DAY 1
Contrasting Flow Fabrics of Phonolite and Trachyte Domes and Implication to their Emplecement Mode: Example from České Středohoří Mts. – North Bohemia

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Introduction

This filed trip focuses on fabrics and structures of phonolite and trachyte volcanic bodies of the České Středohoří Mts. Mesoscopic fabric patterns of three volcanic bodies are accompanied by analysis of anisotropy of magnetic susceptibility (AMS) and electron back scattered diffraction study (EBSD) to discuss complex flow properties of magmas with contrasting viscosities. The fabrics of selected volcanic domes will be discussed in terms of their emplacement mechanisms, microstructure development and geometrical boundary conditions controlling the magma flow.

Since the pioneering work of Cloos and Cloos (1927) the mesoscopic fabrics of phonolitic domes have been studied in several European volcanic provinces (Cloos, 1935; Vabet, 1971; Jančušková et al., 1992). However, the understanding of flow patterns was limited by applied methods as field mapping of macroscopically measurable fluidality and universal stage measurements. These studies allowed only to determine the flattening plane (XY) of the fabric ellipsoid but the flow axis (X) as well as the main kinematic flow plane (XZ) could have not been established. The universal stage measurements of crystal-

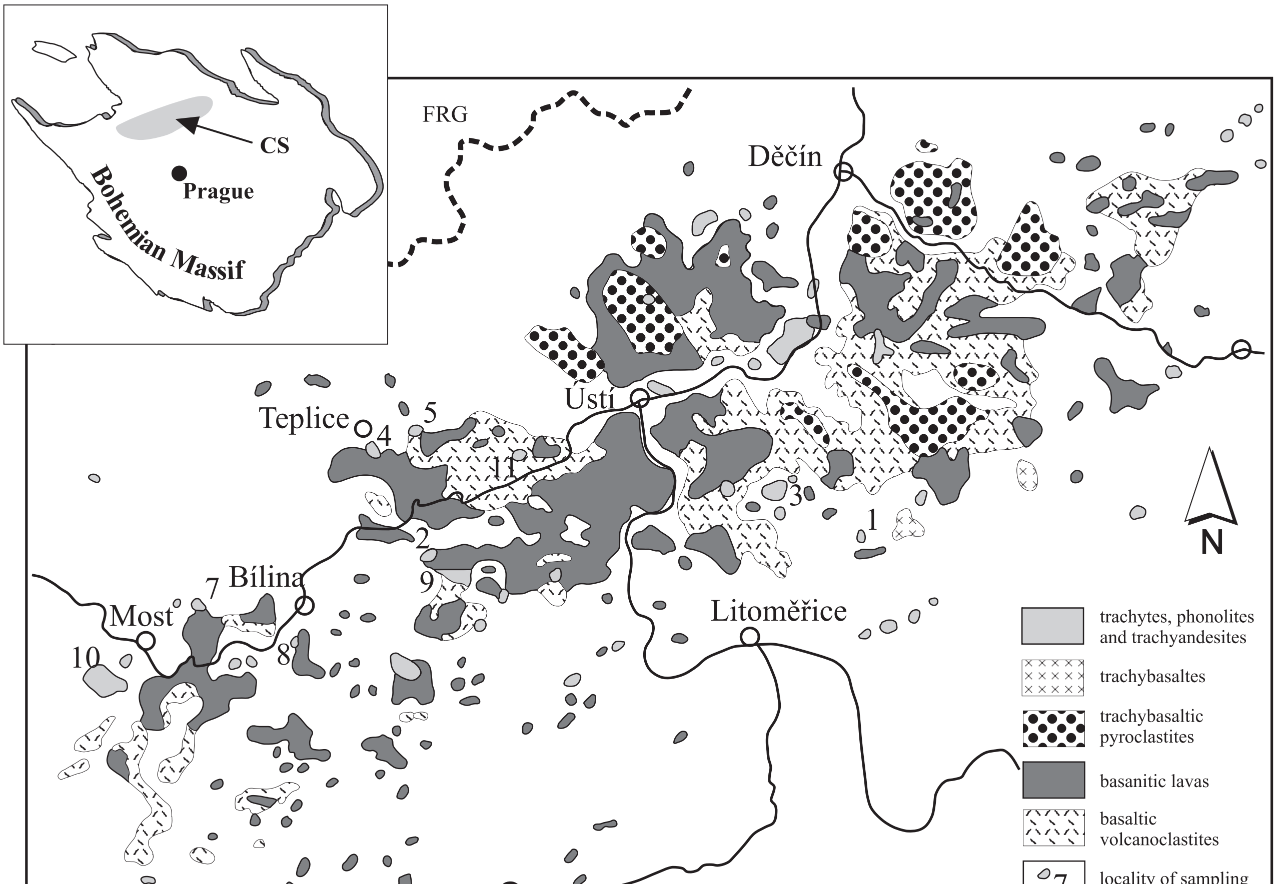

Fig. 1. Map of the Cenozoic volcanism in the České středohoří Mts. and distribution of sampling sites (see table 1).

lographic preferred orientation of sanidine crystals in trachytic volcanics are extremely tedious due to fine to ultrafine grain size of sanidine prisms resulting in small number of measurements (Jančušková, 1992). Consequently, the interpretation of fabric patterns was difficult if not impossible.

The AMS technique has been used as a rapid and extremely sensitive indicator of the preferred orientation of magnetic minerals in all rock types in the past 20 years, (for review see Tarling and Hrouda, 1993). This method is recently widely used as a standard technique to assess the flow patterns of deep-seated magmatic rocks in relation to their emplacement mechanisms. However, the AMS has been used less frequently in volcanic rocks, even though its potential is very high, because the preferred orientation of minerals in these rocks is often so weak that it can hardly be investigated by any other method. In lava flows, dikes and sills the magnetic fabric is mostly planar and the magnetic foliation is near the flow plane in lava flows and parallel to the walls of dikes and sills. The magnetic lineations have been found mostly parallel to the direction of flow, though they can also be perpendicular (Hrouda et al., 1994). However, the AMS technique provides the fabric ellipsoid shape and orientation for magnetic minerals only. Therefore, the interpretation of AMS fabrics in terms of flow of the rock depends on microstructural evidences of magmatic and solid state flows (Vernon, 2000). The quantitative microstructural analysis of minerals forming volcanic rocks is now possible thanks to the EBSD technique and mapping of grain boundaries with help of Scanning Electron Microscopy (SEM).

Geological setting

The studied trachytes and phonolites occur in the SW–NE trending Ohře (Eger) Rift area situated in North Bohemia corresponding to reactivated first-scale Variscan tectonic boundary, which separates the Saxothuringian and Moldanubian basement terranes. Two independent volcanic series have been recognized in North Bohemia (Ulrych et al., 2000). The younger suite of Eocene/Miocene Age belongs to the bimodal tephrite/basanite–phonolite suite. The trachytes and phonolites of the Miocene age penetrate the Cretaceous sediments and Tertiary volcanosedimentary sequences (Fig. 1). Unfortunatelly, the original intrusion level of phonolites is unknown, and the hypotheses about generation of this bodies also differ considerably. The most common opinion considers these domes to be shallow level intrusive laccolithic bodies or fillings of vents.

Rocks under study

The AMS and microstructural studies were performed on eleven volcanic bodies. All the studied rocks are of alkaline, undersaturated felsic compositions. They are composed principally of alkali feldspars and foid minerals (sodalite or hauyne, nepheline, rarely analcime), subordinated plagioclase is present only in several less evolved trachytic rocks (e.g., at Kalich). Amounts of mafic minerals are generally low and decrease rapidly from the plagioclase-bearing rocks to phonolites sensu structo. The prevailing mafic mineral is clinopyroxene changing

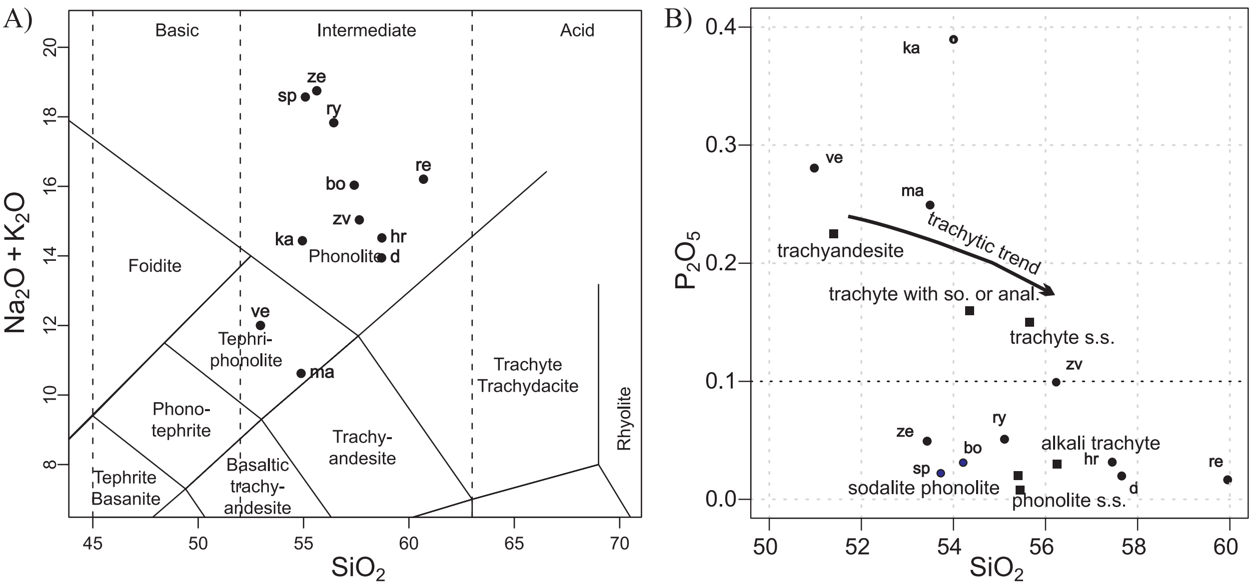

Fig. 2. Chemistry of studied rocks. A) A part of the total alkali – silica (TAS) classsification diagram for volcanic rocks (Le Maitre et al. 2002) with positions of the rocks under study. Oxides are in wt% from analyses, recalculated to 100% free of H_2O and CO_2. For symbols of individual localities see Table 1. B) The P_2O_5 versus silica (both in wt%) plot for rocks under study. Rocks with increased phosphorus contents are generally of a more primitive, i.e. less fractionated nature. Both the phonolites and sodalite-bearing alkali-feldspar trachytes are highly evolved and their various levels of the silica undersaturation may result from distinct characteristics of the parental magmas. For symbols of individual localities see Table 1.

its composition from augite to aegirine-augite to aegirine with proceeding fractionation of the magma. Relics of hornblende are rare. Accessory minerals are sphene, magnetite, apatite, etc.

According to the USGS chemical classification of volcanic rocks (Le Bas et al., 1986) the great majority of studied rocks correspond to the phonolite field with only two exceptions corresponding to tephriphonolite. Petrographic characteristics are, however, more variable. According to them, two major groups of trachytic to phonolitic volcanic rocks occur in the area under study.

1) sodalite-bearing trachytes and sodalite-bearing alkali-feldspar trachytes grading into sodalite phonolites (in the sense of the "modal" IUGS classification). These rocks are known as "trachytic phonoliths" (many papers by Hibsch) or "trachytoid phonoliths (trachytoiden Phonolithen, Rosenbusch 1898). In older Czech literature, the term sodalite trachyte was used for all these rocks including the sodalite phonolite. The most typical features are absence or only sporadic occurrence of nepheline, various amounts of sodalite or hauyne, and well-developed trachytic texture. Thus we may call the entire group as "trachytic rocks" for simplicity.
2) phonolites (i.e., phonolites sensu stricto) containing abundant nepheline +/- any sodalite mineral. These rocks have been referred to as nephelinitoid phonolite (Rosenbusch), nepheline phonolites (Hibsch), phonolites with high amounts of nepheline (Hejtman 1957). The same rocks, however, were called "sodalite phonolites" by, e.g., Shrbený and Macháček (1973). In the IUGS "modal" classification, this variety corresponds to the most common phonolite that needs no additional specification (adjective).

Dome		Petrology
1 Kalich	ka	sodalite-bearing trachyte
2 Majka	ma	sodalite-bearing trachyte
3 Řetoun	re	sodalite-bearing trachyte
4 Doubravská hora	do	alkali trachyte (sodalite phonolite)
5 Věštanský vrch	ve	Trachyandesite
6 Želenický vrch	ze	phonolite s.s.
7 Špičák	sp	phonolite s.s.
8 Bořeň	bo	phonolite s.s.
9 Zvon	zv	sodalite phonolite
10 Ryzelský vrch	ry	phonolite s. s.
11 Hradiště u Habří	hr	sodalite-bearing trachyte to sodalite phonolite

Tab. 1. Studied volcanic bodies.

Analysis of the Anisotropy of Magnetic Susceptibility

Around 70 oriented samples of trachytic and phonolitic rocks were cut to 8 cubes with edges 2 cm long. The AMS measurements were carried out with a KLY-3 Kappabridge (Jelínek, 1980) at magnetic laboratory of Agico, Inc. Brno Magnetic anisotropy data were evaluated using the ANISOFT and CUREVAL softwares.The mean susceptibility is $k_m=(k_1+k_2+k_3)/3$, where $k_1=k_2=k_3$ represents the shape of the ellipsoid of susceptibility. The corrected degree of anisotropy $P'=\exp2[(\ln k_1-\ln k_m)^2+(\ln k_2-\ln k_m)^2+(\ln k_3-\ln k_m)^2]$ gives the intensity of preferred orientation of magnetic minerals in the given rock. The shape parameter $T=2\ln(k_2/k_3)/\ln(k_1/k_3)-1$ (Jelinek, 1981) indicates the symmetry of magnetic fabric, being linear when $-1=T<0$ and planar when $1=T>0$. Variations in magnetic susceptibility with temperature were determined using the KLY-CS3 instrument to identify magnetic minerals carrying the AMS in studied rocks.

Magnetic mineralogy

Although paramagnetic pyroxene is present in the majority of rocks with susceptibility higher than 10 [SI] (pyroxene content is 5–23 vol. %), the only carrier of AMS was identified from thermomagnetic curves (Curie temperature from 440 up to 500 °C) to be Ti-magnetite with approximately 10 % of illmenite component (Nagata, 1961) (Fig. 3). Amount of titanomagnetite in these rocks ranges between 3–7 vol. %, which is enough to cover paramagnetic anisotropy.

The mean susceptibility (Km) varies within different types of rocks (Fig. 3). Km of trachytes ranges in order of 1-4E-2 [SI], while Km values of phonolites range from 1E-4 to 1E-3 [SI]. Low variations in Km values correspond to nearly homogeneous distribution of magnetic minerals within the rock. These values are in a range typical of young volcanic rocks (Tarling and Hrouda, 1993). The low values of Km in phonolites are due to the lack of titanomagnetite and presence of pyroxene as a carrier of magnetic anisotropy.

Degree of Anisotropy and relationship to magma viscosity

Higher degree of AMS of trachytic rocks (relative to basaltoids, Pj parameter ranging from 1.1 to 1.35, Fig. 4) is related to high degree of crystallinity and consequently high viscosity of trachytic magma. Magnetic ellipsoids show mostly oblate shapes in volcanic domes with T values ranging from 0.6 to 1. Only at localities where magmatic feeder zones were studied, the T parameter is in range from −0.5 to +0.5 and Pj parameter decreases to 0.7−1.1. The fabric patterns are stable on the outcrop scale and the ellipsoid shape and degree of anisotropy variations depend on the site location within the cupola (Fig. 4). Three different types of AMS were distinguished in trachyte dome: Most common Type 1 pattern shows a strong planar fabric, where K3 direction are well-grouped, and the maximum and K2 and K1 directions fall within the girdle. The second frequent Type 2 pattern shows symmetry of triaxial ellipsoid with well grouped K1, K2, K3 directions. Rather rare Type 3 fabric is characterized by well-grouped K1 principal direction and consequently by prolate ellipsoid (Fig. 5). Magnetic foliation (K3 axis) agrees with mesoscopic foliation fairly well and this correspondence is well-expressed by an angular difference

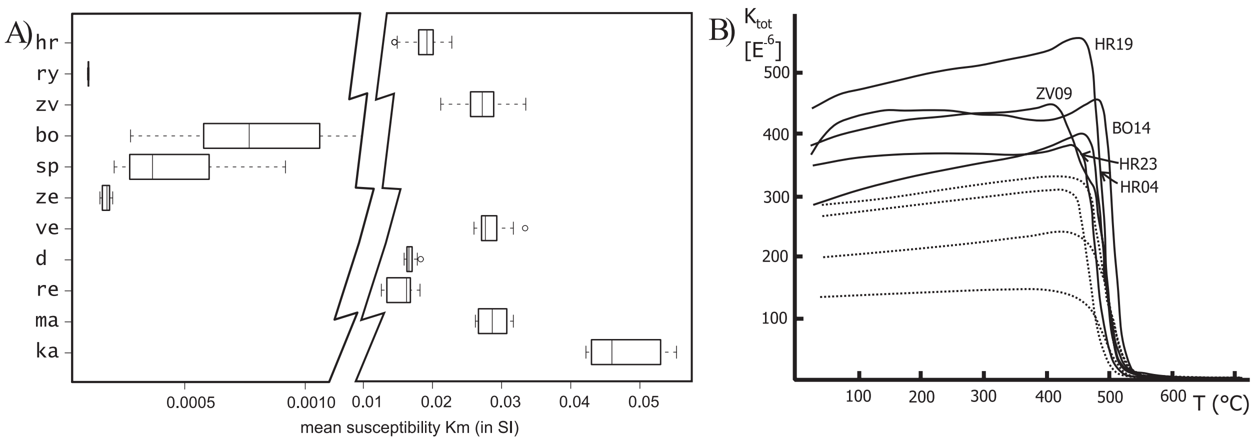

Fig. 3. AMS characteristics and magnetic mineralogy. A) Diagram of medians and first and third quartils (boxplot) showing distribution of mean susceptibility (Km) in studied volcanics. B) Thermomagnetic curves of selected volcanics.

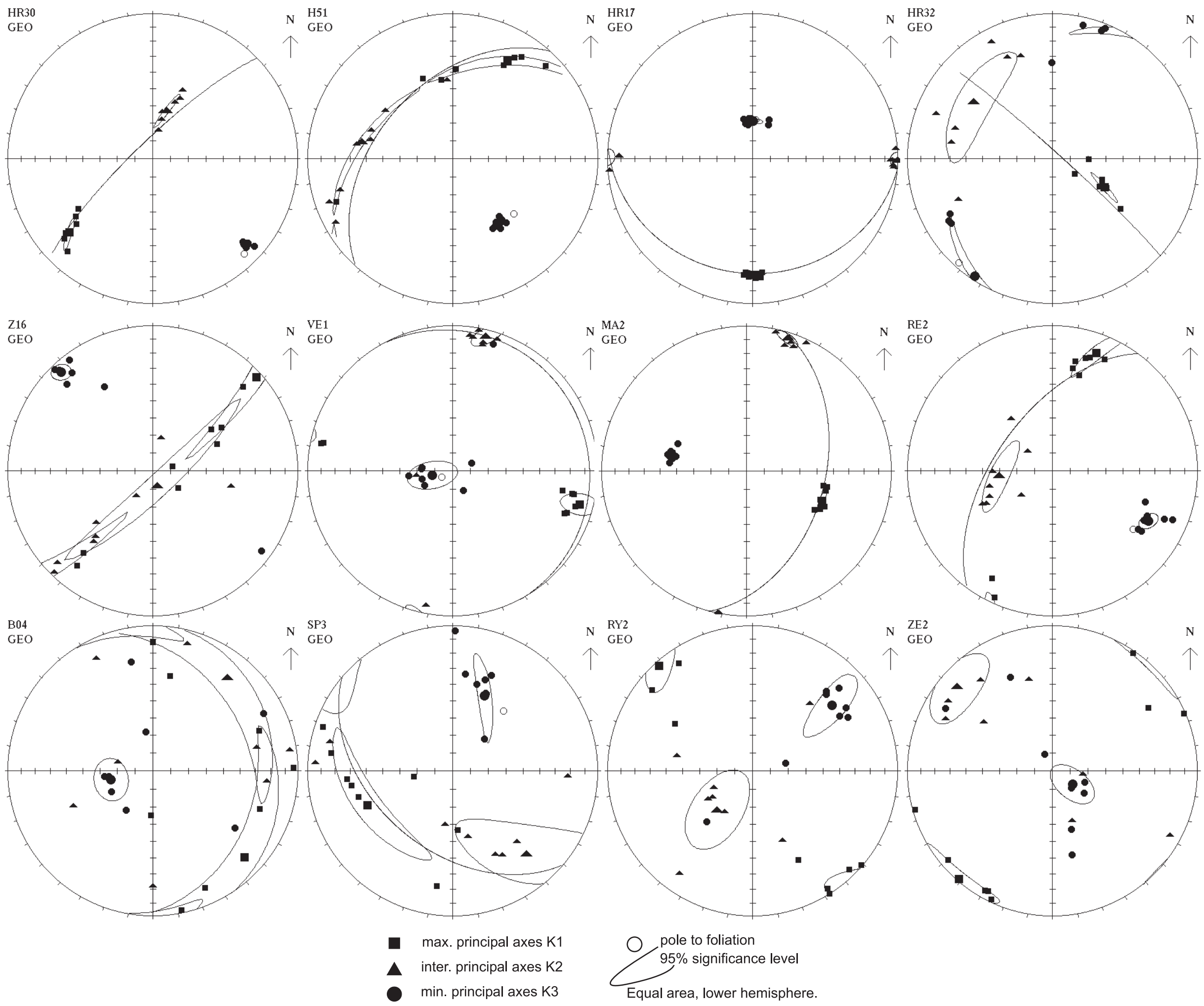

Fig. 4. Examples of anisotropy directional data plotted on a stereographic projection (equal-area, lower hemisphere). A–C) The most common pattern in trachytic rocks (the dome of Hradiste, sodalite-bearing trahyte) depicts homogeneity of anisotropy. D) Sample from part where feeding pipe was found (the dome of Hradiste). E–G) Very scattered patterns indicates phonolites (the dome of Boren, sodalite-bearing phonolite). Open circle = pole to mesoscopic foliation, full circle = maximum principal axes K1, filled triangle = intermediate principal axes K2, full square = minimum principal axes K3, larger dots depict directions of the principal values of the mean tensors. The confidence areas are calculated for the significance level of 95 %.

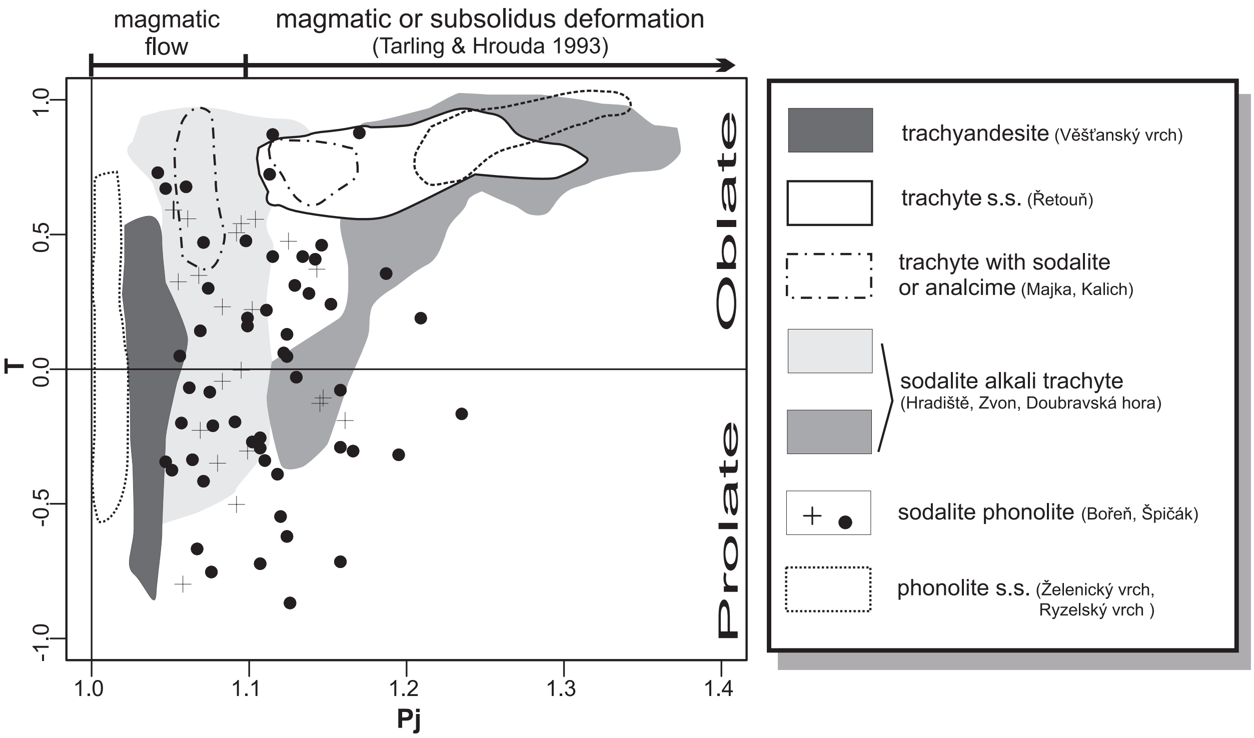

Fig. 5. P-T plot of degree of anisotropy and shape of AMS ellipsoid for studied volcanics.

lower than 10º between K3 direction and pole to macroscopically measured foliation for 82.5 % of samples.

In contrast, the phonolitic rocks in general exhibit lower degree of anisotropy and highly variable degree of anisotropy ranging from Pj = 0.3 – 1.2 and ellipsoid shapes showing T values from −0.9 to +0.9. Pattern of AMS fabric is very scattered indicating variation in flow directions on centimetres scale (see case of locality B25, Figs. 4 and 5). The pole figures show exceptionally scattered K1, K2 and K3 directions without any systematic type of fabric patterns. The fabric patterns vary on the outcrop scale indicating strongly inhomgeneous flow with fabric variations in centimetre scale.

The degree of anisotropy expressed by Pj parameter was correlated with viscosities of silicate magmas calculated on the basis of chemical compositions of studied volcanics using the KWARE Magma software of Ken & Wohletz. The viscosity

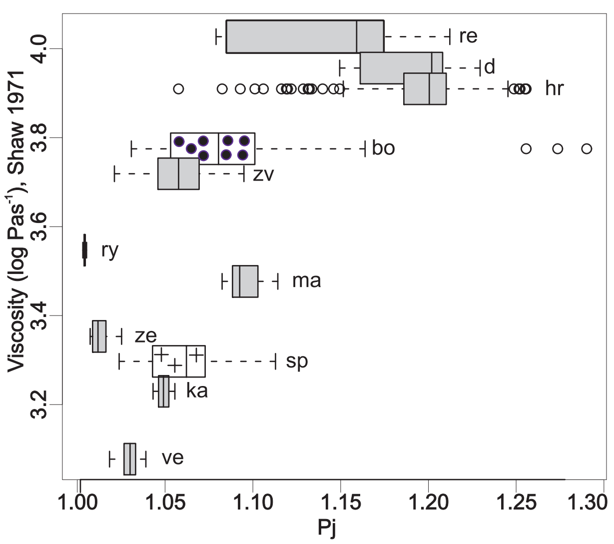

Fig. 6. Diagram of calculated viscosisties of magmatic silicate liquids for studied volcanics versus degree of anisotropy expressed in P_j parameter of Jelínek (1981).

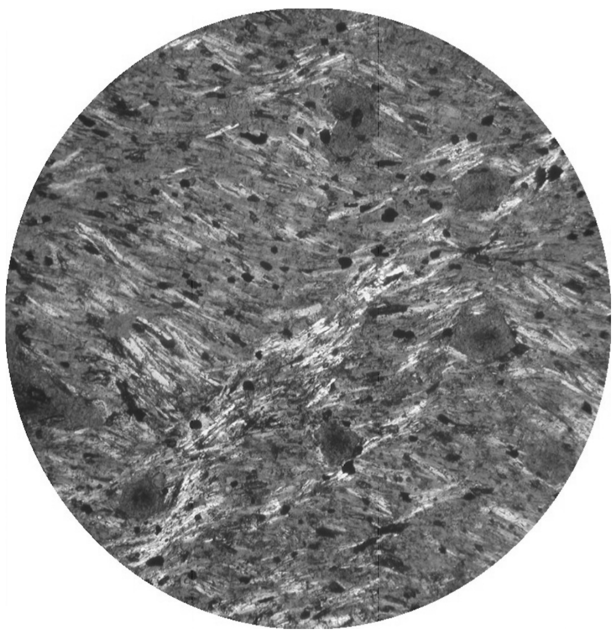

Fig. 7. Microphotograph of sanidine microstructure of trachytic rock. Cross-polarised light enhanced by a λ plate.

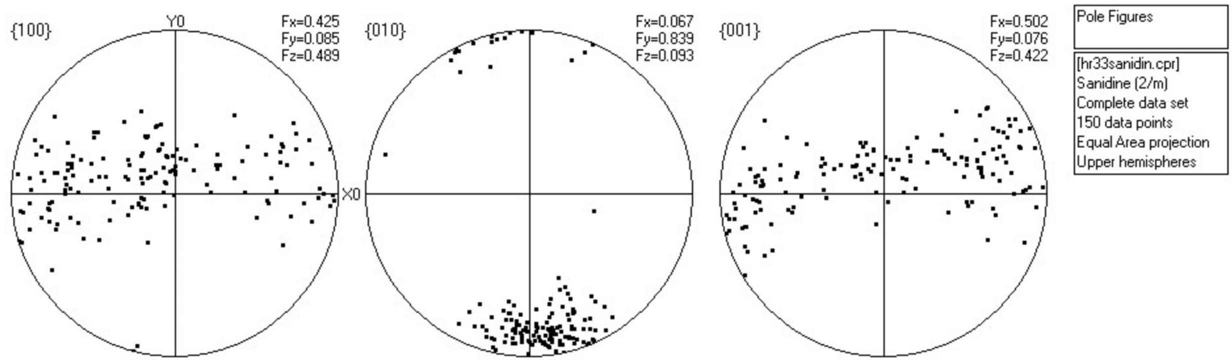

Fig. 8. Stereographic projection of <100>, <010> and <001> directions of 150 sanidine crystals. Sample 33, Hradiště u Habří, Measured by Jakub Haloda.

is strongly dependent on the molar proportion of SiO_2 (Shaw 1972) so that alkali trachyte shows highest viscosity values of around 10^4 Pas^{-1}, while sodalite phonolites and sodalite trachytes exhibit significantly lower viscosities in a range of $10^{3.6 \text{ to } 3}$ Pas^{-1}. Fig. 6 shows good correlation between the degree of anisotropy of magnetic susceptibility and calculated viscosity values so that highly viscous magmas show strong anisotropy of magnetic susceptibility. It is suggested that the high viscosity of magma cotrols rate of extrusion (or emplacement), which change magma rheology from Newtonian to dilatant/shear thickening. The increasing viscosity of magma is related to higher crystallinity of akali trachytes with respect to sodalitic phonolites.

Deformation Textures in Different Types of Volcanics (EBSD)

Trachytic rocks show exceptionally strong shape of preferred orientation of sanidine crystals under optical microscope (Fig. 7). Two differently oriented shear zones are present in each sample and at the areas of zone intersections the displaced groundmass is continuosly curved indicating simulatenous activity of shear zones. Such an alignment of sanidine crystals shows conjugate pattern characteristic of near-solid state flow of progressively solidifying extrusive rock (Smith et al., 19943). The narrow zones of well- oriented crystal fibres are interpreted in terms of development of microshear zones that were intiated after microlites began to grow and formed contemporaneosly with the microlites (Smith et al., 1997). The distribution of hear zones indicate that the general flow controlling final emplacement stage was coaxial or non-coaxial flatteing superimposed on previous highly non-coaxial type of flow.

The crystallographic preferred orientation (CPO) of sanidine crystals was measured using the Electron Back Scattered Diffraction HKL instrument mounted on Camscan electron microscope. Manual mode was used because of low symmetry of feldspars and only measurements with angular deviation lower than 1 degree. Output data are presented in stereographic projections, where foliation is oriented horizontally and calculated magnetic lineation (K1 direction) in the E-W direction. Distribution of crystallographic directions <100>, <010> and <001> is presented. Figure 8 shows example of sodalite phonolite with small amount of microshear zones. The poles largest feldspar faces (010) are oriented almost parallel to the pole of mesoscopic foliation and the distribution of <100> and <001> directions form greate circle slightly parallel to the foliation plane. Such a CPO was not yet determined in trachytic rocks using universal stage measurements (Jančušková, 1992) and indicates coaxial deformation. The deformation is accommodated by fibre slip mechanism exploiting feldspars 010 planes most likely at the presence of melt.

Conclusion remarks

In conclusion, the different AMS fabric pattern in alkali trachytes and sodalite phonolites indicate different flow mechanisms during emplacement and growth of domes. The magmas differ in character of magnetic minerals: titanomagnetite in alkali trachytes and paramagnetic pyroxene in sodalitic phonolites. The calculated viscosities of trachytic magmas are higher than those of phonolites. This is in harmony with higher degree of anisotropy of trachytic rocks, which is due to its higher viscosity and probably lower cooling rate raleted to slower velocity of ascent and possibly to the shallow level intrusion of these volcanics. Textures of these rocks show nearly subsolidus fabric with high degree of crystallinity, where sanidine in matrix is distributed to self-organized fibre-slip domains. Microstructure of phonolites shows fine-grained up to glassy matrix and low degree of sanidine alignment. Very low degree of AMS and almost random orientation pattern could be interpreted in terms of passively rotating ellipsoidal inclusions in viscous flow, modelled firstly by Jeffery, (1922).

Stop No. 1
Zvon (about 1 Hour of Walk and Observations)

Small volcanic body close to the mountain Milešovka (Location see Fig. 1) is composed of sodalite phonolite. The volcanic apparatus exhibits elongate shape with dominantly steep macroscopic planar fabric dipping to the southeast. The structral pattern of this dome is complicated by the presence of late magmatic factures. The relationship between these fractures and magmatic flow pattern will be discussed in the outrop.

The distribution of poles to K3 directions indicate dominant steep foliation trending NE-SW. The K1 direction, magnetic lineation, is also generally steeply inclined. The value of T parametre is close to 0, which indicate plane strain symmetry of magmatic flow. Rather week degree of anistropy (Pj < 1.10) suggest magmatic origin of fabric. This site is interpreted in terms of excellent example of feeder zone with elongated chimney and couette type of flow.

Stop No. 2
Dome Hradiště u Habří (2–3 Hours Walk, 4–5 Sites of Detailed Observations)

This trachyte dome is located 14 km SE of the town Teplice v Čechách (Location see Fig. 1). It is composed of sodalite phonolite of trachytic appearance. Eliptical body elongated in the NW-SE direction shows an excellent macroscopic foliation pattern, which points up the elliptical form of the dome (Fig. 9). The apical part of the dome shows almost flat foliations defined by alignment of sanidine phenocrysts and matrix crystals, while towards the margin the macroscopic foliations become steep (Fig. 10). The magnetic foliations are oriented in fair harmony with macroscopic planar fabric. The magnetic lineations (K1 directions) plunge shallowly in the E-W direction and become steeper in the SW margin of the dome. However, the east and west margins of the dome marked by steep or even overturned foliations show shallow lineations oriented parallel to the dome margins (Fig. 11a,b). This pattern is presented in WNW-ESE cros-section of the dome (Fig. 12), which shows oblate shapes of fabric ellipsoid, high degree of anisotropy and orientations of K1, K2 and K3 directions (Fig. 13).

At the first glance, as follows from Jelínek´s diagram, the whole trachyte body appears to be homogeneous both from the viewpoint of the degree of magnetic anisotropy and even shape of ellipsoid of magnetic susceptibility. Nevetheless, as for the T parameter and distribution of individual samples, the obtained data can be divided in 3 groups: 1) samples showing low T parameter (0.5 up to 0.5), 2) samples with T parameter approx. 0.75‑85, which show 3 maxima in the stereogram – three axial ellipsoid, and 3) samples exhibiting high T parameter around 0.95 up to 1 having strongly oblate ellipsoid. This separation into groups is not exactly artificial because the single groups differ from each other by their distribution in within the trachyte body.

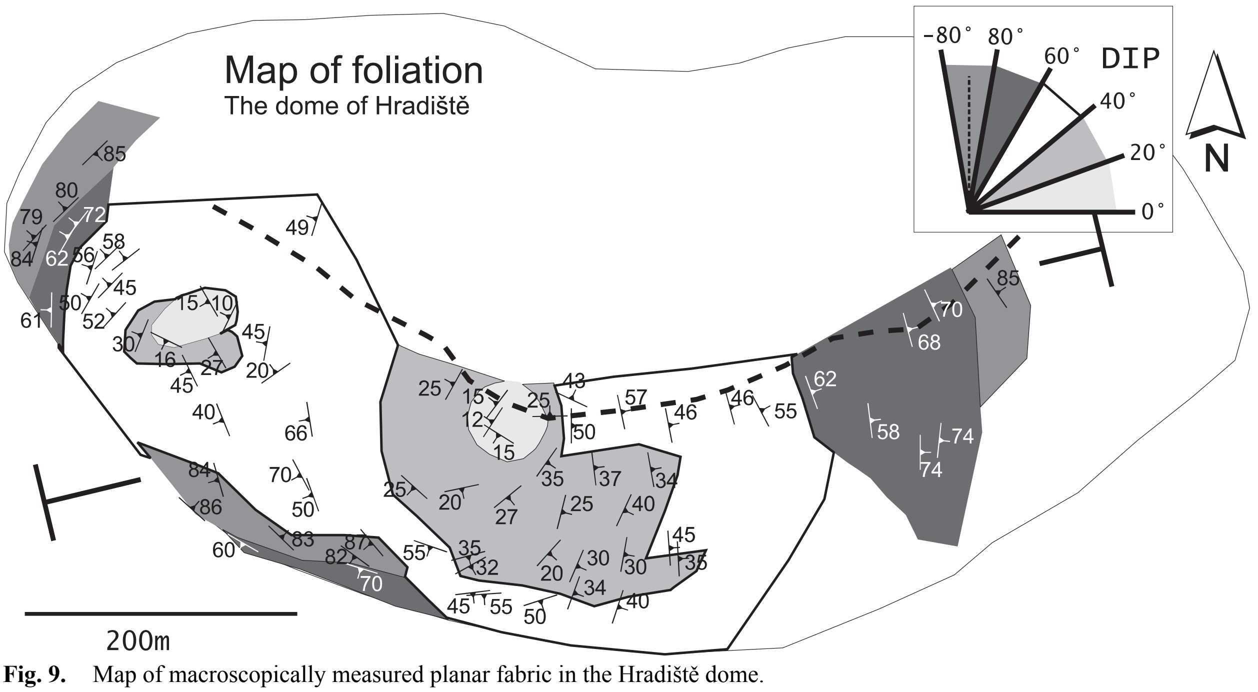

Fig. 9. Map of macroscopically measured planar fabric in the Hradiště dome.

The fabric patetrn is consistent with the model of outflowing magma towards the margins of volcanic body. We interpret this pattern as a result of flattening of the progressively solidifying magma on the top of volcanic cupola???

Fig. 10. Field photographs of flat and steep planar fabric in the apical and marginal parts of the Hradiště dome, respectively.

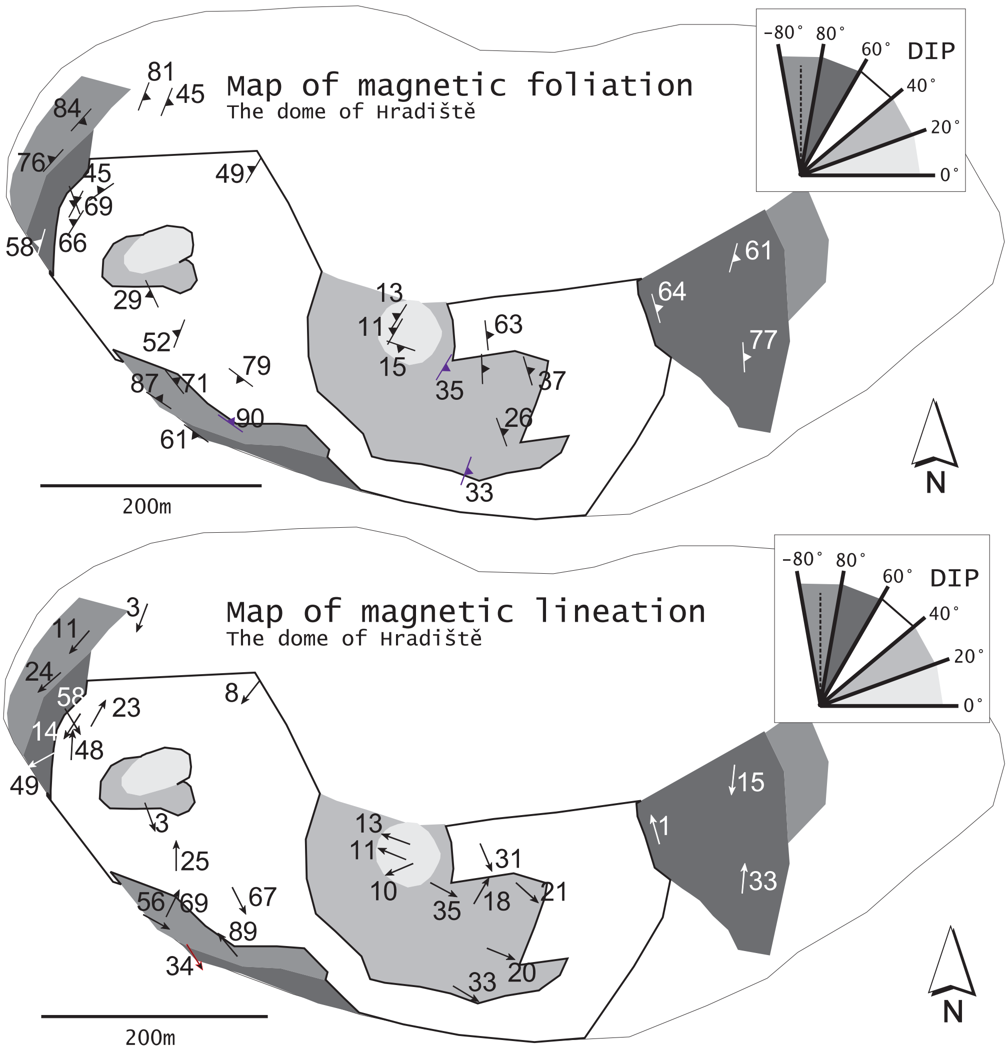

Fig. 11. Maps of AMS foliations and lineations in the dome Hradiště.

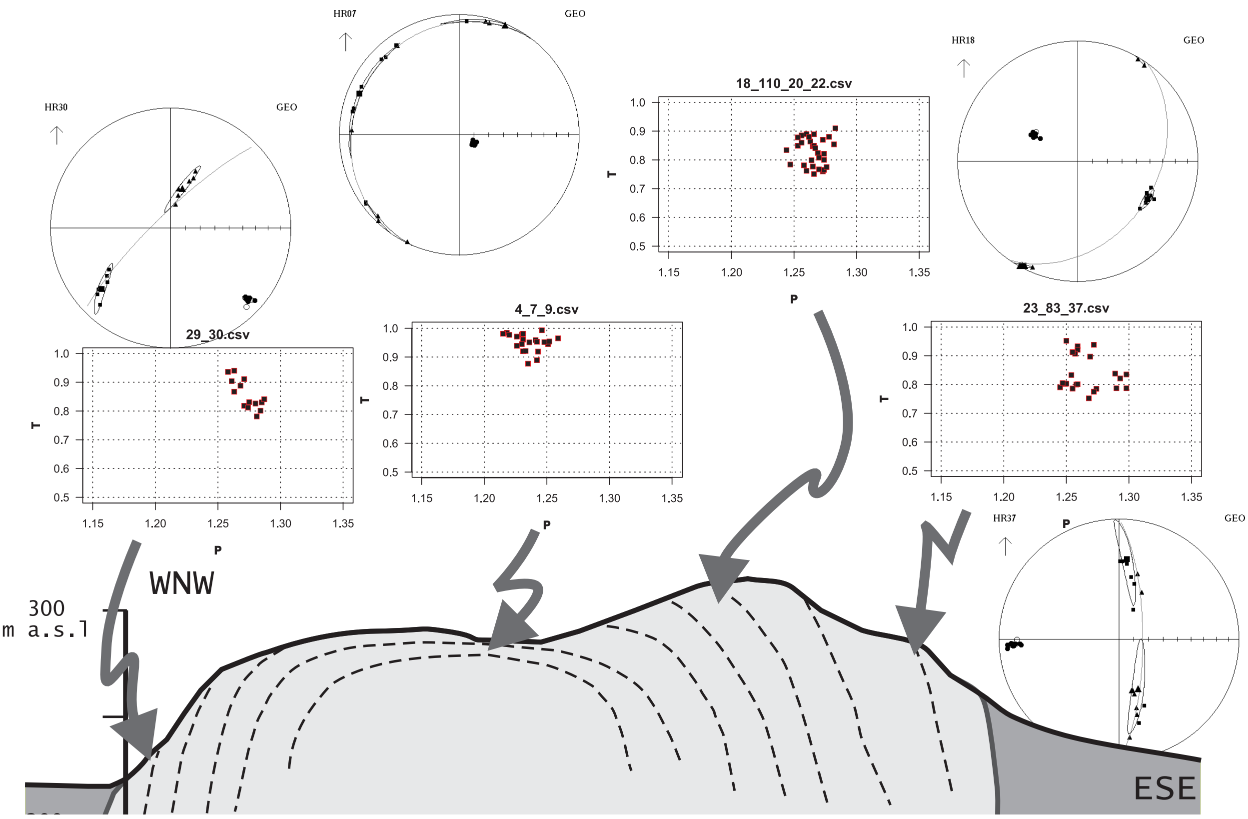

Fig. 12. Cross-section of the Hradiště dome showing characteristic AMS fabric patterns including K1, K2, K3 axes orientations and Pj-T plots.

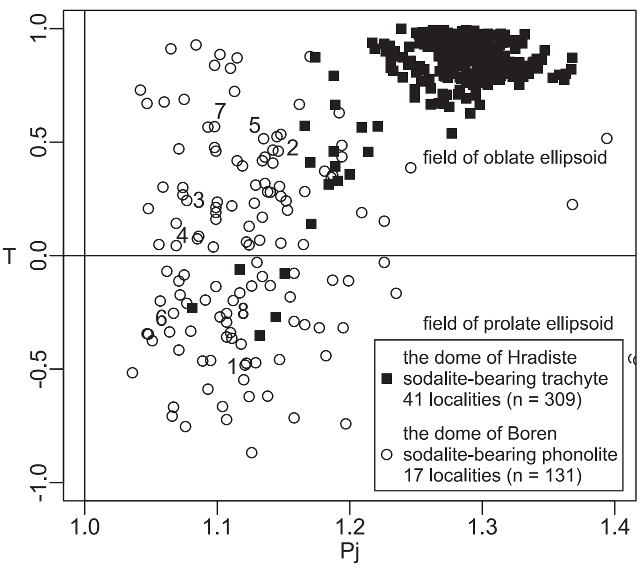

Fig. 13. Pj-T plot of AMS data from Hradiště sodalite-bearing alkali-feldspar trachyte and Bořeň phonolite s.s.

Stop No. 3
Phonolite s.s. Dome Bořeň (1 Hour of Walk and Observations)

This large phonolitic dome is composed of phonolite sensus stricto SW of town Bílina (location shown in the map, Fig. 1). The dome show quite well developped macroscopic fluidality. However, the AMS fabric patterns is extremely heterogeneous showing generally flat magnetic foliations. Degree of anisotropy is weak, ellipsoid shapes are strongly variable ranging from oblate to highly prolate fabrics. The pattern may indicate important variations in AMS fabric already in cm scales and possible local flow turbulencies in the outcrop scale. However, the low viscosity of extruding magma and high cooling rates may be responsible for observed patterns.

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