The relationship of tilt and twist of fringe cracks in granite plutons

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Abstract: Joint fractography in European plutons frequently shows large fringe-tilt angles connected to small fringe-crack twist angles (type A). In contrast to this first type, fringes of joints that tilt at small angles out of the parent joint plane are often associated with high twist angles of en echelon fringe cracks (type B). The interaction of tilt and twist angles gives evidence for the mode (I, II and III) acting at the advancing crack front during fracture propagation and the formation of fringes. The different fringe types depend on the varying influence of mode II or mode III, which establishes the degree of tilt or twist, in addition to opening-mode I that governs the crack propagation. Fringe types A and B are not randomly distributed. Within several plutons the first joints are characterized by a frequency of type A, and in other plutons by the dominance of type B. A third group of plutons is characterized by low tilt and low angle of twist for early joint fringes. The range of tilt/twist ratios of the earliest joints decreases with increasing depth of pluton emplacement and joint formation. The trend of the ratio approaches a value of between 0.5 and 1.0 at greater depth (*c.* 15 km). The ratio seems to be suitable for a prognosis of the possible depth of first joint formation.

The importance of phenomenological studies, now and in the future, is made obvious by our research of granite fractures. Fractographic features that comprise the topography of a fracture surface are common on joints, but were predominantly investigated in sedimentary rocks. The bedding of sedimentary rocks often influences the propagation of fractures to such a degree that, in many cases, they cannot propagate through in an unconstrained process. An unrestricted fracturing can only occur within an isotropic or quasi-isotropic rock such as a massive sandstone cliff (Cruikshank & Aydin 1995; Kulander pers. comm. 2002), or particular plutons. This study demonstrates observations made of varying joint morphology in several granites (Fig. 1). It is probable that the prototype of a rock fracture can grow in an undeformed plutonic rock, and good exposures can represent such preserved earliest joints. Regardless of some degree of faint magmatic foliation or layering, several plutons (e.g. the South Bohemian Pluton in the Czech Republic or parts of the Erzgebirge plutons in Germany) can be considered as quasi-isotropic rocks in relation to the size and the undisturbed formation of joints (length of 10–50 m and more than 100 m at exposures that are large enough).

Statement of the problem

This study contributes to our understanding of the shape that a growing opening-mode fracture will have, and the propagation path the joint follows, if an unconstrained fracture process takes place in a natural geological quasi-isotropic rock. Such conditions can be assumed in plutons at the moment when earliest joints were initiated. Therefore, one purpose of the investigation was to determine the joint sets within the granite and the age relations of joints to establish the joint succession. Another purpose was to determine if the individual joints formed during a single fracture process or if portions of a joint surface developed after the change in direction of the maximum compression. This investigation also aims to ascertain the high-angle or low-angle tilt and the twist of fringe cracks, and to consider what factors influenced their occurrence if previously existing unhealed joints or free surface boundaries are absent at time of fracture. Finally, one objective was to find out whether special joint morphology is associated with specific stages of the pluton history or with different depths of joint formation.

With regard to the joints of the Appalachian Platform, the abrupt fringe planes seen after a kink were the result of a temporal change in the orientation of the remote stress field, indicating an arrest of the initial joint propagation (Engelder & Geiser 1980). The smooth curve at the end of a main joint, and its gradual tilt into the following fringe zone, represents a spatial change in the orientation of the local stresses, caused by the interaction of the advancing crack tip with previous joints or with inclusions (Kulander & Dean 1985; Olson & Pollard 1989; McConaughy & Engelder 1999). An inclusion can comprise small-scale material possessing elastic behaviour in contrast to the matrix, and is generally a more singular phenomenon. Within the granites discussed in this chapter both of the above reasons can be excluded for the formation of many first joints. The early joints initiated within quasi-isotropic granites and mostly without visible inhomogeneities.

Considering the unconstrained formation of earliest steeply dipping joints, one restriction arises from the common temporal sequence of fractures in

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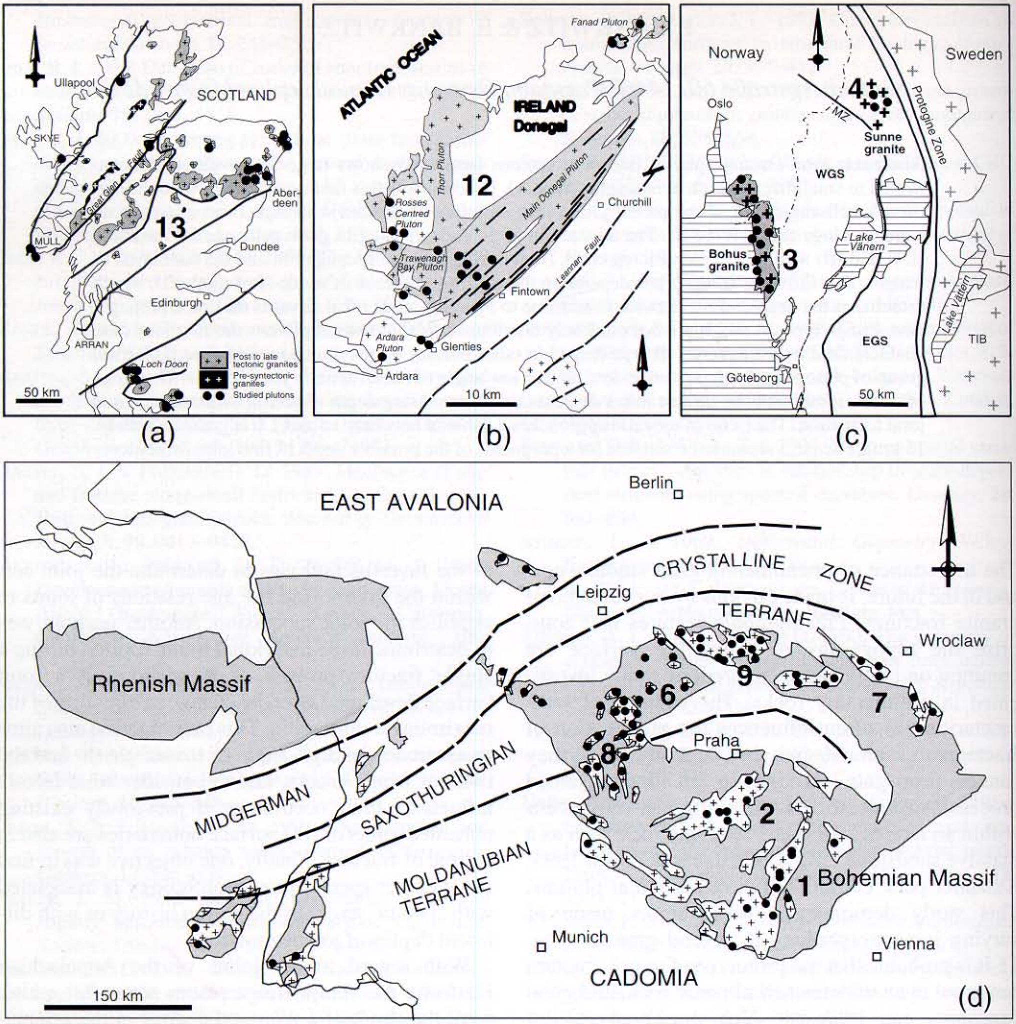


Fig. 1. Granites in Europe. Dots indicate areas in plutons where jointing was studied by the authors at many outcrops. Numbers 1–12: the main areas of joint studies. Denotation of the plutons within the text (list of granites). Simplified geological maps: (**a**) after Harris (in Craig 1991); (**b**) after Pitcher & Berger (1972); (**c**) after Freden (1994); (**d**) after Walter (1992). In (**c**) MZ, Mylonite Zone; WGS, Western Gneiss Segment; EGS, Eastern Gneiss Segment; TIB, Transscandinavian Igneous Belt. (**a**) and (**b**): Caledonian granites; (**c**) and 9 in (**d**): Precambrian granites; (**d**) Variscan granites. Granite localites in Denmark (5), Elba Island (10), the Urals (11) and Cornwall (14) are not shown.

plutons. Within the greater part of the studied plutons the first fractures are widely spaced subhorizontal joints or obliquely dipping joints, mostly at an angle of *c.* 0°–30° up to 40° ('lager' joints according to Cloos 1921). They occur in small numbers and, in some cases, could have influenced propagating vertical joints when approaching pre-existing subhorizontal joints. Pre-existing cracks interrupt a homogeneous stress field, and the wall of an unhealed fracture may prevent the transmission of the advancing crack-tip stress field (Engelder *et al.* 1993). As a consequence, the younger joint terminates at the previous joint. The principal stresses rotate locally in the vicinity of the wall of the pre-existing joints and therefore the propagating younger joint changes in orientation (Pollard & Segall 1987; Dyer 1988) forming tilted fringes. Trend changes in tensile/compressive stresses at the advancing crack tip are responsible for the development of twist hackles or tilt.

The causes of why the local stresses at the crack tip change direction and magnitude in the absence of pre-existing joints and other inhomogeneities are not finally known in each case. Factors influencing the propagation of early joints in granites were considered in an attempt to determine with which temporal moment of the pluton history the joint formation correlates, and at which position of the pluton within the crust the joints developed. If the joints were formed at the depth of pluton emplacement at an early stage of cooling (Bankwitz *et al.* 2004) the cooling and crystallization of the pluton can change the magnitude of stresses.

Peculiarities of the fringe and the fringe cracks in regard to unconstrained fracture propagation are one topic of this study. In many plutons high-angle tilted fringes are combined with low-angle twist hackles (en echelon segments) and, vice versa, fringe cracks with high-twist angle occur at low curved fringes. It was our aim in this chapter to prove if this combination is a common rule or occurs only randomly.

Method of investigation

Natural joints in plutons (Fig. 1) were considered with regard to their geometry, size, spacing, surface morphology and relative timing of formation by means of fractography and other known geological data. Measurements of angle and planes, and analysis of fractographic features, were the tools of the study. Fractographic surface pattern are well known from sedimentary rocks, and have been described and interpreted by many authors (e.g. Woodworth 1895; Bankwitz 1965; Kulander *et al.* 1979, 1990; Pollard & Aydin 1988; Bahat 1991, 1997; Kulander & Dean 1995; Younes & Engelder 1999).

We studied the earliest steeply dipping fractures that frequently represent the dominant systems of joints in undeformed plutons (e.g. in the South Bohemian Pluton of the Bohemian Massif). The relative ages of parent joints (sequence of joints) were ascertained for each pluton using the rotation of younger joints to become either parallel or perpendicular to the older joint (Dyer 1988), or their abutting relationships. We also noted their size (from several metres to nearly 100 m) and the remarkable distance (several metres to >30 m) between them. It was found that the shape and the fractographic features of granite joints differ widely, even of those granites that were similar in composition and dimension, and where the environmental conditions at the time of fracture were probably similar. The difference in joint morphology may be the consequence of the moment of fracturing in the history of the pluton, and with that are dependent on various driving mechanisms and stress conditions.

The joint face and the entire shape were considered, not just traces of fracture planes on a free surface. Younes & Engelder (1999) published tilt and twist angles of joint fringes and their cracks of up to 32° (with a few exceptions) in clastic rocks. Many granite joints propagated continuously into high-angle (30° to >60°) tilted large fringes several metres in length (Fig. 2a), or formed fringe cracks with large twist angles (Fig. 2d). In many cases the advancing crack front of the main joint plane curved gradually into the fringe, thus indicating a single fracture event. It was often found that fringe cracks had already initiated on the main joint face.

At an early stage, during the incipient formation of the joints, the granite supports an unconstrained propagation of fractures. Only such joints leave a record of undisturbed fracture propagation without forced arrest along older fractures or inhomogeneities. In contrast to granites, volcanic rocks consisting of several flows behave more like layered sedimentary rocks when fracturing (Fig. 3).

To be sure that the shape and the morphology of joint surfaces discussed in this chapter are common phenomena in granites, investigations of many plutons were necessary. On the basis of the comparison of jointing in a sufficient number of granites, it was possible to determine characteristic joint features. Our investigation of joint morphology included measurements of strike, dip and bending of main joint planes, fringes and associated en echelon segments, and related tilt and twist angles between them. In addition, the size and frequency of all joints and their echelon fringe cracks were documented. More than 10000 individual joint surfaces and their fractographical features were studied, including the chronological succession of sets.

Plutons studied with regard to their joint features

Plutons hosting joints are often of different ages and have developed due to a variety of different crustal processes. In this study fractographic features were recognized on joints in all investigated granites. Several plutons, such as the Precambrian Bohus and Sunne granites in Sweden (Fig. 1c), and the Bornholm granites (Denmark; Bankwitz & Bankwitz 1994), remain for the most part undeformed after the emplacement, independent of their age. Others intruded prominent shear zones and were strongly deformed, such as the Caledonian granites in Scotland and Ireland (Fig. 1a, b). In our experience, the Caledonian granites are generally less suitable for studying the complete shape of early unconstrained formed joints, and their tilt and twist angles. In part they intruded into shear zones and underwent a strong blastesis (e.g. the Fanad Granite: Fig. 1c) by shearing under intracrustal conditions. In addition, the greater part of the exposures of Caledonian granites are small considering the large size of the granite joints, so that

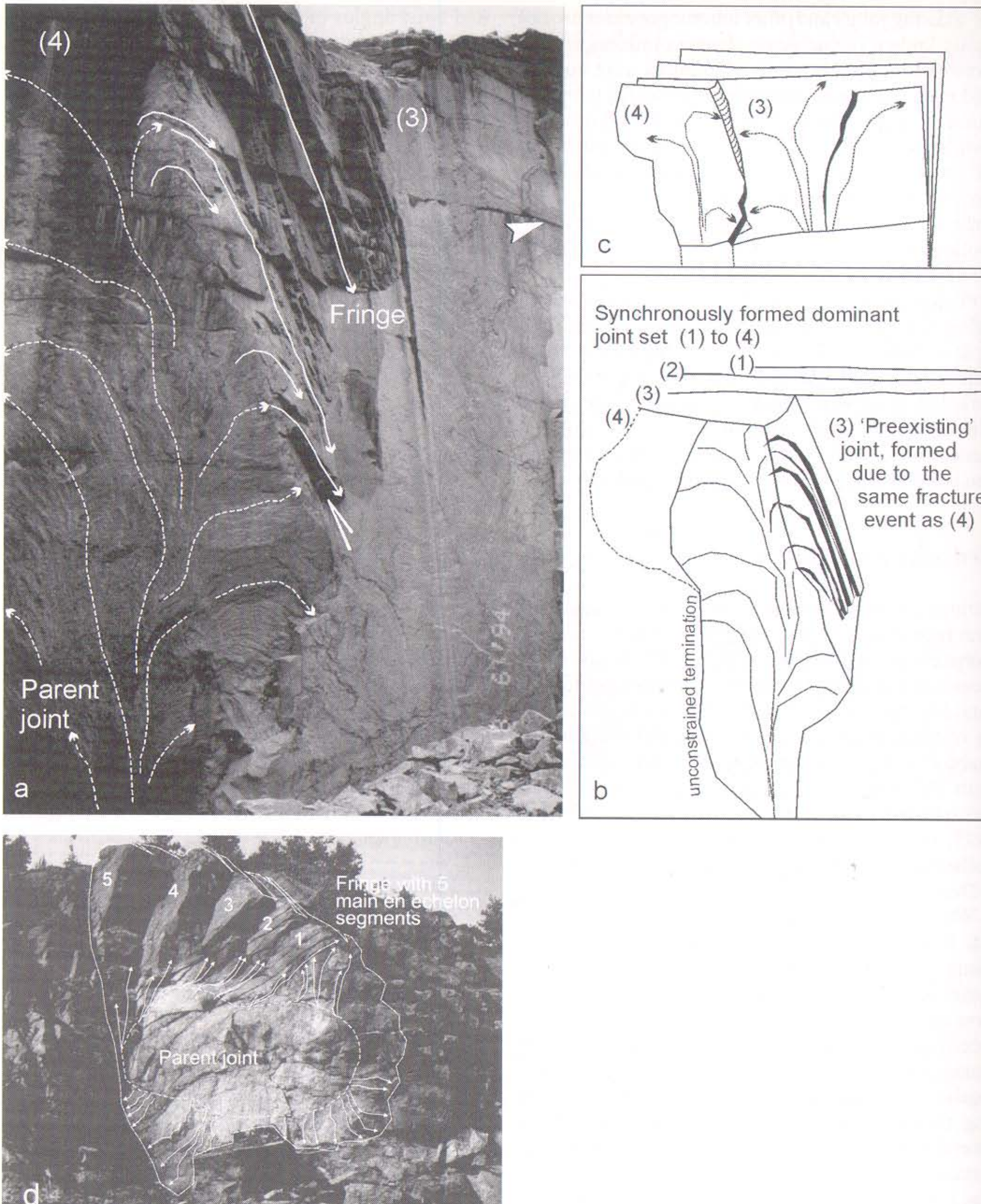


Fig. 2. Flossenbürg Granite, Oberpfalz, Germany. (**a**) One of the earliest 010°-joints: The parent joint (left part of the photograph) is covered with an upward-growing plume. The joint bends at the right end into a fringe tilted at about 65°. In part gradual en echelon fringe cracks initiated on the main plane, but mostly at the boundary, finally arranged subparallel to the fringe orientation. Very small twist angles may exist at the lower end of the fringe (see <). Subhorizontal traces of late post-uplift sheet fractures (large arrow) cross-cut the older vertical parent joint and the whole face. The height of the face is *c.* 18 m. (**b**) and (**c**) The joint is part of a subparallel joint bundle (1–4) more or less contemporaneously formed. The joint bundle is a fan-shaped structure, closely spaced near the bottom and diverging upwards. At the deepest part of the photograph (a) joint 4 and joint 3 approach another nearly in the same plane and form a composite single face (c). (**d**) The parent joint (bright) has an asymmetrical fringe, in its upper part represented by five gradual en echelon segments (1–5) with varying twist angles. The height of the face is *c.* 16 m. The joint initiated anywhere in the central plane and propagated in each direction, but dominantly to the top.

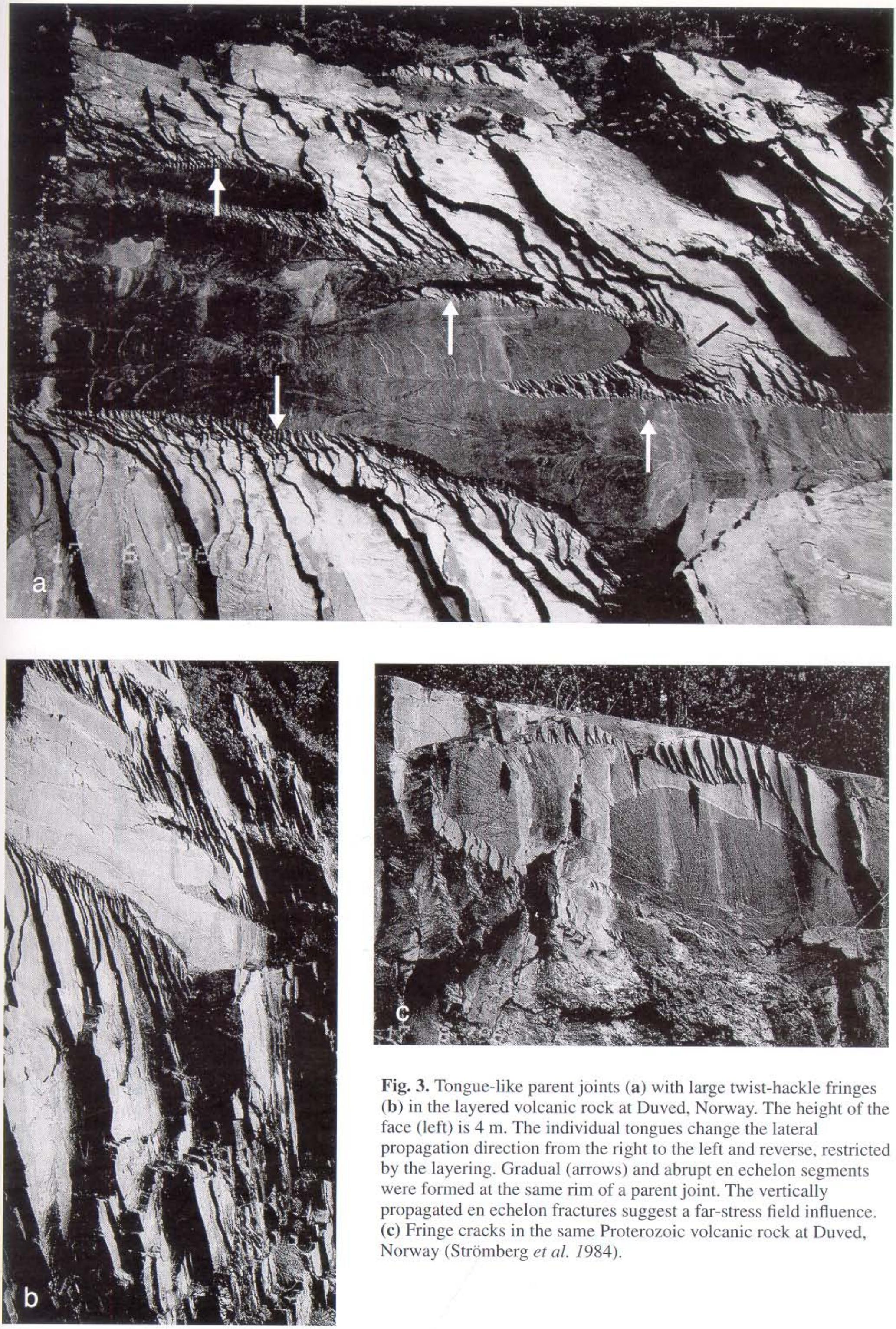


Fig. 3. Tongue-like parent joints (**a**) with large twist-hackle fringes (**b**) in the layered volcanic rock at Duved, Norway. The height of the face (left) is 4 m. The individual tongues change the lateral propagation direction from the right to the left and reverse, restricted by the layering. Gradual (arrows) and abrupt en echelon segments were formed at the same rim of a parent joint. The vertically propagated en echelon fractures suggest a far-stress field influence. (**c**) Fringe cracks in the same Proterozoic volcanic rock at Duved, Norway (Strömberg *et al.* 1984).

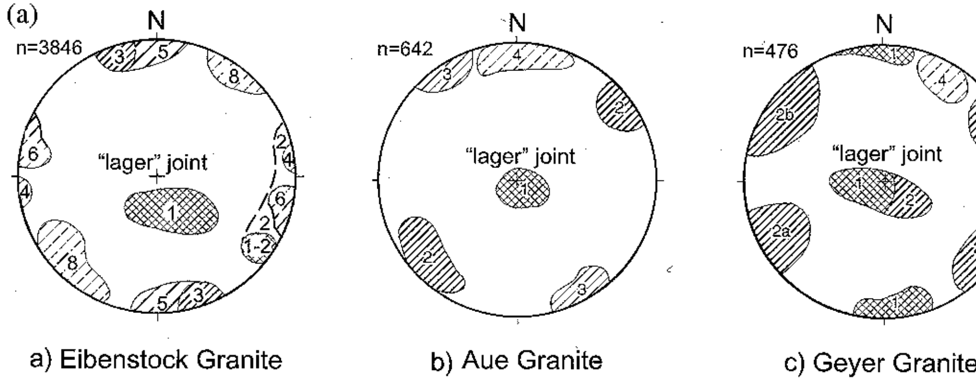


Fig. 4. (**a**) Synoptic diagrams of lower-hemisphere stereographic projection of joints within three Variscan Erzgebirge granites (Germany). Numbers (1–8) of the maxima indicate the relative sequence of joint formation: 1, earliest formed joint set; 8, latest joints (Bankwitz & Bankwitz 1995). The same number in different maxima indicates changes in the interaction of the joint (e.g. 1 and 1–2). (**b**) Schematical illustration of the mapped joint sequence in the Eibenstock Pluton (Bankwitz & Bankwitz 1995) north of the national boundary between Germany (*D*) and Czech Republic (*CZ*). Jointing started with flat to oblique dipping (18°–35°) 'lager' joints. The other sets were steeply dipping, with the exception of set 9. The first subvertical joints (2) followed the shape of the exposed pluton. Numbers 1–10, temporal and spatial varying development of joint sets during three stages. The relative timing of the various joint sets give evidence for an area of preferred fracture formation that shifted in time, e.g. from phase 3 to 4 and 5, and from 6 to 7 and 8. Stage 3 comprises the development of sheet fractures and, finally, a second generation of smaller N–S and E–W-trending joints that terminate at the sheet fractures 'lager' joints (Fig. 8b). Dot, Blauenthal quarry (location of the photographs in Fig. 8). Joint sets 2 and 4 with dense greenish Uranium-micas at the fracture surface).

only parts of joint surfaces can be observed. Some larger quarries and cliffs (Aberdeen and Peterhead in Scotland, and Donegal in Ireland) reveal joints with mostly low surface morphology regardless of some few high-angle tilted fringes.

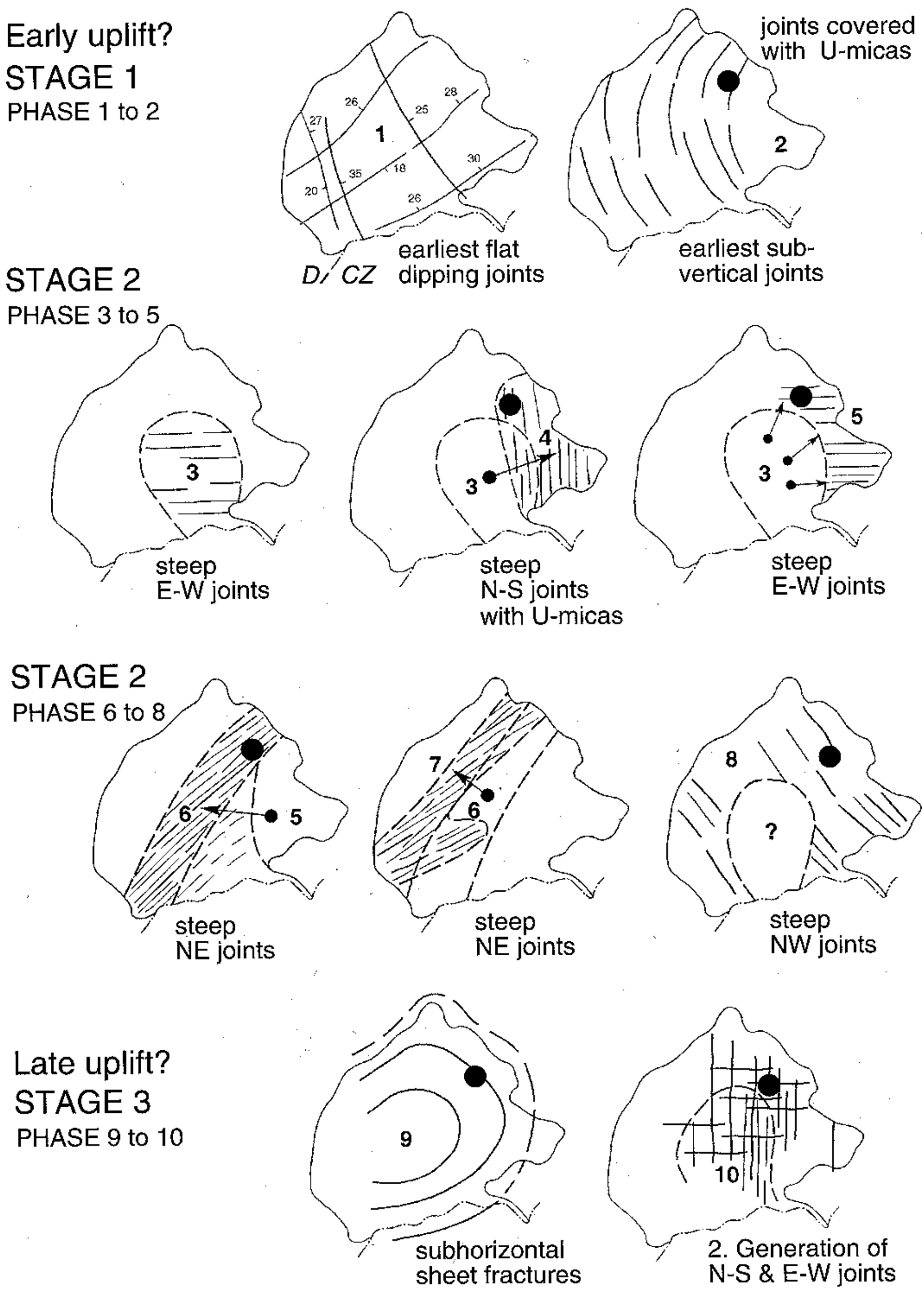
In many plutons multiple joint sets exist. The determination of the relative joint sequence is an important element for this study. However, the timing of the formation of small joints (about 1 m) subparallel to much larger fractures (tens of metres) is problematic. Both can be formed contemporaneously, in which smaller joints are prevented from further propagation by their large neighbours, as Segall & Pollard (1983) found in granitic rocks of the Sierra Nevada; on the other hand, however, the small joints can be formed later. In each case this needs to be established by their interaction with other joint sets. This applies not only to small joints, others can also present a second generation with the same orientation as an older set. Based on detailed joint mapping in the Eibenstock Pluton, two steeply dipping N–S and two E–W joint sets formed at different times could be recognized (Fig. 4b; sets 4 and 5, and set 10) by their peripheric twist-hackle deviation (Bankwitz & Bankwitz 1995). Here, the younger joints of these sets abut onto late formed, subhorizontal sheet fractures. They are distinctly smaller than the earlier joints, which are cross-cut by the sheet fractures, indicating that these vertical joints formed prior to the present erosional surface. Within several granites, for example the Sunne Granite, a similar joint sequence with repeated formation and subparallel joint orientation exists.

The plutons are listed according to their suitability to this problem. Reference is also made to additional granites to demonstrate the wide range of observations. Most of the list numbers are given in Figure 1 (where each dot stands for a number of exposures).

First group: granites with finely developed joint surface features and that are largely well exposed

(1) South Bohemian Pluton (SBP), Czech Republic and Austria (330–320 Ma; Mrákotín (e.g. Mrákotín and Boršov quarry), Eisgarn and Weinsberg granites). Located in the SE part of the Bohemian Massif (CR). The pluton (length in the NNE direction of about 150 km) consists of several late to post-tectonical Variscan granites (geochronology by Scharbert 1998; Breiter & Koller 1999) that are related to the Variscan convergence of the Bohemian and Saxothuringian terranes. Gravity anomalies reflect the roots of the deep intruded bodies at c. 15 km depth (Breiter 2001). The palaeodepth of the granite at the present erosion level was determined by fluid inclusions at 7.4 km in the northern part (Boršov

(b)


Early uplift?
STAGE 1
PHASE 1 to 2
joints covered with U-micas
1
2
27
26
28
25
30
35
18
20
26
D/ CZ
earliest flat dipping joints
earliest sub-vertical joints
STAGE 2
PHASE 3 to 5
3
4
5
steep E-W joints
steep N-S joints with U-micas
steep E-W joints
STAGE 2
PHASE 6 to 8
5
6
7
8
?
steep NE joints
steep NE joints
steep NW joints
Late uplift?
STAGE 3
PHASE 9 to 10
9
10
subhorizontal sheet fractures
2. Generation of N-S & E-W joints

quarry, Mrákotín Granite, Czech Republic) and at 14.3 km in the southern Austrian Weinsberg Granite (Friepeß quarry). Evidence for the minimum age of early fractures comes from muscovites within thin microgranites (1 cm) on exposed fringe crack surfaces 324.9 ± 6.7 Ma in age (Bankwitz *et al.* 2004).

The samples were taken from the en echelon fringe cracks of two 025°-trending early joints: one from the vertically propagated fringe of the 'Trefoil' joint (Fig. 5b), and the other sample from a preferred lateral propagated fringe that is developed almost around the joint. Both samples were used for the determination of the palaeodepths of the exposed granite found today, and for K/Ar-age dating of muscovites within small microgranites at the fracture surfaces (Boršov quarry). Thus, the formation of the 025°-joints, including their fringes, could be post-dated at 324.9 Ma. The muscovite K/Ar-age of samples from a N–S joint surface in the Austrian part of the pluton (Friepeß quarry) was given as 318.9 Ma. The intrusion age of the pluton is 330–318 Ma, and the cooling age ranges between 328–325 and 320 Ma (Mrákotín Granite) and 313–308 Ma (Weinsberg Granite; Scharbert 1998; Breiter & Koller 1999). The Borsov joint was formed prior to or during injection of the micrograniitic vein, that is 3 Ma after the start of cooling. Taking into consideration the fact that first cooling occurs at the boundary of the pluton, we can assume that granite cooling began later in the axial region of the pluton where Boršov is located. This means that the Boršov joints were formed less than 3 Ma after the beginning of cooling within the pluton. These joints are characterized by exquisite fractographic features.

(2) Central Bohemian Pluton (CBP) Czech Republic (340 Ma). The pluton consists of several Variscan granites (e.g. Hudčice and Solopysky quarry) that started to generate earlier than that in the SBP, with crustal conditions similar to those given above (Holub *et al.* 1997). Vertically to obliquely dipping joints, in part with subhorizontal fringes, are conspicuous at several places, as well as huge plumes with very broad branches (up to 5 cm-wide ridges and grooves). Other fractographic features are well developed.

(3) Bohus Granite, Sweden (950 Ma). Located along the west coast of South Sweden between Göteborg and Oslo, the granite intruded during late- or post-Grenvillian–Svekofenian orogenic time (Zheng 1996). The emplacement has been suggested to have been at a mid-crustal level of above 15 km (Eliasson 1992) related to shear-zone movement. The granite massif forms the reefs along the Skagerrak Sea, and is exposed at many intensely fractured cliffs and quarries, offering decametre to several hundreds of metres of extended joints. Some fracture sets represent impressive surface morphology including high-angle tilted fringes, in part with oblique dip.

(4) Sunne Granite, Sweden (1650 Ma). The granite is part of the Eastern Gneiss Segment (Freden 1994) in mid Sweden. Large exposures exist along roadcuts (length of several hundreds of metres; height of up to >20 m). The joints have similar morphology to granite (3).

(5) Bornholm Island granites, Denmark (1400 Ma; e.g. Rönne, Vang, Hammer, Svaneke, Almendingen granites; Larsen 1980). Reefs along the shoreline of the Baltic Sea, cliffs, and large and deep quarries with early formed joints exist. Younger, uplift-related vertical joints cross-cut the older joint system (Bankwitz & Bankwitz 1994). All of the common fractographic features exist in these granites.

(6) Erzgebirge granites, Germany (325–318 Ma; e.g. Eibenstock, Kirchberg, Bergen, Aue, Geyer and Niederbobritzsch plutons). Post-tectonical Variscan granites in SE Germany that are related to the Variscan convergence (Förster *et al.* 1999). The palaeodepth of the granites (today at the erosion level) was determined by fluid-inclusions at <3 km (Thomas & Klemm 1997). These highly evolved intrusions are, in part, of subvolcanic type and enriched in ore deposits (Erzgebirge: Ore Mountains). Fractographic features are common, but predominant with low joint morphology.

(7) Granites of the West-Sudetes, Poland (330–310 Ma; e.g. Riesengebirge/Krkonosze, Strzegom, Strzelin granites). Late syn- to post-tectonic Variscan granites in SW Poland that are related to the Variscan convergence (Mierzejewski 2001). They are the proper 'Cloos granites', where Cloos 80 years ago established for the first time the 'Granite Tectonics'. In part, magmatic and tectonic foliation is weakly developed. The joint morphology is well developed; however, the morphology in the N–S and E–W sets is very different to that recognized in the SBP (1).

(8) Karlovy Vary Granite and Bavarian granites (Fichtelgebirge granites, 320–290 Ma; Oberpfalz granites, 325, 305 and 290 Ma, e.g. Flossenbürg Granite, 312 Ma). Located in the northern Czech Republic and in the SE part of Germany (Bavaria), these plutons are of Variscan age (Siebel 1998). The fracture morphology usable for this study is only partly exposed (Bankwitz *et al.* 2000).

(9) West- and East-Lusatia Granite Massifs, Germany (540–530 Ma). Partly deformed Cadomian (up to Lower Cambrian) granites that were generated at the end of the Cadomian orogeny (Schust

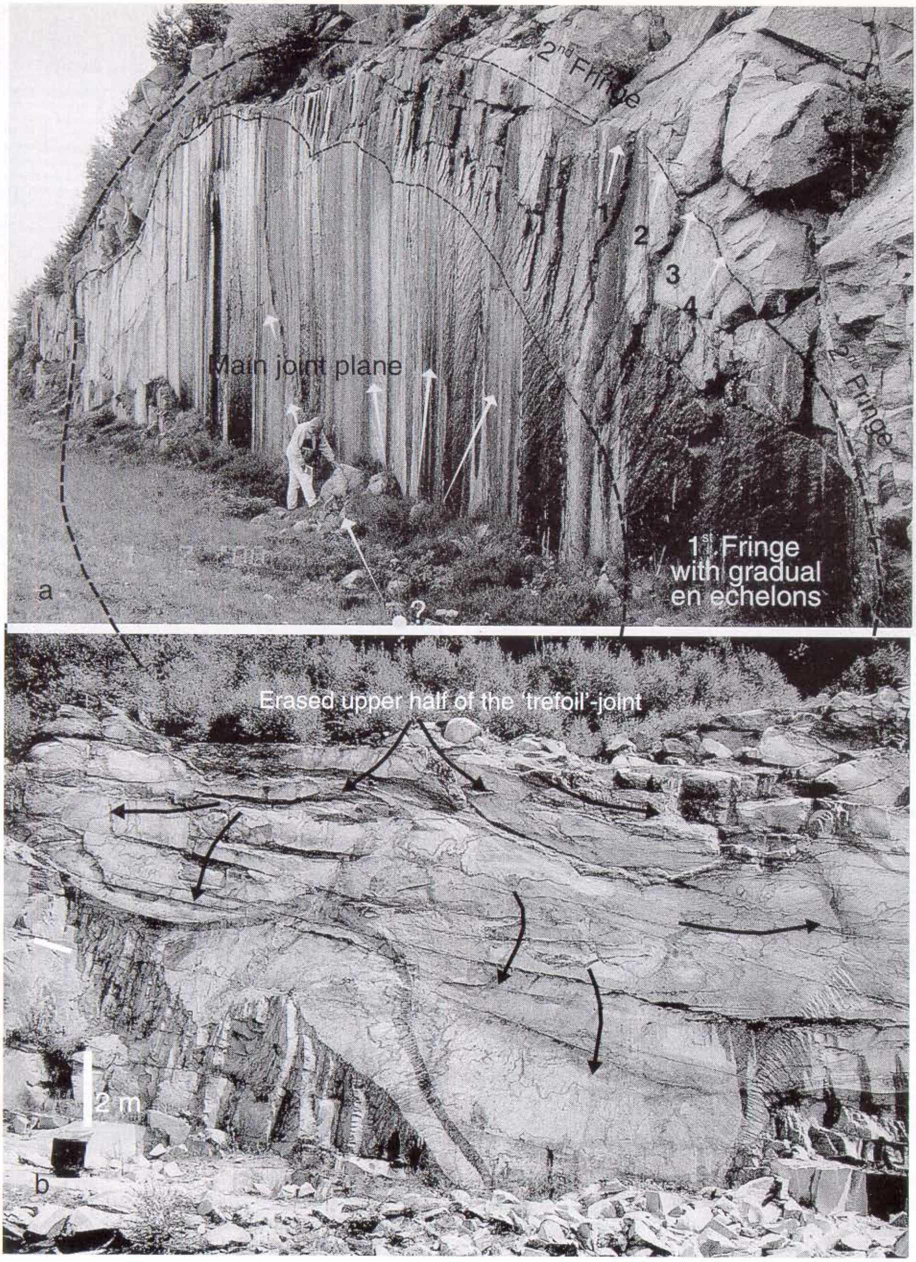


Fig. 5. N-S-trending early joints with a curved boundary of the main plane against the fringes. Curved rims and undulations on the joint face mark the temporary crack front and indicate an unrestricted fracture process resulting as a quasi-circular fracture. Twist hackles (plumes) propagated from the main joint onto the fringe without interruption, partly producing fringe cracks. Such features indicate continuous fracturing. (**a**) Sunne Granite, mid-Sweden, Tossebergsklättan north of Sunne, Värmland. Road cut consisting of a single joint (total length of 25 m; total height of *c.* 12 m). The overall plumose structure becomes visible within wet stripes on the face. Arrows indicate the local propagation direction; arrows 1–4 mark places where steps of the first fringe run directly further to the second fringe. (**b**) South Bohemian Pluton, Boršov quarry. Features as in (**a**). Detail of the 'trefoil' joint face (total length of 28 m; total height of 15 m) with an excellent plumose structure. (**c**) Locality as in (**a**); the structures of the joint surface are similar to the features of cracks in glass, independent of the difference in size. The ellipse marks the site of an pegmatitic injection. From that inhomogeneity the 'augen' fracture initiated.

2000; Eidam & Krauss 2001; Tichomirova 2001). Magmatic and, at many locations, tectonical foliation exists (Eidam & Krauss 2001; Lobst 2001). Several superimposed joint systems indicate repeated events of fracturing and deformation.

(10) Mte. Capanne, Elba Island (6 Ma). This is the youngest granite massif in western Europe (Bussy 1991). The morphology of some joints reflect fracturing under a high stress magnitude that branches early after initiation close to the point of origin into en echelon segments with a large overlap. In some places vertical joint surfaces contained by dense hydrothermal tourmaline crystals with preferred vertical orientation. The temperature of tourmaline crystallization was determined to be 400 °C within a fluid with low fO_2 (oxygen fugacity), indicating a closed system (Y. Fuchs pers. comm. 2002). Good exposures for joint investigations are rare.

Second group: sheared or strongly weathered granites, in part with inadequate exposures

(11) Many granites of the Southern Urals (e.g. Dzabyk Granite, 276 Ma, Sanarka Pluton). Low to strongly deformed syntectonic granite massifs of the Variscan accretion wedge in the South Uralian hinterland (Fershtater *et al.* 1997). Here, in many plutons, magmatic and strong tectonic layering exists, along with foliation; several cleavage plane systems can also be recognized. Most of the granites intruded into shear zones of the accretion wedge and were deformed by transpressive strike-slip movements. Impressive joint-surface plumes with a rough morphology occur in the latest undeformed 'stock' granites.

(12) The granites of Donegal in the Caledonides of NW Ireland (e.g. Ardara, Ross, Thorr, Fanad and Main Donegal granites). Pitcher & Berger (1972) and Hutton & Alsopp (1996) investigated these Caledonian age granites, some of which have magmatic and quite strong syntectonic foliation; the Main Donegal Granite and the Fanad Granite are related to the Gweebarra and the Mossfield shear zone, which belongs together with the Leannan Fault and other wrench faults to the system representing the prolongation of the Great Glen Fault of Scotland. Ardara and Ross are diapirs, others are cauldrons. All of these are considered to be shallow intruded granites. More or less rough joint surface structures with low morphology were recognizable, however, in some parts high-angle tilted fringes were visible.

(13) The younger granites of the Scottish Highlands (456–397 Ma; Loch Doon, Ross of Mull, Aberdeen, Peterhead, Great Glen, Borrolan). Craig (1991) mapped these Caledonian granites (from Peterhead to Fionnphort) that host regular, relatively planar joints with only a smooth fracture morphology.

(14) The granite chain of Cornwall (c. 290 Ma; as the Dartmoor, Bodmin, Austell and Land's End granites). Post-tectonical Variscan collisional granite formation, often kaolinized; the exposures are not suitable for joint studies in the presented sense of this chapter.

Fractography of granite joints

In granites all fractographic features known from other rocks are developed, corresponding with the fact that the same fractographic features can develop in any brittle material. The length of joints range between a few metres and nearly 100 m, therefore shape and surface morphology of granite joints are best exposed in large quarries (e.g. SBP), or in cliffs or roadcuts of decametre height and length in mountaineous areas (e.g. Sunne Granite, Sweden, Fig. 5).

According to our field observation the petrological composition and the lithological grain pattern of the granites can be ignored for the purpose of this study, because in most plutons the grain size and fabric are small features relative to the size of the joints. However, the precise modulation of joint surface features is best developed in fine-grained rock.

Some joints in granites reflect an undisturbed fracture progress from the point of origin to the natural termination of the fracture, including the adjacent unfractured rock. Unconstrained fractures form as quasi-circular or quasi-elliptical surfaces that are seldom truely planar, the low bending of the joint surface is sometimes beyond measurability. Some joint surfaces have multiple curved boundaries between the parent joint and the fringe (Figs 2, 3, 5 and 6c) that demonstrate individual propagating crack-tip sections. Only constrained fracture propagation results in all the other fracture types that are discussed in literature.

Fine or strong plumose structures (Hodgson 1961), consisting of ridges and grooves of mm- to cm-width marking the propagation path, and locally frequent rib marks or undulations in the form of tilted panels or rounded forms (Kulander & Dean 1995) occur on joint faces of magmatic rocks (Figs 3 and 5). Near the periphery the fracture often deviates from the main plane and forms well-developed tilted fringes with twist hackles (Kulander *et al.* 1979). They propagate in the form of gradual en echelon segments, termed by Pollard *et al.* (1982) as dilatant echelon cracks. The fringe is most commonly divided into planar en echelon fringe cracks,

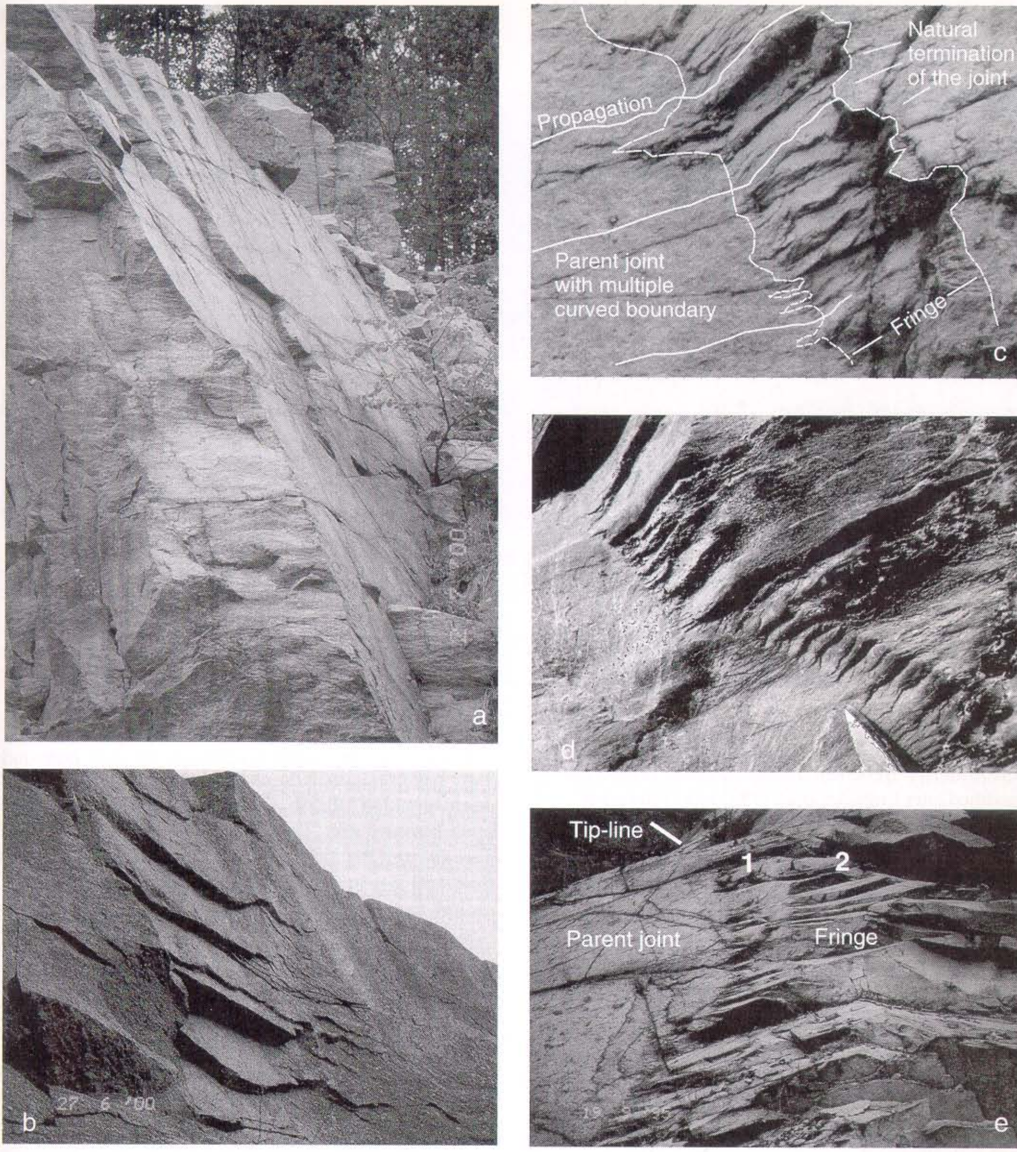


Fig. 6. Gradual en echelon fringe cracks with low twist angles. (**a**) Upper part of a much larger granite joint that was propagating to the top, indicated by the increasing main step. The steps represent the temporary rim of large en echelon cracks that initiated near the centre of the joint like playing cards. One of them formed at the top fringe crack. Height of *c*. 5 m. Sunne Granite, Värmland, Sweden. (**b**) The lateral (left) fringe cracks were initiated at the parent joint (arrow). This N–S-trending joint (entire length >20 m) terminated at the earlier formed E–W joint that forms an open rupture at the face. Height of *c*. 6 m. Bohus Granite, Sweden, part of the Kungsklyftan near Fjällbacka. (**c**)–(**e**) Parent joints and their fringes with gradual twist hackles. Length of the fringe sections was about 70 cm. (**c**) Sunne Granite near Tosseberg, Sweden. (**d**) Fringe in Ordovician shale (Steinach Thuringia, Germany) compared to granite joints (**c**, **e**). (**e**) South Bohemian Pluton, Boršov quarry: fringe (right) with two rows of twist hackles (1) and (2). Length of the fringe section is 1.5 m.

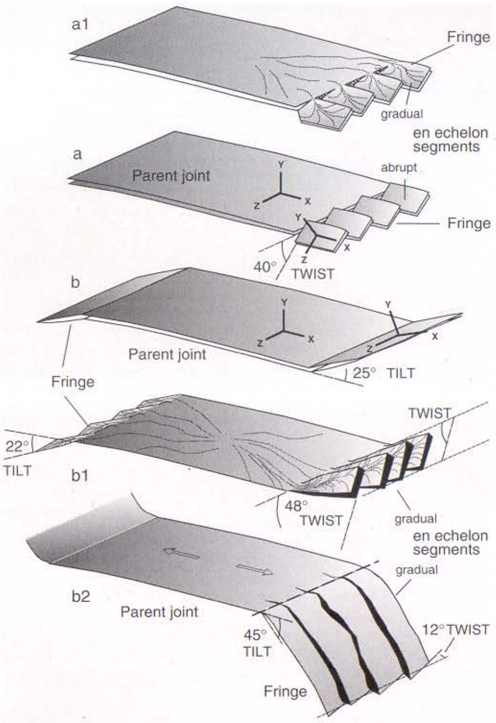


Fig. 7. Sections of joints and their fringes presented schematically. Basic features are shown in (**a**) and (**b**) modified after Engelder *et al.* (1993). (**a**) Joint with untilted fringe, occupied by abrupt en echelon fringe cracks. (**a1**) The untilted fringe with gradual en echelon segments (common in granites). (**b**) The fracture terminates with a tilted fringe, due to the rotation of the local stress field (x, y, z). (**b1**) Example of a parent joint initiated at the centre and propagated into a low-angle (22°) tilted fringe and gradual en echelon segments with large twist angles (48°). (**b2**) This fracture ends with a high-angle (45°) tilted fringe that is covered by low-angle (12°) twisted en echelon segments. The fractures in (b1) and (b2) are the result of mixed modes I + II + III acting at the advancing crack-tip. Type b1 occurs on a decametre scale in the Central and the South Bohemian Pluton, and in the Strzegom Granite of the Sudetes; type b2 occurs within the Bohus, Flossenbürg and Mte. Capanne granites.

whereas the hooked type (Engelder *et al.* 1993) in the studied granites is rare. Figure 7 shows gradual and abrupt fringe cracks, and various degrees of fringe tilt and fringe-crack twist. The figure only illustrates sections of a joint given in the photographs of Figure 6, and not the complete rock fracture. Many gradual fringe cracks occur in various directions around the parent joint, following the curved rim of the parent joint (Fig. 5); however, these fringe cracks are often concentrated at two opposite edges of the joint. Within granites the low-grade curvature of the main planes and the deflection of their fringes reflect the local change in the principal stresses at the advancing crack tip and the response of the fracture to grow perpendicular to the direction of least stress (Lawn & Wilshaw 1975).

It is common knowledge that fractographic features are produced when the joint deviates locally from its mean plane of propagation. Deviations are attributed to tensile crack-tip stresses that are affected by various factors, mainly by the amount of strain energy released, and changes in propagation rate and in far-field stresses. Even though these far-field stresses may cause mode II or III shear loading, according to Kulander & Dean (1995) resultant crack-tip stresses in a brittle material are tensile.

We avoid repeating figures and definitions for the fractographic terms because these have been discussed and illustrated in the literature, especially in general views by Kulander *et al.* (1979, 1990), Pollard & Aydin (1988), Bahat (1991), Engelder *et al.* (1993), Kulander & Dean (1995) and Younes & Engelder (1999), and in early papers, e.g. Woodworth (1896), Hodgson (1961), Bankwitz (1965, 1966) and Bankwitz & Bankwitz (1984).

Key study areas of verified granite intrusion depth

Two key areas provide examples of a shallow and a deep intruded pluton to compare their first developed fracture sets. The shallow intruded Erzgebirge granites and the deep-seated emplaced SBP, of more than 150 km in length, have been well studied with regard to their geology, tectonics, petrology, mineralogy, gravity, magnetic, deep seismic sounding and, finally, also their fractography. Several thousand joints were interpreted by the authors. The Erzgebirge granites (granite (6) given earlier) intruded within the uppermost 3 km of the crust (Thomas & Klemm 1997), the exposed part of the SBP ((1) in the list given earlier) was solidified at 7.4 and 14.3 km (Bankwitz *et al.* 2004), in the northern and southern part, respectively.

Relative sequence of joints: Eibenstock Pluton of the Erzgebirge

A lot of plutons (e.g. Eibenstock, Aue and Geyer) intruded the Variscan metamorphic series of the Erzgebirge (SE Germany). Their joints were formed at relatively shallow crustal levels. The timing of the first fractures has yet to be determined and whether these first fractures formed at the intrusion depth or during uplift by unloading. The Eibenstock Pluton represents a large laccolithic intrusion (exposed area of 20 × 40 km) with complex fracturing. The orien-

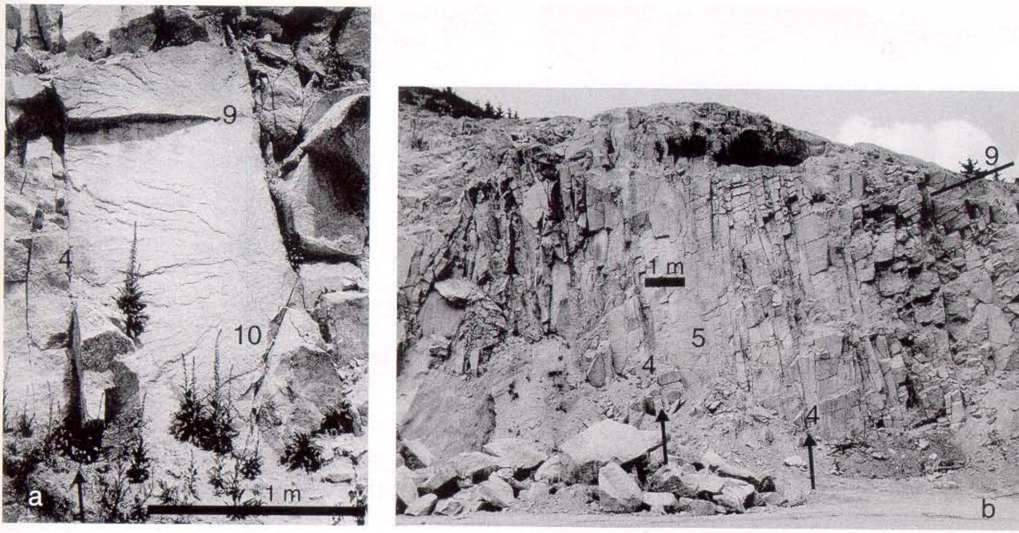


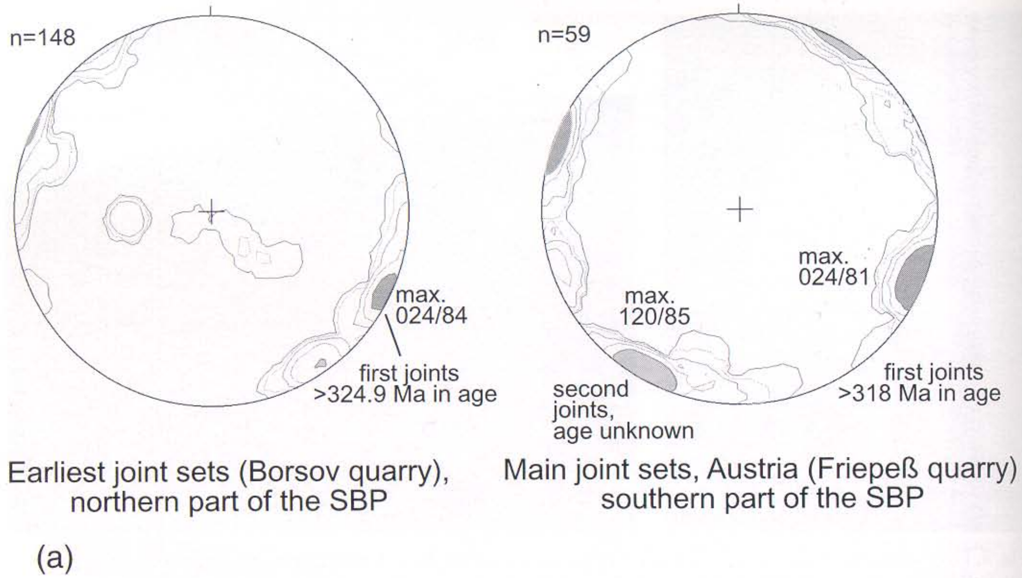
Fig. 8. Eibenstock Pluton, Erzgebirge, Germany (Blauenthal quarry). Bars, 1 m in length. (**a**) Surface morphology of late E–W joints (10) terminating at previous N–S joints (4). (**b**) Fracture sets 4, 5 and 9 (Fig. 4).

tation of the joint sets and their successive formation is shown in Figure 4a. The synoptic diagram from various parts of the pluton is based on 28 single diagrams, each of them with 50–100 relationships between two, or sometimes three, interacting joints (containing 100–200 joint measurements). For each joint its termination at a pre-existing joint was determined. Only the spatial and sequential coinciding maxima of all 28 single diagrams were marked within the synoptic diagram (Fig. 4a). We managed to distinguish between eight dominating joint sets. The earliest formed joints are always flat-dipping 'lager' joints (Cloos 1921). Such subhorizontal joints are significantly different from post-uplift sheet fractures. Steeply dipping orthogonal joint systems consist mostly of joint sets formed at different times. The relative sequence of joint formation is similar in the three granites of Figure 4a. The Aue ((b) in Fig. 4a) and Geyer ((c) in Fig. 4a) granites occur as diapirs within NW-trending prominent fault zones of the Erzgebirge. The fault zones influenced the geometry of the granite bodies and probably the small difference of joint set orientations within the Aue (sets 2 and 3) and the Geyer (sets 2a and 2b) granites.

Each joint set has a definite spatial distribution and orientation. Figure 4b demonstrates schematically that only parts of the pluton fractured at one time (fracture phases 3–8). All joints are steeply dipping with the exception of set 1 and set 9. The jointing-free area within the diagrams of Figure 4b indicate two aspects. First, large regularly arranged and dominating joints were not recognized there. Second, joint relative age data are not equally distributed through the whole pluton due to a lack of good exposures at some locations. At all outcrops within the pluton joints do occur, but not in all cases are these joints suitable for relative age determination. Even so, in certain areas that had regular jointing of defined relative age the age of the joints is seen to shift several times following the formation of a later joint set, mostly with changed orientation. Their temporal relationship could be proved, however; for example, the E–W joints developed first in the centre of the pluton (phase 3) and later in the eastern part (phase 5), determined by the occurrence of joint set 4. The N–S joints (set 4) are subsequent to set 3 in 'area 3', but pre-existing in 'area 5' at the time when joint set 5 was formed. After the earliest fracture formation during stage 1, the jointing shifted temporally in a 'wave-like' manner, first from the centre to the east and than back to the west (stage 2). Finally, sheet fractures (set 9) formed and latest vertical joints of smaller dimension (set 10, stage 3) abutted on set 9. The photographs (Fig. 8) show the closely spaced large N–S joints (set 4) as open fractures and the quarry face consisting of E–W joints (set 5) terminating at the former set.

The dense fracturing is completed by very narrow developed sheet fractures (set 9; 5–20 cm spacing). The earliest joints of set 1 and set 2 were formed at a greater distance of several metres, and in many places is filled with hydrothermal U-mica precipitate. In the Blauenthal quarry (dot in Fig. 4) the NE joints (set 4) are also covered by greenish micas that are not observed at the other younger joint sets.

Within the Eibenstock Pluton low surface morphology of joints is dominant. The joints are



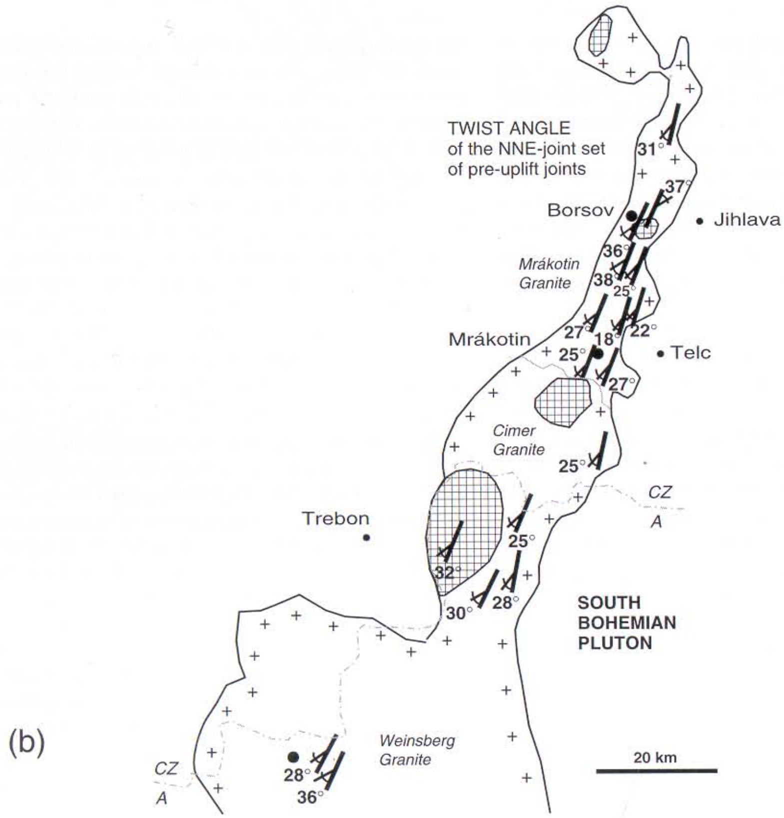


Fig. 9. South Bohemian Pluton (SBP): (**a**) lower-hemisphere stereographic projection of joint orientation within the Mrákotín Granite (Boršov quarry, CZ) and the Weinsberg Granite (Austria). (**b**) Geological sketch map of the SBP showing the regular orientation of first formed vertical fracture. Dots, locations of investigated fluid inclusions (Bankwitz *et al.* 2004) and diagrams in (**a**). Cross-hatched areas are granite bodies in the axial part of the SBP (Breiter 2001).

characterized by low twist angles, and undulations (rib marks) of the joint surface are lacking. At several locations tilt angles are between 30° and 45°, and more are developed.

Relative sequence of joints: SBP of the Bohemian Massif

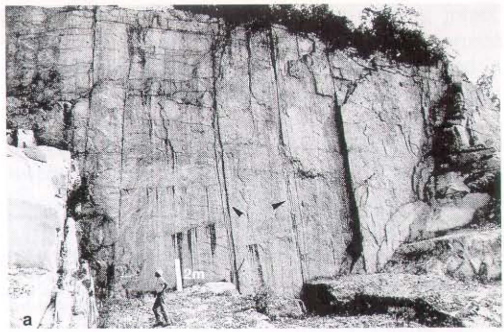
Within the deep-seated SBP fracturing and distribution of joints are quite different from the shallow intruded Eibenstock Pluton. The dominant early subvertical fractures (025°) are regular and remarkably persistent through the whole pluton (Figs 1 and 9) suggesting that these fractures formed contemporaneously.

In the northern Mrákotín Granite of the SBP (e.g. in the Boršov or Mrákotín quarry) some appproximately E–W-trending joints could be recognized as being the oldest subvertical fractures that occur very sparsely, spaced at >50 m. These exceptional joints have not significantly influenced the predominant 025°-set. The NNE-trending joints are, in part, widely-spaced (distance 3–7 m, rarely 2 m), but often developed contemporaneously within the narrow fracture zone (*c*. 40 cm wide). There, several joints are closely spaced, each single joint between 5 and >60 m in size (Fig. 10b; e.g. traced at the free surface of the 120°-joint in Fig. 10a). These narrow initiated joints have interacted several times and during further propagation have moved closer to one another, finally forming a composite joint. The majority of the orthogonal ESE joint sets (*c*. 120°) were clearly formed later (Fig. 10a).

The vertical joint surfaces are seen to be decorated with plume structures, and, in some places, with frequent undulations (rib marks) and twist-hackle fringes. During a late uplift stage large subhorizontal sheet fractures developed close to the present erosional surface, spaced between 0.1 and >3 m apart, but this spacing decreases towards the surface.

Within the southern Weinsberg Granite (deepest exposed part of the SBP with a palaeodepth of 14.3 km), the NNE-trending joints (025°) represent the first formed set and consist of closely spaced large fractures, mostly arranged in zones. These joints were filled with fluids during, or immediately following, formation. The fluids deposited biotite, muscovite and chlorite within the joints. The 120°-joint set with a peculiar low surface morphology was clearly developed later and without any phyllosilicate deposits; it is always seen to terminate at the NNE joints.

In contrast to the shallow Eibenstock Pluton, a large variety of joint surface morphology exists within the SBP with respect to type and size of plume structures, frequency of undulations, and degree of tilt and fringe-crack twist. In general, the amount of fringe tilt ranges between 0° and 25°, which is much smaller than in the Erzgebirge. The fringe cracks show a wide range of twist angles.



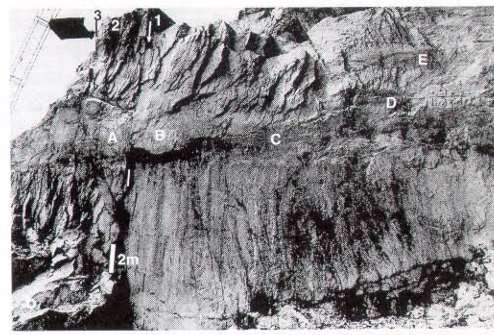


Fig. 10. Mrákotín Granite of the northern SBP (Mrákotín quarry). Bars, 2 m in length. (**a**) E–W joint, later formed as the exposed traces of N–S joints at the face (height is *c*. 16 m). (**b**) Pre-existing N–S joint (60 m long in the photograph) with regard to (**a**); however, demonstrating three traces (1–3) of rare earlier formed E–W joints. Supposedly, both sets were interacting. Height of quarry faces is *c*. 22 m.

Field data referring to regularities of tilt and twist angle combinations

Location and form of fringes

Fringes of granite joints can form around the entire boundary of the parent joint (Fig. 5), but we found that fringes frequently developed at the upper and lower edge of the joint plane. The early, subvertical fractures considered here formed large fringes, in part at great depth, mostly at the fracture edge perpendicular to the *z*-axis (*z* being depth). Usually, the previously laterally advancing fracture front leaves the parent joint propagating vertically (Fig. 10b), and is associated with breaking into gradial en echelon, but disconnected, twist hackles. However,

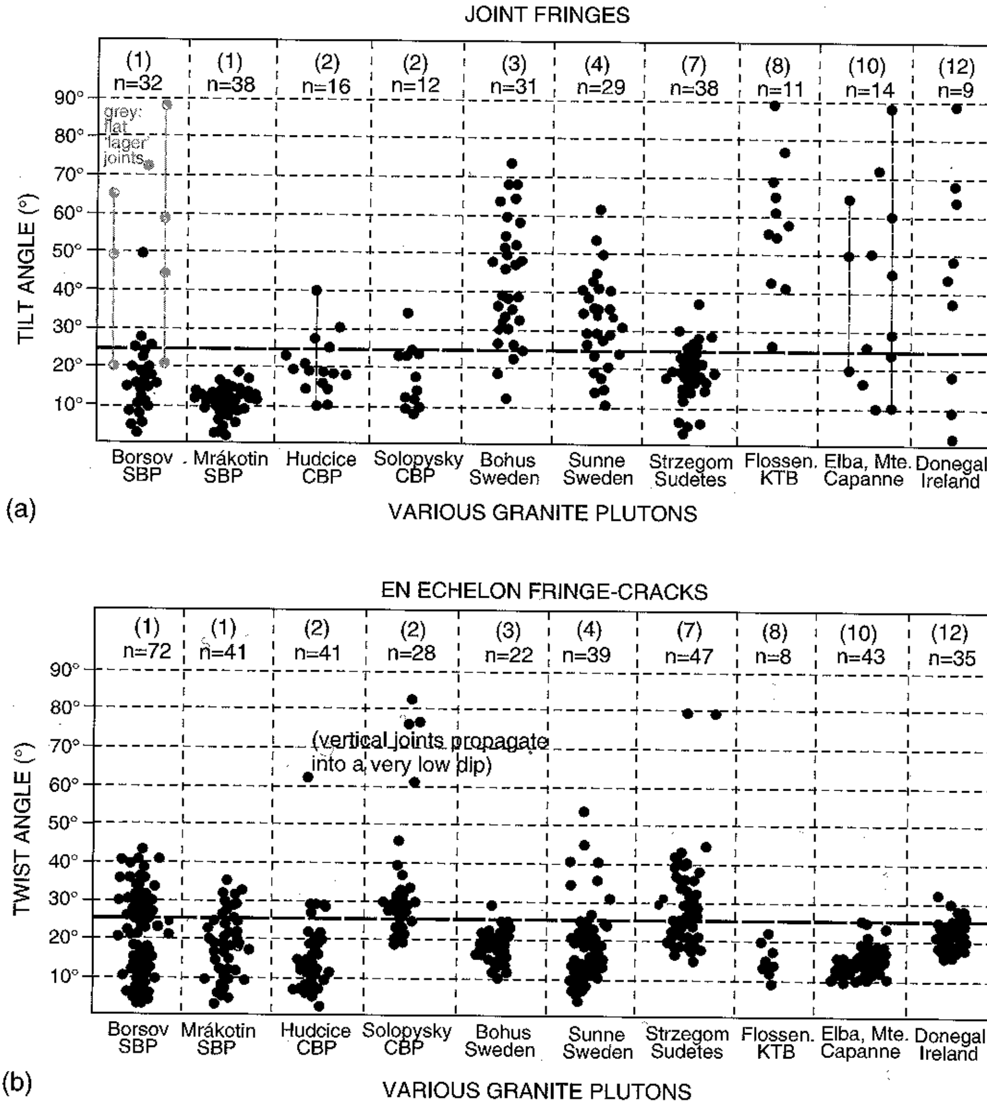


Fig. 11. Joint fringes from eight different plutons. Numbers in brackets are plutons according to the listed numbers in the paragraph section 'Plutons studied with regard to their joint features'. (**a**) Fringe tilt angles. Deviation of the fringe from the plane of the parent joint (grey: fringes of the earliest subhorizontal joints). Lines connect several fringes around the same initial joint. (**b**) Twist angles of en echelon fringe cracks. The angles define the rotation of the en echelon segments about the axis of joint propagation out of the fringe plane. SBP, South Bohemian Pluton; CBP, Central Bohemian Pluton; Flossen. KTB: Flossenbürg Granite (Bavaria), near the KTB (Continental Super-deep Borehole).

lateral fringes at the edges parallel to the z-axis were also developed (Fig. 6b), independent of whether the parent joint propagated laterally or vertically (Fig. 2a). The degree of tilt can slightly change at the various joint edges, but remains below the average tilt values of the defined fringe type.

Within the shallow intruded plutons we found a similar distribution of smaller fringes around the parent joints; however, a preference for vertical progress is absent and lateral fringes may be dominate. The trend of increased tilt angles in shallow intruded granites was recognized on joints of all ages.

Figure 11 summarizes the occurrence of fracture tilt and twist angles in various granites, demonstrating the remarkable differences between them. Also striking is the varying size of the fringes and their fringe–parent joint relationship. The trend of the different fringe/parent joint ratios which ranges in shallow intruded granites between 0.02 and *c.* 0.5, and in deep plutons between 0.2 and 1–>5.

Field data of fracture parameters

The size of granite joints hinder measurements of all twist-hackle orientations, and twist and tilt angles. Thus, Tables 1–4 offer some examples of individual first steeply dipping joints representing dominant types of fractures within the SBP and, in addition, within the CBP. Records of twist angles were sometimes completed using measurements of fringe tilt angles. Table 1 demonstrates the case of subparallel parent joints, initiated nearly in the same plane, that intermatch and form one composite quarry face (length, 60 m; Bahat *et al.* 2001) similar to the joint bundle (1–4) in Figure 2. The parent joints of various dimensions approach the same elliptical joint surface ratio after the formation of their fringes. Table 2 shows the complexity of surface structures of one individual joint that characterizes the predominant fracture set (025°) of the pluton. Tables 3 and 4 demonstrate the peculiarity of early subvertical joints in the CBP to tilt at the lower end into flat fringes. At localities where the deep-seated CBP (Solopysky and, in part, Hudčice) was poorly fractured, particular fringes in the vicinity of the circular or elliptical parent joints were recognized. From the lower edge of some subvertical and some oblique (*c.* 50°) dipping joints, in particular, the fringe was seen to tilt into a flat dip, thus forming elliptical niches several metres in diameter in the rock without undergoing interaction with other joints.

Remarks about plotted data

In Figure 11 tilt and twist data of joint fringes, that are characteristic of each granite, from various plutons in Europe are given. In spite of the numerous measurements, these data represent only a small insight into a number of existing explanations for the history of fracturing plutons. Here, the recorded tilt and twist angles of selected early steeply dipping joints are considered, together with other associated fracture patterns, in an attempt to determine whether defined combinations accumulate at special crustal positions of the plutons and at definable moments of the granite history.

The data in Figure 11 suggest significant variations of tilt and twist angles in different granites. Within the SBP and the CBP (columns 1–4; nos 1 and 2) predominant small tilt angles were observed, as in the Polish Strzegom Granite (no. 7). In addition to the low tilt of the first steeply dipping joints, exceptionally large fringe tilt angles of early formed subhorizontal joints ('lager' joints) were plotted in grey in Figure 11a as anamalous values. All other granites show a remarkably wide range of tilt angles, including large tilt angles up to 90°, such as the Bohus and the Sunne granites (nos 3 and 4), the Flossenbürg Granite, NE Bavaria (no. 8), the Mte. Capanne Granite, Elba (no. 10), and the Main Donegal Pluton, Ireland (no. 12).

The twist-angle diagram (Fig. 11b) presents, however, the converse, that is larger twist angles in the Boršov, Solopysky and Strzegom granites, and in part in the Mrákotín Granite (nos 1, 2 and 7), and contrasting low angles in the Flossenbürg, Mte. Capanne and Donegal granites (nos 8, 10 and 11). These records suggest the combination of large tilt and low twist angles, and vice versa. However, two exceptions exist; joint measurements within the Hudčice and the Sunne granites do not well concide with these combinations.

Furthermore, the identification of this combination of angles involves only trends, indicated by the frequent occurrence of the two main combinations of angles, sometimes related to only one defined joint set. Other joint sets with formation at another time, however, may show another type of tilt–twist combination. In Figure 11 the first steeply dipping joints of a granite were considered. Relatively later formed sets of the whole joint sequence may follow another trend of tilt and twist angle combination, depending on a later moment of pluton history and, thereby, on different crustal-level conditions or, perhaps, on a change in the former stress anisotropy.

In this context it is of note that the joints within the Mrákotín Granite (South Bohemian Pluton, Fig. 9) vary significantly at two places that have a different geological position. Figure 9b shows the greater part of the SBP with the northern Mrákotín Granite and the southern Weinsberg Granite, which have nearly the same intrusion age (330–320 and 328–318 Ma, respectively; Breiter & Koller 1999). There are some other granitic bodies, but this chapter is not the place to report on them. Čiměř Granite is, in fact, a local name for the Mrákotín Granite, and, accordingly, the Mrákotín quarry is located in the centre, and the Boršov quarry in the northern part, of this granite.

- The Mrákotín quarry is characterized by a predominantly orthogonal system of early subvertical joints, each set having a different surface morphology. Both sets have interacted in a few places, indicating, in part, a contemporenous development of both sets. But the NNE set was predominant in the first formation, characterized by relatively low tilt and low twist angles (Table 1). Only this first steeply dipping NNE set (025°) was considered in Figure 10.

Table 1. *Fracture parameters of one 025°-joint bundle, Mrákotín quarry (SBP)*

Joint	Main joint L × W (m)		Main joint ratio L/W (m)	Lower fringe L × W (m)		Upper fringe L × W (m)		Joint ratio L/W (m)	Mean twist angle of the fringe cracks
A	17.0	4.0	4.4	16.0	4.0	16.0	4.0	1.3	**26°**
C	13.0	1.6	8.1	13.0	8.0			1.4	**20°**
F	10.0	0.5	4.3	10.0	4.0	10.0	1.0	1.4	**25°**

Explanation: L × W designates (length × width), i.e. lengths of long and short axes of ellipses, respectively; L/W designates ratio of long/short axes. In Tables 1–4, bold numbers are values from Figures 13 and 14.

Table 2. *Fracture parameters of one individual 025°-joint, Boršov quarry (SBP)*

'Trefoil joint'	Fringe tilt angle		Twist angle of the en enchelon fringe cracks		Mean	Range (±2°)
Northern rim:	Fringe 1	+9°	Northern rim:	Fringe 1	–	
	Fringe 2	−8°		Fringe 2	–	
	Fringe 3	–		Fringe 3	**37°**	**26°–41°**
Southern rim:	Fringe 1	+3°	Southern rim:	Fringe 1	–	
	Fringe 2	+17°		Fringe 2	–	
	Fringe 3	+4°		Fringe 3	–	
	Fringe 4	+2°		Fringe 4	–	
	Fringe 5	–		Fringe 5	(a) **30°**	**25°–33°**
					(b) **41°**	**36°–44°**

Table 3. *Fracture parameters of selected Hudčice joints (CBP)*

			Twist angle of echelon fringe cracks		Tilt angle of the fringe	
Joint	Main joint orientation	Lower fringe orientation	Mean	Range	Mean	Range
A	261/55	F_1: 093/75, 080/75, 073/75			**18°**	**15°–25°**
		F_2: 097/87	–		12°	
B	282/40–45	*c.* 300/17–30	**6.5°**	**2°–18°**	**21.3°**	**10°–28°**
C	302/*c.* 90	342/75			***c.* 30°**	
D	299/*c.* 85	318/80			***c.* 20°**	

Table 4. *Fracture parameters of one of the Solopysky joints (CBP)*

Joint	Main joint orientation	Lower fringe orientation	Twist angle of the en echelon fringe cracks	Tilt angle of the fringe: Mean	Tilt angle of the fringe: Range
The en echelon segments (length: 8 m) initiated on the initial joint plane (length: >20 m) and tilted together with the fringe where they additionally twisted.					
1	110/80	F_1: 055/80	**18°–25°**	**25°**	**5°–28°**
		F_2: 050/56–29	**65°–70°**	**25°**	**20°–39°**
		F_3: 050/80	**24°–51°**	**30°**	**20°–35°**

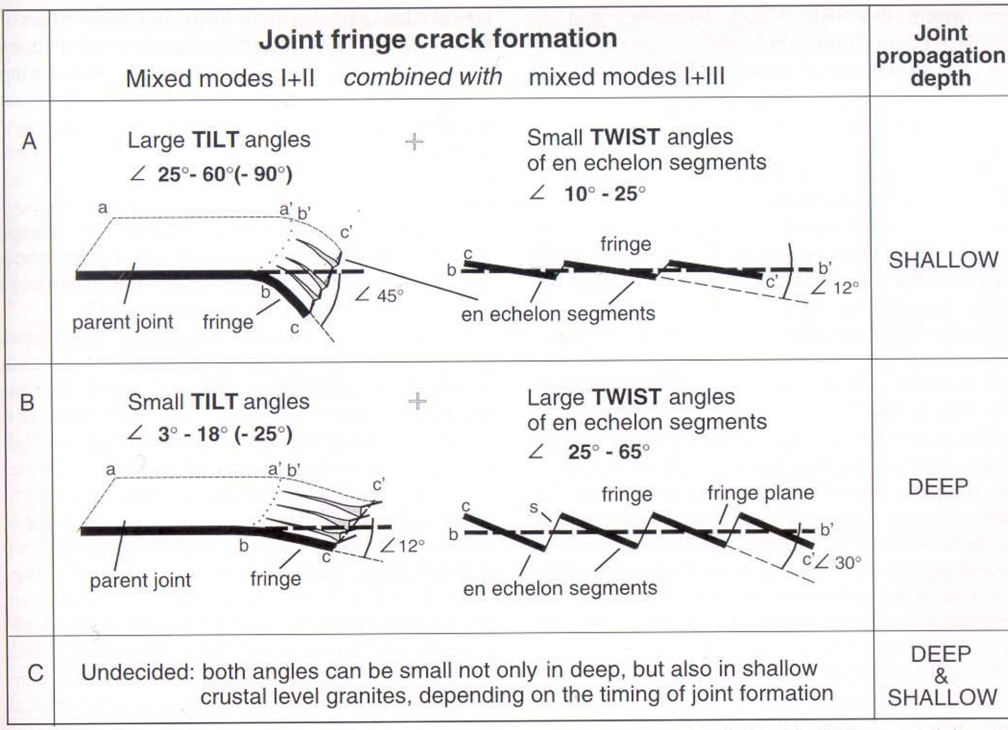


Fig. 12. Three groups of the tilt and twist angle relationship of granite joints can be distinguished. The parent joint plane a–a′ propagated out-of-plane into the fringe b–b′ to c–c′. Type A, high-angle tilted fringes (e.g. 45°) occur in most cases together with low-angle twisted en echelon segments (e.g. 12°). Type B, low-angle tilted fringes (e.g. 12°) are in most cases associated with high-angle twisted en echelon segments (e.g. 30°). The schemes illustrate sections of the joint. s, steps between the individual en echelon fringe cracks.

- The Boršov quarry to the north is governed only by a very regularly developed NNE set (025°/90°) that demonstrates a wide spectrum of fractographic features, including much higher twist angles, as found in the Mrákotín quarry. Obviously, tilt and twist angle are more uniform at the centre of the pluton. The map in Figure 9b shows larger twist angles, with average values of >35° in the southern and northern parts of the pluton.

In Boršov the joint features range between very low morphology associated with frequent undulations and joints with high-angle twisted fringe cracks (Bankwitz *et al.* 2000; Bahat *et al.* 2003). The Boršov quarry is located close to a former conduit of the ascending magma (Breiter in Bankwitz *et al.* 2001). But, in general, the trend of tilt and twist angle combination remains the same in both the Mrákotín and Boršov areas of the plutons.

Likewise within the Polish Sudetic granites, the early joint system occurs with different surface features depending on the orientation of the single sets. The dominating first N–S-trending set (0°–010°) is commonly characterized by small tilt angles and large fringe-crack twist angles (e.g. Strzegom, Fig. 11). By contrast, the relatively younger E–W joint planes are poorly covered with low fractographic indications, and in several places show only weak and smooth features. Such relationships between two early formed subvertical joint sets were recognized in various plutons.

Combinations of tilt and twist angles

One set of observations from this study involves the correlation of tilt and twist angles. Three main combinations were found (Fig. 12):

(A) strongly tilted joint fringes developed only en echelon cracks with very low twist angles within granites such as Eibenstock, Erzgebirge and Mte. Capanne, Elba (Fig.13);

(B) conversely, low tilted or almost untilted fringes are associated with fringe cracks that have high twist angles; the advancing fringe front remained within the initial fracture plane, e.g.

within the SBP (Czech Republic) and the Strzegom Granite (Poland);

(C) the third group of joints combines low tilt with low twist angles; these joints remain roughly within a plane.

The joints plotted in Figure 11 developed their characteristics (parent joint and gradual twist-hackle fringe) during the same fracture event and can be traced back to a single origin. We can consider the amount of the tilt and twist angles as the product of a single propagation event. However, Boršov joints and others with frequent undulations on the parent joint did not form in one pulse, instead they formed in increments within a period of slow propagation (e.g. Figs 3c and 5).

The occurrence of a special range of fringe angles within different granites suggests, in part, a correlation with the crustal depth of joint formation. The palaeodepth of pluton emplacement was determined for the SBP, and inferred from petrological, geological and geophysical investigations for the other granites. Taking this information into account, Figure 11 demonstrates depth-related tilt and twist relationships.

It is also important to consider when the fractures formed. In some cases, the first fractures may be initiated shortly after emplacement, during the early cooling of the granite. Evidence for that relationship comes from investigation of the SBP and the Bavarian Oberpfalz granites (Bankwitz *et al.* 2004). Mostly, the timing of joint formation is only estimated using associated features, such as fabric elements or the age determination of magmatic dykes, etc. Only the relative sequence of joint formation is commonly recognized. Nonetheless, one can ascertain that the deep-seated Bohemian plutons first fractured with small tilt and larger twist angles. However, the present-day shallowly intruded exposed parts of the Flossenbürg, Mte. Capanne and Donegal granites demonstrate first fractures with a large range of tilt angles and only small twist angles. Using this relationship, the trend derived from many investigated granites is noted in Figure 12 (right column).

Difficulties arise with the interpretation of the Bohus and the Sunne granites because neither their palaeodepth nor the timing of joint formation is well known. Both are intensely and complexly fractured, and may be related to the Precambrian age of the plutons and their long history. Concerning the trend derived from the plotted data (Fig. 11), it seems likely that the Bohus Pluton was fractured originally at more shallow crustal levels.

The graph in Figure 12 illustrates the geometry of two individual joints that are characteristic of the two main combinations of angles. We consider subvertical joints with fringes that formed both at the lateral edges and also at the lower and upper edges of the joint plane. The tilt and twist angle combinations associated with lateral or vertical propagating fringes are the same if the joints are part of the same set; although type A and type B are not related to a preferred location on the joint. It is of note that types A–C in Figure 12 have nothing to do with the fact that on one individual fringe, surrounding a quasi-circular joint, tilt and twist angles can change slightly producing sections with varying morphology. These variations range below the differences between fringe types A and B.

Significantly, changing occurrence of fringe types A and B within an identical joint set was not observed. More shallow initiated joints demonstrated a mixture of different fringe types because it is understood that such joints do not form only high tilt angles. Nevertheless, most of the large tilt angles associated with early subvertical joints are concentrated within shallow intruded granites, and fringe cracks with high twist angles are absent. Within deep granites fringe type B predominates, and fringe types A or C will only be connected to other joint sets of various relative ages, or those that also occur as first formed joints, within other plutons of various intrusion depth. Later formed joint sets could not develop in an homogeneous and isotropic material, which is the premise to recognize unconstrained mechanical behaviour of cracks. We are focused only on first formed joints, therefore we have to consider the depth-related variation of angles.

Figures 13 and 14 provide visuality for the data and the argument for depth-related variations by plotting tilt and twist and depth together. The two groups of plutons in Figure 13 show significantly different patterns of joint tilt v. twist. Only first formed steeply dipping joints were used. Both groups contain one pluton with an exactly determined palaeodepth of emplacement (Thomas & Klemm 1997; Bankwitz *et al.* 2004): the deep-seated SBP and the shallow intruded Eibenstock Granite (Erzgebirge, Germany), respectively. The detailed plotted joint pattern of both groups suggest that they are correlated with the depth of joint formation, noted in Figure 12, that low tilt and high twist form associates with deep intrusions, and, conversely, that a high tilt–low twist combination is present in shallow emplaced granites. Both groups also involve strikingly low values of tilt and twist within a wide range of data from each of the granites.

In general, this assumed relationship is contradictory to the stress (σ) conditions, because σ_{zz}. (z being depth) should not influence the tilt angle of a vertical joint. The fringe is caused by rotation of the local maximum tensile stress in the x–y plane (Fig. 4). The vertical stress component (σ_{zz}) is in the fracture plane and all shear components in this direction equal zero. Only shear stresses perpendicular to the

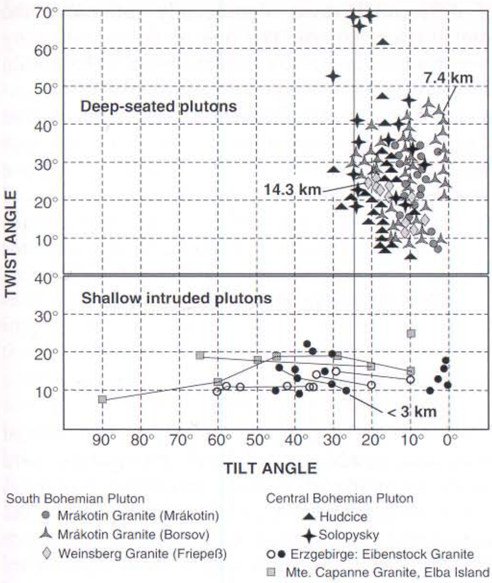


Fig. 13. Characteristic relationships between twist and tilt angle of early granite joints in different plutons. The trend occurs that in deep-seated plutons first formed joints developed small tilt and large twist angles. In contrast to this, in shallow intruded granites widely spaced early joints occur often with high-angle fringe tilt and low-angle twist of the fringe cracks.

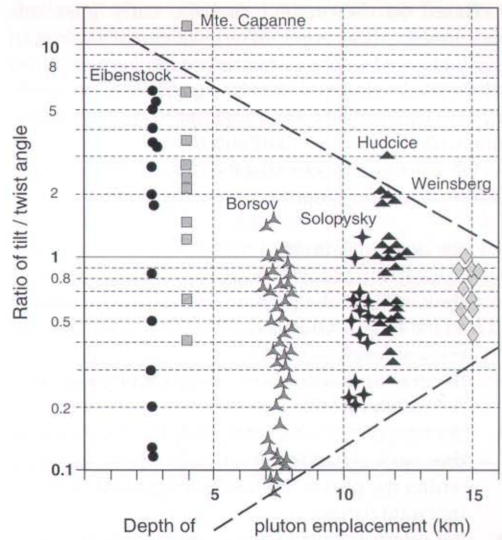


Fig. 14. Logarithmic tilt/twist ratio v. palaeodepth of pluton emplacement for values are plotted in Figure 13. They show a noteworthy relation. The most shallowly intruded pluton (Eibenstock, Germany) represents the widest range of ratios, the deepest pluton (now exposed) is characterized by the smallest range of data between 0.5 and 1.0. Symbols as in Figure 13.

fracture plane could force it to tilt. Therefore, the degree of tilt should be independent of depth (Younes, pers. comm.). But, exposed steeply dipping joints are not always strictly vertical and often dip about 80°–70°, so that σ_{zz} can act at the joint plane. The dominance of type A or B associated with different intrusion depths of the granites is evident.

The favoured occurrence of fringe types A and B in defined plutons implies that the tilt/twist ratios should decrease from the shallow to the deep-seated granites. If further detail is required, Figure 14 reveals a specific trend of granite joints with respect to the depth of formation. The range of tilt/twist ratios differs widely and decreases, in fact, with increasing depth of the plutons and joint formation. The deepest formed joints (Weinsberg Granite, SBP) concentrates at a ratio of between 0.5 and 1. It is of note that the large ratios do not simply become smaller (Eibenstock to Weinsberg Granite), but the smallest ratios increase (Boršov to Weinsberg) and finally the plot field, limited by lower and upper broken lines, narrows at about a ratio of 1, or, to be exact, between a ratio of 0.5 and 1. Measurements of data leading to ratios below 0.1 for depths between 3 and 5 km are possible but need more attention. Obviously, a deviation of one order from ratio '1' exists, not only when increasing from deep to shallow crustal levels but also when decreasing. This data distribution probably indicates the increasing influence of the confining pressure.

Considering only first formed joints, one can possibly try to use tilt/twist ratios in certain granites to infer the possible depth of first joint formation. However, the depth of joint formation is not the only factor that decides the amount of tilt and twist angles, but it should be taken into consideration.

Discussion

Dependence on intrusion depth

On the basis of measurements of joints, angles of fringes and fringe-crack series in the Eibenstock Pluton (Erzgebirge, Germany), and in the granite plutons of the Sudetes (Poland) and of Bohemia (Czech Republic) we recognized a characteristic difference in joint morphology. The tilt and twist of fringes differs in granites with a shallow emplacement of less than 3 km, such as the Erzgebirge plutons (Thomas & Klemm 1997), and in granites emplaced at deep crustal levels, such as the SBP at a depth of between 7.4 and 14.3 km (Bankwitz *et al.* 2004).

Based on the premise that the early joint sets developed at the depth of emplacement during an early stage of cooling, which proved correct in the SBP (Bankwitz *et al.* 2004), the fracture morphology was considered in an attempt to find a correlation with the depth of joint initiation.

We have to consider that the difference in surface morphology may depend on several factors:

- the *depth* of intrusion of the pluton, with regard to early formed first joints;
- the *timing* of the fracture initiation, with regard to the emplacement, cooling and uplift into the erosion level;
- the *driving mechanisms*, as defined by Engelder & Fischer (1996);
- the type of *stress sources*: only local stresses, or those associated with regional stresses, included within the pluton that cause a regionally consistent joint pattern;
- the *relative tensile stress* (average remote stress plus internal fluid pressure) according to Segall & Pollard (1983);
- the *magnitude* of differential stress;
- the *stress intensity factor* and fracture velocity estimated in comparison with the Wiederhorn curve (Bahat *et al.* 2003).

Depth

From field investigations evidence for joint initiation at different crustal levels has been found. The palaeo-intrusion depth of several plutons was determined by fluid and melt inclusion; however, the greater part of the intrusion depth was derived from gravity data (Meurers 1992; Breiter 2001), seismic reflection data (Bohus Granite, Sweden, Lusatian plutons and Bavarian granites), modelling (Vigneresse 1999) and petrological data (Zulauf 1993; Siebel 1998). The Boršov joints initiated very early at 7.4 km depth, the Weinsberg Granite joints possibly at about 14 km. We suppose that many granites intruded at a similar depth between approximately 7 and 15 km, supported by geophysical modelling (Vigneresse 1999). Other plutons of different age (e.g. Caledonian, Ireland; Variscan, Erzgebirge; Cenozoic age, Elba Island) are assumed to have been intruded into shallow crustal levels. The joints within these granites can be formed between 3 km and several hundreds of metres below the present surface, because these pre-existing joints were cross-cut by subhorizontal sheet fractures.

Timing

The moment of fracture initiation, with regard to the emplacement and cooling stage, and the magnitude of differential stress significantly influences the joint-surface pattern. The age of the vein-bearing twist hackles in Boršov is determined to be within the early period of granite cooling and thereby connected with its depth. Evidence for no loss of argon comes from the method used, where purified micas were ground carefully in pure alcohol to remove alterated rims that might have suffered a loss of Ar or K. In this way, only the fresh cores of the muscovites were analysed. The excellent quality of the separates from the SBP is confirmed by the K_2O-content of more than 10% (Bankwitz *et al.* 2004).

Driving mechanism

The initiation of pre-uplift joints at deep crustal levels and, in addition within closed systems, were conducive to, in part, fluid-driven fracture formation in granite. Evidence for an internal fluid drive is the incremental propagation of joints (Lacazette & Engelder 1992) reflected among other features by frequent closely spaced rib marks in the form of tilted panels (undulations) of the initial planes and partly by multiple fringes (Bankwitz *et al.* 2000). Such features, known from sedimentary rocks that underwent compaction but were never deeply buried, are not common within granites and are best exposed locally in the Boršov (SBP) and Hudčice quarry (CBP), and the Bohus, Sunne, Bornholm and Mte. Capanne granites. Although igneous rocks have a very low permeability, fluids are present and not only as hydrothermal liquids. Fluids, including rest melts, are frequent in magmatic rocks (Thomas *et al.* 2000) and play a major role in the early period of cooling, e.g. after water separation from the crystallizing melt near the solidus, producing an overpressure (Bankwitz *et al.* 2004). This pressure increase in the cooling range between liquidus and solidus (Thomas 1994) can initiate fractures.

Secor (1969) predicted that fractures in impermeable rocks such as granites would be short and closely spaced, whereas the fractures in permeable rock would be long and widely spaced. However, the first formed joints in granite are often long and widely spaced, thus probably indicating that pressurized fluids were present at the moment of fracture formation.

Frequently, the fringe propagated into strongly twisted gradual fringe cracks (length of 2–4 to 8 m) with large overlap (metres), indicating the influence of regional stresses. This means that, after a first period of slow and incremental fracture growth, remote stresses increasingly governed the further propagation of the parent joint into such complex fringe cracks. Thus, the fluid-driven fracturing may operate together with other driving forces when progressing.

Stresses

Such joints indicate at least a relatively high magnitude of the remote stress and high differential stresses even at crustal levels of about 10 km in depth, as was also found at the KTB (Bavaria). (KTB stands for Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland, or German Continental Deep Drilling Programme.) Segall & Pollard (1983) calculated for joints in granitic rocks of the Sierra Nevada relative tensile stresses (average remote stress plus internal fluid pressure) of approximately 0.1–0.4 kbar. Within a solidifying magma the overpressure after water separation near the solidus amounted to 1.5 kbar (theoretically up to several 10 kbars for constant volume conditions: Burnham 1979). The increase in H_2O pressure of 1.5 kbar, measured in the Erzgebirge granites (Student & Bodnar 1996) and in the SBP (Bankwitz *et al.* 2004), can initiate fractures. The initial driving force within igneous rocks may be fluids, even, or particularly, during the first period of fracturing. Younes & Engelder (1999) assumed the initial pressure during jointing in sedimentary rocks to be approximately 0.8 kbar, this is half of the pressure increase in solidifying magmas at the solidus. Thus, the fluid pressure near the solidus, within the early period of cooling, could initiate fractures.

However, jointing and the breakdown of the parent joint into regular twist hackles depends on the orientation and magnitude of the remote stress field, internal fluid pressure and the elastic properties of the rock. Supposedly, a large difference between σ_1 and σ_3 favours parallel joint sets and fracture-cleavage formation as recognized in Mrákotín. The more σ_1 is lowered, the more the joints will develop out of the main plane (Olson & Pollard 1989). The Mrákotín Granite (SBP, no. 1 on the list of granites given earlier in this chapter) provides examples for a high stress magnitude reflected by early parallel jointing of parent joints in bundles and of large en echelon fringe cracks.

Stress intensity factor and fracture velocity

Both stress intensity factor and fracture velocity correlate, as predicted by Wiederhorn *et al.* (1974) and, among other authors, by Rabinovitch & Bahat (1979). Compared to the parameters of the Wiederhorn curve, the position of the observed joint types can be estimated (Bahat *et al.* 2003). Obviously, the early formed pre-uplift joints of shallow intruded plutons are frequently low-energy fractures (significantly smooth, often covered only with faint plumes, both high- and low-angle fringes, and small fringe cracks), in spite of the general opposite assumption or expectation. Because shallow granites cool down faster and their fractures formed closer to the surface, one could expect that the joints should have higher energy for propagation, similar to unloading sheet fractures near the topographic surface. But numerous observations on first formed joints differ from this.

In contrast, within deep-seated plutons, high-energy fractures frequently occur with large fringes and dominant low tilt and high twist angles of the fringe cracks. Fracturing at great depth has not yet been completely studied. In part, first formed joints show characteristic high-energy style twist hackles, according to Bahat *et al.* (2001*a*, *b*) even hackle fringes were formed at some locations in the SBP.

However, locally restricted domains exist within the granites (e.g. Boršov) where initially cyclic growing low-energy fractures occur that after a period of slow propagation change the style, producing high-energy twist hackles.

Joint interactions

As far as possible we took care in this chapter to consider only first formed joints, and to avoid the research of joints that interacted with joints of other sets. Our purpose was to study the style of earliest joints in plutons. Therefore, the photographs mostly show joints that were not formed at their present location, even if their dominant upper fringes appear to correlate with the free surface. Within the Swedish plutons (Bohus and Sunne) Precambrian, Devonian and Permian dykes fill previously formed joints, thus confirming the ages and the defined palaeodepth of the hosting joints. These joint walls represent the same surface features as in Figures 5a, b and 6a, b at the present exposures.

Conclusions

Within granites, three frequent types of fringes can be distinguished by their tilt–twist relationship: Type A, high tilt angles correlate with low twist angles; type B, low tilt associates with high twist; type C, both angles are very small. Each of these fringe types, associated with first formed joints, occur preferentially in plutons with different intrusion depths. This points to depth being one factor in the development of various fringe styles. For three joints within the SBP the palaeodepth (7.4 and 14.3 km) and the timing of the joint formation (324.9 Ma) were determined, confirming the correlation of low tilt–high twist forms with deep joint propagation.

Deep-seated plutons frequently demonstrate high-energy fractures (fringe type A), but with typical differences of tilt and twist angles between the single sets in the joint sequence. The first formed joints have large, low tilted fringes with well-developed en echelon twist hackles and high twist angles. In contrast to this, the secondly formed joint surfaces are smooth, planar, and without or with low fringe angles.

In general, it seems to be a rule that in the case of high tilt angles the fringe plane breaks down only with a low-angle twist of its en echelon segments (low-energy fractures). Such a combination is characteristic of shallow plutons. If low-angle fringe tilt occurs, both variations of twist-hackle progress were observed, forming high or low twist angles. Which type of twist angle occurs depends on the driving mechanism and the fracturing condition (e.g. the magnitude of stresses, the time of jointing, pre- or syn-uplift related and the level of intrusion, deep-seated or shallow intruded pluton).

The tilt/twist angle ratio differs significantly in the various plutons. A wide range of ratios occur in shallow granites (0.1–8.0), which decreases towards a ratio of 1 with increasing depth of intrusion (to 0.5–1.0), thus indicating fringe tilt and twist formation under restrictive conditions due to the confining pressure at a depth of approximately 14 km.

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