Fabric of porphyritic magmatites inferred from the preferred orientation of feldspar phenocrysts

Vnitřní stavba porfyrických vyvřelin stanovená dle přednostní orientace živcových vyrostlic (Czech summary)

(6 text-figs., 2 photos)

ZDENĚK VENERA - KAREL SCHULMANN - RADEK MELKA - JOSEF JEŽEK

Faculty of Science, Universita Karlova, Albertov 6, 128 43 Prague, Czech Republic

The determination of foliation and lineation in magmatic rocks can be often a difficult problem. Moreover, there are only a few sound kinematic criteria for determination of a shear sense during magmatic flow. Therefore we improved the method of optical goniometry that helps recognise the fabric of porphyritic rocks. This method enables: (1) determination of shape preferred orientation (SPO) of feldspar phenocrysts, (2) more precise definition of magmatic foliations and lineations, and (3) assessment of the kinematics of the combined coaxial and non-coaxial flow using asymmetries in feldspar subfabrics (Fernandez 1987).
The application of the method is demonstrated on samples of the Třebíč durbachites (E of the Bohemian Massif) in which K-feldspar phenocrysts reveal strong magmatic preferred orientations gained during the emplacement. Asymmetry between more anisotropic and less anisotropic feldspar subfabrics in the XZ plane is compared with theoretical models for the fabric evolution of particles in a slowly flowing viscous matrix (Jeffery 1922).

Key words: reflection goniometry, preferred shape orientation, motion of rigid particles, durbachite

Introduction

Magmatic planar and linear fabrics are important tools in studies of architecture and mechanisms of emplacement of intrusive bodies. A common problem encountered in fabric studies of coarse-grained magmatic rocks is the correct determination of these structures, namely magmatic lineations. Magmatic planar fabrics are generally marked by flattened mafic inclusions (Ramsay 1989), schlierens (magmatic segregations) and shape preferred orientation (SPO) of different platy minerals, e.g., biotite and feldspars (Paterson et al. 1989). Usually it is possible to measure the orientation of magmatic foliations directly in the field. On the other hand, a reliable determination of linear magmatic fabric is often impossible due to the scarcity of sufficiently elongated particles. The most pronounced fabric constituents of magmatic rocks can be usually formed by large feldspar phenocrysts. The determination of linear fabrics in the field using such markers is very difficult because they have a general triaxial shape and magmatic foliation planes are usually not exposed.

Understanding the mechanisms of emplacement of magmatic bodies requires the knowledge of the sense of flow under (sub)magmatic conditions. In the last decade, several methods have been proposed in order to determine the sense of magmatic flow using spatial relationship of platy and tabular minerals (Den Tex 1969, Blumenfeld 1983, Fernandez et al. 1983, Fernandez 1987, Blumenfeld - Bouchez 1988, Fernandez - Laporte 1991). Nevertheless, the sense of magmatic flow is still difficult to recognise in the field due to the above mentioned uncertainties in defining the lineation and consequently due to the lack of suitable "kinematic" XZ sections in outcrops. Moreover, the sense-of-flow criteria such as tiling of phenocrysts (Blumenfeld - Bouchez 1988) are relatively scarce and give ambiguous results.

Our contribution presents one of the ways, even though tedious, to overcome these difficulties. The proposed method of optical reflection goniometry allows precise determination of shape preferred orientation of large phenocrysts (e.g. feldspar, biotite) from rock samples. Obtained fabrics enable the determinati-

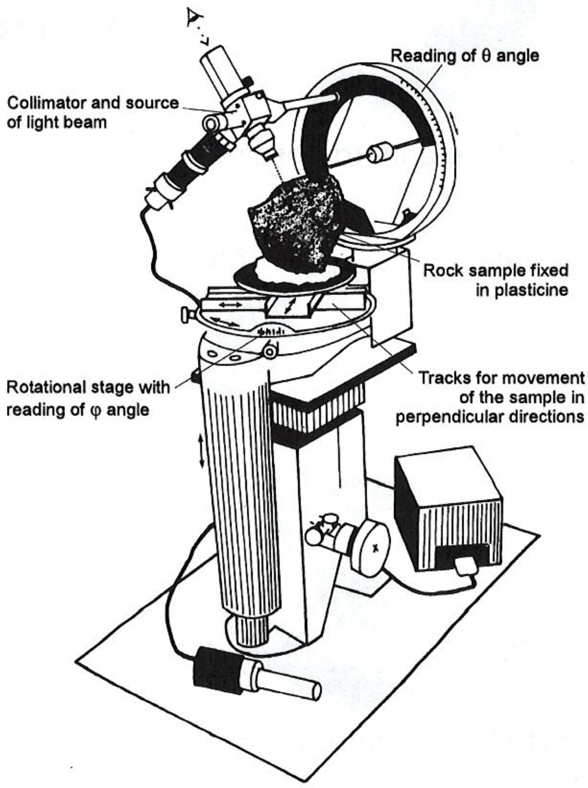


Fig. 1. The reflection goniometer and its main components

on of magmatic lineations and foliations and may be compared with theoretical models of fabric evolution based on Jeffery theory (1922). As a result, the method allows to define the sense of magmatic flow more precisely.

Optical reflection goniometry and measurement of phenocryst preferred orientation

Description of the goniometer

The two-axial optical reflection goniometer (Fig. 1) was constructed for the purpose of measuring orientations of large crystals exhibiting good quality cleavage planes on a sampled piece of rock.

The apparatus yields reading of two angles which define the position of the measured reflecting cleavage plane.

One of the essential components of the goniometer is a stage rotating around a vertical axis in a range of 360° . This stage bears tracks for movement of the sample along two perpendicular directions in a horizontal plane. The oriented sample with a mark on the plane oriented in the field is fixed on the tracks with plasticine in such a way that the oriented plane is parallel to the stage and the strike and dip mark is parallel to the tracks. Once fixed, the sample is movable together with the stage in a vertical direction. The second rotational constituent is a vertical circle bearing a collimator combined with a source of light beam. This part of apparatus can be rotated around a horizontal axis in a range of 180°.

The measurement consists in localising a position of the maximum reflection of cleavage which is reached when the light beam is exactly perpendicular to the measured plane. The selected cleavage is set to this

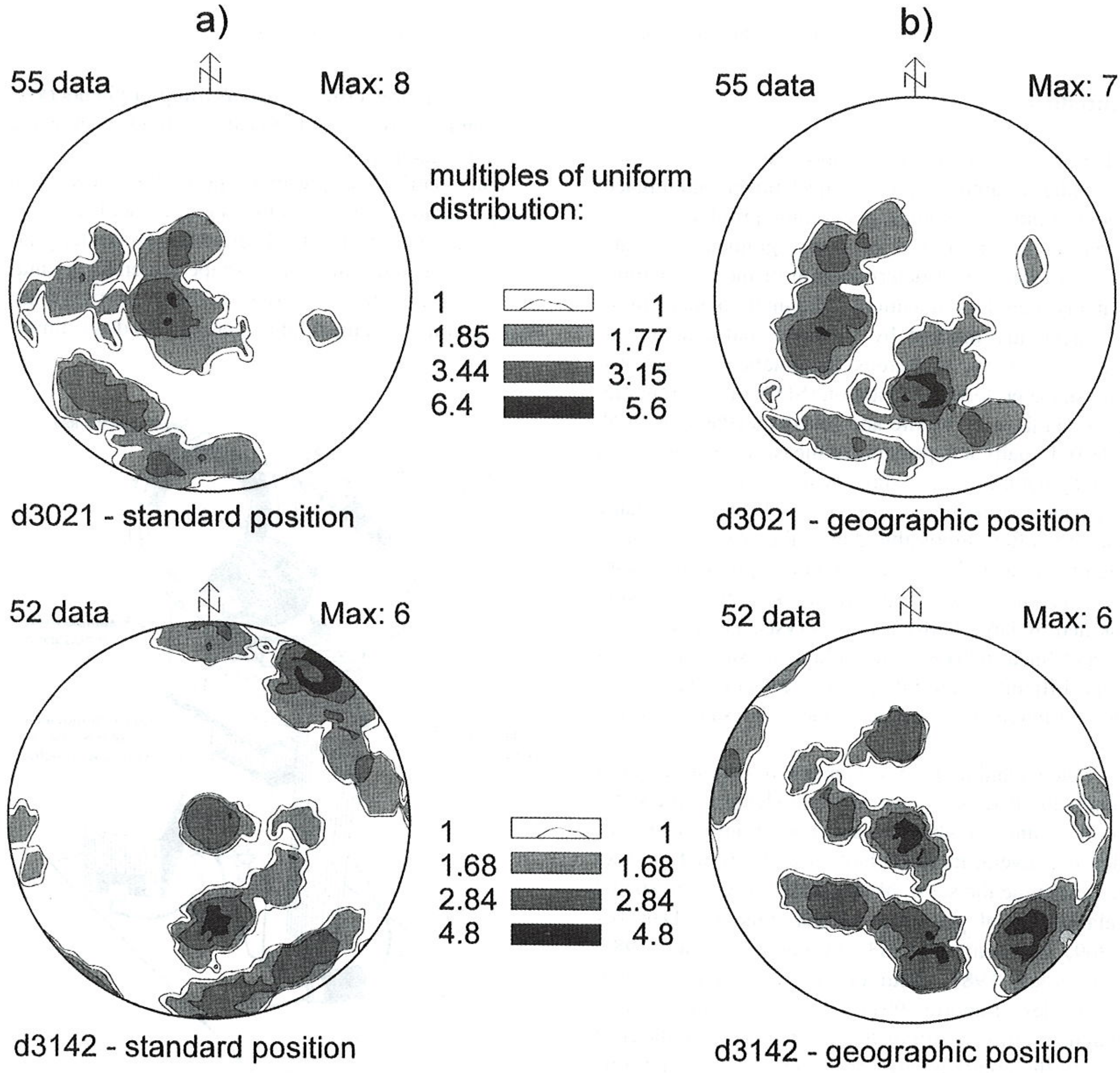


Fig. 2. a) Stereoplots of poles to (001) cleavage planes of feldspar phenocrysts; b) the above stereoplots rotated to the geographical position according to the orientation of the samples

position by simultaneous rotations of the sample and the collimator around the vertical and horizontal axes, respectively. An azimuth angle of the measured planar element is read on the angular scale of the rotational stage and an inclination angle on the vertical circle.

Determination of magmatic foliation and lineation

The goniometer was designed to measure relatively large minerals, several millimetres up to several centimetres in size, containing refractory cleavage planes, e.g., micas and feldspars. On micas, the orientations of basal (001) planes can be determined. If applied to feldspar phenocrysts, the orientation of (001) and (010) cleavages can be determined. Under favourable conditions, these two cleavages are distinguished during the measurement according to morphology of the phenocryst and better quality of (001) cleavage planes. Poles to (001) surfaces, measured as reflections in the goniometer, approximately confine the projection of the longest crystallographic axes while poles to (010) planes are normal to the largest face of the crystal. At least 50 data are required to obtain a realistic picture of the phenocryst spatial distribution.

Mica flakes commonly exhibit anisotropic planar shapes. That is why micas may be compared with nearly ideal planar particles and the preferred orientation of poles to their (001) planes tends to coincide with the XY plane of the strain ellipsoid. On the other hand, feldspars are triaxial particles with shapes corresponding to general fabric elements (Fernandez 1984). Assuming that they crystallised relatively early during the cooling of ultrapotassic magma, they may be compared with rigid particles moving in a viscous flow. Such particles are supposed to form complex fabrics depending on their shape and the flow geometry.

Examples of preferred orientation of feldspars from the porphyritic Třebíč durbachite measured by the reflection goniometer are shown in Fig. 2.

Statistical methods may be used to determine the maximum and minimum density values of the distributions. Most of the observed distributions display double maxima or girdle patterns. All the measured data are obviously related to the co-ordinate system of the goniometer. After the appropriate rotation of the data, they refer to the real geographic spatial orientation. Such fabrics can be most easily quantified using the orientation tensor statistics (Fara - Scheidegger 1963, Scheidegger 1965) by evaluation of the eigenvectors and eigenvalues of the orientation tensor. The positions of eigenvectors define the X, Y, and Z axes and the principal planes of the fabric ellipsoid. The precise orientations of magmatic foliations can be recognised according to the maxima of the poles to mica flakes or from feldspar (010) planes. The orientation of magmatic lineation is given by the maxima of poles to the feldspar (001) cleavage planes (see Discussion bellow).

Comparison with theoretical models

Jeffery's (1922) equations describing the motion of rigid ellipsoidal particle in slow viscous flows represent the basis for modelling of the fabric evolution in magmatic state. The model presumes 1) non-interacting particles and 2) viscous behaviour of the fluid. Despite the fact that these conditions are not fulfilled in many natural conditions, modelling of fabric evolution using multiparticle system formed by general triaxial particles in different flow geometries (Ježek et al. 1994) may provide useful comparison with real fabrics.

Consider a right-handed co-ordinate system (x_1', x_2', x_3') with axes in fixed directions in space and another co-ordinate system (x_1, x_2, x_3) coincident with axes of an ellipsoidal particle. Consider further an undisturbed flow characterised by the velocity gradient tensor:

$$V_{ij}' = dv_j' / dx_i'$$

with E'_{ij} and Ω_{ij} representing the symmetric and skew-symmetric parts of the tensor. The equations describing the motion of a general triaxial particle with axes a, b, c are (Jeffery 1922):

$$\begin{aligned} w_1 &= B_1 E_{32} - \Omega_{32} \\ w_2 &= B_2 E_{13} - \Omega_{13} \\ w_3 &= B_3 E_{21} - \Omega_{21} \end{aligned} \qquad (1)$$

where w_i, i = 1,2,3 are the angular velocities of the particle around its axes and

$$\begin{aligned} B_1 &= (b^2-c^2)/(b^2+c^2), \\ B_2 &= (c^2-a^2)/(c^2+a^2), \\ B_3 &= (a^2-b^2)/(a^2+b^2). \end{aligned}$$

Using the Euler angles, and describing the rotation of the particle with respect to the fixed co-ordinate system, three differential equations may be derived using the known relations between the angular velocity **w** and the time derivatives of the Euler angles:

$$\begin{aligned} \dot{\varnothing} &= (w_1 \sin\psi + w_2 \cos\psi) / \sin\theta \\ \dot{\theta} &= w_1 \cos\psi - w_2 \sin\psi \\ \dot{\psi} &= w_3 - \dot{\varnothing}\cos\theta \end{aligned} \qquad (2)$$

The trajectory of the general triaxial ellipsoidal particle in the flow may be computed by numerical solution of equations (2). Considering an initially isotropic multiparticle system, it is possible to model the evolution of fabrics formed by population of triaxial particles in any flow geometry. More details about the modelling of the fabric evolution in a multiparticle system are given in Ježek et al. 1994 and 1996.

To compare the real preferred orientations of feldspar phenocrysts with the theoretical model, we have studied the evolution of fabric in a multiparticle system

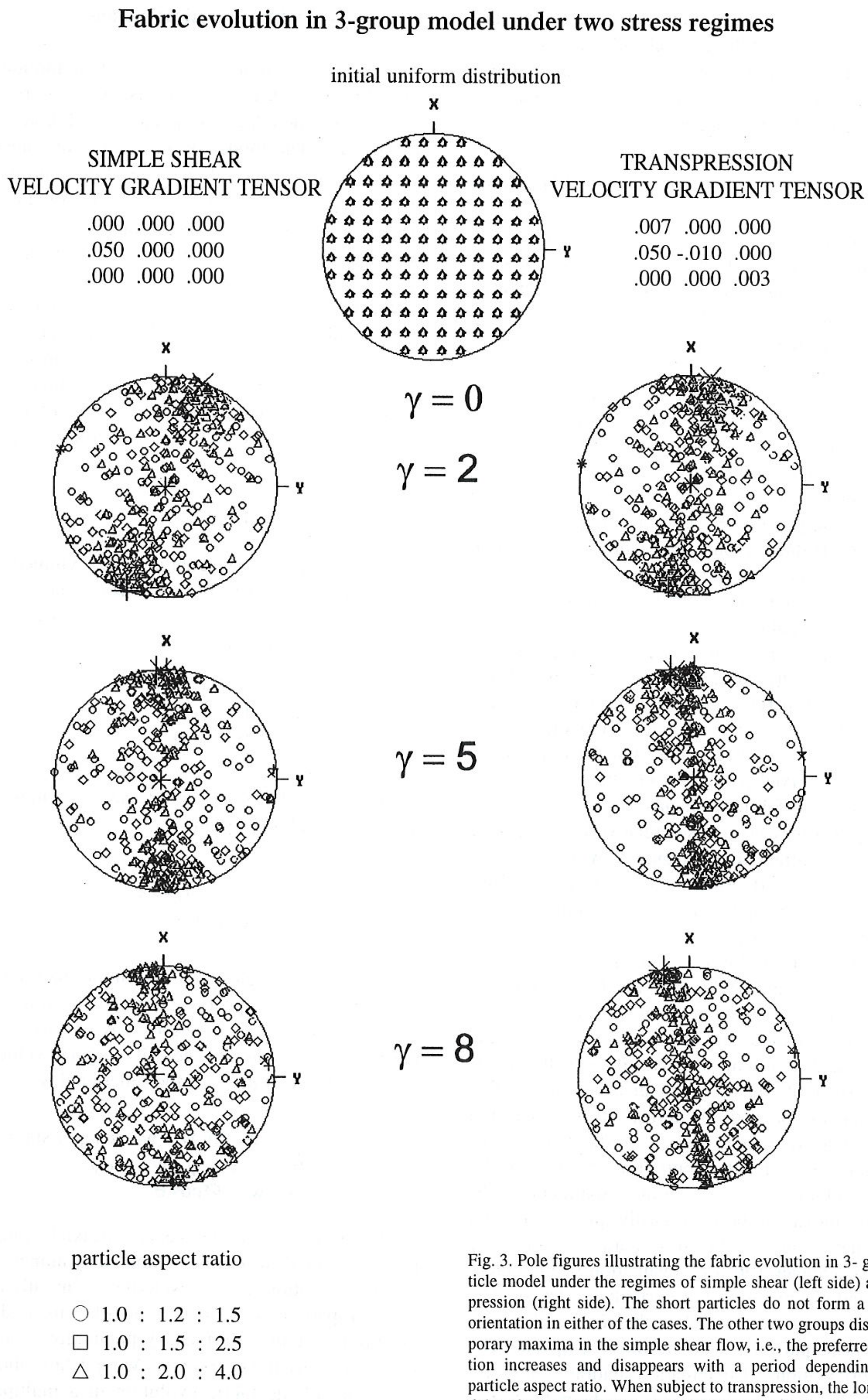


Fig. 3. Pole figures illustrating the fabric evolution in 3- group particle model under the regimes of simple shear (left side) and transpression (right side). The short particles do not form a preferred orientation in either of the cases. The other two groups display temporary maxima in the simple shear flow, i.e., the preferred orientation increases and disappears with a period depending on the particle aspect ratio. When subject to transpression, the longest particles show a maximum stabilised near the X direction while the shorter ones rotate faster and stabilise with a larger angular offset from the XZ plane

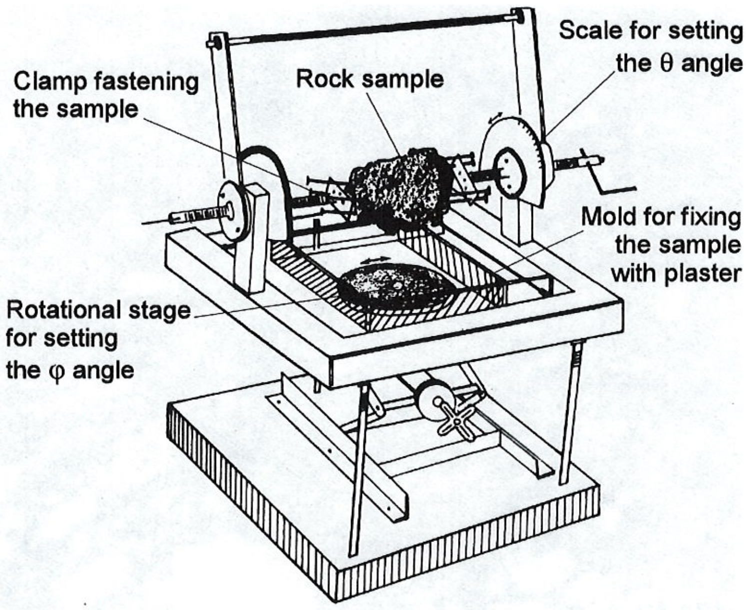


Fig. 4. The apparatus for delineation of the XZ plane

formed by triaxial particles with axial ratio similar to that of K-feldspars. The stereoplots in Fig. 3 illustrate the fabric evolution in 3- group particle model under the regimes of simple shear and transpression.

The short particles do not form a preferred orientation in either of the cases. The other two groups display temporary maxima in the simple shear flow, i.e., the preferred orientation increases and disappears with a period depending on the particle aspect ratio. When subject to transpression, the longest particles show a maximum stabilised near the X direction while the shorter ones rotate faster and stabilise with a larger angular offset from the XZ plane. The sense of angular difference between the longest and shorter particle maxima is significant for the determination of the sense of shearing.

Method for determination of the sense of magmatic flow

The available methods for determination of the sense of magmatic flow are based on (a) angular differences between subfabrics formed by particles of different shapes (Fernandez and Laporte 1991) in space or in XZ section, or on (b) mutual interactions of particles (tiling - Den Tex 1969, Blumenfeld - Bouchez 1988). The determination of XZ plane in magmatic rocks in the field is often impossible and consequently the field application of the above mentioned method is equivocal. However, the determination of fabric axes using the reflection goniometry enables to obtain the XZ section which is most convenient for kinematic observations.

For this purpose, a special apparatus was devised (Fig. 4).

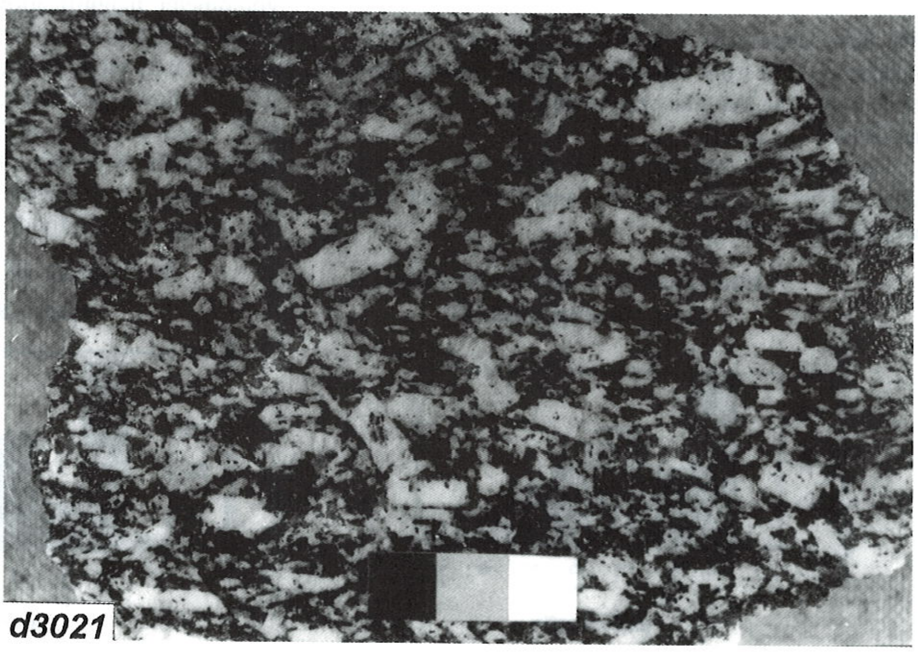
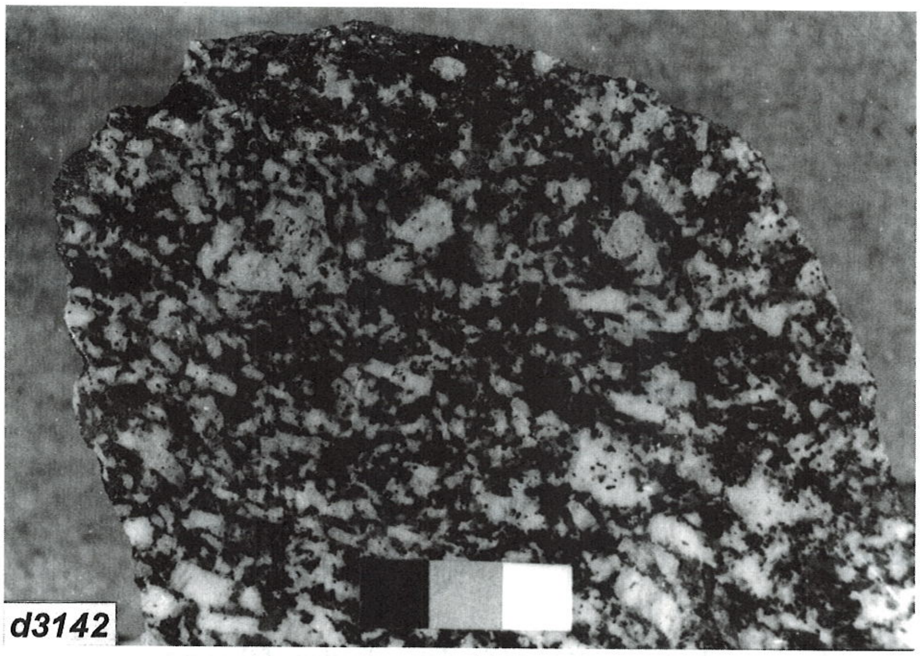


Photo 1 a, b: The sections cut through the samples along the calculated XZ planes, showing a distribution and shapes of feldspar phenocrysts. In these sections the frequency of phenocrysts' aspect ratio and angular preferred orientation were quantified

Photo 1b



It enables biaxial rotation of the sample into such a position that the calculated XZ plane becomes vertical, fixing of the sample position with plaster and cutting parallel to XZ plane of the fixed sample. The device consists of a horizontal stage rotational around a vertical axis and bearing a mould for stabilisation of the sample with plaster. The stage allows the rotation of sample into the position when the strike of XZ plane becomes parallel to the east-west horizontal axis of the apparatus. The sample is fastened by a lateral clamp which can be rotated around the east-west horizontal axis so that the dip of the XZ plane turns vertical. Then the mould is lifted up to a level of the sample that will be fixed with plaster, and the sample can be cut by a vertical saw.

Kinematic analysis in the XZ plane

We have attempted to determine the kinematics of magma motion from the samples of the Třebíč durbachite analysing the feldspar distribution in the XZ plane (Photo 1 a, b).

In this plane, orientations of feldspars' long axes with respect to a reference line and their aspect ratios were measured (Fig. 5).

The phenocrysts were divided into two groups according to their aspect ratio, thus yielding two subfabrics. Angular differences in the orientations of the maxima of both sub-fabrics, shown in rose diagrams (Fig. 6), with two distinct classes of aspect ratio were found.

They may be used as a sense of non-coaxial flow criterion (Fernandez - Laporte 1991). Yet, the use of these relationships between different subfabrics as a kinematic criterion is not straightforward and requires the following discussion.

Discussion

In the limelight of the discussion is the applicability and reliability of the method. Undoubtedly, it depends on favourable size of phenocrysts with regards to the goniometer magnification, and a crystallisation succession that provides conditions under which rigid particles may move in the matrix. The reflection goniometry allows determination of SPO of the minerals with good cleavage such as biotites or porphyritic feldspars. Measurement of SPO of both the minerals in one sample can reveal the flow geometry and kinematics, which are usually difficult to obtain by other me-

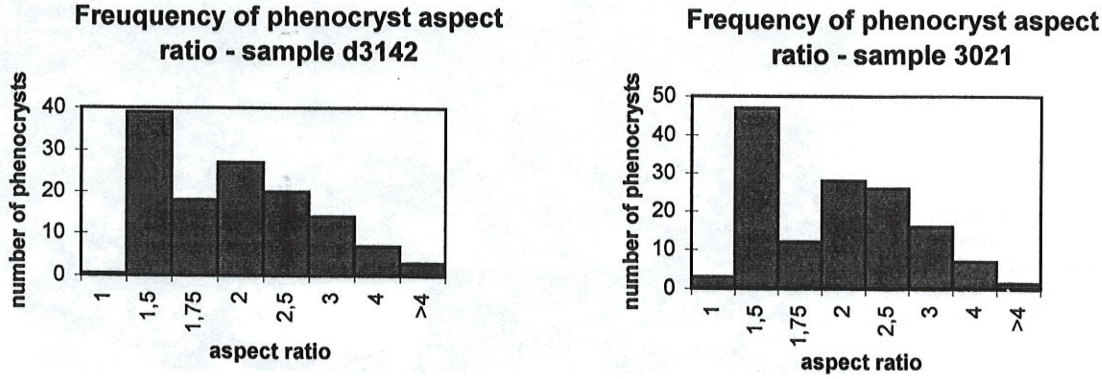


Fig. 5. Frequency of aspect ratio of feldspar phenocrysts measured in the calculated XZ plane

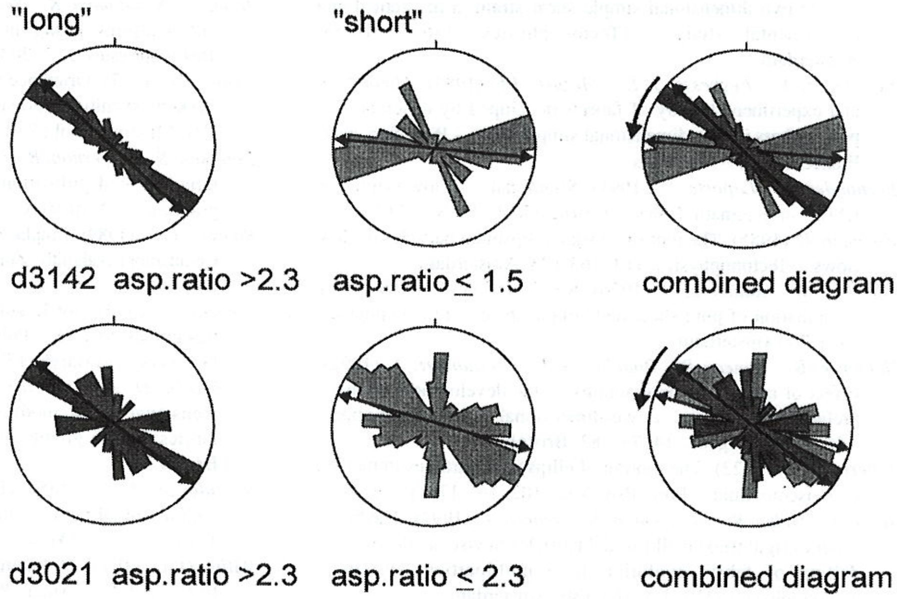


Fig. 6. Orientation rose diagrams of the phenocrysts. Long particles display a sharp maximum while the orientation of the short ones are contained in a wider range. Diameters of the roses indicate the mean orientation for each population. The arrows between the maxima of long and short particles in the combined diagrams indicate the anti-clockwise rotation of phenocrysts, i.e., sinistral sense of shearing

ans. As stated above, micas may be compared with planar markers and it is possible to deduce the flow symmetry directly from their SPO (e.g. Sanderson - Meneilly 1981). On the other hand, feldspars exhibit general triaxial shapes and their fabrics are more complex (Ježek et al. 1994) and not related unequivocally to the flow geometry. Nevertheless, the comparison of feldspar and mica subfabrics may yield constraints on flow kinematics. Another problem is caused by twinning of feldspars. Ideally, basal cleavage of both parts of twins should be measured, thus yielding two maxima with an angular difference about 50° and a shape preferred lineation lying in the axis of the angle. A limited work space of the goniometer, however, sometimes prevents the regular measurement of both parts of all twins. In spite of this technical drawback, the comparison with observable lineations in the field indicated by an elongation of mafic enclaves proved that the application of this method is substantiated.

Angular differences between subfabrics formed by particles of different shapes appear during non-coaxial flows (Fernandez - Laporte 1991). This is due to different rotation velocities of relatively short and long particles in the flow: short particles spin faster than the long ones (see e.g. Ghosh - Ramberg 1976). However, numerical models of fabric evolution (Freeman 1985, Ježek et al. 1994) indicate that the motion of rigid particles is (quasi)periodic in many non-coaxial flows, even if a certain component of flattening across the XZ plane is present. Consequently, fabrics resulting from a general non-coaxial flow are irregularly oscillating and do not form stable subfabrics which could be used for deducing the sense of flow. It depends on the amount of shearing (γ) and on the particle shapes, whether the resulting fabric will be stable or not. It follows that the angular difference between different subfabrics cannot be used as a kinematic marker directly in all geometries of non-coaxial flows, without further consideration of the flow geometry and particle shapes.

Conclusion

The fabric of magmatic bodies, in particular magmatic lineations, are usually difficult to obtain directly in the field. The proposed method of measurement of SPO of large phenocrysts in magmatic rocks by means of reflection optical goniometry enables the quantitative determination of magmatic foliations and lineations in porphyritic igneous rocks. Moreover, it allows to quantify the differences between the SPO of different subfabrics formed by minerals of unequal shapes and to compare the SPO of measured minerals with theoretical models of fabric evolution. Conclusions on the kinematics of non-coaxial flows may be drawn with higher precision than if scarce and ambiguous field criteria are used only.

Acknowledgements. The reflection goniometer and the apparatus for delineation of a flow plane was constructed by Ivan Fischer, the technician of the Institute of Petrology and Structural Geology, Universita Karlova. We thank F. Hrouda and J.-B. Edel for their expert reviews. This work was supported the Grant Agency of the Czech Republic through the project 205 - 940689.

References

Blumenfeld, P. (1983): Le "tuillage des mégacristaux", un critere d'écoulement rotationnel pour les fluidalités des roches magmatiques. Application au granite de Barbey-Seroux (Vosges - France). - Bull. Soc. géol. France, 7, 25, 3, 309-318. Paris.

Blumenfeld, P. - Bouchez, J.-L. (1988): Shear criteria in granite and migmatite deformed in the magmatic solid states. - J. struct. Geol., 10, 361-372. Bristol.

Den Tex, E. (1969): Origin of ultramafic rocks, their tectonic setting and history. - Tectonophysics, 7, 457-488. Amsterdam.

Fara, H. D.- Scheidegger, A. E. (1963): An eigenvalue method for the statistical evaluation of fault plane solutions of earthquakes. - Bull. Seismol. Soc. Amer., 53, 811-816. Baltimore.

Fernandez, A. (1987): Preffered orientation developed by rigid markers in two dimensional simple shear strain: a theoretical and experimental study. - Tectonophysics, 136, 151-158. Amsterdam.

Fernandez, A. - Feybesse, J. L. - Mezure, J.F. (1983): Theoretical and experimental study of fabrics developed by different shaped markers in two-dimensional simple shear, - Bull. Soc. geol. France, 25, 319-326. Paris.

Fernandez, A. - Laporte, D. (1991): Significance of low symmetry fabrics in magmatic flows. - J. struc. Geol., 13, 337-347.

Freeman, B. (1985): The motion of rigid ellipsoidal particles in slow flows. - Tectonophysics, 113, 163-183. Amsterdam.

Ghosh, S. K. - Ramberg, H. (1976): Reorientation of inclusions by combination of pure shear and simple shear. - Tectonophysics, 34, 1-70. Amsterdam.

Ildefonse, B. - Laneau P. - Bouchez, J. L. - Fernandez, A. (1992): Effect of mechanical interactions on the development of shape preferred orientations: a two-dimensional experimental approach. - J. struct. geol., 14, 73 - 83. Bristol.

Jefferry, G. B. (1922): The motion of ellipsoidal particles immersed in a viscous fluid. - Proc. Roy. Soc., 102, 161-179. London.

Ježek, J. - Melka, R. - Schulmann, K. - Venera, Z. (1994): The behaviour of rigid triaxial ellipsoidal particles in viscous flows - modelling of fabric evolution in a multiparticle system. - Tectonophysics, 229, 3-4, 165-180. Amsterdam.

Ježek, J. - Schulmann, K. - Segeth, K. (1996): Fabric evolution of rigid inclusions during mixed coaxial and simple shear flows. - Tectanophysies, 257, 203-221. Amsterdam.

Němec, D. (1957): Orientace vyrostlic orthoklasu v třebíčsko-meziříčském syenitu studovaná pomocí goniometru Rosického. - Čas. Mineral. Geol., 2, 2, 169-171. Praha.

Paterson, S. R. - Vernon, R. H. - Tobish, O. T. 1989. A review of criteria for the identification of magmatic and tectonic foliations in granitoids. - J. struct. Geol., 11, 349-363. Bristol.

Ramsay, J. G. (1989): Emplacement kinematics of a granite diapir: the Chindamora batholith, Zimbabwe. - J. struct. Geol., 11, 191-209. Bristol.

Rosický, V. (1933): Sur le goniomètre a réflexion pour mesurer les très grands cristaux. - Publications de la Faculté des sciences de l'Université Masaryk, 179, 3-9. Brno.

Sanderson, D. J. - Meneilly, A. W. (1981): Analysis of three-dimensional strain modified uniform distributions: andalusite fabrics from a granite aureole. - J. struct. Geol., 3, 109-116. Bristol.

Scheidegger, A. E. (1965): The analysis of finite strain using lines with an initial random orientation. - Bull. Geol. Soc. Amer., 4, 1519-1528. New York.

Willis, D. G. (1977): A kinematic model of preferred orientation. - Bull. Geol. Soc. Amer., 88, 883-894. New York.

Vnitřní stavba porfyrických vyvřelin stanovená dle přednostní orientace živcových vyrostlic

Určení magmatických foliací a lineací je obvyklý problém, s nímž se setkáváme při terénním studiu vyvřelých hornin. Ještě obtížnější bývá snaha určit orientaci pohybu tekoucího magmatu. Z těchto důvodů předkládáme zdokonalenou metodu optické reflexní goniometrie, která se využívá pro podrobné studium vnitřní stavby porfyrických magmatitů. Tato metoda umožňuje: 1. určení tvarové přednostní orientace živcových vyrostlic, 2. přesnější určení magmatických foliací a lineací a 3. stanovení smyslu kombinovaného koaxiálního a nekoaxiálního magmatického toku, založené na asymetriích dílčích staveb (Fernandez 1987).

Využití této metody je demonstrováno na vzorcích třebíčského durbachitu, v němž živcové vyrostlice vykazují přednostní orientaci získanou během vmísťování plutonu. Změřené magmatické stavby jsou porovnány s výsledky matematického modelovaní pohybu pevných částic, unášených v toku viskózní kapaliny (Jeffery 1922).