PRELIMINARY RESULTS FROM THE TASLADJA BAIR'S DYKE'S STUDY, AN INDICATOR FOR THE STRUCTURAL EVOLUTION OF THE PROHOROVO COPPER PORPHYRY SYSTEM IN SOUTHEASTERN BULGARIA

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ABSTRACT. The Prohorovo pluton is intruded in a complex geological environment in the south-eastern part of the Sveti Ilija ridge, municipality of Nova Zagora, Sliven district. This magmatic body is of interest, because it is related to a copper–molybdenum, vein-porphyry mineralisation. The pluton occupies a hypabyssal intrusion level, as the intrusion of the main magmatic body, as well as the smaller sub-intrusions are controlled by two fault systems striking to northeast and northwest. During the eighties and nineties of the last century, there were efforts to study the faults in the vicinity of the pluton and an agreement was reached, that they determine the geometry of the hydrothermal system. However, there are still unsolved issues regarding the degree to which the faults control the intrusion of the igneous bodies, screen the hydrothermal fluids or create fractured environment favourable for mineral deposition. So far, it is not clear if the ore hosting fractures are product of the faults or of the sub-intrusive process itself, which can also lead to fracturing of the host rocks. Several NE striking dykes have been recently exposed in a dolomitic quarry, in the locality of Tasladja bair, which is adjacent to the Prohorovo pluton. The dykes were hydrothermally altered and hydraulically brecciated. A fault slip analysis reveals that the faults, the pluton and the dykes were created by the same stress field. It confirms the assumption that the dykes are synchronous to the metal bearing hydrothermal mineralisation and offer an opportunity to model the intrusion of the pluton in a straightforward manner using the geometry of the faults, which controlled it.

Keywords: dyke swarm, copper porphyry hydrothermal system, faults, fractures, fault-slip analysis, principal stresses

ПРЕДВАРИТЕЛНИ РЕЗУЛТАТИ ОТ АНАЛИЗА НА ДАЙКИТЕ ОТ ТАСЛАДЖА БАИР, ИНДИКАТОР ЗА СТРУКТУРНАТА ЕВОЛЮЦИЯ НА ПРОХОРОВСКАТА МЕДНО-ПОРФИРНА ХИДРОТЕРМАЛНА СИСТЕМА В ЮГОИЗТОЧНА БЪЛГАРИЯ)

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РЕЗЮМЕ. Прохоровският плутон е внедрен в сложна геоложка обстановка в югоизточната част на Светиилийските височини, община Нова Загора, област Сливен. Магматичното тяло представлява интерес, защото с него е свързана медно-молибденова минерализация от прожилково порфирен тип. Плутонът е внедрен на хипоабисално ниво, като както внедряванено на плутона, така и многообройните по-малки субинтрузивни тела са контролирани от две разломни системи с посока североизток и югоизток. През осемдесетте и деветдесетте години на миналия век са положени усилия за изучаване на разломите в околностите на плутона, като е постигнато съгласие, че те определят геометрията на хидротермалната система. Съществуват обаче недоизяснени въпроси за това, до каква степен тези разломи контролират внедряването на интрузиите, екранират флуидните системи или създават подходяща за рудовместване среда. Не е изяснен въпросът до каква степен напукването, което вмества рудната система, е продукт на тези разломи, и до каква степен играе роля спецификата на субинтрузивния процес, който също води до напукване и създаване на благоприятна за рудоотлагане среда. Няколко дайки с посока североизток са разкрити неотдавна в доломитната кариера, разположена в местността Тасладжа баир, в съседство с рудоносния Прохоровски плутон. Дайките са хидротермално променени и хидравлично брекчирани. Анализ на напреженията чрез разломни стриации разкрива, че разломите, плутонът и дайките са формирани при действието на едно и също поле на напреженията. Това потвърждава идеята, че дайките са синхронни на рудната минерализация и дава възможност да се моделира еднозначно внедряването на плутона, като се използва геометрията на разломите, които са го контролирали.

Ключови думи: дайков сноп, медно порфирна хидротермална система, разломи, пукнатини, анализ на разломни придвижвания, главни напражения

Introduction

The copper-molybdenum porphyry deposit Prohorovo is located in the middle part of the Saint Ilija heights in Southeast Bulgaria. It was prospected in several stages, starting from 1931 and continuing to present day, each one of them bringing new details and emphasising the significance of the structural control on this mineralisation.

The deposit is located at the roof of a small quartz-diorite pluton with the shape of the letter "L" as one arm of the intrusion is striking to northwest and the other is striking to northeast (Fig. 1). Both directions coincide with the dominant fault structures of the region. The regional structure, on which the faults were superimposed, is the Sveti Ilija monoclyne, which was originally mapped by Nedialkov (1964) as the ages of the rock formations were scrutinised by Čatalov (1963; 1965; 1985; 1990) and the overall structural environment by Varhotov et al. (1983) and Tsankov (1983).

The works of Bogdanov (Bogdanov, Bogdanova, 1984; Bogdanov, 1987) provide the understanding of the hydrothermal alteration processes around the Prohorovo pluton, which Ignatovski (1989) summarised into a simple zonation model comprising: 1 – K-feldspar alteration in the internal part, mainly in the intrusion itself; 2 – quarts-white micas-pyrite-lepidolite alteration in the endo-contact and the immediate contact area; 3 – quartz-kaolinite-chlorite alteration in the immediate vicinity, and in the exo-contact; 4 – propylitic alteration at large, around the intrusion, being the most external zone of hydrothermal affects. The structure of the deposit itself and its vicinity was studied by Ignatovski who published several works, of which most detailed is Ignatovski (1986).

It is important to note that this pluton was not injected into very reactive host rocks. Although some skarns exist, formed in the Triassic carbonates, the dominant lithology of the host rocks of the intrusion is that of a silica rich Paleozoic volcanic lava and pyroclastic flows and Paleozoic clastic deposits, mainly conglomerates with minor sand and breccia, which are also very silica rich and non-reactive in geochemical sense.

In spite of this, significant amount of metals was accumulated, which according to Ignatovski (1980) and Chobanova (1981) was controlled by the intense fracturing of the host rocks and the intrusion. They studied the small scale fractures that formed the ore bearing veinlets and revealed their systematic nature (Ignatovski, 1980) and at the same time their indirect relationship to the main faults.

This prompted Ignatovski (1986) to emphasise on the hydraulic faulting as a very important process in this deposit, however he did not manage to clarify the mechanical nature of this process, partly because the hydraulic faulting and brecciation were not well understood in Bulgaria at that time.

This paper contains preliminary results of a study of a dyke swarm in the vicinity of the Prohorovo pluton, which was recently exposed in a dolomitic quarry. This swarm can be judged to pass through the pluton, or at least through its vicinity, and obviously expose structural features that can be spread over the roof of the intrusion. In this sense, the study will contribute with data about the evolution of the deposit itself.

The preliminary nature of the study follows from the fact that not all field data are processed to this point and they are not assembled in a unified model, so it is mainly reporting interesting features that will be examined in depth at future.

Geological setting

The middle part of the Sveti Ilija heights, where the Prohorovo pluton was intruded, comprises Upper Cretaceous, Jurassic, Triassic and upper Paleozoic volcanic and sedimentary rocks (Fig. 1). All rocks older than the Triassic were metamorphosed in lower greenschist facies. Abundant veins of milky quartz called “quartz segregation veins” by Čatalov (1990) injected the rocks during this metamorphic event.

According to Kamenov et al. (2000) the Prohorovo pluton was intruded about 90 Ma BP.

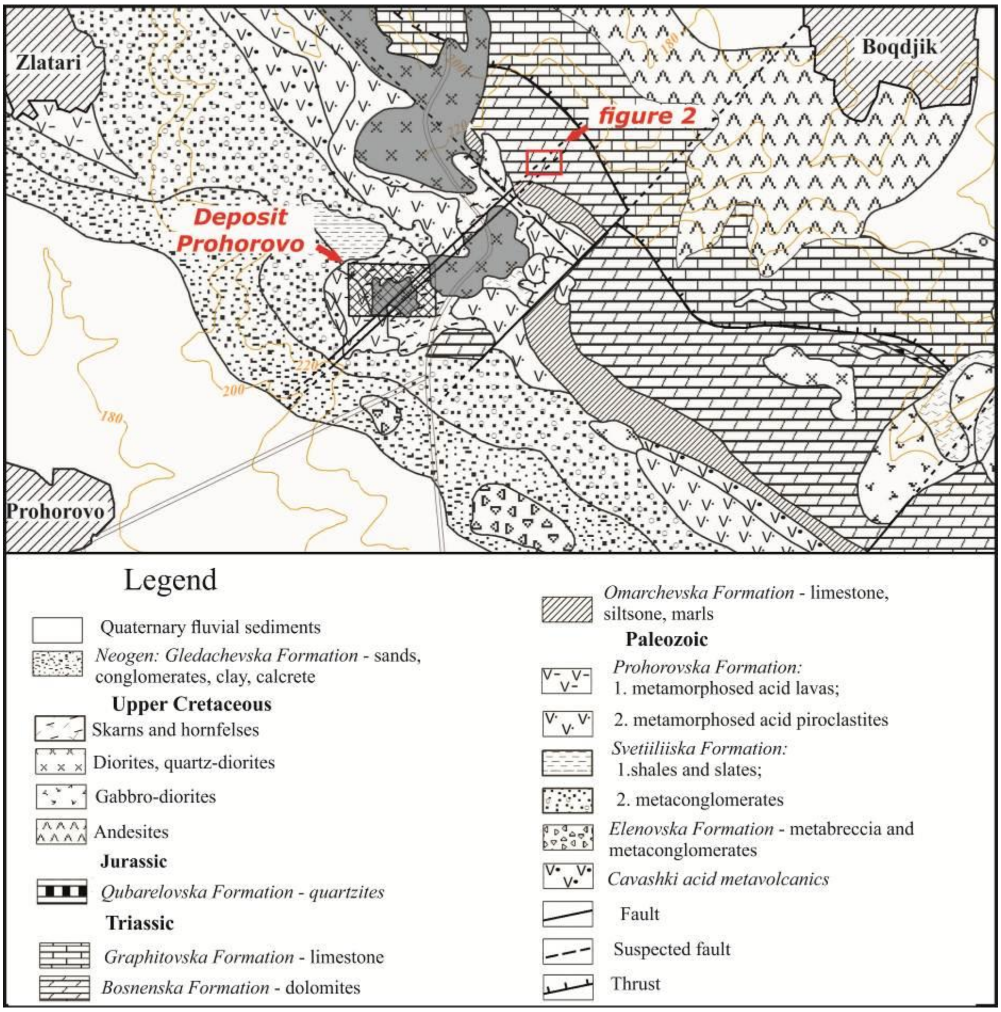

Fig. 1. Geological map of the Prohorovo area of the Sveti Ilija heights (modified after Čatalov, 1985)

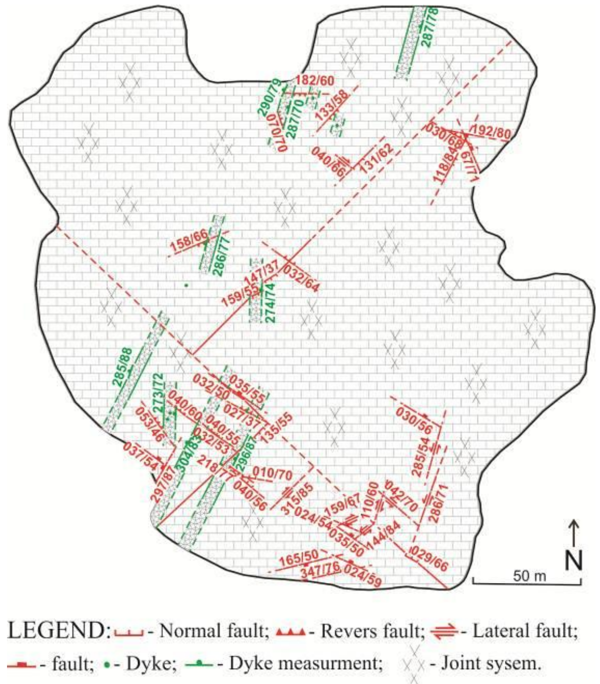

Fig. 2. Exposed area of the Tasladja Bair's quarry with indicated position of dyke segments and larger faults

The main structure of the heights is a monoclinal antiform (a step-like fold) younging to NE, with hinge striking NW-SE. Parallel to the hinge is the Saint Ilija fault, striking to NW and parallel to the bedding, which was partly utilised by the Prohorovo diorite intrusion. Another set of faults, striking to NE, crosscuts the monocline. Some of the faults proven beforehand that cut the intrusion are shown in Figure 1. Not far from the intersection of the two fault sets, a quarry was developed in the dolomitic marbles (Fig. 2). The quarry provided the field material for this paper.

Petrological features of the dykes

The dykes from the Tasladja Bair were sampled and studied in laboratory conditions by examination in thin sections and by chemical assay. For the thin section examination a polarising microscope NIKON Eclipse LV100ND was used and the assay was made in the geochemical laboratory of UMG Sofia using s spectrometer ICP-OES-720 of Agilent Technologies.

The rocks that contain the dykes are layered, fine-grained dolomites (Fig. 3a) with minor alteration. They were stained with iron hydroxides along fractures and were reworked into breccia. In the brecciated zones calcite veins and voids filled with spar crystals are quite common. The carbonates are pure with only a minor amount of fine quartz up to 0.15 mm in size. Fine veinlets of calcite about 0.04 to 0.2 mm thick are the only inhomogeneity visible under microscope.

The dykes of diorite- porphyry injected into the dolomites are 1.5–3 m thick. They are displaced by faults, so only short segments from each one can be observed (Fig. 2). All of the observed dykes have been brecciated and the brecciation is more intense near the contacts. The diorite-porphyry is green, light green or yellow, thin-grained with rare phenocrysts of plagioclase and altered mafic minerals. The texture is massive and the magmatic structure is porphyritic. They comprise primary magmatic plagioclases, amphiboles, biotite, apatite, magnetite and secondary chlorite, carbonate, epidote, zoisite, albite and quartz. The phenocrysts (porphyries) are of plagioclase and amphiboles. The plagioclases are prismatic or plate-like and are replaced by thin-grained carbonate and small amount of chlorite as the peripheral parts of the crystals are relatively fresh (Fig. 3b). Some of them were replaced by thin flakes of white mica and chlorite. They might contain inclusions of apatite and reach a size of up to 0.9 x 1.7 mm, but it is usually around 0.5 x 1 mm.

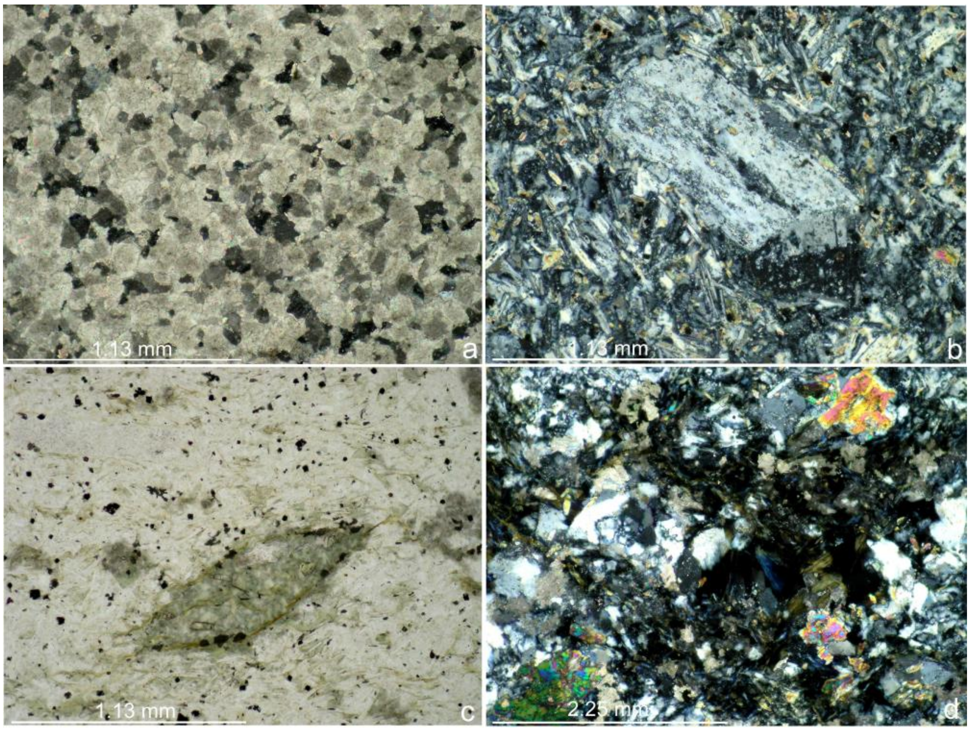

Fig. 3. Micro-photographs of rock varieties from dykes observes in the Tasladja Bair's quarry

a, thin-grained, equigranular dolomite, crossed polarisers; *b*, porphyritic plagioclase, partially replaced by chlorite, crossed polarisers; *c*, fully altered mafic mineral, parallel polarisers; *d*, aggregate of epidote, chlorite and quartz, crossed polarisers

The mafic minerals were prismatic, but the nearly complete alteration by chlorite and epidote made their shape unrecognizable. The crystal shapes indicate that the mafic minerals were amphiboles (Fig. 3c). In the more altered parts of the dykes the mafic minerals were completely altered, so they are not recognizable. The main accessory minerals are prismatic to needle-like apatite and magnetite. The matrix of the rock comprises also micro-prismatic minerals. These are mainly plagioclases but also biotite, chlorite, carbonates, albit, xenomorphic quartz, magnetite and apatite.

The fresh plagioclase crystallites are with average size of 0.03x0.15 mm, and show a well discernible parallel flow pattern.

The biotite is presented by small, overgrown by chlorite, flakes. At some places lens-like aggregates of secondary minerals – zoisite, epidote, chlorite and quartz in various amounts mark the position of replaced primary crystals. The secondary minerals are not distributed evenly as in the domains they predominate. Thin veins of quartz up to 0.2 mm thick are also present.

Hydrothermal alterations**.** The dykes were affected by secondary hydrothermal changes expressed in deposition of chlorite, epidote, carbonate, and albite characteristic for a propylitic type alteration (Table 1). The primary rock forming minerals have been partially or completely replaced as the change of the mafic minerals is more pronounced. The alteration is more intensive in the peripheral brecciated zones of the dykes, where the easy access of hydrothermal fluids resulted in thorough conversion to clay minerals.

Table 1. *Description of the hydrothermal alteration of the dykes from the Tasladja Bair*

Sample №	Rock type	Primary minerals	Hydrothermal mineral alteration
Smpl. 4-2	Diorite porp-yry	Plagioclases, mafic minerals (amphibo-les), biotite, apatite, magnetite	Chlorite, carbonate, epidote, zoisite, albite, quartz

Petrochemical peculiarities**.** On the alkaline – silica classification diagram the dykes appear in the field of the granodiorites (Fig. 4). The rocks are oversaturated with silica and with predominance of Na_2O over K_2O, as the ratio K_2O/Na_2O is 0.62. The al' coefficient is 2.66 and the per-alkaline index is 0.56 (Table 2). On the Peccerillo and Taylor (1976) diagram, in coordinates K_2O-SiO_2, the dyke appears in the field of the *calcium – alkaline series* (Fig. 5). It is likely that the SiO_2 was enriched by secondary processes, such as introduction of quartz in the rock mass.

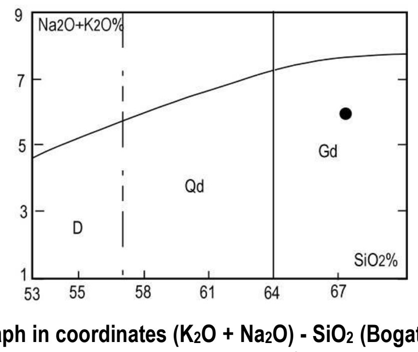

Fig. 4. Graph in coordinates (K_2O + Na_2O) - SiO_2 (Bogatikov et al., 1981) for petrochemical separation of volcanic rocks. The position of the dyke from Tasladja Bair is indicated with a dot

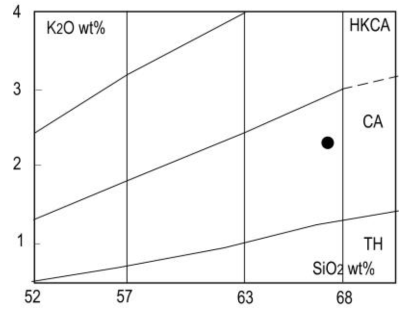

Fig. 5. Graph in coordinates K_2O – SiO_2 (Peccerillo, Taylor, 1976): *TH*, tholeiitic series; *CA*, calcium alkaline series; *HKCA*, high potassium–calcium alkaline

Based on the thin section study, and the petrochemical analysis, it can be concluded that the dykes, that intruded the Triassic dolomites, have modified chemistry, so their protholite was most likely that of diorite porphyry, the same as the main variety of the Prohorovo pluton.

Table 2. *Chemical composition (wt%) of a dyke (Smpl. 4-2) from the Tasladja Bair; K/Na = K_2O/Na_2O; al' = $Al_2O_3/(Fe_2O_3$ + FeO + $MgO)$; Pl=Na_2O + K_2O/Al_2O_3 (mol). UMG, Sofia, analyst D. Dragoeva*

Parameter	value	Parameter	value
SiO_2	67.55	K_2O	2.29
TiO_2	0.44	P_2O_5	0.09
Al_2O_3	15.22	SO_3	0.05
$Fe_2O_3^t$	3.44	LOI	3.43
MnO	0.05	Total	99.92
MgO	2.27	K/Na	0.62
CaO	1.41	al¢	2.66
Na_2O	3.68	Pl	0.56

The name diorite porphyry is adopted following the principles of the International Union of Geological Sciences (IUGS), according to which the fully crystalline igneous rocks are classified based on their modal composition (Le Maitre, 1989).

Structural setting

In the quarry the strike of the beds is varying between 120° and 130° to SE and the dip is 40–60° to NE, so the quarry exposes the geometry of the Saint Ilija monocline.

The dolomites are moderately jointed as the joints were developed in two sets: a NW striking set and a NE striking set (Fig. 6).

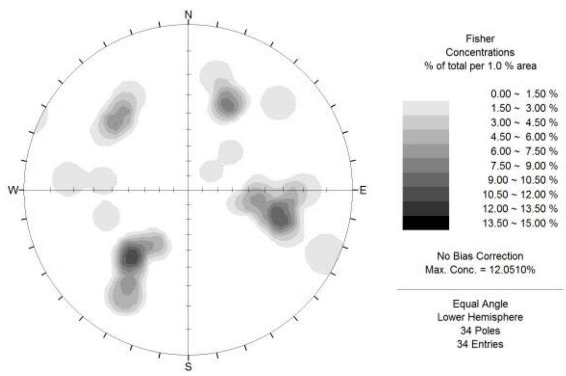

Fig.6. Statistical diagram of 42 joints from the Tasladja Bair's quarry. The statistic is made with the package Geoorient, distributed by Rod Halcomber

In the quarry, faults of two sets are observed: one striking to the NW quadrant and the other striking to the NW quadrant.

The range of the faults cannot be judged straightforward but it appears that some of the NW striking ones are splays of the main Saint Ilija fault, which is of strike-slip kinematics, and most likely control the NW arm of the Prohorovo pluton (Fig. 1). The NE set of faults is also very common in the heights and was also utilised by the intrusion, so even though the measured faults are not the most important structures in the region; they are still representative of the regional kinematics and informative about the evolution of the Prohorovo pluton.

Effects of the hydraulic brecciating

At first glance the rocks of the observed dyke segments appear faulted. One of the possible interpretations is that they were injected along faults, which later were reactivated and the material inside was sheared. This idea can be rejected based on three premises. The first one is that the dikes are usually extensional features with their walls perpendicular to the minimal (σ3) tectonic stress, so shearing is usually not involved but rather pure extension at the time of their formation. The second is the observation of a very serrated dyke walls, that exclude shearing along them, and the third is the texture of the brecciated rock fragments (Fig. 7) inside the dykes, which imply fragment separation without much rotation (rotation is equivalent to shearing) of the fragments relative to one another.

Fig. 7. Hydraulically brecciated dyke, (under the hammer) and serrated dolomitic contact of the dyke on the right side of the pictures

The action of a hot fluid is implied as the culprit for the brecciation. This has the implication that being hot also means that the fluids were pressurised. And it coincides with the observation of hydrothermal alteration of the dykes, which was described earlier. As it was observed on the field all dyke segment shown in Figure 2 were brecciated in various degrees.

Fault slip data analysis

Slicken-lines on a fault plane represent the direction of some relative displacement between the two blocks separated by the fault. Fault data include both the fault plane and slicken-line orientations (Fig. 8), the latter including the relative sense of movement along the line.

The goal is to use these measurements to calculate the so-called paleostress tensor (Almendinger at al., 1989; Marrett, Allmendinger, 1990). Paleostress tensors provide a dynamic interpretation (in terms of stress orientation) to the kinematic (movement) analysis of brittle features. The calculation does not yield a true paleostress tensor since it is a statistic calculation on fractures that integrate a geologically significant amount of time.

The systematic relationship that exists between brittle structures and principal stress directions provides a basis for interpreting paleostress directions. In particular, it is important to separate, in the field, the different compression directions that may correspond to separate paleostress tensors responsible for a successive deformation event.

The principal stresses' directions are distinguished by fault slip analyses, i.e. the eigenvectors of the stress tensor, represented by the three unit vectors, and by the principal stress magnitudes, i.e. the corresponding eigenvalues, taken positive in compression. $\sigma1 \geq \sigma2 \geq \sigma3$.

Fig. 8 Example of marking the fault kinematic axes on a fault surface from Tasladja Bair quarry, using the Aki-Richards format, described in the manual of the FaultKin software (Marrett, Allmendinger, 1990) for rakes of striae on planes

In the course of the present study, fault slip data were collected for 22 faults, which were processed separately based on their directions and all together (Figs 9–11). The results are very straightforward and geologically meaningful. In spite of their orientation, the faults indicate for a maximum compressive stress oriented NE-SW. It is the same even for the NW striking faults. The calculations are made using Linked Bingham approximation with software FultKin distributed free for academic purposes by R. Almendinger as the theory is described by Marrett and Allmendinger (1990).

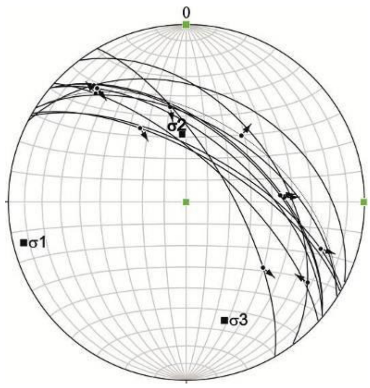

Fig. 9. Principal stress orientations from 10 faults measured in the Tasladja Bair's quarry. The faults are striking in the NW quadrant. The axis of the maximum principal stress is plunging to W-SW. The calculations are made with FaultKin

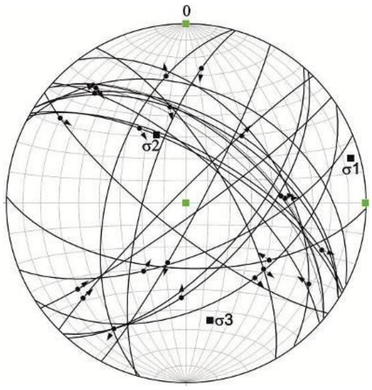

Fig. 10. Principal stress orientations of all 22 faults measured in the Tasladja Bair's quarry. The axis of the maximum principal stress is plunging to E-NE. The calculations are made with FaultKin

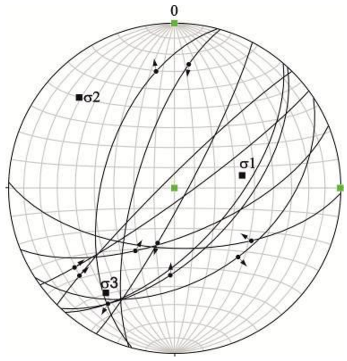

Fig. 11. Principal stress orientations from 10 faults measured in the Tasladja Bair's quarry. The faults are striking in the NE quadrant. The axis of the maximum principal stress is plunging to NE. The calculations are made with FaultKin

Discussion and conclusions

The dykes were of primary dioritic composition but were enriched with silica during the hydrothermal alteration. They are intensely brecciated by a hydraulic process. Inferred from the faults slip data, the principal stress axis acting around the Prohorovo pluton was oriented in SW-NE direction, which is also the direction needed for extensional formation of the dykes (they must be close to parallel with the σ1). So the dykes and the faults are linked. It also suggests that the studied fault orientations have been active from the Late Cretaceous till present. The inferred stress orientation is the only possible one that can create opening of the both arms (the NW and the NE) of the intrusive body, so this stress field is obviously responsible for the creation of the pluton itself.

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