units covered by a system of alluvial fans composed mostly of plug-derived material.

The plug lies in complicated structural knot of intersecting N-S, NW-SE, NE-SW and NNE-SSW photolineations on satellite images. According to air photos, the plug is displaces by NE-SW and NNW-SSE faults in its western part.

#### Petrological characteristics:

Halite prevails in the northern plug segment, forming morphologically distinct pinnacles. Gypsum produced by weathering of chemogenic and evaporitic sediments covers top parts of the plug surface. Overlying them occur and in the central plug part prevail grayish brown, dark gray, purple to brownish red siltstones, often pulverized and containing abundant hematite. Arenites are mostly fine-grained, laminated, reddish and little cemented. Dark gray shales occur sporadically. They pass into dark nodular impure dolostones-limestones, which are connected with varicolored gypsum forming diapir-like folds, in places. Fetid dolostone is common, too. Zoisite-hornfels can be easily mistaken for a certain color type (light pinkish brown) of fine-grained siltstone or shale, unless their pebbles contain veinlets and accumulations of blue asbestos and/ or actinolite. These rocks belong to facies series of high-pressure - low temperature metamorphism (blueschist facies). Similar or identical rocks occur in most plugs in the NW part of the area studied.

Along the thrust plane, rocks are more intensively altered, which is evident especially in igneous rocks. They are represented by volcanic rocks: strongly altered rhyolites (kaolinized, chloritized and limonitized, probably after higher tectonization), as well as by propyllitized andesites. Green basic igneous rocks occur in larger blocks in the SE. Medium to coarse-grained varieties with ophitic structure prevail over dark basaltoid rock (in places with vesicular structure).

Pebble composition of the streambed draining the majority of plug extent is as follows: 70 % of varicolored siltstones, 5 % of dark shales, 5 % of dark dolomitic limestones to dolostones, 5 % of basic igneous rocks, 5 % of gypsum and 10 % of sandstones.

### 48. DARMANDAN



Figure A46. Sketch of the Darmandan plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 25°45' N, 55°22' E, Shape: flat elliptical (W-E trending longer axis), Max. length: 6 km, Max. width: 3 km, Activity: 3b (Fig. A46)

The ruin of plug in distinct and morphologically diversified cauldron. The lowest point occurs at 600 m a.s.l. in the S, summits lie in the plug center at 818 m a.s.l. and at 860 m a.s.l. on the E. It is very probable, that rocks of the Hormoz Complex fill the whole cauldron bottom. They are covered in many places with Recent and Subrecent deluvial material derived mostly from Lower Tertiary sediments of the cauldron rim. Relics of plug material protrude from deluvia as rounded hills. Moreover, several meters thick remnants of the Hormoz Complex occur on cauldron walls.

The cauldron is morphologically highly diversified, exhibiting indications of double structure on the E. Causes of formation of double cauldron can be seen in the cyclicity of diapirism, less probably in landslides due to irregular evaporite dissolution and subrosion, or in combination of all processes together with erosion in suitable lithologies. The lowest part of the cauldron is situated along the internal perimeter at 750 to 780 m a.s.l. Cauldron summits lie at 1,982 m a.s.l. in the S, 1,570 m a.s.l. on WNW, at 1, 301 m a.s.l. in the N, at 1,579 m a.s.l. in the E, and at 1, 072 m a.s.l. in the SE, showing that the cauldron is open to the S.

Longer period from the end of the plug activity is indicated also by terrace system in deluvial deposits inside the cauldron. The system proves also cyclic movements of anticline uplift and/or movements inside the cauldron only. Erosion recently prevails over accumulation, streams deeply entrench. Therefore the youngest terrace at +5 m is recognizable, as well as older terraces at about +10 and +20 m.

#### Hydrological characteristics:

The plug is drained by the dendritic network of intermittent streams with general direction to the S into Rud-e Shur. Spring areas of streams are situated at cauldron rims owing to longlasting backward erosion. Springs were not observed even after a long rainy period, but depressions in clastic deposits of streambed are sometimes filled with water, which infiltrates after short distances.

#### Regional geological position:

The western end of the Kuh-e Darmandan Anticline, its axial part. The plug is obviously connected to the thrust plane continuing from surroundings of Muran plug to Khain plug. The thrust turns here from NE-SW to W-E direction.

Photolineations in plug surroundings form complicated knot with detectable NNW-SSE, NNE-SSW, NW-SE, NE-SW trends. On air photos, NW-SE, NNW-SSE and some NE-SW trends are visible, the former two displacing the plug on several places.

#### Petrological characteristics:

Sedimentary and volcanoclastic rocks of the Hormoz Complex prevail. Reddish shales to siltstones with interbeds of grayish green tuffogenic(?) pelites are abundant. Yellowish pink to red sandstones are less frequent. Evaporites are represented by some gypsum and gypsum breccias with iron compounds.

High alteration is very distinct in unstable minerals accompanied with intensive limonitization. Surface of the majority of rounded hills is covered by marked rusty brown crust (iron compounds), sunken zones have character of gossan, proving longlasting plug destruction in relatively slow groundwater flow to the S.

# 49. ALIABAD



Figure A47. Sketch of the Aliabad plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°38' N, 54°36' E, Shape: irregular (NE-SW trending longer axis), Max. length: 2 km, Max. width: 1,5 km, Activity: 1b (Fig. A47)

Small active plug of irregular to elliptical shape with germs of a glacier flow in the SE. The summits lie at 1,327 and 1,290

m a.s.l. Above 1,250 m a.s.l., the vaulted summit plateau is indistinctly developed. Plug foothills descend from the S (1,100 m a.s.l.) to the N (900 m a.s.l.).

Indistinct cauldron is composed of Lower Tertiary formations. It is open northward. The elevation varies from 1,130 to 1,505 m a.s.l.

#### Hydrological characteristics:

The spring area with initiations of the periclinal and dendritic network of intermittent streams is drained to the N. The morphology indicates stable but indistinct plug activity. Numerous karren and embryonic cave systems in limestones indicate relatively slow water circulation. Karst forms are filled with Recent and Subrecent proluvial deposits. Substantial run off was observed during rainy season.

#### Regional geological position:

The eastern end of the Kuh-e Gach Anticline, its northern flank. The axial zone is composed of Bangestan Group, Pabdeh-Gurpi and Jahrom Formations, the northern flank contains also Gachsaran Formation and Guri Member. The plug is cut by indistinct NNW-SSE and N-S photolineations. According to satellite images, NW-SE trends occur in a broader plug vicinity.

#### Petrological characteristics:

The chief mass is represented by evaporites, especially green banded salt. Gypsum is subordinate constituent. The summit plateau is covered with gypsum crust. Other rocks were detected mostly in pebble material of deluvia. Reddish siltstones to clayey sandstones, both highly hematitized, prevail. Abundant are also green, slightly altered (epidotized) basic igneous rocks with massive, sometimes amygdaloidal and brecciated structure and tuffogenic rocks. Gray siltstones and dark dolostones are sporadic. Dolostones are often stromatolithic, finely laminated. According to Kent (1979) they contain Middle Cambrian(?) algae.

References: Harrison 1930; Kent 1979.

### 50. TANG-e ZAGH



Figure A48. Sketch of the Tang-e Zagh plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°57' N, 55°59' E, Shape: bean-shaped (NE-SW trending longer axis), Max. length: 5 km, Max. width: 3 km, Activity: 2a (Fig. A48)

The plug of the irregular shape with ceasing activity. Summits lie at 1,188 m a.s.l. in the NW and at 1,288 m in the SE. Both summits are surrounded by the NW-SE elongated indistinct vaulted top plateau above 1,150 to 1,220 m a.s.l. Plug foothills are at about 900 m a.s.l. in the NW and at about 1,000 m a.s.l. in the SE. The total height difference doesn't exceed 400 m. Nevertheless, the relief is highly rugged with marked height differences. Longer plug axis follows tectonic zone, which is distinguishable also in the stream network. Classical cauldron is missing.

#### Hydrological characteristics:

The spring area. The plug is drained by a network of short intermittent streams. Small river flows through the plug at its northeastern margin. The western plug margins are rimmed by another intermittent stream flowing from the southwestern flank of the Ku-e Muran Anticline. The general drainage is directed to the NW, i.e. into Rud-e Kul. Springs were observed in depressions of fluvial deposits of the largest intermittent stream in the eastern plug margins even in dry season. Their yields were about 0.1 l.s⁻¹ and temperature reaches 28 °C. Water infiltrates after a short distance.

#### Regional geological position:

The eastern end of the Kuh-e Muran Anticline, its axial zone,

which is built of Asmari-Jahrom, Razak Formations and Guri Member, possibly by the rest of Mishan Formation. Mishan rocks are highly tectonized (brecciated) along plug margins in thickness of about up to 2 m. They often contain iron mineralization (botryoidal aggregates). Agha Jari clastics occur at the eastern plug margin. According to Gansser (1960), Bakhtyari Conglomerates transgressed over the plug. The plug is developed along regional photolineament of SE-NW direction dissecting N-S trending, less distinct photolineations.

#### Petrological characteristics:

Complex of blocks composed of purple gray (probably tuffitic), purple brown and red shales to siltstones and fine-grained sandstones, accompanied by subordinate gray to brownish gray shales is very distinct feature here. Plates are pulverized at plug margins. Gansser (1960) noted up to 2 km size of this complex. Tuffogenic admixture is expressed by green color, and intensive carbonatization and has probably intermediate character. Grayish, usually silicified lithic sandstones are common. Complex of dark gray to black fetid dolostones passing vertically to beige limestones with pyrite crystals overlays gray sandstones with light-colored interbeds. Brecciated limestones of yellowish color containing fragments of positively weathered limestones and impregnated by gypsum in the upper part represent fossil calcrete horizon.

Dark green basic magmatic rocks are less abundant. They are represented by variously altered amphibole diorites. More often occur complexes of greenish tuffs and tuffites, sometimes accompanied by complexes of intermediate volcanics of andesitic composition, which are pyritized. Andesitic sequence (alternation of tuffs and lava flows) reaches up to 20 m and overlays brownish red shales with sandstone one intercalations. Acid volcanic rock involve altered rhyolites of appearance similar to andesites, ignimbrite. An alkaline trachyte of interesting mineral composition indicates alkali metasomatism (albitized plagioclase, magnesioriebeckite, epidote). Blue amphibole asbestos (fibrous magnesioriebeckite) was also found in hornfels-type rocks in the alluvium.

The amount of whitish and gray gypsum increases toward plug margins. Gypsum is often brecciated, sometimes having character of gypsum breccia. Varicolored halite was registered sporadically. Higher contents of iron compounds can be observed at plug margins in all petrographic types, sometimes forming distinct crusts or layers. Along tectonized zones, Tertiary sediments are locally hematitized and limonitized at plug surroundings.

*References:* Fürst 1970, 1976; Gansser 1960; Harrison 1930; Kent 1979; Nili et al. 1979; Richardson 1924; Walther 1960, 1972.

### 51. PALANGU



Figure A49. Sketch of the Palangu plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 28°01' N, 55°52' E, Shape: elliptical (SE-NW trending longer axis), Max. length: 2,5 km, Max. width: 1,5 km, Activity: 3a (Fig. A49)

Small plug. Although in the initial stage of ruination, the domed structure is still preserved. Plug foothills lie at 700 to 720 m a.s.l. and its summit reaches 840 m a.s.l. Plug protrudes from structural depression (syncline) covered by alluvial fans (to the S of plug) and fluvial deposits of broad alluvial plain (to the N of plug). Karst depressions were occasionally registered in the plug.

#### Hydrological characteristics:

The spring area with the centripetal net of short intermittent streams is drained generally northwestward, where streams disperse in a broad depression which is a part of Rud-e Shur (Kul) basin. No spring were observed.

#### Regional geological position:

Although protruding from the structural depression, the plug is situated on plunged eastern promontory of small Durs Anticline (to the N of the Konar Anticline) composed of youngest Tertiary Agha Jari and Bakhtyari Formations covered by thick sequence of Recent and Subrecent deluvial deposits. No distinct photolineations occur within the plug.

#### Petrological characteristics:

Evaporites are represented only by gypsum, which is the weathering/dissolution relic in the form of grayish or reddish mass or brownish crust on the surface. Other rock types are mostly represented by gray, probably tuffitic highly pulverized siltstones to fine-grained sandstones often passing to brownish red thinly bedded shales. The latter are intercalated by layers of pink carbonates few centimeters thick. Pale red and gravish pink hornfels containing actinolite and lazulite on small fissures was found in several places. It represents product of high-pressure, low-temperature metamorphism (blueschist facies). Other metamorphic rock found is actinolite-rock, containing abundant epidote. Black shales with organogenic admixture, dark gray laminated shales, dark gray stromatolithic limestones and fetid carbonates are other rocks of the Hormoz Complex commonly found here. Blocks of greenish slightly porous epidotized vitroclastic tuffs (probably of rhyolite composition) occur especially at the western plug margin.

References: Harrison 1930; Nili et al. 1979; Walther 1972.

### **52. MESIJUNE**



Figure A50. Sketch of the Mesijune plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 28°00' N, 54°55' E, Shape: subrectangular to oval (NW-SE trending longer axis), Max. length: 15 km, Max. width: 8 km, Activity: 1c (Fig. A50)

The structure is composed of two parts, i.e. of the plug itself and of the large areal glacier flow completely encircling the core. The plug core is small and circular elevated structure with diameter of 2 km. The summit lies at 1,368 m a.s.l. and it is surrounded by the summit plateau about 1 km wide, with the basis at 1,300 m a.s.l. The plug foothills are at 1,100 to 1,180 m a.s.l. Triangular scarp (facet) of Tertiary sediments protrudes from steep south-eastern plug slope.

The remaining part of the structure is represented by debris and extensive glacier flow. The glacier extended rather to structural valley in the NW and SE (syncline axes), than in the perpendicular direction where the flow was blocked by morphological elevations of anticline core built of Tertiary sediments. Distinct morphological plateau surrounds slopes of the plug core in the SW, NW and NE with elevations of 1,100 to 1,000 m a.s.l., from which softly diversified glacier flow descends at 760 m a.s.l. to the NW. The surface of glacier flow in the SE has a character of slightly inclined slope, then, at 900 m a.s.l., morphologically more diversified zone appears with foots at 700 m a.s.l. The marginal glacier zone has a greater height differences in its front. There, karstification is frequent - karren to pinnacles, dolines, collapsed structures, swallow holes and small caves.

The size of plug core and of glacier flow indicate intensive diapirism, whose beginning is difficult to date (?Pliocene), as no plug-derived material was discovered in Tertiary formations of the anticline.

#### Hydrological characteristics:

The spring area of intermittent streams. The initiation of the centripetal drainage network is visible in the plug core. The linear net of the NW-SE direction is characteristics for the southeastern part of the glacier and linear to dendritic net for the northwestern part. Valley bottoms are relatively broad, often flat. Valley shape is close to U-morphology. The thickness of alluvial deposits in valleys is highly variable up to high meters. Plug rocks form distinct vertical steps in valley bottoms, indicating impoised river grade. Alluvia are composed of poorlysorted and poorly-rounded fragments to pebbles of purple gray siltstones. They are cemented in places, mostly by gypsum. General drainage is directed south-eastward into Rud-e Shur basin. Outflows from fissures were observed during rainy season and groundwater outflows especially in depression of fluvial valley deposits. Water infiltrated to sediments in broadening valley portions at plug margins

#### Regional geological position:

In complicated structure of the Mesijune Anticlinorium composed by tectonic slices along several W-E overthrusts with wavy course of fold axes. The anticlinorium is composed of many stratigraphic units without logical connection (morphologically positive units of Jahrom, Guri and Bakhtyari and units forming morphological depression as Gachsaran and Mishan Formations). Except of the western side, where plug material is in the contact with Tertiary formations, debris and glacier flow are surrounded by a system of broad inclined Recent and Subrecent telescoping alluvial fans.

The plug is dissected by the NNW-SSE and NW-SE trending photolineations on satellite images.

#### Petrological characteristics:

The plug is composed mostly of brownish gray to purple gray, sometimes pale red, purple or reddish brown siltstones, which occur also in its surrounding (plateau, slope), but here in highly crushed to pulverized form. Reduction of  $Fe^{3+}$  to  $Fe^{2+}$  can be seen in crushed zones. Green reduction spots are usually situated around pyrite, sometimes form zones along discontinuities (crushed zones, bedding planes, etc.). Thin, mostly light-colored to white, laminae to beds of tuffogenic material are visible, in places. Dark gray shales with organogenic admixture passing to dark dolomitic limestones are sporadic.

Petrological spectrum at marginal parts and frontal zone of the glacier is somewhat broader. Aleuropelites, mostly pulverized, and fine-grained sandstones, which are sideritized or pyritized, in places, dominate. Dark green magmatites (subvolcanic provenience) in the tight contact with altered green tuffs and tuffites (without contact metamorphosis) are sporadic. Brownish silicites and light-colored limestones (Tertiary?) are accessoric. Somewhat more abundant are various types of carbonate rocks in bedded sequences, laminated to banded dolomitic limestones and limestones with bands of sandy material, intercalations of darker dolostones, intrabasinal breccias (limestone conglomerates), tuffogenic rocks (containing siderite and pyrite crystals) and gypsum.

Halite commonly occurs at plug margins. It is bedded to banded, often translucent or green, beige or orange, highly recrystallized in places. Toward the plug center, halite is covered with sedimentary rocks of the plug. Salt contains fragments to blocks of different rock types, sometimes arranged to beds resembling fossil scree, and gypsum interlayers to blocks with interbeds of dark dolostones, ferrugineous and tuffogenic rocks and limestones. Salt is usually overlain by grayish gypsum beds (weathering and dissolution residuum). Crystalline gypsum occurs most often in brecciated forms with fragments of black shales, light-colored limestones and grayish brown siltstones. Dark gypsum with organic admixture and local intercalations of iron compounds are common, too. Brownish gypcrete up to 5 m thick covers some parts of glacier plateaus.

References: Harrison 1930.

# 53. KURDEH



Figure A51. Sketch of the Kurdeh plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°44' N, 54°38' E, Shape: irregular - amoeba-like (NE-SW trending longer axis), Max. length: 5 km, Max. width: 3 km, Activity: 1c (Fig. A51)

The structure is composed of the plug itself situated in the center, glacier flows in the NE and possibly also in the SE and vein-like body in the SW. The plug center has an elliptical shape with area of 2x3 km, the summit at 1,085 m a.s.l. and the summit plateau at 950 to 1,000 m a.s.l. (the same elevation has the plateau developed on sedimentary rocks linked with plug on the W). Karst phenomena in salt are abundant (vertical solution pipes, collapsed dolines, karren, etc.). The plug is situated between two large blocks or ridges of Middle Cretaceous Khami Group, which are highly tilted and tectonized, representing detached blocks uplifted by diapirism. The foothills of plug core can be identified with problems depending on the interpretation of other plug segments. Glacier flows is developed in the NW without any doubts. Its front lies at 700 to 740 m a.s.l. Semicircular break off zone is linked to it in the W. The southeastern segment can be classified as small initial glacier, broken off the plug core. Vein-like promontory of the plug with the NW-SE direction on the SW encircles partly one of the hills of Khami carbonates.

The plug is encircled by indistinct cauldron in the NW, whose rim ascends from the NE to SW (up to 1,500 m a.s.l.). The double cauldron is poorly distinguishable in the SW (pseudocauldron?). Except of blocks of Khami Group, the plug is surrounded in other places by alluvial fans descending into the structural depression (syncline axis) at 620 m a.s.l. Relatively distinct depression situated to the NE of plug is filled with salt-bearing deluvia and encircled by cauldron-like structure open southward.

#### Hydrological characteristics:

The spring area with the periclinal network of short intermittent streams initiated mostly on the summit plateau with collection ring-like (circular) region along plug margins. The general drainage by a system of valleys in alluvial fans is directed to the SE into Rud-e Shur basin.

Stable spring was observed to the NW of plug on tectonic line. Its yield was about 8 l.s⁻¹ and temperature 36°C. Hydrogen sulfide emanations are distinct.

#### Regional geological position:

The eastern end of the Kuh-e Parak (Kurdeh) Anticline (anticlinorium), its southern flank. The cauldron and detached blocks in the plug are built of the Khami Group. Bangestan Group, Pabdeh-Gurpi, Jahrom and Gachsaran Formations are completed in limestones of Guri Member in the sequence. Mishan (Kermaran) and Agha Jari sediments are probably covered by alluvia. Smaller crests of Bakhtyari Formation, highly cemented by carbonate, protrude from alluvia. Typical for them is special weathering surface. Bakhtyari conglomerates contain small amount of plug-derived material, indicating plug activity in Pliocene. Harrison (1930) noted plug-derived material already in Middle Miocene limestones (Guri Member?) and greenish marls (Mishan/Anguru?).

The plug occurs on zone of distinct NNW-SSE photolineation dissecting with some NE-SW lines. According to air photos, plug contains photolineations of NW-SE and NNE-SSW directions.

#### Petrological characteristics:

The plug is composed mostly of evaporites. The chief rock species is colorless, sometimes varicolored halite. White crystalline gypsum, less frequently varicolored, form beds or occurs in blocks in alluvia. Brownish gypsum crust, several meters thick, in places highly limonitized and carbonatized usually covers irregular layers of sponge-like gypsum. At plug margins, gypsum is reddish, earthy and hematitized.

Blocks of the Hormoz Complex are mostly composed of brownish gray shales to siltstones, often reddish with voids after leached salt crystals and with crystalline hematite or siderite. The promontory in the SW consists of a complex sequence of red, purple and pale red "paper" shales intercalated by thin beds of green tuffitic rock, whitish "tonstein"-like tuffogenic altered rocks, greenish gray sandstones with red dots and altered siderite crystals or purple gray siltstones. Shales alternate with several horizons of gray laminated limestones passing upwards into brecciated gypsified limestones and banded gypcretes. The termination of whole sequence is represented by amygdaloid greenish gray basic magmatites enclosed in shales. Similar character of single shale-limestonegypcrete cycles can allow two explanation, i.e. rhythmical structure of the sequence and/or multiplication as tectonic slices thrusted along minor thrust planes. Disintegrating reddish brown, medium to coarse-grained well-sorted sandstones to

fine-grained conglomerates are not frequent, while finds of silicified quartzites with veins of colorless crystalline quartz are rare. Hematitization represents common rock alteration. Specularite occurs abundantly in coarser-grained crystalline aggregates.

Smaller blocks of greenish tuffs and tuffites are common. Thinly bedded white layers with brown spots and gypsum laminae form intercalations in clastic sediments. Tuffogenic admixture was observed also in light-colored coarse-grained sand-

# 54. DEH KUYEH



Figure A52. Sketch of the Deh Kuyeh plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°54' N, 54°28' E, Shape: irregular, Max. length: 11 km, Max. width: 3 km, Activity: 1b (Fig. A52)

The plug is composed of several segments, i.e. of the plug core and two glacier flows (in the E and in the W), and of veinlike eastern promontory. The plug can be classified rather as a vein-like body carrying detached block of Tertiary sediments (Jahrom Formation) at the top.

The plug core lies in the western part of the structure and has horseshoe-like shape with the diameter of about 2.5 km. the internal part of the structure is built of Tertiary sediments (detached block?). There, the plug summit (situated at 1,735 m a.s.l.) is surrounded by slightly vaulted summit plateau at 1,650 to 1,700 m a.s.l. elongated in the NNE-SSW direction. The plateau is developed both on the Hormoz Complex and on Tertiary sediments. The steep slope is linked up to the plateau. Plug foothills are at 1,400 to 1,350 m a.s.l.

The western glacier flow is not extensive, in some moments it resembles rather salt glacier fall descending to 1,120 m a.s.l. The eastern glacier is substantially more extensive with front foots at about 1,000 m a.s.l. In both cases, frontal slopes of glaciers are up to 60 m high. Karst forms are abundant in them, dolines being the most common features. Glaciers on both sides are surrounded by a system of alluvial fans.

The plug is not encircled by a classical cauldron, which is given by its position along important tectonic zone. The plug itself, carrying detached block of Tertiary sediments, has higher elevation than sedimentary rim with 1,455 m a.s.l. in the S and 1,540 m a.s.l. in the N.

#### Hydrological characteristics:

The spring region with areal periclinal drainage of the summit plateau and initiated periclinal network of intermittent stones. Igneous rocks are represented by blocks of dark green diabases and fragments of melaphyres with calcite amygdales, enclosed in tuffitic matrix.

Alluvial material, more than 8 m thick, shows variable wear (depending on rocks contained), poor sorting and weak cementation (gypsum, carbonates).

References: Harrison 1930; Kent 1958; Nili et al. 1981; Walther 1972.

streams on plug slopes and dendritic network of streams on glacier flows (with swallow holes and karst springs). The general direction of drainage does not depend upon plug shape, but on the structure of sedimentary complexes in surroundings. The drainage is directed to the W into closed depression and to the E into a salt depression near Mesijune plug (Rud-e Shur drainage basin). During wet season, numerous springs were registered with yields up to 30 l.s⁻¹, outflowing from glaciers mostly, often from karst springs. The total outflow from both valleys highly exceeds 200 l.s⁻¹.

#### Regional geological position:

The southern flank of the Namak Deh Kuyeh Anticline. The anticline is built of Jahrom Formation (anticline core), with Gachsaran (Razak) Formation in the southern flank (morphological depression) and about 8 to 15 m thick Guri Member (morphologically distinct ridge) passing into green marls of the Kermaran Member (both Mishan Formation). The southern anticline flank represents a complicated structure with one regional overthrust and several local thrusts (in Gachsaran/Razak Formation) and local detailed disharmonic folding (e.g., in Agha Jari Formation). The region is cut by distinct NNW-SSE and NE-SW trending photolineations.

#### Petrological characteristics:

The plug is composed mostly of evaporites with dominating halite. The percentage of gypsum rapidly increases in glaciers owing to dissolution of salt. Gypsum is mostly visible as white material, but also brownish gypsum is common as several meters thick crust on the plug and glaciers, respectively. Red, hematite-rich gypsum was registered at plug margins.

Blocks of rocks are represented mostly by the Hormoz Complex, but large block covering the top part of the plug can represent uplifted, detached block of Tertiary carbonates (Jahrom Formation?). Sediments of the Hormoz Complex are represented mostly by grayish to purple siltstones, sometimes by pale green, in glaciers highly pulverized shales, as well as red shales and lithic sandstones with siderite rhombs, in places. Thin laminae to interbeds of whitish to greenish tuffs and tuffites occur in shales. At the eastern margin, intercalations of limestones occur in red shales, sometimes accompanied by beds of black fetid gypsum. The alternation of shales and carbonate rocks is typical for this plug, sometimes prevailing shales and siltstones with tuffogenic intercalations, sometimes prevailing over carbonate rocks. Limestones are mostly gray, laminated to thinly bedded, sometimes crystalline and highly tectonized (crushed). Horizons of stromatolithic carbonate rock to Collenia-like stromatolites are common. Some limestones are overlain by basic hydrothermally altered igneous rocks, with veins containing hematite. In some places, carbonates are sideritized. Dark dolostones are rare.

Except of tuffogenic rocks mentioned, magmatic rocks are

# 55. NINA



Figure A53. Sketch of the Nina plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°41' N, 54°07' E, Shape: complex vein (octopus-like) with WNW-ESE trending axis, Max. length: 17 km, Max. width: 3 km, Activity: 2b (Fig. A53)

Very complex morphology given by the plug position along important tectonic zone of regional overthrust. The plug center is of generally flat lenticular shape up to 3 km long, which is accompanied by a system of salt veins, in average 0.5 km thick, containing material of the Hormoz Complex. The plug shape and its material are highly tectonized. The lowest plug position descends in the northern margin from 880 to 820 m a.s.l. Here, the plug is surrounded by a complex of alluvial fans, descending down at about 790 m a.s.l. to a structural depression (syncline) covered by large salty plain with flat bottom. The remaining plug segments occur in the S above distinct escarpment (with height difference up to 300 m), composed of Agha Jari sediments containing plug-derived material indicating Pliocene activity of Nina plug or of Namaki plug in a close neighborhood. The plug summits lie at about 1,200 m a.s.l. The elevation in promontories (veins) exhibits descending character from the E to W, and plug material constitutes positive morphology, mostly. Depressions separating veins are structurally controlled by fault tectonics. Karstification of plug material was registered in places, mostly as dolines and solution pits.

#### Hydrological characteristics:

The spring region is drained by a network of intermittent

represented by common dark green basic rock with variable texture and structure.

References: Harrison 1930.

streams going northward to closed salty depression. Only the southern segment of the plug is a part of Rud-e Shur drainage basin.

#### Regional geological position:

The complex structure of the plug/vein lies in the synclinorium which is hard to characterize. It is composed of youngest Tertiary sediments (Agha Jari and Bakhtyari Formations) thrusted over a system of tectonic slices with alternation of Tertiary formations and plug material.

Although on satellite images photolineation network is relatively very simple with not abundant lines, photogeological study of air photos showed very complex internal structure of the plug and its closest vicinity. The plug is dissected by NNE-SSW and NNW-SSE faults (main system displacing the plug), accompanied by less distinct NW-SE and NE-SW trending faults. Also WNW-ESE trending thrusts were detected. They are displaced along younger fault/fissure systems.

#### Petrological characteristics:

The predominant material of the plug is halite and gypsum. Salt is covered with more resistant gypsum as a product of dissolution. Gypsum forms up to several meters thick reddish brown crusts, in places. Pulverized and tectonized gray, purple, reddish or brownish siltstones with abundant hematite (specularite) on fissures or filling voids after leached-out salt crystals. Reddish purple or green (tuffogenic) interbeds occur occasionally. Dark carbonates and reddish brown fine-grained sandstones are sporadic.

Green basic magmatites with amygdaloidal or brecciated textures occur less frequently. Gabbros or diabases are often epidotized. Grayish green tuffitic breccias and light grayish green tuffs with amygdaloid texture were registered, too. Grayish white ignimbrites occur in places.

Strong hematitization and limonitization is characteristics for thrust zones both in plug material and in Tertiary sedimentary formations.

### 56. NAMAKI



Figure A54. Sketch of the Namaki plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°52' N, 54°08' E, Shape: elliptical (NW-SE trending longer axis), Max. length: 6 km, Max. width: 4 km, Activity: 1c (Fig. A54)

Active plug of the domed character. The plug center proper lies in the eastern part of the structure. Its longer axis (about 4 km long) has NW-SE direction - parallel to numerous structural elements in surrounding sediments. The summit lies at 1,315 m a.s.l., and together with several other peaks at about 1,250 m a.s.l. it is surrounded by the vaulted summit plateau at about 1,080 m a.s.l. In the NW, the summit plateau passes into evident glacier flow. The initial stages of a glacier are developed also in the S. The geomorphological classification of the southeastern margin is very difficult as it is represented by a part of the plug which started to break off, but this promontory cannot be classified as glacier proper. This part is flat topped with plateau margins at about 1,060 m a.s.l. The plug core is then represented by nearly circular structure with diameter of about 2 km in the northeastern part of the whole plug.

The plug foothills at the southwestern and southeastern margins are in the contact with a salty depression and lie at about 800 m a.s.l. At the northwestern margin, the plug is surrounded by a system of alluvial fans, along which the foothills rise up to 950 m a.s.l. The highest point of foothills lies at 980 m a.s.l. in the NE, where the plug contacts with Upper Cretaceous sediments. The maximum height difference is 500 m. Karstification is abundant, with numerous solution and collapse dolines, and solution pits up to 30 m deep.

#### Hydrological characteristics:

The spring region with initiation of the periclinal network of short intermittent streams drains the region directly to salty depression.

#### Regional geological position:

The central part of the Kuh-e Parak Anticline, its southeastern flank. The region is built of Bangestan Group plunging under Quaternary sediments of proluvial-lacustrine origin.

On satellite images (air photos were not at our disposal), the plug is cut by N-S trending photolineations accompanied by NE-SW trending lines.

#### Petrological characteristics:

Evaporites build the plug. Grayish halite prevails. Whitish gypsum appears in upper zones and at margins (weathering product). Horizons of brownish gypsum, up to 3 m thick, are common on summit plateaus.

Blocks of flyshoid reddish purple shales and siltstones to fine-grained sandstones are common. They contain intercalations of green to purple siltstones with positively weathered silicified or limonitizsed horizons. Dark green magmatites of basic composition were registered at plug margins.

# **57. SARMAND**



Figure A55. Sketch of the Sarmand plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 28°02' N, 56°07' E, Shape: wedge-like (about NE-SW trending axis), Max. length: 9 km, Max. width: 1,5 km, Activity: 2b (Fig. A55)

The plug is composed of two segments. The plug center is situated in the NE with elliptical shape and the W-E trending longer axis (about 5 km, shorter axis about 1.5 km). The south-western segments represents relatively narrow promontory of vein-like character and several hundreds meters wide.

The plug core is composed of two morphologically different parts. The western one shows substantial altitudinal differences of 250 m over a short distance. The summit lies at 1,513 m a.s.l. and it is surrounded by a summit plateau (above 1,500 m a.s.l.). The plug foothills descend from about 1,300 m a.s.l. in the E to about 1, 250 m a.s.l. in the W. This part of the plug is surrounded by the anticlinal structure of NW-SE direction. The plug shows the direct contact with sediments of Lower Tertiary in the SE (summits at 1,500 to 1,700 m a.s.l.). In the NW, the plug is encircled by deluvia developed along NNE-SSW trending fault structure. The eastern plug segment is characterized by soft morphology with a maximum height difference of 80 m. Depressions are filled with deluvia. The plug surface rises from the S (1,300 m a.s.l.) northward, where it touches a complicated anticlinal structure of semicircular shape (cauldron or pseudocauldron). The southeastern margins are surrounded by Recent and Subrecent deluvia of the structural depression.

The vein-like segment is linked with the southwestern end of the plug and follows distinct tectonic line, which turns to the NE-SW direction at the margin of anticlinorium (with summit at 1,884 m a.s.l.). The plug crops out as isolated islands from alluvial fans on areas several hundreds to thousands of square meters. The vein is highly destructed and covered by young deposits (Pliocene Bakhtyari Formation cannot be excluded under alluvial fans). Individual outcrops are exposed in erosion cut-downs or gullies. The level of islands peaks decreases from 1,300 m a.s.l. in the NE to 1,200 m in the SW.

#### Hydrological characteristics:

The region is drained by intermittent streams springs of which occur in Upper Cretaceous to Lower Tertiary sediments in plug surroundings. Streams cut the plug on several places from the N to the S, but in other places make plug margins more distinct (erosional valley at plug/sediment interface). The region is generally drained southward into Rud-e Shur (Kul) drainage basin. Springs were not observed during dry season.

#### Regional geological position:

The plug occurs between anticlinoria of Kuh-e Gahkun and Kuh-e Furghu in a structural intersection of NE-SW and about N-S trending photolineaments. The structure of both anticlinoria, owing the proximity of the Thrust Zone and Colored Melange, is highly complicated, composed of thrust slices along several overthrusts. The rock sequence is composed of Upper Cretaceous up to young Tertiary formations. Tectonic disturbances are distinct and influence the plug position. The thrust plane is of Pliocene age (most probably) and since that time the plug activity can be dated. The plug shape and its position allow to assume origin and deformation already in Pliocene.

#### Petrological characteristics:

The plug composition is highly variable. Evaporites represent only minor percentage. Gypsum was registered in softly modeled plug portions as weathering products (after halite dissolution?). At plug margins, gypsum is varicolored, often red (hematitized), accompanied by abundant hematite ochres and grayish gypsum breccias.

The plug summit is represented by one block practically, which lies on grayish purple gypsum with abundant rock fragments. The block is composed of gray silicified and laminated tuffs (now silicites) about 2 m tick, overlain by a complex of yellowish white bedded tuffs (8 m), light-colored finely bedded sandy tuffs (1 m) and light-colored distinctly grained tuffs in the thickness up to 25 m. This tuffogenic horizon (with total thickness of 35 m) is covered with varicolored effusive rocks with stromatolite-like texture. Micropetrographic study revealed their composition corresponds to rhyolite. Their fabric indicates they may have originated from subaquatic effusions, or, rather, subaquatic lava flows. Some portions of their sequence exhibit large phenocrysts of quartz. Another portion of this effusive sequence exhibits features typical for ignimbrite. Joint occurrence of laminated colorful rhyolites and ignimbrites may be explained either by rapid changes of the environment in the time of their formation (subaquatic lava flows/sub-aerial volcanic activity), or, rather, as a typical sheet of welded tuff. In the latter case, the upper portion, where preserved, exhibits signatures typical for pyroclastic material comprising lots of glass; below this, in the layers where the heat was not lost so rapidly as in the upper layers, compaction and welding of the tuff fragments can be observed, until, in the lowest portions, a pseudolava may have apparently developed. In the latter case, the only difficulty is to explain the conspicuous changes in the colors of individual relatively thin layers.

Of other rocks found in the plug, dolostones and epidotiterocks deserve to be mentioned.

### 58. GAHKUM - EAST



Figure A56. Sketch of the Gahkum-East plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 28°04' N, 56°03' E, Shape: elliptical (NW-SE trending longer axis), Max. length: 3 km, Max. width: 2 km, Activity: 1b (Fig. A56)

Small domed active plug with the summit at 1,820 m a.s.l.

#### and foothills at 1,480 m a.s.l. as the lowest point. The position of the plug off the cauldron center indicates the possibility of the polyphase diapirism, especially because there are indications of plug coverage by deluvia in the SE.

The cauldron is very distinct. The highest summits are in the W at 2,218 and 2,141 m a.s.l., above the plug itself summits reach up to 2,400 m a.s.l.

#### Hydrological characteristics:

The drainage (into Rud-e Shur {Kul} basin) by a dendritic network of intermittent streams which spring from cauldron slopes (in the E) and in anticlinal ridge (in the W) is controlled by an important thrust fault of the westward direction.

#### Regional geological position:

The axial part of the eastern margins of the Kuh-e Gahkum Anticline built of the Bangestan Group. The anticlinal structure is highly tectonized here with normal faults and overthrusts. Regional diverging photolineaments of NW-SE direction in the plug and its surroundings are distinct.

#### Petrological characteristics:

According to Harrison (1930) the plug is composed mostly of reddish gypsum and debris of the Hormoz Complex. Detailed specification cannot be given here owing to the fact that plug was not visited.

References: Harrison 1930.

### 59. SAADAT ABAD



#### Morphological characteristics:

Coordinates: 28°08' N, 55°52' E, Shape: circular, Max. length: 4 km, Max. width: 4 km, Activity: 1b (Fig. A57)

Distinctly circular plug with flattened summit part composed of several plateaus. The summit at 1,082 m a.s.l. (center of plug activity?) lies in the northeastern segment. The highest, less distinct vaulted plateau occurs at about 1,020 m a.s.l. and can be correlated with plateau developed on rocks of surrounding sedimentary rim. The lower plateau, below steep slopes, lies at about 900 m a.s.l. The third one with the small extent is developed at about 800 m a.s.l. only in the SW. The system of plateaus with longer axes of the NW-SE direction separated by steep slopes indicates not regular movement of the plug material (flow over obstacles or cyclicity of accretion or cyclicity in anticline uplift). Numerous karst forms were registered. Plug foothills are situated at 700 m a.s.l. on the SW passing into alluvial plain. The plug front is 100 to 150 m high. Toward the NE, on both sides, foothills ascend up at 800 m a.s.l. and they are surrounded by a system of alluvial fans. On the SE at 1,000 m a.s.l., the plug is linked up directly to the southwestern flank of anticline along narrow valleys filled with Quaternary deluvia. The plug activity is documented by numerous quakes.

Figure A57. Sketch of the Saadat Abad plug; scale bar=1 km.

### Hydrological characteristics:

The spring region with imperfectly developed periclinal and dendritic network of intermittent streams and marginal (circular) drainage in the NE. The drainage is generally directed southwestward into Rud-e Shur (Kul) basin. Small springs yielding up to 1.5 l.s⁻¹ of water 28 °C warm occur at plug margin. Springs and short stream courses are covered by salty crust.

#### Regional geological position:

The axial part of the Kuh-e Gahkum Anticlinorium which is highly tectonized (normal faults and overthrusts) causing a rapid plunge under Recent sediments of a salty depression. The anticline is built of formations starting even by Triassic sequences, but the plug surroundings is built of Khami and Bangestan Groups. On satellite images, important regional photolineament of NE-SW direction is traceable and oblique photolineations of NW-SE and about N-S directions are linked up.

#### Petrological characteristics:

The plug is composed dominantly of evaporites, especially halite. Gypsum is somewhat less frequent, and occurs mostly at

plug margins, where it forms whitish or varicolored, banded, folded to disharmonically folded sequences up to 100 m thick. Evaporites cover tilted Bakhtyari conglomerates at the eastern plug margin (30°). On summit plateaus, gypsum constitutes brownish gypsum crusts.

Pebble material of alluvial cones gives a good review of lithologies of the plug: sedimentary rocks, i.e. red, brown, purple, gray, green shales, siltstones and fine-grained sandstones prevail, black paper shales with organic admixture are subordinate as well as light gray laminated limestones, calcareous shales, dark fetid limestones and gray dolostones. Some of those rocks form small hills (decomposed and broken blocks) at the plug front. Blue veins of fibrous amphibole asbestos occur in some rocks (shales, limestones?).

Igneous rocks are represented by grayish, sometimes pink tuffs and tuffites with variable grain-size, accompanied by tuffitic sandstones to sandy tuffs. Brownish green gabbroid rocks and grayish mottled andesites are common. Both rock types are altered and limonitized.

*References:* Fürst 1970, 1976, 1990; Harrison 1930; Hirschi 1944; Nili et al. 1979; Trusheim 1974; Walther 1960, 1972.

# 60. GAHKUM



Figure A58. Sketch of the Gahkum plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 28°13' N, 55°08' E, Shape: circular, Max. length: 3 km, Max. width: 3 km, Activity: 2c (Fig. A58)

The passive plug to ruin with preserved signs of the circular shape and summits at 1,021 m a.s.l. in the SW and at 892 m a.s.l. in the NE. The central plug part is highly denuded with distinct (erosional?) plateau at about 760 m a.s.l. Plug foothills are at about 720 m a.s.l. The total height difference is up to 300 m, but plug relief is soft. The cauldron, open to SSW, can be recognized with problems. It is built of Tertiary sediments. The summits lie at 1,200 m a.s.l. in the E and at 1,065 m a.s.l. in the N. The cauldron is substantially broader than plug relics, which is caused by plug degradation and by structural patterns of the region complemented by lateral erosion (pedimentation?).

#### Hydrological characteristics:

The denudation and erosion of plug reached such a degree which is characterized by the combination of the dendritic and periclinal network of intermittent streams. The marginal plug zone in the N, W and S is probably highly altered and destructed due to the fact it was utilized by Rud-e Shur (Kul) River and its tributaries, forming a circular network. Two springs yielding about 0.2 1.s⁻¹ were registered at the base of low terrace of Rud-e Shur (Kul) off the northeastern plug margin.

#### Regional geological position:

The western end of the Kuh-e Gahkum Anticlinorium, its axial zone to southeastern flank. The anticline is highly disturbed by faults parallel to axial plane. Anticline is composed mostly of Pabdeh-Gurpi and Asmari-Jahrom Formations transgressively overlain by Agha Jari clastics. Owing to a great denudation degree of the plug and its surrounding, Quaternary sediments are represented by extensive proluvial and alluvial deposits. Initial terrace system is developed along Rud-e Shur. Geological position and lithological sections indicate that plug activity ceased long ago.

### Petrological characteristics:

Evaporites are represented only by gypsum, which is the weathering/dissolution relic in the form of grayish or reddish masses, mostly covered by clastic rocks of the Hormoz Complex. Gypsum also often occurs as brown crusts up to 3 m thick. Grayish gypsum breccias and lenticular gypsum interbeds in shales were registered, too. Rare thick gypsum beds occur as blocks (debris).

Clastic rocks are represented mostly by dark grayish purple (tuffitic?) shales, sometimes passing, especially in the northern part, into blackish gray shales with some organic admixture. Grayish green tuffites without distinct bedding are less frequent, as well as yellowish to brown, slightly limonitized, sometimes white clayey sandstones to sandy siltstones and fine-grained quartz sandstones. Sandstones contain intercalations of dark fetid sandy dolostones with white carbonate veinlets. Impure limestones with shale interbeds are subordinate. Gray to purple, probably tuffitic, siltstones passing place to place into green tuffs are relatively common. Conglomerates were rarely observed in the western part of the plug.

Igneous rocks are represented by grayish green quartz diorite, highly altered (carbonatization). Metamorphic rocks of the blueschist facies, containing abundant veinlets and accumulations of blue amphibole asbestos occur in many places, especially in the southern part.

References: Fürst 1976; Harrison 1930; Nili et al. 1979.

# 61. MURAN



Figure A59. Sketch of the Muran plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°50' N, 55°44' E, Shape: vein (NE-SW direction), Max. length: 9 km, Max. width: 0,5 km, Activity: 1c (Fig. A59)

Classical vein separated into more parts by boudinage. The vein morphology results from linkage to distinct overthrust plane (NE-SW direction) and transversal to oblique faults of NW-SE to about N-S directions. Transversal tectonics separates the vein into several segments of not equal length. Faults are utilized also by rivers to cross this structure. The south-western segments has its summit at 1,158 m a.s.l. with glacier flow ending at 900 m a.s.l. The central segment is divided into two parts.

The western one forms wedge between two rivers and represents a plateau at 800 to 900 m a.s.l. It is separated from the south-western segment by Recent deluvia and fluvial deposits. The eastern part has its summit at about 800 m a.s.l. and the lowest point at about 600 m a.s.l. along streams. The northeastern segment, built of several small relics separated on surface only by deluvia, lies between 600 to 680 m a.s.l. and 740 m a.s.l.

#### Hydrological characteristics:

The region is drained by Rud-e Shur (Kul) representing boundary of the southwestern and central plug segments. Shorter tributaries of intermittent character utilize less resistant zones along faults of longitudinal (NE-SW directed) and transverse orientation.

#### Regional geological position:

The plug is situated along important thrust line (Muran thrust) in the southeastern flank of the Kuh-e Muran Anticline (Anticlinorium). The anticline is built of Guri, Razak, Jahrom and in places also Bangestan sediments. Thrust is situated on boundary of less resistant and resistant lithologies. Photolineations and photolineaments on satellite images and air photos mutually dissect in complex knot (main N-S directions, subordinate NW-SE and NE-SW trending lines).

#### Petrological characteristics:

Evaporite rocks (halite and gypsum) are covered by blocks of reddish purple to purple gray shales to siltstones, often pulverized. Red hematite ochres were observed in places.

References: Harrison 1930; Walther 1972.

# **62. QALEH SHUR**



Figure A60. Sketch of the Qaleh Shur plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°44' N, 55°03' E, Shape: circular to elliptical, Max. length: 1 km, Max. width: 1 km, Activity: 3c (Fig. A60)

The ruin of plug in elliptical depression composed of several elevations of the Hormoz Complex. Plug foothills lie at about 700 m a.s.l.; maximum elevations are at 800 m a.s.l. The depression among plug relics is covered with deluvial and fluvial deposits developed sometimes as terraces along stream courses. The cauldron is indistinct, relatively morphologically diversified, more pronounced in the SE, where the anticline closure is developed. Cauldron elevations vary from 1,062 m a.s.l. in the E, 1,247 m a.s.l. on the N, 1,252 m a.s.l. in the S to 1,450 m a.s.l. in the W. The western part of the cauldron is affected by a fault and can represent fault slope.

#### Hydrological characteristics:

The region is drained by the dendritic network of intermittent streams with springs farther to the NW in the axial zone of the anticline. The drainage is generally directed to the SE into the Rud-e Shur basin.

#### Regional geological position:

The eastern plunge of the Qaleh Shur Anticline, the axial part with Bangestan, Tarbur and Jahrom sediments. Air photos and satellite images show complex structural knot with the dissection of the N-S and NW-SE directed photolineaments and NE-SW trending photolineations.

#### Petrological characteristics:

Petrological characteristics cannot be given as the plug was not visited.

# 63. GORU



Figure A61. Sketch of the Goru plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 27°43' N, 55°03' E, Shape: irregular, Max. length: 1 km, Max. width: 1 km, Activity: 3a (Fig. A61)

The ruin of plug composed of several morphologically positive rounded hills with an elevation of 700 to 800 m a.s.l. and with distinct linkage to tectonic structures without cauldron.

#### Hydrological characteristics:

The drainage by dendritic network of intermittent streams with springs to the W of the plug. Partial linearity of drainage network is bound to tectonics. The drainage is directed both to the SE and to ENE into Rud-e Shur basin.

#### Regional geological position:

The eastern end of the Qaleh Shur Anticline, the southeastern flank with sediments of Mishan, Guri and Gachsaran-Razak units. The plug is undoubtedly connected with distinct NE-SW normal fault in dissection with about N-S trending photolineaments.

#### Petrological characteristics:

Purple gray to reddish purple siltstones dominate over shales and fine-grained sandstones. Plug material can be misinterpreted from air owing to the presence of Razak red beds, especially when pulverized. Harrison (1930) noted also dark carbonate rocks, dark basic magmatites and keratophyres.

References: Harrison 1930.

# 64. BANA KUH



Figure A62. Sketch of the Bana Kuh plug; scale bar=1 km.

#### Morphological characteristics:

Coordinates: 28°03' N, 54°28' E, Shape: circular, Max. length: 2 km, Max. width: 2 km, Activity: 1c (Fig. A62) Small plug with low activity with signs of the concentric structure. The summit at 1,283 m a.s.l. is encircled by summit plateau with the base at 1,200 to 1,220 m a.s.l. Although elevations do not differ substantially, the plateau is divided distinctly (tectonics enhanced by stream network?). Karst forms are abundant with common dolines. The plug foothills are at 1,060 m a.s.l. on the S and up at 1,100 m a.s.l. on the N. The plug is encircled nearly completely by alluvial fans.

The cauldron is not distinctly developed. Its morphological diversity is caused by dissection by stream network. Cauldron summits are at 1,610 to 1,973 m a.s.l. in the NW. The cauldron is open southwards. Its genesis is still unclear.

#### Hydrological characteristics:

The spring region with areal periclinal drainage of the summit plateau and initial periclinal network of short intermittent streams on slopes with altitudinal difference up to 150 m. Most streams empty into collection circle of dendritic nature, beginning in the northern part of anticlinal axis, or rather at the rim of the cauldron. The plug is drained into the Rud-e Shur basin.

#### Regional geological position:

The central part of the Mesijune Anticline, the southern flank

built of Jahrom and Pabdeh-Gurpi Formations. The southern flank of the anticline is highly tectonized, i.e. reduced by overthrust. Tectonic boundary with syncline filled by Agha Jari and Bakhtyari Formations is covered by a system of alluvial fans. The plug and its surrounding are dissected by relatively dense network of NW-SE and NE-SW photolineations showing character of normal faults in places.

#### Petrological characteristics:

Evaporites prevail, i.e. bedded halite and grayish gypsum (as weathering product, but gypsum does not constitute the brownish crusts so common in other plugs). No other data are available, as the plug was seen only from helicopter.

References: Harrison 1930.

# 65. BONARUYEH

#### Morphological characteristics:

Coordinates: 28°10' N, 54°10' E, Shape: circular, Max. length: 2 km, Max. width: 2 km, Activity: 1c

Small plug with signs of concentric structure in the distinct cauldron.

#### Hydrological characteristics:

The spring region of intermittent streams drained westward into closed depression with the general drainage into Rud-e Mond basin.

#### Regional geological position:

The structural position is not completely clear. The plug

occurs in morphologically indistinct region built of Pliocene to Pleistocene deposits to the W of the Mesijune Anticline. Deposits mentioned are partly covered by large alluvial fan passing into flat alluvial plain.

#### Petrological characteristics:

The plug is composed mostly of evaporites. Except of halite, brownish gypsum crust occurs. Blocks of reddish shales to siltstones were registered. Green basic magmatites can be seen in the southeastern plug part.

References: Harrison 1930.

# 66. JALALABAD

#### Morphological characteristics:

Coordinates: 28°02' N, 54°01' E, Shape: elliptical (NE-SW trending longer axis), Max. length: 4 km, Max. width: 2 km, Activity: 2c

The passive plug in high ruination stage up to ruin localized in morphological depression between two anticlinal structures. Plug summits lie at about 1,100 m a.s.l. and the lowest point at about 900 m a.s.l. The plug is not encircled by distinct sedimentary rim (cauldron).

#### Hydrological characteristics:

Partly spring region connected with dendritic network of intermittent streams directed from the anticline axis in the S to N into closed depression belonging to the Rud-e Mond basin.

#### Regional geological position:

The plug is located in partial plunge of the anticline axis (unnamed anticline). The anticline is built mostly of Jahrom carbonates. Bakhtyari clastics discordantly overlay Tertiary sediments and form plug rim. No distinct photolineations occur within the plug on satellite images. Some NNW-SSE trends cut broader plug surroundings.

#### Petrological characteristics:

The prevailing part of the plug surface is covered with Subrecent brownish gypsum crusts. Blocks of light-colored tuffogenic(?) siltstones and greenish purple tuffogenic(?) shales were registered in the northern plug part.

# 67. KUSHK KUH-WEST

#### Morphological characteristics:

Coordinates: 27°39' N, 56°33' E, Shape: elongated elliptical to veiny (NW-SE trending longer axis), Max. length: 2 km, Max. width: 0,1 km, Activity: 3a

Small passive plug to ruin (due to the position highly eroded by river). The plug position and its elongation are clearly controlled by overthrust line running 1 km to the E of the plug. The eastern plug margin is covered with river terrace indicating present inactivity of the plug.

#### Hydrological characteristics:

The direct drainage by Rud-e Jamas (Jalabi) River passing through the plug. Groundwater appears in morphological depressions remaining after exploitation of hematite ochres.

#### Regional geological position:

The northwestern part of the Kush Kuh Anticlinorium, its

southeastern flank. The site is highly disturbed by normal faults and overthrusts causing reduction of the anticlinorium. Rock units are represented mostly by Gachsaran and Mishan Formations making negative morphological forms utilized by the river. Plug surroundings are cut by important N-S trending photolineaments.

#### Petrological characteristics:

Helicopter reconnaissance proved the presence of reddish purple to purple gray shales to siltstones, probably containing tuffogenic admixture, and purple red, highly hematitized shales (ochres), which are locally quarried. Reddish hematitized gypsum occur, too, as well as dark carbonate rocks. Harrison (1930) noted also presence of dark coarse-grained magmatic rocks of basic composition.

References: Harrison 1930; Heim 1958; Kent 1958.

### 68. DARBAST

#### Morphological characteristics:

Coordinates: 27°34' N, 56°42' E, Shape: irregular (NW-SE trending longer axis), Max. length: 2 km, Max. width: 1,5 km, Activity: 1c(?)

Small plug of the irregular to elliptical shape with indications of the summit plateau at about 850 m a.s.l., from which the summit protrudes (910 m a.s.l.). The lowest points of the plug occur at 400 m a.s.l. on the S. The total height difference is about 500 m. The plug is connected with thrust zone. In spite of that, it hasn't the character of a vein, cauldron is missing.

#### Hydrological characteristics:

The combination of circular and parallel network of intermittent streams drains the plug. Streams have their springs in the summit part of the Kush Kuh Mountains.

#### Regional geological position:

The southwestern flank of the Kush Kuh Anticlinorium at

its eastern end. The anticlinorium is reduced by thrust zone (NW-SE direction). Sediments of Jahrom and Gachsaran Formations occur in plug vicinity. Detailed data necessary to date the intrusion of the Hormoz material are not available. Harrison (1930) assumed four possibilities of the origin (diapirism in submarine conditions in two alternatives, product of tectonic brecciation due to nappe movements and horizontal intrusion). No collapse structure has been registered.

#### Petrological characteristics:

Harrison (1930) noted dark fetid dolostones contained in reddish debris. Dolostones are mostly thinly bedded and overlay tectonically Lower Cretaceous marls. Reddish sandstones and aleuropelites were detected in pebbles of alluvial cones, as well as dark volcanic rocks of basaltoid character. No detailed description can be given as the plug was not visited.

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