Riftogenic Volcanism in the Western Carpathian Geological History: a Review

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ABSTRACT. Riftogenic volcanic rocks occur in all three megaunits, i.e. in the Outer, Central and Inner Western Carpathians (OWC, CWC, IWC). Volcanic rocks were formed during several events from Early Paleozoic to the Tertiary/Quaternary. Based on geochemical and petrological data they can be divided into two groups: (1) within-plate alkali volcanic rocks and (2) transitional tholeiitic volcanic rocks mostly with E-MORB or CT signature. The former were generated during incipient stage of continental crust rifting, the latter during further rift evolution tending to the back-arc basin opening. Alkali volcanic rocks associated with early rifting were formed during: (1) Early Paleozoic (IWC), (2) Ladinian–Carnian (IWC), (3) Upper Cretaceous (CWC and OWC) and (4) Tertiary/Quaternary. Except for the Cretaceous event every rifting seems to be preceded by arc volcanism. Transitional tholeiitic volcanic rocks related to the back-arc basin opening were formed in: (1) Devonian (IWC and CWC), (2) Late Carboniferous (IWC) and (3) Triassic (IWC). There are indices of spatial and temporal relations to preserved oceanic crust relics.

KEY WORDS: volcanism, rifting, back-arc basins, Western Carpathians.

Early Paleozoic volcanic rocks

Alkali basalts in the Early Paleozoic rock complexes of the Western Carpathians are very scarce. A sole typical representative only of these rocks has been found in the Malé Karpaty Mts. crystalline complex (Central Western Carpathians – CWC; Fig. 1.). It forms a dyke several tens of cm thick which cuts metagabbro of the Pernek Formation – an ancient (Devonian?) oceanic crust relic. The basalt was, together with the surrounding rocks, metamorphosed in the amphibolite facies conditions but original phyric texture of the basalt is still discernible. Its within-plate alkali character follows from REE pattern (La_N/Yb_N = 11.67; La_N = 113.2) and other immobile trace element (e.g. HFSE) distribution (Figs. 3A, 4A).

In the volcano-sedimentary Smrečinka Formation (Gemeric Unit, Inner Western Carpathians – IWC) small metabasaltic bodies rarely occur. Preliminary study of the metabasalt composition has shown a similarity to fractionated alkali basaltic rocks (Figs. 3A, 4A).

Early Paleozoic volcanic rocks transitional between alkali basalt and ocean floor tholeiites have been found in the CWC (the Pezinok Formation of the Malé Karpaty Mts. crystalline complex) and also in the IWC (the Gelnica and Rakovec Groups of the Gemeric Unit; Fig.1)

The Pezinok Formation is a volcano-sedimentary sequence Upper Silurian to Devonian in age dominated by metasediments (Ivan et al., in press). Basalts originally formed small lava flows, hyaloclastic and pyroclastic beds in carbonate environment or small subvolcanic bodies (dykes?). Basalts of the Pezinok Fm. underwent strong multi-stage metamorphic recrystallization. No primary magmatic minerals were found in the metabasalts and primary textures are preserved only sporadically. Major element, REE and HFSE distributions point to their primary subalkaline (tholeiitic) character.

Enrichment in LREE (La_N = 35.2–74.8) and differentiated LREE/HREE enrichment (La_N/Yb_N = 4.8–9.6) typical for enriched mantle melting indicate the geochemical characteristics close to E-MORB or CT (Figs. 3C, 4A). Major and selected trace element distribution in ambient metasediments indicates that the protolith of these rocks was represented by relatively immature sediments of back-arc basin provenance, derived from an acid magmatic source and deposited in the sedimentary environment resembling ensialic island arc (Ivan et al. in press).

Based on the above mentioned arguments about metabasalts of the Pezinok Fm., their generation during initial stage of back-arc rifting on the ensialic island arc or active continental margin is proposed.

Transitional alkali/tholeiitic basalts in the Gelnica Group, a volcano-sedimentary complex with dominating calc-alkaline acid volcaniclastics Silurian–Devonian in age, form small subvolcanic to less frequently effusive bodies metamorphosed in the greenschist facies conditions (Fig. 1). REE-normalized patterns and immobile trace element distribution resemble those of transitional types of basalts between E-MORB/OIT and CT (Figs. 3B, 4A). Positive or negative Eu-anomaly in some samples as well as occurrence of picritic rocks indicate fractional crystallization processes during their magmatic evolution (Ivan 1994).

Volcanic rocks of analogus type constitute the main component of the Rakovec Group (Devonian?) (Fig. 1). They are formed mainly by lava flows, less frequently by small subvolcanic bodies and volcaniclastics. The volcanic rocks are basaltic or basalt-andesitic in composition, more acidic members occur rarely. Despite multi-phase metamorphism including high to medium pressure event, magmatic textures and minerals are often preserved. Aphyric and phyric types with phenocrysts of clinopyroxene and/or plagioclase have been found. Metabasalts are geochemically close to the E-MORB/OIT (Hovorka et al. 1988; Ivan 1994). This follows from typical LREE/HREE fractionation (La_N/Yb_N = 4.5–7.6) and distribution of HFSE in comparison to the ocean floor basalts (Figs. 3B, 4A). Clinopyroxene, olivine and sometimes also plagioclase and ilmenite fractionation resulted in variations in SiO_2, MgO, TiO_2, Cr, Sc as well as total REE contents (La_N = 29.8–143.3). Plagioclase fractionation is typical especially for subvolcanic bodies from the present upper part of the Rakovec Group.

Similar (or partly identical) geochemical type of metabasalts in the Gelnica and Rakovec Groups is a result of their generation in similar geodynamic settings, i.e. during initial stage of back-arc rifting on the destructive plate margin. While transi-

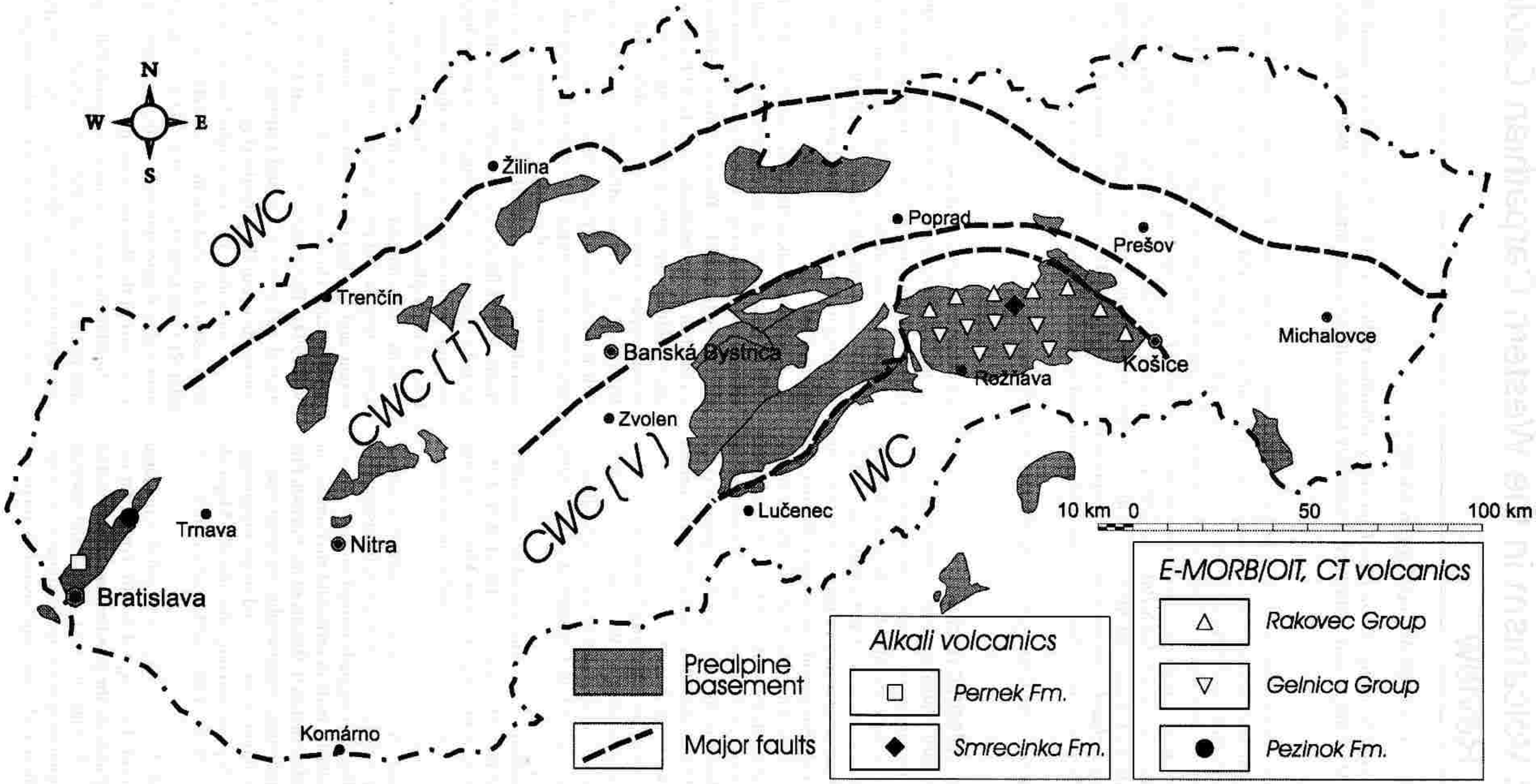

Fig. 1. Spatial distribution of the Paleozoic riftogenic volcanic rocks of the Western Carpathians. Explanations: OWC – Outer Western Carpathians; CWC – Central Western Carpathians; T – Tatric Unit; V – Veporic Unit; IWC – Inner Western Carpathians

tional volcanics of the Gelnica Group were formed on the back side of ensialic magmatic arc just on the back-arc basin margin, the metavolcanics of the Rakovec Group are relics of the back-arc basin crust from more internal part of this basin (Ivan 1994).

Late Paleozoic volcanic rocks

Only transitional alkaline/tholeiitic volcanics were reported from the Late Paleozoic complexes of the Western Carpathians. In the volcano-sedimentary Lower Carboniferous in the Ochtiná and Črmeľ Formations (IWC) they form small conformly oriented bodies metamorphosed in the greenschist facies conditions in the dominant clastic metasediments. Pre-existing ophitic texture of the metavolcanics is locally preserved. Geochemical data, mainly REE patterns (La_N/Yb_N = 1.2–2.0; La_N = 10.4–33.9) and HFSE distribution indicate their transitional character between typical E-MORB and N-MORB (or BABB). They were probably related to the immature stage of the opening of a back-arc basin, the crust of which from a more evolved stage of the opening is preserved in the Late Carboniferous Zlatník Formation (Ivan 1996, 1997).

Mesozoic volcanic rocks

Riftogenic volcanism in the Mesozoic period of geological evolution of the Western Carpathians is represented mainly by typical alkali basalts. They occur in the CWC and also in the Outer Western Carpathians (OWC). Not only alkali basalts but also occurrences of the transitional alkali/tholeiite basalt were recorded in the IWC.

The alkali basalts of the CWC are located : (1) in the pre-Alpine basement of the Tatric megaunit and in its Mesozoic (Lower Triassic to Lower Cretaceous) cover as well and (2) in the Krížna nappe (Fig. 2).

Alkali volcanics in the basement rocks and also in the pre-Cretaceous Mesozoic rocks of the cover form small dykes. Only in the Cretaceous strata biostratigraphically dated to the Berriasian to Aptian they occur as small (a few metres, rarely a few tens of metres) lava flows or as hyaloclastites. Lava flows are massive or amygdaloidal, containing as a rule numerous carbonate xenoliths with well-preserved organic remains in some of them (Hovorka and Spišiak 1988). Lavas are both crystalline and vitric. Phyric texture with olivine, clinopyroxene, and locally even hornblende phenocrysts is the most common. Among them, clinopyroxene is the most abundant and corresponds to diopside or augite. Clinopyroxene phenocrysts are compositionally zoned, the composition of rims equals to that of the clinopyroxenes in the matrix.

Major and trace element distribution in the volcanics indicates their alkali character and originally basanitic composition. Low content of SiO_2 (40–47 wt.%; LOI-free) and Mg-number varying between 0.50–0.69 are typical. Alkali within-plate character of these volcanics is also obvious from normalized REE patterns displaying LREE enrichment (La_N = 334.0–179.8) combined with LREE/HREE fractionation (La_N/Yb_N = 32.2–19.3) as well as from HFSE distribution (Fig. 3D; Fig. 4B; Hovorka et al. in press).

The most typical occurrences of the above mentioned volcanics are known in the Tatry Mts. and the Nízke Tatry Mts. Alkali volcanics of the Krížna nappe (CWC) are represented by several tens of occurrences in the Malé Karpaty Mts., the Malá Fatra Mts. and the Veľká Fatra Mts. All of them form small bodies, a few metres or tens of metres in diameter, including small, shallow-level intrusive bodies, chimney breccias and hyaloclastites locally associated with volcanogenic "tempestites", i.e. unconsolided muds disturbed by subaqueous volcanic activity (Hovorka and Sýkora 1979; Hovorka and Spišiak 1988, 1993). Breccia fragments show various degrees of crystallization from holocrystalline to vitric. Intimate interactions of volcaniclastite bodies with biostratigraphically dated, originally calcareous mud indicate Aptian–Albian age of the volcanics. Two main facies have been distinguished within the Krížna nappe (Mahel' 1968): deep-water and shallow-water one. Volcanics occur in the deep-water environments.

Their petrological and geochemical characteristics are very close even identical with those of the CWC Cover Unit.

Despite the fact that the spatial distribution of both sedimentation areas, i.e. the cover unit and the Krížna nappe, were widely geographically separated, products of volcanic activity penetrated to the bottom of the basin in identical time span and their petrology and geochemistry are also identical. Short-lived rifting processes in both the above mentioned sedimentary basins were considered the cause of volcanic activity (Gucwa and Wieser 1985; Hovorka and Spišiak 1988, 1993; Narebski 1990). These rifting processes are now correlated with the initial stage of the opening of the Penninic–Vahic Ocean (Plašienka 1997).

Cretaceous riftogenic volcanics in the OWC are represented by the teschenite–picrite rock association (TPRA). Volcanic rocks are located in the Silesian Unit forming a partial unit of the Flysh Zone (Belt) which is composed of huge, allochthonous Cretaceous–Paleogene complexes of mostly sedimentary origin (Fig. 2). This area is the type locality for teschenite and picrite association both representing prevailing rock type. Besides teschenite and picrite, numerous other types (alkali basalts, monchiquites, ouachitites, ankaramites, pyroxenites and others) were described in the past (Kudělásková 1987 and references therein). Dostal and Owen (1998) newly named the whole rock association as lamprophyres. Volcanics form mostly dykes, in less amount also lava flows and even very rare hyaloclastites. Several hundreds of volcanic bodies are documented on the territory of the Czech Republic and Poland. Teschenite–picrite association is Hauterivian–Aptian in age.

Volcanics of the TPRA represent a wide range of rocks with variable fabric, structure and also modal composition. Total mineral association is similar in all types: clinopyroxene ± olivine, kaersutite, biotite, plagioclase, K-feldspar, analcime, apatite. Olivine is magnesian (Fo_{87}), clinopyroxene is represented by Ti-augite and aegirine and also by diopside as xenocrysts.

In terms of their major element compositions the TPRA are characterized by low SiO_2 content (42–52%) and variable Mg number (40–60). High contents of TiO_2, P_2O_5, alkalies and incompatible elements indicate their pronounced alkali character (Hovorka and Spišiak 1988, 1993). Differences in chemical composition result from fractional crystallization and variable degree of melting and secondarily also from carbonaceous xenolith assimilation, metasomatic processes and hydrothermal alteration. Steeply-sloped normalized REE patterns (Fig. 3E) as a result of LREE enrichment (La_N = 70.0–429.3) and LREE/HREE fractionation (La_N/Yb_N = 15.3–26.9) are typical for within-plate alkali volcanics (Hovorka and Spišiak 1993; Dostal and Owen 1998). Sr and Nd isotope data suggest derivation from a similar mantle source as the Cenozoic within-plate alkali basalts of western and central Europe (Dostal and Owen 1998).

Production of TPRA in the sedimentary basin of the original Silesian Unit was interpreted as a result of an incipient rifting (Hovorka and Spišiak 1988; Narebski 1990). Akin to the CWC, this rifting could be related to the initiation of the Penninic–Vahic Ocean opening. During nappe structure evolution

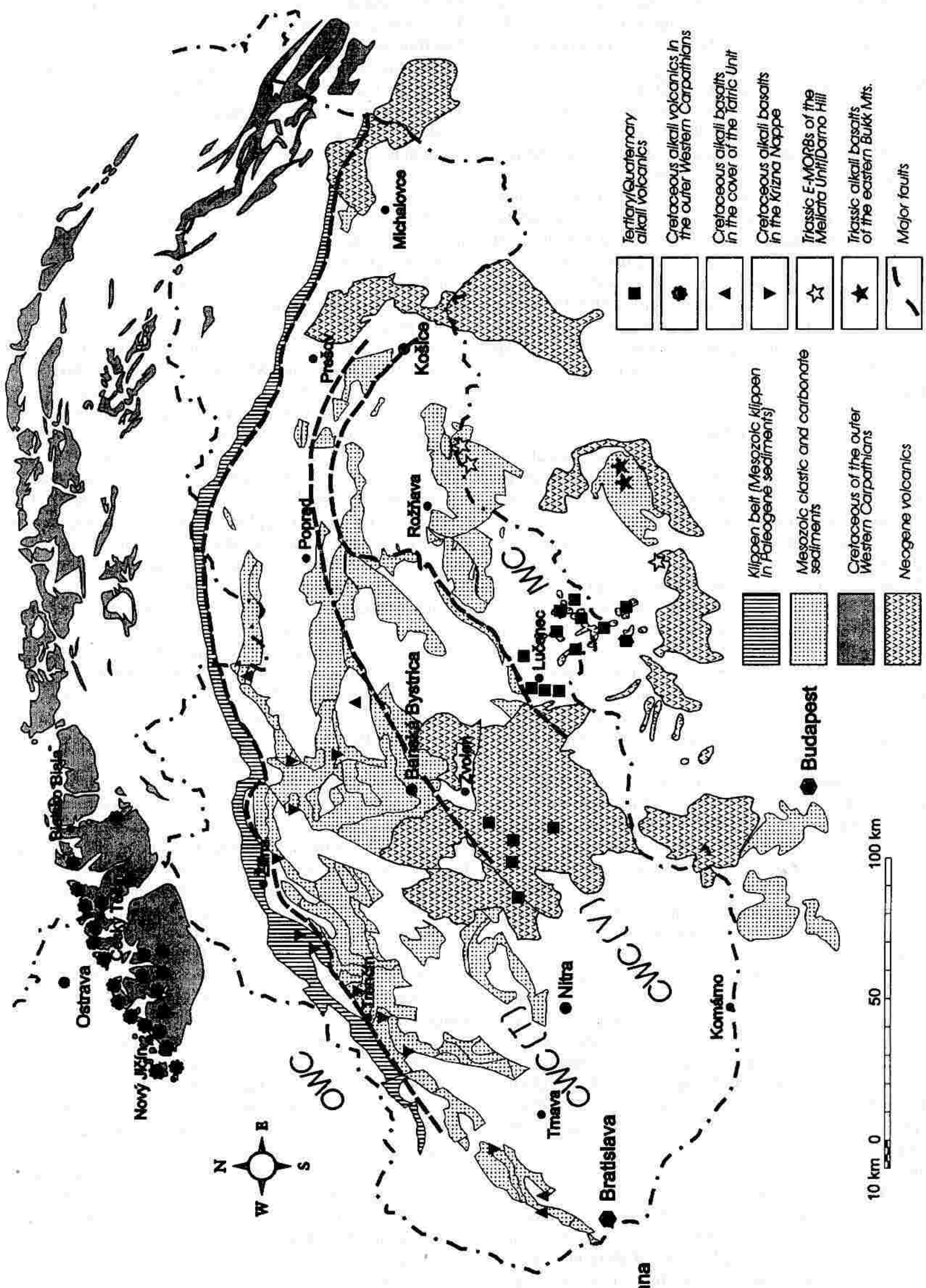

Fig. 2. Spatial distribution of the Mesozoic and Tertiary riftogenic volcanic rocks of the Western Carpathians. See Fig. 1 for explanation of abbreviations.

TPRA was tectonically transported together with adjacent sedimentary complexes in northwesterly direction.

Occurrences of alkali basalts as well as transitional tholeiitic/alkali basalts have been found in the Mesozoic complexes of the IWC (Fig. 2). Slightly metamorphosed alkali basalts forming several lava flows occur in the Upper Ladinian–Lower Carnian formation of Triassic carbonate platform sediments in the eastern Bükk Mts. They show phyric or subophitic textures mostly with Ti-augite phenocrysts and Ti-augite, plagioclase, Fe-Ti oxides and some secondary minerals in groundmass. Within-plate character of volcanics obviously follows from REE and incompatible trace element distribution (La_N = 75.6–143.1, La_N/Yb_N = 5.7–10.8). According to Harangi et al. (1996) their generation could have been related to continental rifting at the northwestern edge of the Tethys, but occurrences of calc-alkaline volcanics in the Anisian–Lower Ladinian sequence of the same unit rather testify to the initiation of back-arc rifting.

Basalts (dolerites, ferrogabbros) with transitional E-MORB/N-MORB signature (La_N = 45.4–69.5, La_N/Yb_N = 2.1) are sporadically embedded together with more frequent typical ocean-

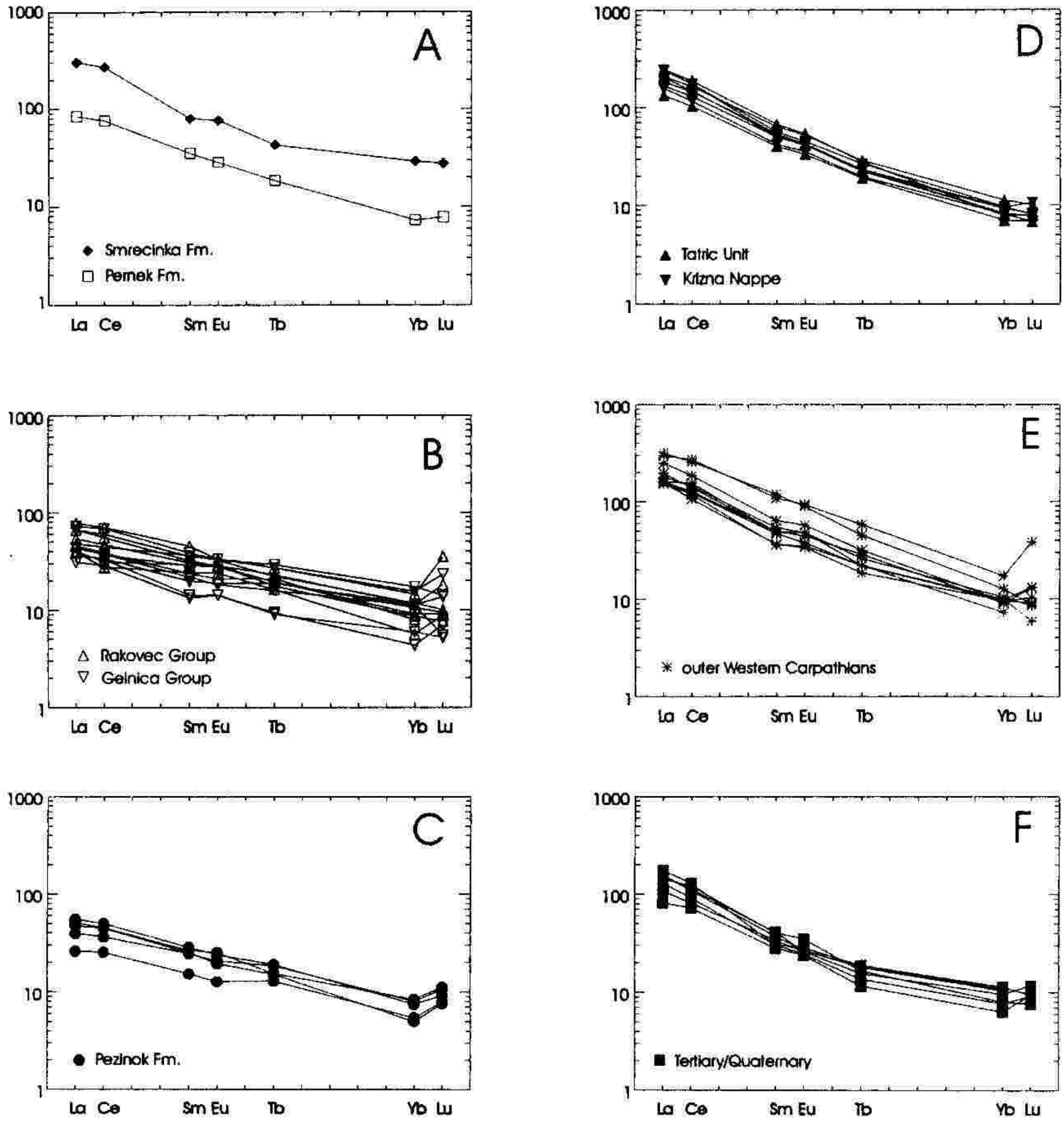

Fig. 3. Chondrite-normalized REE patterns of the riftogenic volcanic rocks of the Western Carpathians. A – Early Paleozoic Smrečinka and Pernek Fms.; B – Early Paleozoic Gelnica and Rakovec Groups; C – Early Paleozoic Pezinok Fm.; D – Cretaceous basic volcanics in the Tatric Mesozoic cover and in the Krížna nappe; E – Cretaceous basic volcanics of the Outer Western Carpathians; F – Neogene/Quaternary basic volcanics. Data sources: Dostal and Owen (1998), Hovorka et al. (1988), Hovorka and Spišiak (1993), Ivan (1997), Ivan et al. (in press), Ivan and Hovorka (1993), Kudělásková (1987) and unpublished data. Normalization after Sun (1982).

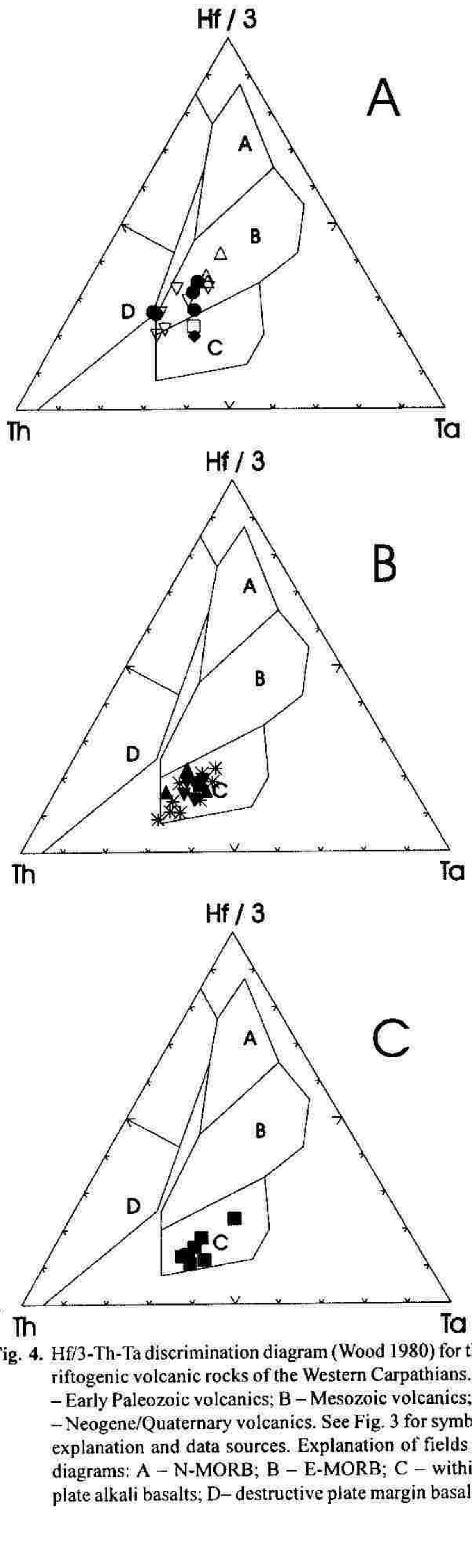

Fig. 4. Hf/3-Th-Ta discrimination diagram (Wood 1980) for the riftogenic volcanic rocks of the Western Carpathians. A – Early Paleozoic volcanics; B – Mesozoic volcanics; C – Neogene/Quaternary volcanics. See Fig. 3 for symbol explanation and data sources. Explanation of fields in diagrams: A – N-MORB; B – E-MORB; C – within-plate alkali basalts; D– destructive plate margin basalts.

ic rocks of N-MORB signature in a strongly tectonized mélange of the Meliata Unit (Harangi et al. 1996) and may be related to the initial stage of the Meliata–Hallstatt Ocean opening. Basalts of the same composition, moreover accompanied by oceanic basalts with N-MORB or BABB signature, have been also found as olistolites in the Middle Triassic and Upper Jurassic olistostroma series in Darnó Hill (Downes et al. 1990; Harangi et al. 1996).

Tertiary–Quaternary volcanic rocks

Tertiary–Quaternary alkali volcanic rocks are concentrated into two areas in the inner part of the Western Carpathian arc: (1) Slovenské stredohorie Mts. and (2) Lučenec–Fiľakovo–Salgotarján area. Volcanic rocks were formed during several volcanic phases between ca. 7 to 0.5 Ma (Balogh et al. 1981). Typical forms are lava flows, dykes, diatremes, necks, ash and cinder cones and maars (Konečný et al. 1995). Petrographically they are represented mainly by basalts, basanites and trachybasalts, to a lesser degree also by trachyandesites. Phyric, subphyric and aphyric textures are most common. Phyric types contain plagioclase, olivine and clinopyroxene phenocrysts. Matrix is composed of the same minerals and also of apatite, Fe-Ti oxides, biotite, volcanic glass and rarely of nepheline. Alkali volcanics contain spinel peridotite xenoliths (Szabó and Taylor 1994), olivine, clinopyroxene, plagioclase and ilmenite xenocrysts as well as megacrysts of olivine, clinopyroxene and amphibole. Composition of olivine phenocrysts varies in the range of Fo_{88}–Fo_{67}, with central parts being richer in magnesium (Fo_{88}–Fo_{83}) than rims. Composition of olivine megacrysts varies between Fo_{85}–Fo_{83} (Ivan and Hovorka 1993). Clinopyroxene phenocrysts vary in size and display concentric, sector or irregular zoning. They are represented Ti-diopside to Ti-augite by composition. Al and Ti contents increase to the rims, whereas Na contents decrease. Some clinopyroxene phenocrysts contain cores of different colour, which represent xenocrystic clinopyroxene–chromdiopside, ferrosalite or ferrian aluminian diopside (Dobosi 1989). The amphibole of the megacrysts is kaersutite, locally replaced by rhönite.

Alkali character of basalts is indicated by high contents of such major elements as Ti, P or alkali elements. Restricted variability of silica content is typical. Enrichment in LILE and HFSE is consistent with within-plate tectonic setting of these rocks. Typical steep-sloped chondrite-normalized REE patterns result from LREE/HREE fractionation (La_N/Yb_N = 10–19) and LREE enrichment (La_N = 110.0–235.1). The relation between the decrease in Ni and Co concentrations and the decrease in Mg-number indicates olivine fractionation. There are some relations between chemical composition and age: older basalts seem to be lower in total REE and also display lower La_N/Yb_N and higher Na_2O/K_2O ratio than younger ones. Mineralogical and geochemical data indicate generation of these basalts by 10–15% partial melting of metasomatically enriched mantle source. Basaltic magmas were modified during their ascent by reactions with the host rocks of conduits walls producing ferrian aluminian diopside xenocrysts and megacrysts and substantial part of the mantle xenoliths. These processes resulted in the olivine fractionation effect and small LREE depletion in the basalt composition (Ivan and Hovorka 1993). Fractionation of the alkali basalt magma in the crust was reported from igneous xenoliths occurring in some maar volcaniclastics (Huraiová et al. 1996; Hurai et al. 1998).

Tertiary to Quaternary alkali basalts of the Western Carpathians differ in Nd, Pb and Sr isotope contents from the most alkali volcanics of the Central-European volcanic province (Salters et al. 1988; Ivan and Hovorka 1994). They are spatially related to calc-alkaline volcanism and were generated as a result of back-arc extension immediately after cessation of southward subduction of the European plate below northern margin of the Pannonian fragment of Gondwana (Tomek and Hall 1993).

Conclusions

Riftogenic volcanism in the Western Carpathians was generated in relation to (1) incipient stage of rift evolution in the continental crust or (2) immature stage of rift opening. Within-plate alkali volcanic rocks were produced in the first geodynamic setting, transitional types between within-plate alkali basalt and N-MORB formed in the second setting. Evidence for rift initiation was found in: (1) Early Paleozoic (IWC, Smrečinka Fm.), (2) Ladinian–Carnian (IWC, eastern Bükk Mts.), (3) Upper Cretaceous (CWC, Tatric cover unit and Krížna nappe; OWC, Silesian Unit) and (4) Tertiary/Quaternary. Except for the Cretaceous event every rifting seems to be preceded by arc volcanism. Further rift evolution tending to back-arc basin opening was identified in the: (1) Devonian (IWC, Gelnica and Rakovec Grps.; CWC, Pezinok Grp.), (2) Late Carboniferous (IWC, Ochtiná and Črmeľ Fms.) and (3) Triassic (IWC, Meliata Unit and Darnó Hill Fm.). Spatial and temporal relations of the volcanism produced in the above mentioned geodynamic setting to the preserved relics of the ancient oceanic crust (Ivan et al. 1994) indicate continuous evolution to the small oceanic basins.

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