*Acta Mineralogica-Petrographica, Szeged 2004, Vol. **45/1**, pp. 123–131*

ACTA
Mineralogica
Petrographica

APPLICATION OF STUDIES ON FLUID INCLUSION PLANES FOR EVALUATION OF STRUCTURAL CONTROL ON VARISCAN AND ALPINE FLUID MOBILIZATION PROCESSES IN THE MONZOGRANITE INTRUSION OF THE VELENCE MTS. (W-HUNGARY)

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ABSTRACT

Studies on fluid inclusion planes of quartz from granite and pegmatite revealed that hydrothermal fluids related to Palaeogene andesitic volcanism penetrated the Variscan intrusion. Comparison of field observations on faults and joints with orientation of fluid inclusion planes revealed that the development of fractures in granite had taken place under rather similar orientations of palaeo-stress field both in Variscan and Alpine times and therefore many fractures of granite may have re-opened during the Palaeogene events. The common stress orientations are NW–SE and E–W. NE–SW orientation is characteristic to Palaeogene fluid inclusion planes only, whereas N–S oriented fluid inclusion planes are related to Variscan events only. Results also suggest that intense syn-volcanic faulting took place during the Palaeogene igneous activity, and therefore the same volume of Variscan granite was affected by both subvolcanic-type and epithermal type Tertiary fluids.

Key words: Variscan granite, Alpine andesite, hydrothermal systems, fluid inclusion planes, fracture development

INTRODUCTION

Determination of temporal and spatial evolution of fracturation in granite intrusions has importance in modelling of hydrothermal processes and in evaluation of various environmental issues (e.g. nuclear waste disposal, occurrences of radon anomalies). Field observations on mineralized veins, hydrous alteration zones, faults and joints may support the establishment of a large-scale model about major structural controls of fluid circulation events in the past, evaluation of density of open fractures for recent fluid and gas percolation and extent of healing of macro-fractures during the geological evolution of the area. However, permeability and porosity is also influenced by the presence of micro-fractures and their extent of healing. Therefore it is also important to know orientation and density data for micro-fractures and pressure-temperature-composition (P-T-x) parameters of fluids that used these micro-channels for their circulation during different tectonic phases. Fluids circulating in a rock unit may be trapped as fluid inclusions during the healing of micro-fractures of minerals and the healed fractures form planes of fluid inclusions. Orientation data (dip-direction – dip-angle) of fluid inclusion planes and P-T-x parameters of their inclusions may be different for various tectonic stages, therefore using these data may support the establishment of temporal evolution of fracturation. Conditions of re-opening of healed micro-fractures that determinates the propagation of macro-fractures in rocks are also fundamental parameters in modelling of evolution of permeability. Re-opening of healed fractures, for example due to increase of temperature, highly depends on the properties of fluids trapped in fluid inclusion planes, thus characterization of fluid properties are also fundamental for modelling those processes.

Fluid inclusion planes in a mineral form mostly during brittle deformation of a rock and they represent mode I simple extensional fractures (Pécher et al., 1985, Lespinasse, 1999). The orientation of those fractures is independent from the structure of the host mineral if that mineral has isotropic behaviour under stress; this kind of mineral in granite is the rock forming quartz (Tuttle, 1949; Kowallis et al., 1987; Lespinasse and Cathelineau, 1995). In quartz, planes of fluid inclusions develops with strike-orientation perpendicular with the direction of σ_3 in a stress field of brittle deformation, thus orientation of fluid inclusion planes can be correlated with the major axes of local palaeostress at the time of their for formation (Tuttle, 1949; Wise, 1964; Lespinasse and Pecher, 1986; Guegen and Palciuskas, 1992). This is especially important in igneous rock bodies where lack of bedding and difficulties in observation of linear elements on faults surfaces result in ambiguity in determination of relative movements of adjacent bocks of rocks.

Earlier fluid inclusion studies (Molnár, 2003) revealed that both Variscan and Alpine fluid mobilization processes affected the granite intrusion in the eastern part of the Velence Mts. Fluid inclusion associations trapped during those hydrothermal events are different regarding their P-T-x parameters, therefore studies of their secondary planes in rock forming quartz of granite offer a unique method for the evaluation of structural control of fracturation at different stages of the geological evolution of the region.

GEOLOGY, HYDROTHERMAL SYSTEMS AND MAJOR STRUCTURAL FEATURES OF THE VELENCE MTS.

The main mass of the Velence Mts. consists of a Variscan biotite monzogranite intrusion that intruded Lower Paleozoic metamorphic shale (Fig. 1). The S-type granitoid crystallized from a water-saturated melt at around 2 kbars pressure between 520–700°C temperature about 280–300 Ma ago (Buda, 1985). Most of aplite and granite-porphyry dikes of the granite intrusion are characterized by NE–SW strike-direction. Their orientation can be correlated with the existence of a predominantly NNE–SSW oriented compression at the time of granite crystallization in the collision zone of micro-continents that were originated from the boundary of Laurasia and Gondwana (Fülöp, 1990). Contemporaneously with emplacement of aplite dikes, numerous quartz-feldspar pegmatite bodies were also formed in the apical zone of intrusion. Fluid inclusions trapped in quartz during pegmatite crystallization are characterized by low - to intermediate salinities (1.2–5.7 and 7.6–13.7 NaCl equiv. wt.%) and homogenization temperatures between 220–280 and 280–320°C. Combination of results of two-feldspar thermometry and fluid inclusion data suggests 300–400 and 500–550 °C temperature and 1.5–2.5 kbars pressure for crystallization of pegmatite (Molnár et al., 1995). The high-temperature stages (at around 300 °C) of the granite-related hydrothermal circulation deposited quartz-molybdenite stockwork mineralization and they are characterized by entrapment of carbonic-aqueous fluid inclusion associations in quartz. Late hydrothermal veins with predominantly NE–SW and less frequently NW–SE strike-directions were formed from Ca-rich fluids with elevated salinities (up to 25 $CaCl_2$ equiv. wt %). Inclusions that were trapped from these fluids are characterized by less than 250°C most common homogenization temperatures (Molnár, 2003).

The granite mass was intruded by a few lamprophyre dikes of Cretaceous age (Horváth and Ódor, 1984). These rare dikes were emplaced in simple extensional fractures that were developed according to the Alpine compression at that time. There is no hydrothermal alteration associated with those dikes in the host granite, therefore it is assumed that this sparse magmatic event did not trigger intense fluid circulation.

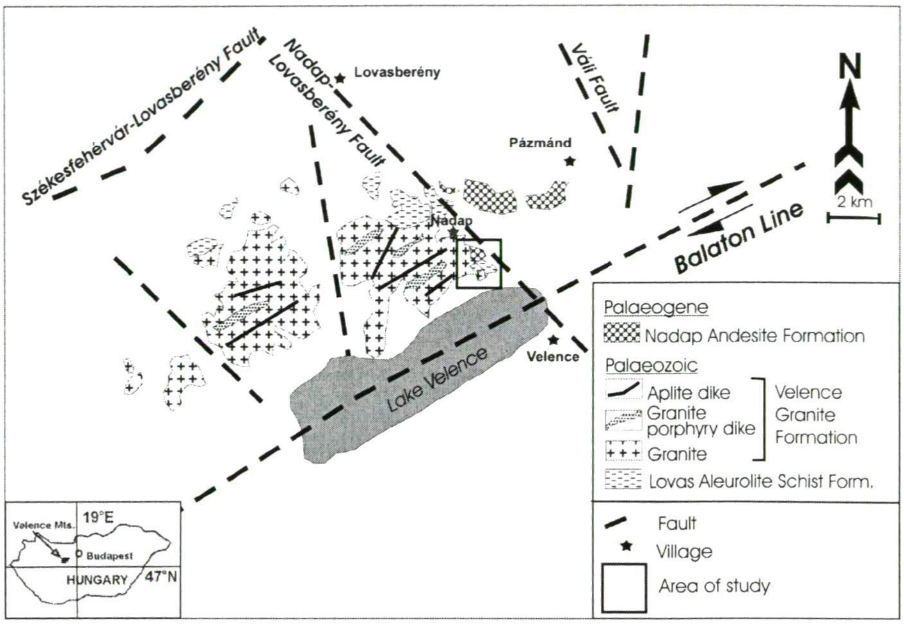


Fig. 1. Geological and structural sketch map of the Velence Mts. without formations younger than Palaeogene (after Gyalog and Horváth, 1999).

During Upper Eocene–Lower Oligocene, the Variscan granite body was situated along the southern boundary of the European plate in the Meso-Alpine subduction and collision zone. Igneous activity resulted in emplacement of andesite dikes and stocks in the eastern zones of the granite body and development of an andesitic stratovolcano with subvolcanic diorite intrusions (Darida-Tichy, 1987) in the eastern part of the Velence Mts. (Fig. 1). Intense hydrothermal activity associated with the Palaeogene volcanism and resulted in high sulphidation type epithermal mineralization of the stratovolcanic units and porphyry copper type mineralization at subvolcanic levels (Molnár, 1996). The Palaeogene hydrothermal system also invaded the eastern zones of the Variscan granite intrusion (Molnár and Török, 1995; Molnár, 2003). Fluid inclusion associations in both levels of hydrothermal activity of Palaeogene age are significantly different from those related to Variscan hydrothermal system (Molnár, 2003). The most peculiar feature of the Palaeogene fluid inclusion associations is the occurrence of low-density vapour-phase rich fluid inclusions together with high-density liquid-phase rich ones due to their trapping in low pressure (20–300 bars) hydrothermal systems. Liquid-rich fluid inclusions from subvolcanic-level mineralization are characterised by high homogenization temperatures (300–500 °C) and also contain halite and other daughter minerals due to their high salinities. Liquid-rich fluid inclusions from epithermal zones have relatively low homogenization temperatures (250–350 °C) and low salinities (0–13 NaCl equiv.wt.%).

The present location of the Variscan and Alpine units of the Velence Mts. is the result of the escapement of their host block from the Alpine collision zone during the Oligocene and the Lower Miocene (Kázmér and Kovács, 1985). The large scale lateral displacement in the order of hundreds of kilometres took place in northeastward direction along the Periadriatic Lineament and the Mid-Hungarian (Zagreb-Zemplén) Line and the related Balaton Line. The Balaton line has NE-SW strike-direction and now forms the southern boundary of the Velence Mts. (Fig. 1). Another important structure in the Velence Mts. is the NW–SE trending Nadap-Lovasberény fault (Fig. 1) between the Palaeogene volcanic and the Variscan granitoid unit. This fault appears to be synchronous with the Palaeogene volcanism because west of it the presence of fluids that are characteristic both to subvolcanic and volcanic level of hydrothermal activity can be traced in fluid inclusions, whereas east of it only volcanic level (epithermal) type of fluid inclusions and alteration zones are present at the same elevation on the present surface (Molnár, 2003). This is in agreement with the geology of area; west of the Nadap–Lovasberény fault only subvolcanic dikes and stocks intruding the old granite crop out and east of it there is a stratovolcanic sequence with lava flows and pyroclastics. According to fluid inclusion data, the synvolcanic faulting resulted in about 500 to 700 meters uplift of areas west of the fault relative to the volcanic sequence east of it.

The youngest structural elements of the Velence Mts. are characterized by NNW–SSE orientation and are related to tectonism of Neogene age (Gerner, 1992).

METHODS OF STUDIES

For evaluation of the temporal evolution of the development of fracture systems in the Variscan granite intrusion, the area of the Gécsi Hill in the eastern part of the Velence Mts. was selected (Fig. 1 and Fig. 2). In that relatively small area, several andesite dikes and stocks intrude the old granite and there are occurrences of various mineralization (pegmatite, quartz-molybdenite stockwork, argillic alteration zones) in the granite body proving that this zone was affected by intense fluid percolation events. Selection of this area for detailed study was also supported by the occurrence of numerous outcrops, road cuts, several small and a large quarry which offered enough exposures for detailed field observations.

Field observations were carried out on vertical and sub-vertical walls of quarries and road cuts. Along the selected sections, horizontal base-lines were set up on the rock surfaces and orientation (dip angle – dip direction) of every structural element (including minor fractures) that cut the base line was measured by Freiberg-type compass. More than 800 field data were collected on joints, faults, fault surfaces and mineralised veins. Oriented samples of granite and pegmatite were collected along the sections.

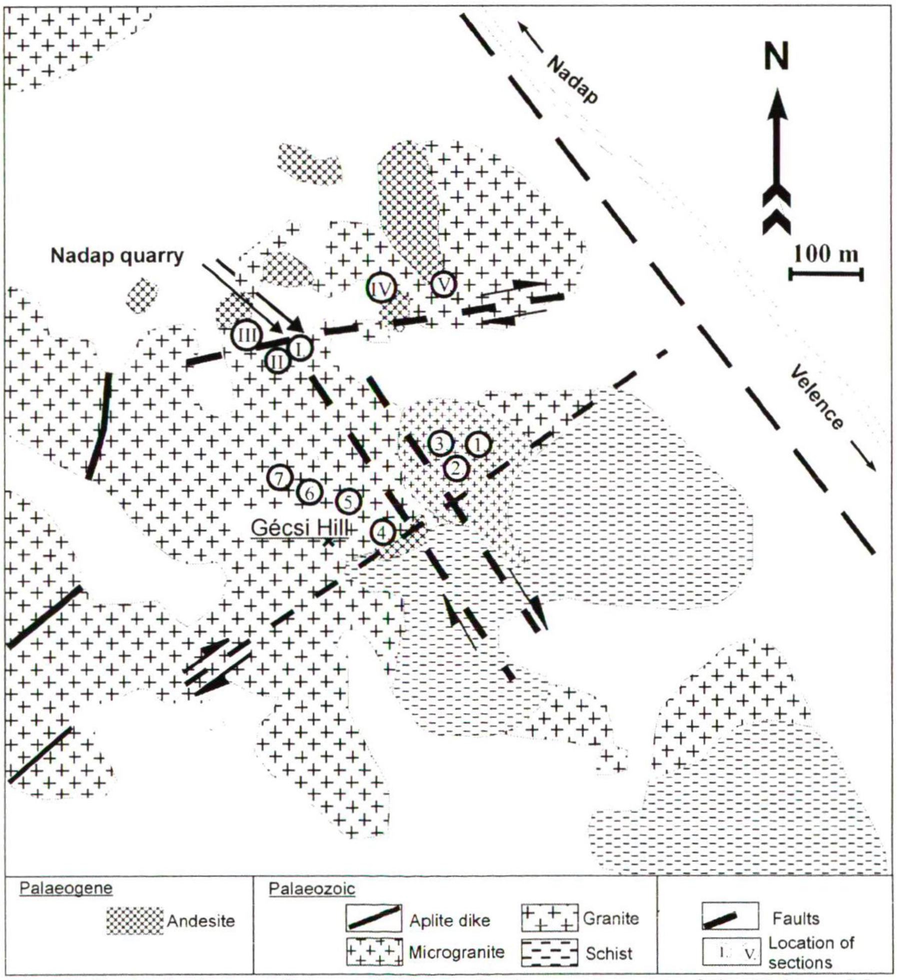


Fig. 2. Geological map of the studied area in the eastern part of the Velence Mts. with the location of sections for field surveying and major Neogene faults.

Fluid inclusions from rock forming quartz were studied in oriented double polished thin sections (100–150 μm thickness). Phase assemblages of fluid inclusions and their associations were studied in polarizing microscope and dip-direction – dip-angle data for fluid inclusion planes were measured on a Universal stage. The sections used for this purpose were horizontal sections, thus planes with dip angle higher than 55–60° were measured. These vertical-subvertical dips are characteristic to about 90% of fluid inclusions in quartz from the area of study. Microthermometric analyses of fluid inclusions were carried out using a Chaixmeca MTM 90 type apparatus standardized for ±0.1 °C reproducibility below 0 °C and ±1.0 °C reproducibility at high temperatures. Fluid inclusion data processing was carried out by using the FLINCOR computer program (Brown, 1989).

RESULTS

Field data

Field observations were carried out in 7 sections (6 in granite and 1 in andesite) of small quarries and road cuts on the Gécsi Hill and in 4 sections (3 in granite and 1 in andesite) in the Nadap quarry (Fig. 3 and Fig. 4).

In all of the studied sections of granite, the vertical-subvertical open fractures (dip angle is more than 70° in about 90 percent of them) form conjugate sets with NW–SE and NE–SW strike directions. In the 1st section of the Gécsi Hill (Fig. 3), the two strike-directions are equally developed in the granite. Occurrence of a few small scale thrust faults forming pairs of Mohr planes in this quarry also reveals a NW–SE oriented compression event. A less common set of fractures with NNE-SSW and ENE-WSW strike directions is also present in the granite. The 2nd section of the Gécsi Hill is in a pegmatite pocket. Here the NE–SW striking branch of the conjugate joint set is prevailing and the strike-direction of quartz veinlets that cut the pegmatite body is parallel with that branch. The pegmatite body is sheared (direction of movement could not be determined) and the orientation of shear plane is

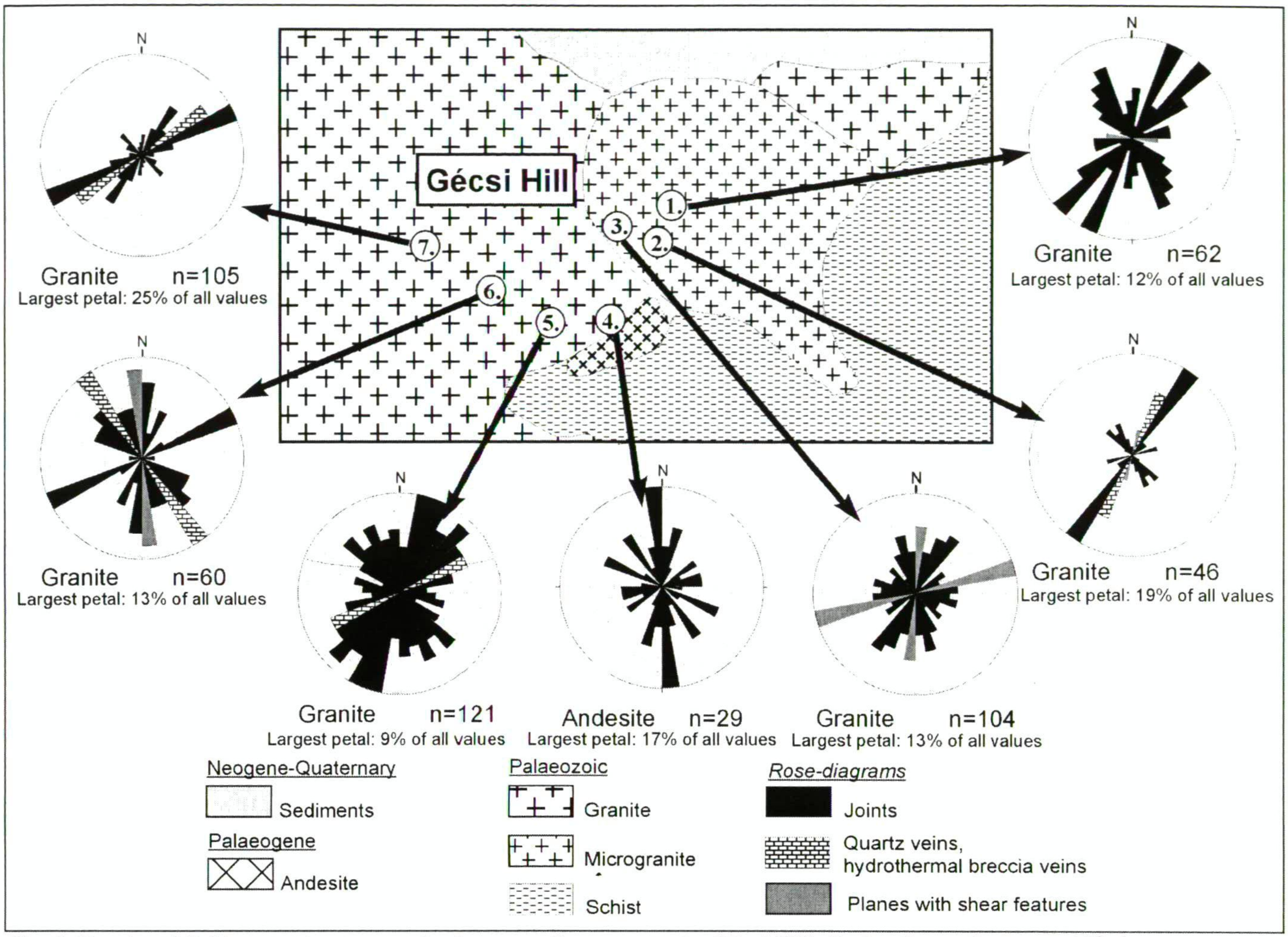


Fig. 3. Results of field surveying summarised on rose diagrams on the Gécsi Hill. Scale of rose diagrams: 10° classes.

parallel with the prevailing NE-SW strike of fractures and veins. In the 3rd section of granite on the Gécsi Hill, the conjugate set of joints is superimposed by NNE–SSW and ENE–WSW striking shear planes. In the 5th section of granite, occurrence of a subhorizontal fracture system was also observed in addition to the conjugate joints. It is assumed that development of those fractures can be connected to the cooling of intrusion or to fracture development due to decrease of lithostatic load during uplift. This section also contains a NE–SW striking siliceous hydrothermal breccia vein. In the 6th section of granite on the Gécsi Hill, the orientation of quartz veinlets is parallel with the NW–SE striking branch of the conjugate joint system, whereas in the 7th section the orientation and prevailing direction of quartz-filled and limonitic veins, as well as open fractures is rather similar to those in the pegmatite of the 2nd section. The 7th section also contains several small-scale normal faults which are younger than veins and conjugate fractures. The 4th section on the Gécsi Hill is in an andesite dike, thus there the age of the structural elements is Palaeogene or younger. The conjugate fracture system that is characteristic to granite is absent, and fractures with highly variable orientation developed in almost equal abundance, though N–S orientation is slightly more common. The fracture pattern is probably highly influenced by those fractures which were originated due to cooling contraction of the andesite dike.

The Nadap quarry (Fig. 4) exposes hidrothermally altered (along the southern and western walls) and weathered (along the northern walls) granite and remnants of an andesite stock that has almost completely been exploited to the bottom of the quarry. The most characteristic feature of hydrothermal alteration in granite is the presence of an argillic (illite) zone along an ENE–WSW striking dextral fault which offsets a parallel set of vertical-subvertical quartz-sulphide veinlets having almost the same orientation (No. I, II and III sections on Fig. 4). Another set of quartz veinlets and the associated silicification have NW–SE strike (No. IV section, Fig. 4), and this zone overprints the argillic alteration zone. Joints in the granite are characterised by the usual NW–SE, NE–SW, N–S and E–W strike-direction. In andesite (No. V section, Fig. 4), open fractures have predominantly NW–SE orientation. Quartz veinlets in andesite have similar orientations to veinlets in granite.

Fluid inclusion petrography and microthermometry

Fluid inclusion studies were carried out on secondary fluid inclusion planes in quartz of pegmatite and in rock forming quartz of granite from the Nadap quarry. For reference, primary and secondary fluid inclusions in hydrothermal quartz of geodes with quartz-fluorite-zeolite pagagenesis from the Palaeogene andesite stock of the Nadap quarry was also studied. Quartz from various occurrences contains the following types of inclusion associations along

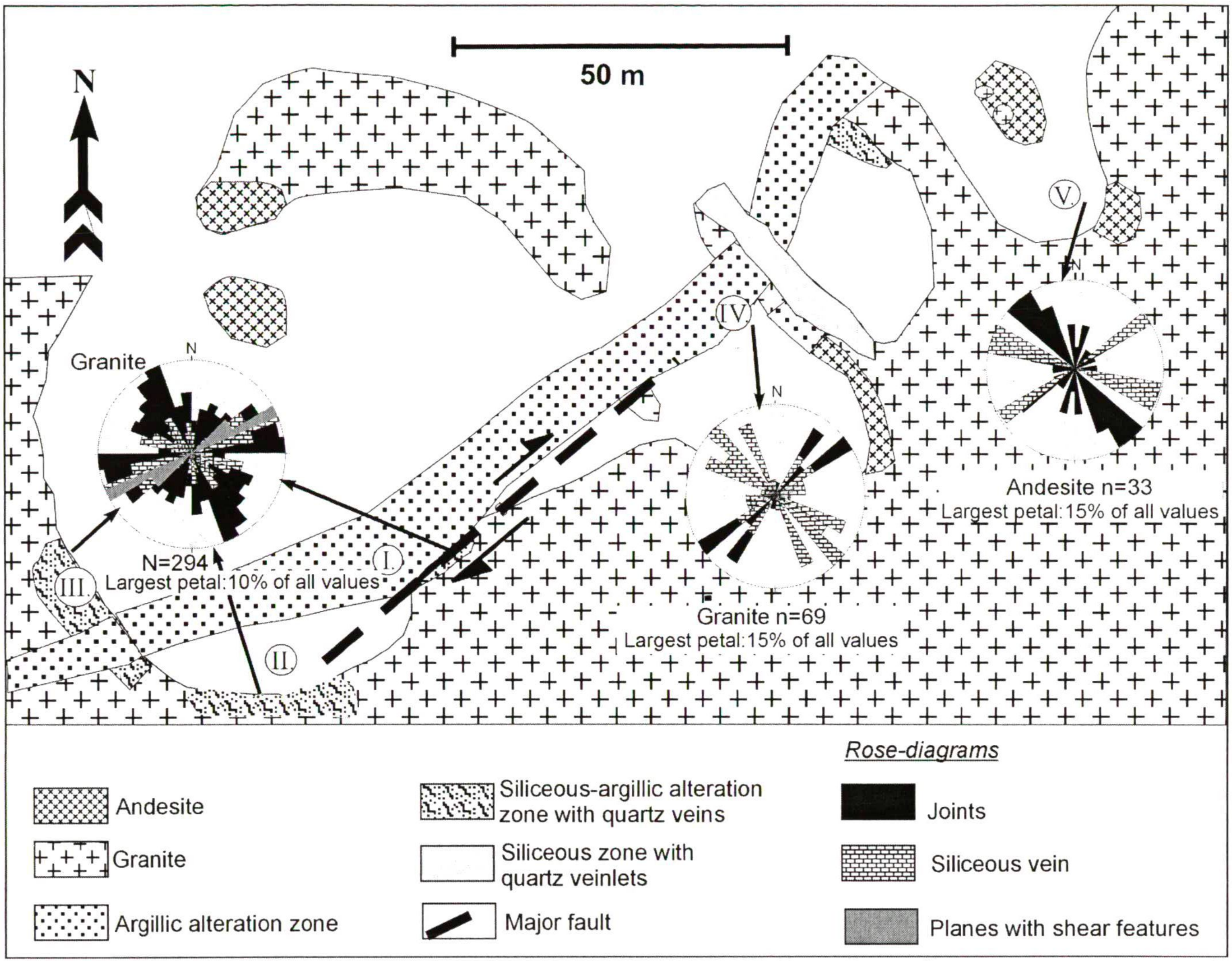


Fig. 4. Plan view of the Nadap quarry with results of field surveying. Scale of rose diagrams: 10° classes.

fluid inclusion planes according to their phase compositions at room temperature:

Type I: Association of vapour-rich aqueous inclusions (<10 vol.% liquid phase or apparently without liquid phase) with liquid-rich aqueous inclusions (20–30 vol.% vapour phase in pegmatite and about 30–40 vol.% vapour phase in granite). Liquid-rich inclusions from this association homogenized between 240 and 270 °C into liquid phase and their salinities calculated from ice-melting temperatures are between 4.4 and 10.5 NaCl equiv. wt.% in quartz from pegmatite (Fig. 5A). In granite, homogenization of liquid-rich inclusions into liquid phase and vapour-rich inclusions into vapour phase took place between 390 and 450 °C and salinities for liquid-rich inclusions are between 1.6 and 7.7 NaCl equiv. wt.% (Fig. 5B). In quartz from geodes of andesite, one group of liquid-rich inclusions of Type I association homogenized at around 300–320 °C and their salinities are lower than 3 NaCl equiv. wt% (Fig. 5B). An other group of liquid-rich inclusions homogenized at around 240–280 °C and their salinities are rather high (around 25 NaCl+$CaCl_2$ equiv. wt.%), approaching almost halite saturation. The occurrence of liquid-rich and vapour-rich fluid inclusions along same fractures and their similar homogenization temperatures into different phases suggest that they were trapped during a fracturation event that was accompanied by boiling of fluids. Pressure of boiling calculated from microthermometric data are between 30 and 45 bars for pegmatite and between 250 and 400 bars for granite. Comparing these data with results of previous fluid inclusion studies on mineralization of the Variscan granite and mineralization of Palaeogene andesite (Molnár, 2003) it is evident that fractures capturing those boiling fluids were formed in conjunction with the Palaeogene volcanism, but in two different stages of hydrothermal activites.

Type II: Association of halite-bearing aqueous fluid inclusions (around 20 vol.% vapour phase and around 5–10 vol.% halite) with vapour-rich aqueous fluid inclusions (less than 10 vol.% liquid phase) occur along fractures of quartz from granite. Dissolution of halite occurred between 80 and 200 °C and total homogenization into liquid took place between 230 and 270 °C in the halite bearing inclusions. Halite melting temperatures correspond to 27.7–32.0 NaCl equiv. wt.%. In one vapour-rich inclusion homogenization into vapour phase was observed at 232 °C. The association of fluid inclusions with different phase compositions and their homogenization behaviour confirm their entrapment during boling. Using a calculation method from Bodnar and Vityk (1994), pressure of boiling is between 20 and 40 bars; thus fractures hosting type II inclusion association were also formed during the Palaeogene hydrothermal activity.

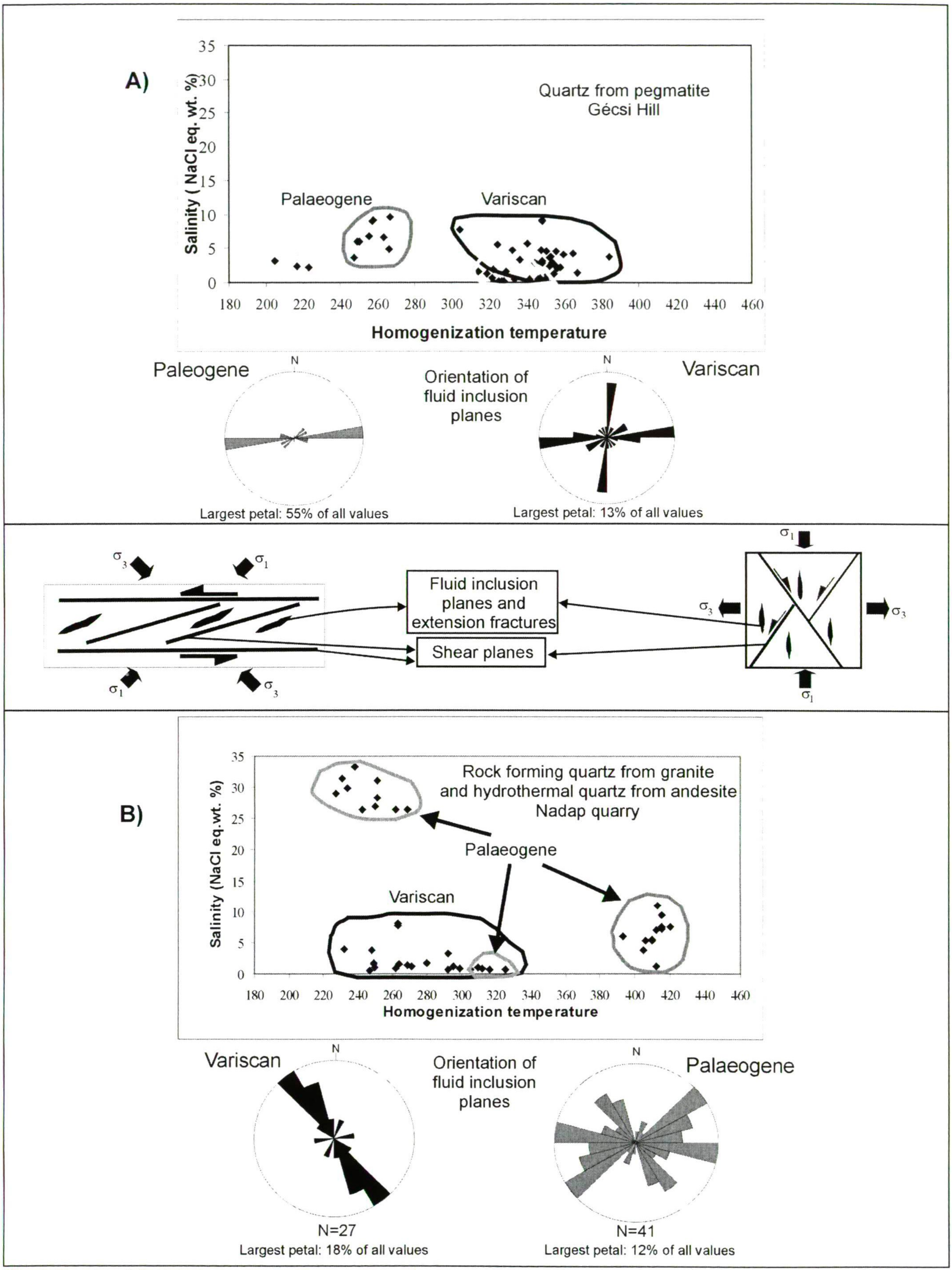


Fig. 5. Results of fluid inclusion microthermometry and measurements on the orientation of fluid inclusion planes. ***(A)*** – Gécsi Hill pegmatite. ***(B)*** – Nadap quarry, ganite. Scale of rose diagrams: 10° classes.

Type III: Association of carbonic-aqueous fluid inclusions with variable aqueous liquid/carbonic gas phase ratios were found in quartz from granite. These inclusions did not achieve total homogenization before decrepitation upon heating. Their carbonic phase melted between –56.6 and –57.4 °C suggesting that they may contain small amount of CH_4, H_2S and N_2 in addition to CO_2 (Burruss, 1981). Clathrate melting temperatures are between 7.5 and 9.4 °C corresponding to 1.4–4.8 NaCl equiv. wt.% salinity of the aqueous phase. Homogenization of carbonic liquid phase took place into gas between 24.4 and 30 °C. Decrepitation of these inclusions during heating reveals that these inclusions were trapped under high-pressure conditions. Carbonic-aqueous fluid inclusions with similar microthermometric behaviour were found in the granite-related quartz molybdenite mineralization in the area of the Velence Mts. (Molnár, 1997; Molnár, 2003) and their estimated pressure of entrapment is higher than 1 kbar. Therefore fractures of rock-forming quartz hosting carbonic-aqueous fluid inclusion associations are related to the Variscan structural evolution of the studied area.

Type IV: Aqueous fluid inclusions containing about 20–30 vol.% vapour phase with no carbonic-aqueous or vapour-phase rich inclusions along the same fracture. These inclusions homogenized into liquid between 320 and 370 °C in pegmatite and between 240 and 300 °C in granite. Their salinities are between 0.7 and 8.8 NaCl equiv. wt.% (Fig. 5A, B). These results are very similar to data for inclusions related to pegmatite formation and data of secondary aqueous fluid inclusions in the quartz-molybdenite stockwork mineralization (Molnár, 2003). On the other hand, data for the low temperature inclusion association from granite are rather similar to those for some of liquid-rich inclusions trapped in the boiling Palaeogene hydrothermal system. However, petrographic evidence of boiling was not found in fractures with Type IV inclusions and therefore it is assumed that they were trapped during the Variscan, high-pressure hydrothermal circulation.

Orientations of fluid inclusion planes and their comparison to field observations

In quartz from pegmatite (Fig. 3, section No. 2), planes of Type IV fluid inclusions related to the Variscan fluid circulation have almost E–W and N–S orientation, whereas planes containing Type I fluid inclusion associations that were trapped during boiling of fluids of Palaeogene age have almost E–W orientations (Fig. 5A and Fig. 6). These data suggest that the predominantly NE–SW and subordinately NW–SE oriented fractures and veins in the outcrop are probably Variscan shear planes related to N–S oriented major stress indicated by the orientation of fluid inclusion planes. This is in agreement with that field observation that pegmatite is sheared along a NE–SW oriented fault. Because orientation of fluid inclusion planes of Palaeogene age is parallel with one group of Variscan fluid inclusion planes it is expected that several old fractures were re-activated during the Palaeogene fluid circulation. Extensional macro fractures that may also be related to N–S and E–W oriented major stresses are present only in a subordinate amount (e.g. No. 1 section, Fig. 3).

Fluid inclusion planes of Variscan age (Type III and Type IV associations) in rock forming quartz of the Nadap quarry have almost exclusively NW–SE orientation (Fig. 5B and Fig. 6). This orientation is the same as one branch of the conjugate fracture system of granite both on the Gécsi Hill (Fig. 3) and in the Nadap quarry (Fig. 4). Many quartz veins in the studied area also have this orientation. Thus it can be concluded that many of the NW–SE oriented fractures are simple extensional ones and some of them were sealed by quartz during their propagation. These fractures started to develop during the Variscan fluid percolation, however, one branch of fluid inclusion planes of Palaeogene age from the Nadap quarry also have the same orientation (Fig. 5 B) and majority of fractures in the outcrop of the andesite in this quarry (No. V section, Fig. 4) also follow this orientation. The high temperature (390–450 °C) Type I fluid inclusions are characteristic to fluid inclusion planes with this orientation. Thus NW–SE oriented major stress occurred both in Variscan and Palaeogene time and related extension fractures are present both in granite and andesite. It is

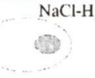
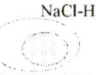
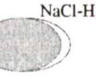
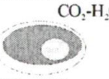
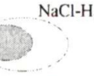
Type of inclusion	Homogenization temperature(Th)	Melting temperature (To)	Salinity NaCl ekw. Wt.%	Type of planes	Age	Direction
$NaCl-H_2O$  L=70%, G=30%	~350°C	~-1°C	~5	Secondary	Variscan	N-S, E-W
$NaCl-H_2O$  L=50% V=50%	~250°C	~-4°C	~7	Secondary	Palaeogene	E-W
$NaCl-H_2O$  L=10% V=90%	~250°C	~-4°C	~7	Secondary	Palaeogene	E-W
CO_2-H_2O  LCO_2=40% VCO_2=30%	Tocl.=~-8°C $ThCO_2$= ~25°C	$TmCO_2$= -56.8°C	~4	Secondary	Variscan	E-W
$NaCl-H_2O$  L=30% V=70%	~250°C	~-1°C	~5	Secondary	Palaeogene	NW-SE
$NaCl+CaCl_2+H_2O$  L=20% V=80%	~250°C	T_mNaCl= 88-202°C	~28	Secondary	Palaeogene	E-W, NW-SE
$NaCl-H_2O$  L=30% V=70%	~420°C	~-2°C	~4	Secondary	Palaeogene	E-W, NW-SE

Fig. 6. Summary of characteristics of fluid inclusion planes.

interesting that open fractures with this orientation are not mineralized in andesite, though fluid inclusion planes indicate that fluid percolation may have occurred along them. However, existence of a channel for fluid migration does not necessarily mean that fluids should mineralize them because mineral precipitation depends on various parameters which did not necessarily exist during fluid percolation at a specific part of the system. The NW–SE orientation of fluid inclusion planes of Palaeogene age and open fractures of andesite is parallel with the Nadap-Lovasberény fault which was active during the Tertiary volcanism. Similar orientation of Variscan fluid inclusion planes suggest that this fault zone may be an old structure which has been re-activated during the Palaeogen tectonic and magmatic events.

Fluid inclusion planes of Palaeogene age also have NE–SW and almost E–W orientations in the rock forming quartz of granite in the Nadap quarry. These fluid inclusion planes contain Type I low-temperature and Type II fluid inclusion associations. Their orientations are also characteristic to quartz veins in andesite, too, which thus were formed in extensional fractures. Quartz from mineralized geodes of andesite also have Type I low temperature and Type II high salinity fluid inclusions which confirms mineralizing capacity of fluids during the formation of fractures that were filled up by quartz. Quartz-filled fractures with mostly NE–SW orientation in granite also occur. However, it cannot be determined whether they are extension fractures related to Palaeogene tectonism or wether they are shear-fractures that were filled up with quartz during the Variscan hydrothermal circulation.

Comparison of orientation data for fluid inclusion planes of various ages reveals that there are only two orientations that are characteristic to a specific stage of fluid percolation: this is the NE–SW oriented branch of fluid inclusion planes of Palaeogene age and N-S oriented branch of fluid inclusion planes of Variscan age (Fig. 5A, B). As N–S oriented joints are atypical in granite, it is reasonable to conclude that the majority of fractures of Variscan age with NW–SE and NE–SW strike-direction probably represents shear fractures. This is in agreement with earlier data suggesting that fracture development at the time of the emplacement of granite was controlled by NNE–SSW oriented major stress (Fülöp, 1990). The NE–SW and E–W oriented fluid inclusion planes contain similar fluids both in rock forming quartz of granite and pegmatite and these planes trapped fluids from low-pressure boiling hydrothermal system. Characteristics of this low-pressure system are similar to the epithermal hydrothermal system affecting the volcanic rocks east of the Nadap–Lovasberény fault. On the other hand, trapping conditions of the NW–SE oriented Palaeogene fluid inclusion planes correspond to circulation of boiling fluids at subvolcanic level. These observations suggest that during the Palaeogene volcanism the orientation of stress field was variable and intense tectonism was associated with the poly-stage hydrothermal evolution. This is in agreement with the conclusions regarding the syn-volcanic nature of the Nadap–Lovasberény fault. The high variation in the Palaeogene stress field can be correlated with the original position of the Palaeogene volcanic unit in the Alpine collision zone along the E–W trending syncollisional dextral Periadriatic Lineament (Csontos et al., 1992; Fodor et al., 1999). However, the recent orientation of fluid inclusion planes of Palaeogene age cannot be directly related to the major stress orientations at the time and place of their entrapment due to the up to 60° conterclockwise rotation of the Palaeogene units during and after their escape from the Alpine collision zone (Márton, 1997).

CONCLUSIONS

This paper is the first attempt for using orientation data of fluid inclusion planes for modelling of temporal evolution of fracturation in a garnitoid intrusion in Hungary. Comparison of data of field observations on faults and joints with orientation of fluid inclusion planes and P-T-x properties of fluid inclusions from the eastern part of the Velence Mts. revealed that fracture development in the Variscan granite was also highly affected by the tectonism associated with the Alpine (Palaeogene) andesitic-dioritic igneous activity. At the time of circulation of the Variscan granite-related post-magmatic fluids under high pressure, fracture development was controlled by N–S, E–W and NW–SE oriented stress. Development of fractures of Palaeogene age took place under NW–SE, E–W and NE–SW oriented stress field. The N–S orientation of fluid inclusion planes is characteristic only for the Variscan system and the NE–SW orientation only for the Palaeogene system. Occurrences of similar orientations of fluid inclusion planes indicate that most of Variscan fractures were re-activated during the Palaeogene events. However, fractures corresponding to shear planes in the Variscan post-magmatic system may have reopened as extensional fractures in Palaeogene. Many of re-opened fractures were sealed by quartz precipitation, because quartz veinlets with similar orientation occur both in granite and andesite.

During the Palaeogene igneous activity both epithermal and subvolcanic type hydrothermal fluids penetrated the Variscan granite indicating vertical faulting and contemporaneous fast erosion. Field evidences, data for Variscan and Palaeogene hydrothermal systems and the new observations on fluid inclusion planes indicate that the re-activation of the NW–SE oriented Nadap–Lovasberény fault was responsible for the important vertical movements during the Palaeogene magmatic-hydrothermal events.

The area of study is also characterized by the occurrence of NE–SW oriented dextral faults. Observations on fluid inclusion planes and argillic alteration along some of them may indicate that these faults can be connected to the E–W oriented stage of the Palaeogene stress and they may have became extensional fractures at a later stage of hydrothermal activity or vice versa. These strike-slip faults may also have been re-activated during the Upper Oligocene–Lower Miocene dextral movement along the similarly oriented Balaton Fault.

ACKNOWLEDGEMENTS

This work was supported by the HNSF (OTKA) No. T 035095 grant to F. Molnár. The authors owe special thanks to Prof. M. Lespinasse (Henry Poincaré U., Nancy) for inspirative discussions both in the field and laboratory and for the revision of the manuscript.

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