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Fluid inclusion planes and paleofluid records in the Podlesí granite, Krušné hory Mts., Czech Republic

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Abstract. Three generations of fluid inclusion planes (FIP) were distinguished in rocks of the PTP-3 borehole from the Podlesí granite stock (Krušné hory Mts.). The oldest generation of FIP is believed to have followed the propagation of proto-tectonic subhorizontal aplite dykes and steep veinlets of greisen mineralization, at temperatures of about 400 °C and pressures less than 100 MPa. The later FIP contain fluid inclusions with homogenization temperatures from 140 to 270 °C, and likely represent hydrothermal fluids associated with the repeated opening of fractures during the late stages of intrusive complex development.

Key words: Bohemian Massif, Krušné hory Mts., alkali feldspar granite, greisen, fractures, fluid inclusions, fluid inclusion planes

Introduction

For the purpose of studying the geochemical interactions between fluids and fractured rock environments, two drill holes, PTP-3 and PTP-4A, were drilled to a depth of 300 m into the granitic body of the Podlesí granite stock. Geological, geophysical, geochemical, and hydrological methods were applied by the Czech Geological Survey and other organizations to characterize this fractured aquifer and its associated fossil and recent fluids.

This contribution presents the preliminary results of the microscopic examination of fluid inclusion planes (FIP) in oriented samples from the PTP-3 borehole. We further compare the FIP orientation with that of the mesoscopic fractures in the PTP-3 borehole, the latter of which was studied by Maros et al. (2002).

The study of fluid inclusion planes aids our understanding of the circulation of fossil fluids in granitoid rocks, fluid-rock interaction and mass transport, paleofluid regime development, and the geometry of paleopermeability in hard-rock environments (Roedder 1990, Cathelineau et al. 1994, Lespinasse 1999).

Fluid inclusion planes result from the healing of open cracks, and therefore appear to be fossilized fluid pathways (Cathelineau et al. 1994, Lespinasse 1999). FIP are non-penetrative cracks interpreted as extensional fractures that formed subparallel to the average strike of σ_1 (Segall 1984). The cracks correspond to the propagation of a fracture in a plane that favours the maximum decrease of the total energy of the system (Gueguen and Palciauskas 1992). Quartz seems to be the best mineral for FIP study, as the healing of fractures in quartz occurs quickly in relation to geological conditions (Brantley 1992).

Geological setting

The Podlesí granite stock is located in the western part of the Krušné hory Mts. in northwestern Bohemia. It represents the most fractionated part of the late Variscan Nejdek-Eibenstock pluton in the Saxothuringian zone of the Variscan orogen in central Europe (Breiter 2002). The stock intruded Ordovician phyllites and biotite granite of the "younger intrusive complex" (though biotite granite was found only in the boreholes). The Podlesí granite stock consists mainly of albite-protolithionite-topaz granite (stock granite). In its uppermost part, the granite is penetrated by several flat-lying dykes of albite-zinnwaldite-topaz granite (dyke granite). The phyllite that surrounds the granite was extensively altered into protolithionite-topaz hornfels, and is crosscut by aplite dykes and numerous steep topaz-albite-zinnwaldite-quartz veinlets, accompanied by greisenisation and tourmalinization of the surrounding rocks.

Táborská and Breiter (1998) measured the magnetic anisotropy of the stock and dyke granite from surface outcrops. Only a primary magnetic fabric was identified, manifested by steep foliation and very steep lineation. The rocks were not affected by later deformation.

In contrast to surface outcrops, the anisotropy of magnetic susceptibility of granite cores from the PTP-3 borehole show more variable patterns: steep foliations prevail in the stock granite, while lineations vary, being mostly subhorizontal (Chlupáčová and Mrázová 2001, preliminary results). Both very steep and/or subhorizontal magnetic foliations were found in the biotite granite. Subhorizontal lineations predominate in the biotite granite.

Materials and methods

A total of 17 oriented samples were prepared from the oriented core of the PTP-3 borehole, ranging in depth from 20 to 348 m (20 m intervals). Moreover, 9 oriented samples of biotite granite, stock granite, dyke granite, pegmatite, quartz veins, quartz-rich and biotite-rich greisens were collected from outcrops and an abandoned quarry near the borehole site.

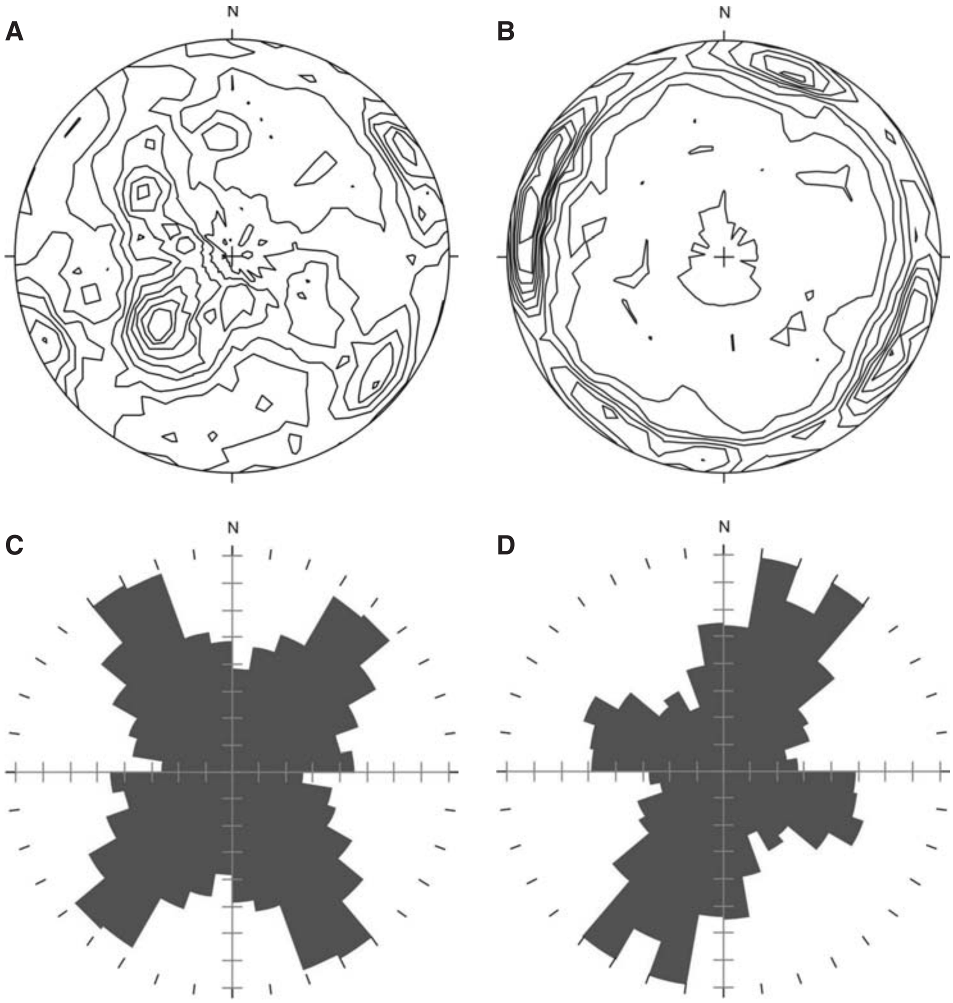

Figure 1. A – contour diagram of poles of fractures from the PTP-3 borehole from depth 20–348 m (lower hemisphere, polar equal area, increment 1%, number of points = 877). B – contour diagram of poles of FIP from the PTP-3 borehole (lower hemisphere, polar equal area, increment 1%, 17 samples, number of points = 1554). C – rose diagram of fractures from the PTP-3 borehole from depth 20–348 m. D – rose diagram of FIP from the PTP-3 borehole.

The methodology of FIP measurements is comprised of the following steps:

- collecting oriented samples from outcrops and from the PTP-3 borehole;
- preparing oriented petrographic slices and double-polished wafers for fluid inclusion study;
- structural measurements of FIP in rock samples, including the length, strike, and dip of FIP using a standard microscopic stage;
- evaluation of FIP using stereograms and pole distribution diagrams (StereoPro software), and estimating FIP length.

Fluid inclusion microthermometric studies were carried out with a Chaixmeca heating-cooling stage. This apparatus, which enables the determination of the temperature of phase transitions in the range from –180 to 600 °C (Poty et al. 1976), was calibrated by Merck's chemical standards, the melting point of distilled water, and phase transitions in natural, pure CO_2 inclusions.

The following phase transitions were measured:

Th – homogenization temperature;

Tm_{ice} – melting temperature of the last ice crystal, for salinity determination (Bodnar 1993);

Te – eutectic temperature, for determination of the salt system (Borisenko 1977);

Ts – dissolution temperature of daughter crystal, for determining the bulk salinity (Roedder 1984).

Results

Structural measurements from the PTP-3 borehole and from the abandoned quarry

Well logging methods for borehole PTP-3 utilised an Acoustic BoreHole TeleViewer (BHTV), a Heat Pulse Flowmeter (HPF), and additional logs that are very sensitive to the fractures. Full wave sonic, resistivity, caliper, and temperature measurements (Zilahi-Sebess and Szongoth 2002) were also conducted. The core was scanned with an ImaGeo mobile corescanner (Maros et al. 2002).

The combination of these methods enabled the study of the orientation and distribution of various geological phenomena, such as the depth, dip, and strike of fractures, rock boundaries, the occurrence of aplite and quartz veins, foliation, alteration, infillings, and the geometry of the fractures intersected by the core.

The fracture frequency, which they found to be 3.04 fractures per metre in the borehole, is very low. The granite body cannot be termed as a fractured one, even though a

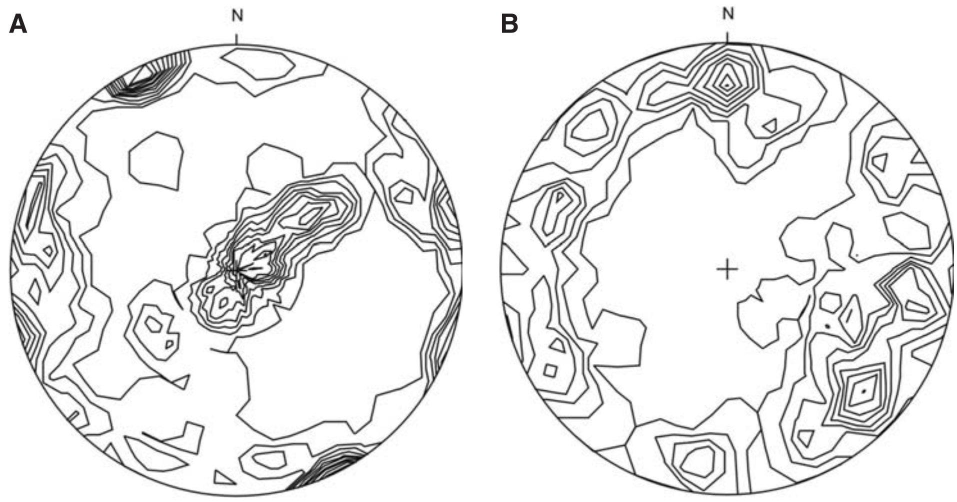

Figure 2. A – contour diagram of poles of fractures in the stock granite from the abandoned quarry in Podlesí (lower hemisphere, polar equal area, increment 1%, number of points = 130). B – contour diagram of poles of FIP in the stock granite from the abandoned quarry in Podlesí (lower hemisphere, polar equal area, increment 1%, number of points = 111).

few remarkable fracture zones were distinguished. Altogether 877 open or closed fractures were identified in the PTP-3 borehole. The fractures are predominantly oblique to subhorizontal with NW-SE strike with and dip to the NE, or of NNE-SSW strike and dipping both to the NW and SE. Steep fractures strike mainly NW-SE and NE-SW (Fig. 1A, C). Moreover, two theoretical paleostress orientations were determined with main stress orientations to the NE-SW and NW-SE (Maros et al. 2002).

Stereograms of the fractures from the stock granite of the abandoned quarry near Podlesí were calculated from the data of Mrázová (2000). Fractures with moderately dipping to subhorizontal attitudes, with dips to the SW and NW, were found. The steeper fractures are of NNE-SSW, ENE-WSW and NW-SE strike (Fig. 2A).

Microstructural measurements of fluid inclusion planes

A total of 17 oriented samples were collected from the oriented core of the PTP-3 borehole (depth 20–348 m, interval 20 m). FIP length, strike, and dip were measured in quartz and topaz of the oriented samples using a standard microscopic stage (Fig. 3A, B). The lengths of the measured FIP range from 0.1 mm to 3.2 mm. The density of FIP in quartz is estimated to range from 30 to 75 FIP/cm^2 in both the stock and the biotite granites.

More than 1500 FIP were measured in samples from the PTP-3 borehole. Most of them are steep, with various strikes. However, orthogonally striking steep FIP predominate: NNE-SSW and WNW-ESE (Fig. 1B, D). Subhorizontal and moderately dipping FIP seem to be less frequent. Only 196 FIP dip at angles lower than 60°. It should be mentioned that the microstructural measurements of FIP used to be more complicated, resulting in their relatively low number.

Samples of the stock granite from the abandoned quarry were found to have mostly steep FIP of NNE-SSW to NNW-SSE strike, and perpendicular FIP of WNW-ESE strike (Fig. 2B). Similar results were obtained from the dyke granite and pegmatite outcrops.

Fluid inclusion measurements

Fluid inclusions in biotite-rich and quartz-rich greisens from outcrops

Primary inclusions in 3D distribution were found in the quartz and topaz of biotite-rich and quartz-rich greisens. The inclusions have oval or negative crystal shapes, and are up to 120 μm in diameter. Two-phase vapour-rich (V > L) inclusions with liquid to vapour ratios (LVR = L/L + V) from 0.3 to 0.05 predominate in both greisen types. Furthermore, inclusions with LVR = 0.7 and poly-phase L + V + S inclusions were also found. All the above mentioned inclusions contain only aqueous solutions, while the presence of CO_2 or other gasses was not confirmed by cryometric measurements. Homogenization temperatures of vapour-rich inclusions range between 368 and 414 °C. Tm_{ice} values (–2.8 to –7.7 °C) correspond to salinities from 4.7 to 11.3 wt% NaCl eq.

Solid phases, mostly halite daughter crystals, were only rarely found in the inclusions. The dissolution temperatures of the crystals were not observed, as the inclusions decrepitated prior to crystal dissolution (at temperatures around 450 °C).

Fluid inclusions in quartz veins

Two generations of aqueous inclusions were found in vein quartz from the depth 114.9 m of the PTP-3 borehole. Both inclusion generations have irregular to oval shapes and measure up to 60 μm in diameter.

Inclusions with LVR of about 0.1 homogenized to vapour at temperatures ranging from 356 to 395 °C. Their Tm_{ice} ranged from –2.6 to –4.6 °C, corresponding to salinities between 4.3 and 7.3 wt% NaCl eq.

The second generation of inclusions with LVR = 0.8–0.9 homogenized to liquid at temperatures from 158 to 184 °C, and are probably younger than those described above. Their salinity is low, from 0.9 to 1.6 wt% NaCl eq. (Tm_{ice} = –0.5 to –0.9 °C). Eutectic temperatures were observed between –36.8 and –39.5 °C, indicating the Na-K ± Mg ± Fe chloride content of the solutions.

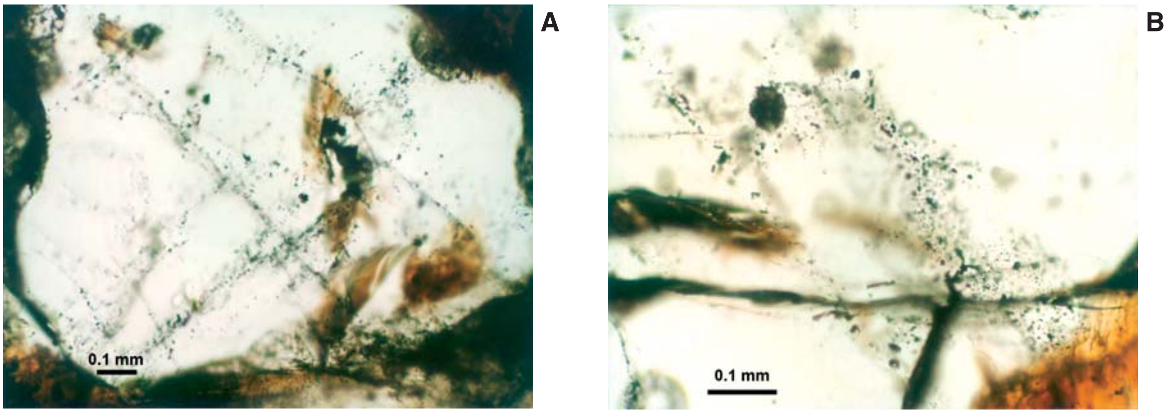

Figure 3. A – crossing of FIP of various strikes in rock-forming quartz, PTP-3, 161.15 m, // n. B – moderately dipping FIP in rock-forming quartz, PTP-3, 41.05 m, // n.

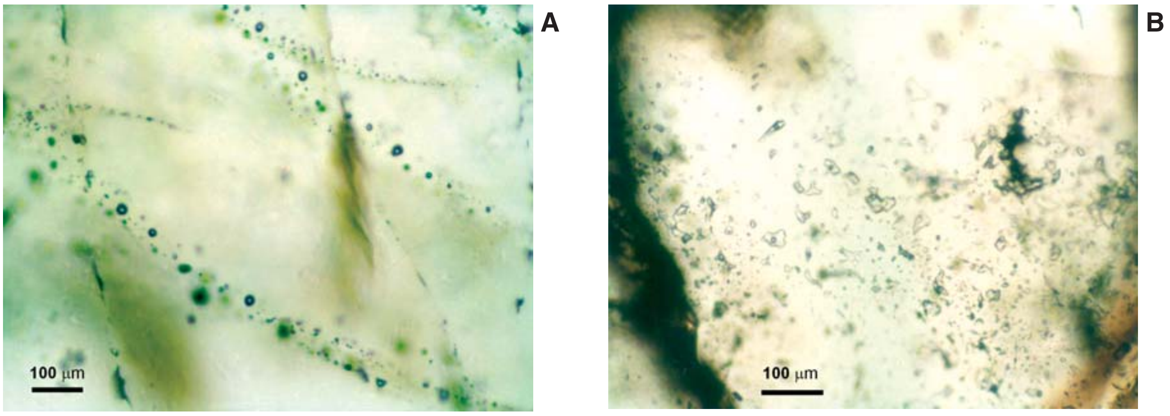

Figure 4. A – vapour-rich (V > L) fluid inclusions (generation 1) along steep FIP in quartz, PTP-3, 161.15 m, // n. B – fluid inclusions (generation 3) with LVR = 0.9 along subhorizontal FIP in quartz, PTP-3, 81.2 m, // n.

Fluid inclusions in FIP

Fluid inclusions in FIP are clearly secondary in relation to the host mineral. Inclusions in FIP of various strikes and dips were measured. Homogenization temperatures were measured mainly in groups of fluid inclusions with relatively consistent liquid to vapour ratios.

Three generations of water-rich fluid inclusions were found in FIP (Fig. 4A, B):

1. Vapour-rich (V > L) fluid inclusions with homogenization temperatures (Th) from 350 to 430 °C.
2. Liquid-vapour inclusions with Th between 200 and 270 °C.
3. Liquid-vapour inclusions with Th from 140 to 230 °C.

The salinity of fluid inclusions was relatively low in all samples and did not exceed 10 wt% NaCl equiv. Eutectic temperatures (Te) could be measured only in a few FIP of the third generation. Te between –35.6 and –42.5 °C indicate the presence of Na, K, Fe, and Mg chlorides in solution.

Fluid inclusions of generations 1 and 3 occur along the steep FIP of NE-SW, NW-SE and E-W strike, and along the moderately dipping FIP. Second generation FIP are not frequent, and occur only in NE-SW strike.

Discussion

The Podlesí granite stock represents a very compact body with clear magmatic structures that were not affected by later deformation (Táborská and Breiter 1998).

While both vertical and/or subhorizontal magnetic foliation and lineation are found in the stock granite and the biotite granite, subhorizontal structures predominate in the dyke granite (Táborská and Breiter 1998, Chlupáčová and Mrázová 2001). The orientation of the later structures appears to have been influenced by magma intrusions along flat-lying L-joints.

Subhorizontal aplite veins dipping to the E and NW (Fig. 5A), and the pegmatite dyke, are probably related to the L-joints of the prototectonic joint system that originated during the period between the viscous and elastic character of the magma.

The development of steep fractures is associated with the greisen mineralization and postmagmatic quartz veins (Fig. 5B).

Moderately dipping to subhorizontal fractures were probably opened during the decompression of the granite massif at the final stages of its geological development.

Some differences are found when correlating the strikes

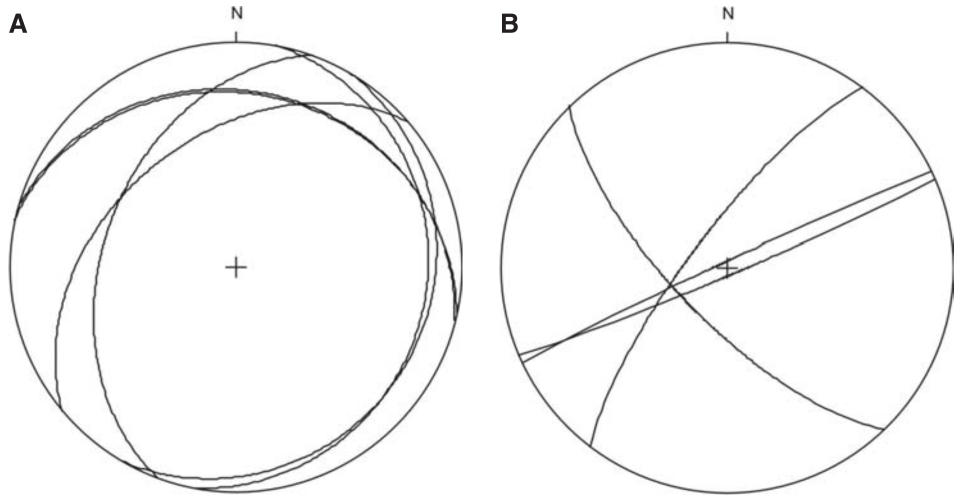

Figure 5. A – orientation of aplite dykes in the PTP-3 borehole. B – orientation of topaz-quartz veins in the PTP-3 borehole.

of fractures from the PTP-3 borehole and those of the FIP in oriented samples. In steep FIP orthogonal strikes are evident (NNE-SSW, to NNW-SSE and WNW-ESE) (Fig. 1B, D), while moderately dipping and subhorizontal FIP are less common. In contrast, mesoscopic, moderately dipping to subhorizontal fractures (NW-SE dipping to NE and NNE-SSW dipping both to NW and SE) predominate in the studied borehole, while steep fractures are primarily of NW-SE strike, and less often of NE-SW strike (Fig. 1A, C).

Three generations of secondary fluid inclusions were distinguished based on petrographic criteria and fluid inclusion patterns in individual FIP. Fluid inclusions of the first and third generations occur both in steep (NE-SW, NW-SE, and E-W) and in moderately dipping FIP. Fluid inclusions of the second generation are rare, and occur only along healed microfractures of NE-SW strike (Fig. 6).

Fluid inclusions with high Th values (from greisens, quartz veins, and first-generation FIP) probably correspond to the fluids related to the greisenization. Economic greisen mineralizations in the western Krušné hory Mts. were studied by Ďurišová et al. (1979) and Ďurišová (1984). They found two types of coexisting inclusions in quartz and topaz. The first type represents two-phase V > L inclusions, with 1 to 2 mol% of CO_2, Th up to 400 °C, and low salinity to 10 wt% NaCl eq. The second type corresponds to poly-phase inclusions with daughter crystals (halite and sylvite), with total Th up to 500 °C and a high salinity of about 40 wt% salt. Based on the presence of immiscible, vapour-rich, and highly saline liquid-rich fluids, the pressure conditions of greisen formation could not have reached 100 MPa.

Considering the above data, it can be assumed that the FIP of the first generation originated by the healing of microfractures during an early postmagmatic process connected to the propagation of the greisen mineralization, at temperatures around 400 °C and pressures less than 100 MPa.

Ďurišová et al. (1979) and Ďurišová (1984) also described inclusions with lower contents of vapour phases and Th in the interval from 140 to 280 °C, representing secondary relics of a later hydrothermal process (i.e. post-greisenization).

In the present study, fluid inclusions with lower Th values were also found in quartz veins and in the second- and third-generation FIP. They likely represent a later tectonic processes accompanied by the repeated opening of microfractures during the later stages of the granite stock development. Numerous quartz veins, sometimes with sulphide mineralization (Veselovský, pers. comm.), were also formed at this stage.

Conclusions

The orientation and character of the healed microfractures (fluid inclusion planes) were studied in oriented samples from the PTP-3 borehole of the Podlesí granite stock in the Krušné hory Mountains. Orthogonal strikes of steep FIP are predominant: NNE-SSW, to NNW-SSE and WNW-ESE. Moderately dipping to subhorizontal FIP are significantly less frequent.

Fluid inclusions in FIP are only of the H_2O type with low salinities (< 10 wt% NaCl eq.). Three generations of FIP were distinguished based on fluid inclusions patterns and petrographic relationships:

1. FIP with high Th between 300 and 430 °C.
2. FIP with Th in the range from 200 to 270 °C (relatively rare).
3. FIP with Th between 140 and 230 °C.

The origin of the first-generation FIP is believed to have followed the propagation of proto-tectonic subhorizontal aplite dykes and steep veinlets of greisen mineralization. These FIP are interpreted as a result of an early postmagmatic process connected to the formation of topaz-albite-zinnwaldite-quartz veinlets accompanied by greisenization at high temperatures and pressures up to 100 MPa. The data are in agreement with those from greisen assemblages of the western Krušné hory Mts. (Ďurišová et al. 1979, Ďurišová 1984).

The FIP with homogenisation temperatures lower than 270 °C likely represent postmagmatic tectonic processes associated with the repeated opening of various fractures during the late stages of the Podlesí granite's evolution.

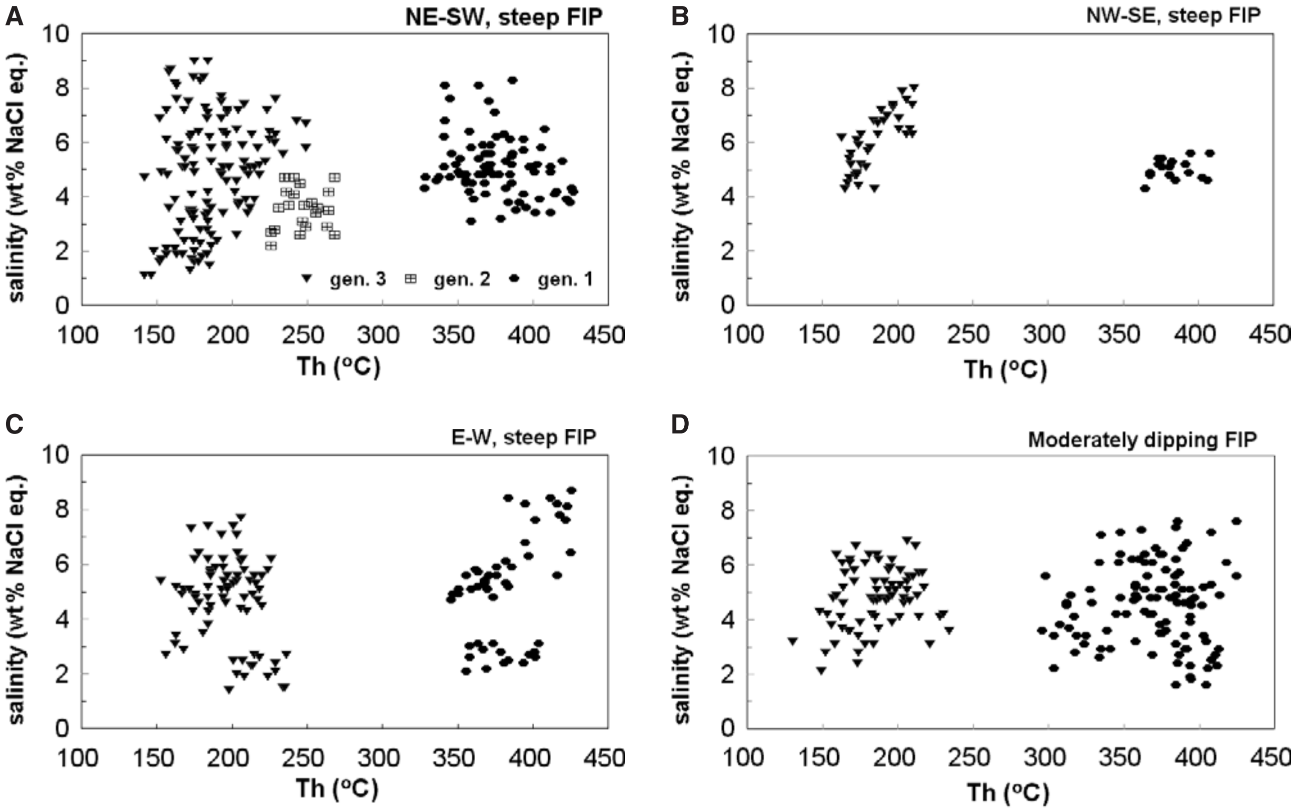

Figure 6. Diagrams of homogenization temperatures (Th) versus salinity of fluid inclusions from FIP of various orientations.

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