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Changes of crack velocities at the transition from the parent joint through the en échelon fringe to a secondary mirror plane

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Abstract

A 'trefoil' joint in granite of the Bohemian Massif, in the Variscan belt of Europe, displays intriguing surface morphologies. It consists of 'primary' and 'secondary' mirrors as well as 'primary' and 'secondary' fringes, an arrangement not previously described. These fractographic features are seen to record two cycles of increase and decrease in fracture velocities. Fracture velocities increased along the propagating mirrors in association with the increase of released energy. However, beyond a certain velocity energy dissipated along the new multi-surfaces at the fringes, and this involved reduction in fracture velocities. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The transition from the parent joint to the fringe involves a characteristic increase in the morphological topography from delicate striae (plumes) to coarse en échelon segments (Fig. 1). There have been disagreements in the literature regarding whether fracture velocity decreases (Tipper, 1957; Kulander et al., 1979) or increases (Bahat, 1991, pp. 191–195) at this transition. Tipper (1957), working on fractures in mild steel plates, suggested that the curvature of the barbs (striae that mark the local direction of fracture propagation along a plume) outward towards the plate surfaces seemed to be accounted for by plastic flow which increased towards those surfaces with a corresponding retardation of velocity propagation. Also, arrested fractures showed that the center of the plate fractured ahead of the surfaces. Kulander et al. (1979) illustrated hypothetical fracture surfaces illustrating the use of plume geometry to approximate past fracture fronts, fracturing stress distributions, and relative fracture propagation velocities. In their diagram parabolic fracture fronts drawn at constant time intervals (and crossed orthogonally by plume barbs) indicated that actual fracture velocity and the corresponding effective fracture stress increased to a maximum along the plume axis, and decreased towards the joint fringe. Also, Bahat (1991, p. 192) pointed out that the fracture patterns on a glacier surface which reflected various degrees of retardation along the glacier banks somewhat resembled the experimental observations by Tipper (1957). Bahat (1991, pp. 191–195) on the other hand, presents seven arguments why stresses and fracture velocities could increase at the transition to the fringe.

The remarkable fringe of the trefoil joint from the Borshov granite quarry (see below) provides a unique example that should give an insight into the nature of energy and crack velocity changes at the transition from the parent joint through the fringe into a secondary mirror.

The objectives of this paper are to characterize the trefoil joint and to explain its mechanical features by referring to recent experimental results (Müller and Dahm, 2000), coupled with some fundamental concepts on fracture (Sommer, 1967, 1969; Sharon et al., 1995; Sharon and Fineberg, 1999). In order to facilitate the discussion we assume that crack branching (Sharon et al., 1995) and crack breakdown into en échelon segments belong to the same fracture 'spectrum' (Bahat, 1998), and their creation reflects conditions with different mode I/mode III ratios (opening mode/tearing mode, respectively) (Sommer, 1967, 1969). It is also important to note that research into crack branching criteria involves several basic physical parameters of interdependent relationships, three of which are mentioned below: (1) the critical velocity criterion; (2) the critical stress intensity (Lawn and Wilshaw, 1975); and (3) the energy requirements for branching (Johnson and Holloway, 1966).

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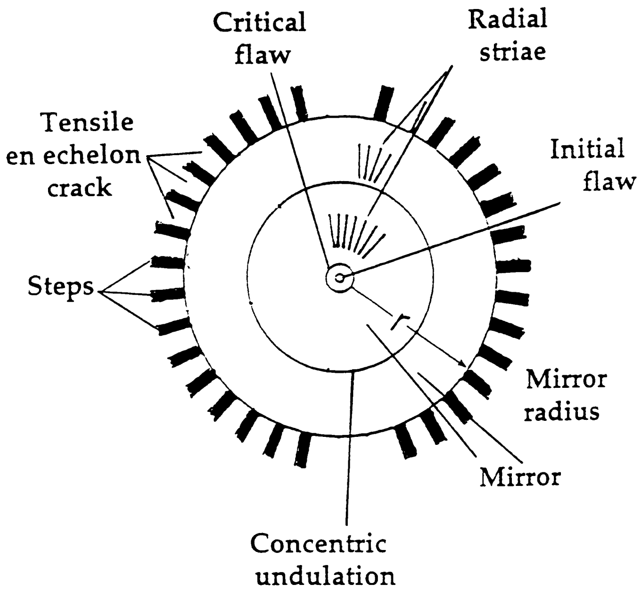

Fig. 1. Schematic representation of a fracture surface showing various fractographic elements: initial flaw (fracture origin), critical flaw, mirror plane, radial striae, concentric undulations (ripple marks) and the mirror radius, *r* (arrow), which is measured from the critical flaw to the inner boundary of the segmented fringe. Each segment in the fringe exhibits an en échelon tensile surface (white) and a sheared surface—the step (black) (not scaled).

2. Geological setting

The study area is located in the Bohemian Massif which is part of the internal zone of the Variscan belt of Europe (Fig. 2a). The South Bohemian pluton has late-tectonically intruded the core of an antiform composed of gneisses and schists (Benes, 1971). Its exposed crest runs NNE–SSW through the Czech part of the Bohemian Massif to northern Austria down to the Danube River over a distance of more than 170 km. The granite massif consists of two phases: the coarse-grained Eisgarn granite and the fine-grained Mauthausen granite. The studied Borshov quarry (Fig. 2b) exploits granite of the Eisgarn type. The intrusion age of this granite is 330 Ma according to Matte et al. (1990).

3. The trefoil joint

The 'trefoil joint' has an unusual appearance and its mirror plane deviates considerably from the common circular shape. Part of the mirror boundary extends downward as a 'big tongue' beyond the common circular perimeter and it forms the shape of a three petal flower (Fig. 3a, b). The mirror is marked by two types of undulation, concentric cu, and lateral ones, lu. There are two lu undulations on

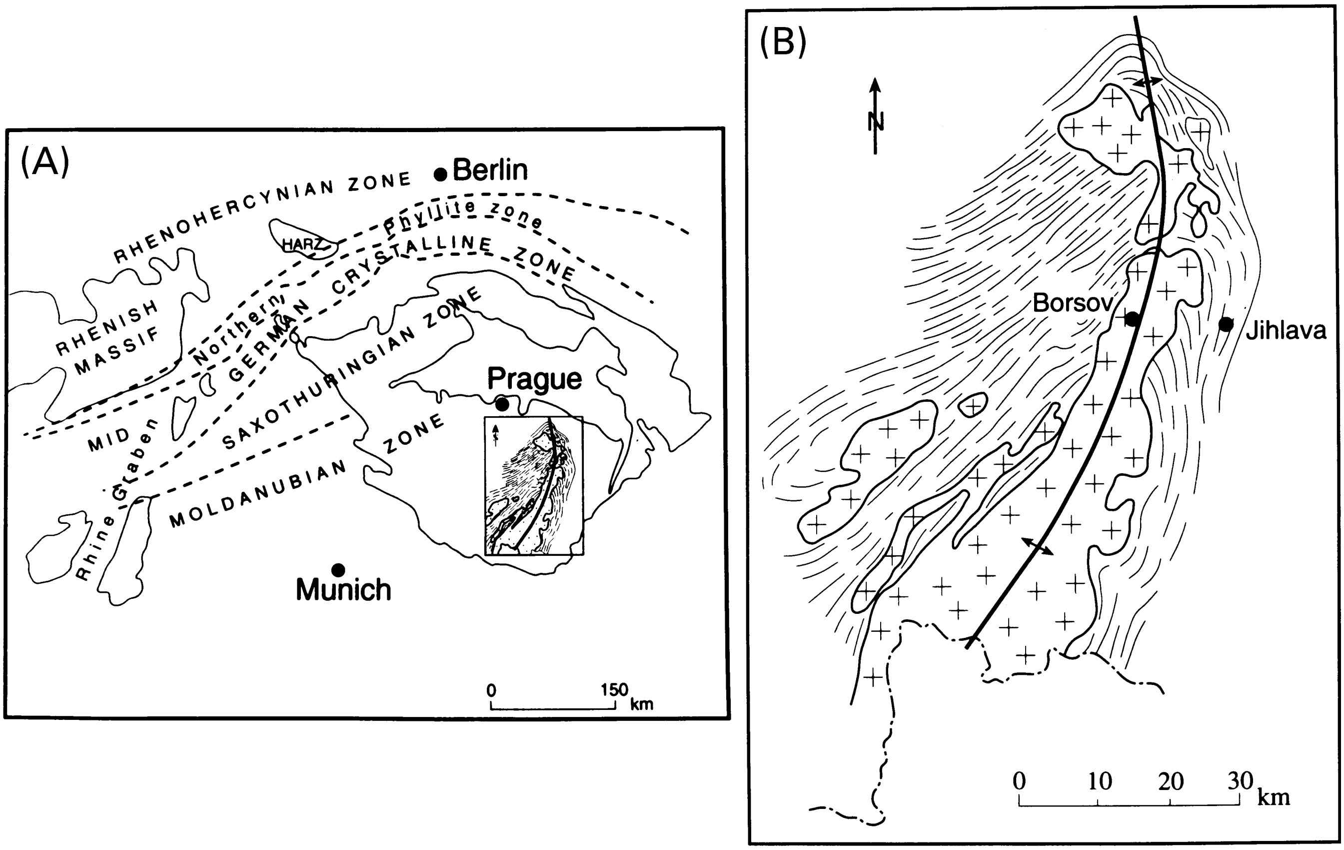

Fig. 2. (a) Simplified geological map showing the extent and internal makeup of the central European Variscides (modified after Dallmeyer et al., 1995); (b) is framed. (b) A simplified geological map of the South Bohemian Pluton (marked +). The axis of a major fold, the orientation of foliation of gneiss country rock on various sides of the pluton and the location of the Borsov quarry are marked (after Benes, 1971).

the left side of the mirror front, but there are no equivalent ones on its right side. A faint radial plume (not visible in the photograph) superposes both types of undulations, indicating downward and radial joint propagation. The two sides of the tongue contain large fringes that are intensely fractured, and their fracture styles differ considerably from each other. There is a resemblance in shape between the curvatures of the lateral undulations on the left side of the mirror and the curvatures of a

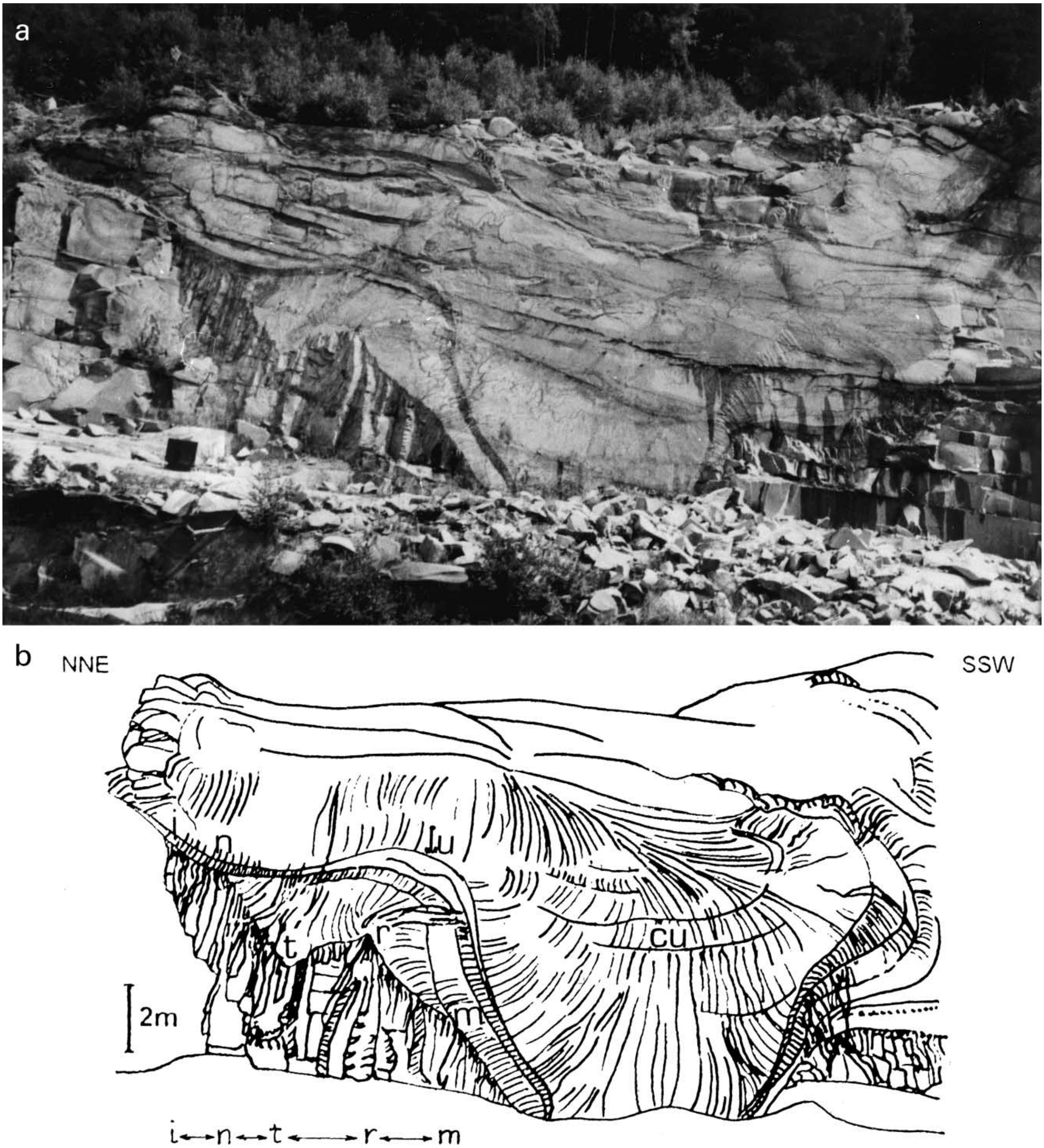

Fig. 3. (a) Photograph of the 'trefoil joint' that forms the shape of a three petal flower. (b) Drawing of (a). The primary mirror (PM) is marked by two types of undulation, concentric **cu**, and lateral ones, **lu**. A very delicate plume (invisible in the picture) is superposed on the undulations. The two sides of the PM contain intensely fractured fringes. The fringe on the left side is divided into four sections, bounded by i, n, t, r and m. The fringe on the right side of the PM has the shape of a fan which starts at a low side next to the mirror, and opens upward away from the mirror. This fringe is divided into five distinct sub-fringes. (c, d) Photograph and diagram of a 'normal' breakdown at r, resulting in alternating tensile en échelon segments, e and shear steps, "s". (e, f) Photograph and diagram of the 'secondary mirror' (SM) at t. The convex fringe of the SM is shown by an arrow. The vertical scale on the left of the SM is 2 m.

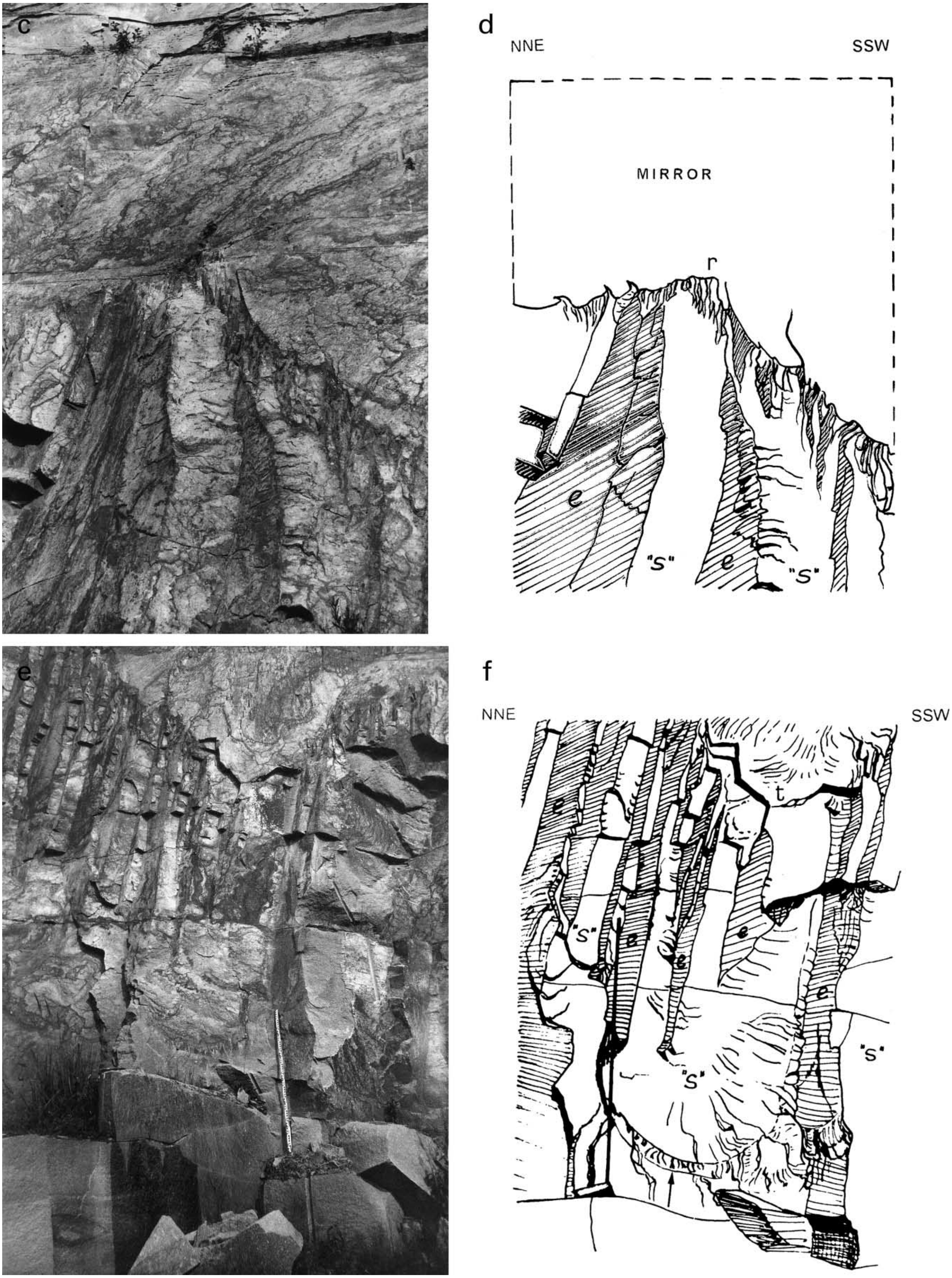

Fig. 3. (*continued*)

series of sub-fringes on the right side of the mirror. The mirror is divided by sub-horizontal parting planes that generally slightly dip from left to right; several of them cut the mirror and the two fringes without displacing them. Full descriptions of the fringe on the left (NNE) side of the tongue and the fringe on the right (SSW) side of the tongue are beyond the scope of this study. In this paper we focus on a particular relationship between a 'primary mirror', a fringe and a 'secondary mirror' that occur on a single joint. To the best of our knowledge such a fracture combination has not been discussed before in the geological literature.

The boundary between the mirror and the fringe on the left side of the tongue is not a continuous curve but a zigzag one. The fringe is divided into four sections that generally correspond to the zigzag boundary. These are from left to right, i-n, n-t, t-r, and r-m (Fig. 3b). Two breakdown types from the primary mirror to the fringe are shown from locations r and t. The first type relates to a 'normal' breakdown at r, resulting in alternating tensile en échelon segments, e and shear bridges (steps), "s" (Fig. 3c, d). The second type shows an 'abnormal' transition from mirror to fringe at t, where one of the bridges shows characteristic tensile features (Fig. 3e, f). We concentrate on the structure at t. Two growth styles of en échelon segments and steps can be distinguished in this location. The first style displays a vertical downward growth of alternating segments and steps from the boundary of the mirror of the 'trefoil joint' (the primary mirror) (Fig. 3e, f). The second style exhibits some six segments that merge into one step which is marked by a 'secondary' mirror plane with a semi-circular boundary and a fringe that are convex downward in continuation with the lengths of the segments that form the merger. Whereas all known bridges that link adjacent dilational en échelon segments in sedimentary rocks are shear surfaces, the linkage between adjacent segments shown here (Fig. 3e, f) is a dilatational one, exhibiting a 'tensile step'. Here we have a cycle starting from a primary mirror of the trefoil joint that transformed into a primary fringe which then continued to fracture into a secondary mirror transforming into a secondary fringe. What were the conditions under which this fracture process occurred?

4. Crack dynamics—previous experimental results and theory

We compare the observations on the mirror–fringe relationship of the trefoil joint (Fig. 3) to experimental results. Müller and Dahm (2000) formed plumes and fringe zones on surfaces of desiccation tensile cracks that were created by drying starch–water mixtures. Experiments were carried out on disk specimens of 50–100 mm in diameter and 2–40 mm in thickness. Fracture speeds in the range from spontaneous nucleation through initial dynamic velocities of 100–200 mm s^{-1} to quasi-static velocities of 0.1 mm s^{-1} or less were measured by videos and estimated from photos. Particularly relevant to the present study were their observations that, at transitions from the parent joints to fringes, the increase in topographic amplitudes, that is, enlargements in crack area were associated with reduction in fracture velocities.

The latter findings resemble the results obtained by Sharon et al. (1995). They experimentally applied tensile stresses perpendicular to a thin plate (0.8 or 3 mm in thickness) made of cast polymethyl methacrylate glass (PMMA). These authors found that cracks discontinue their straight propagation and become "unstable' beyond a critical velocity, V_c, of $0.36V_R$, where V_R is the Rayleigh wave speed in the material (the velocity at which a wave moves along a free surface). This transition from quasi-static velocities to dynamic ones involves two coupled phenomena, velocity oscillations and secondary micro-branching from the primary parent crack. Sharon et al. (1995) observed that the increase in new crack area by the formation of the micro-branches was associated with reduction in fracture velocities. These observations match quite well with previous theoretical calculations (Yoffe, 1951), 2D lattice modeling (Marder and Liu, 1993) and simulations of crack motion by molecular dynamics (Abraham et al., 1994).

A basic physical tendency of a cracked body is to minimize its stored 'strain energy'; that energy which reflects the condition and sum of the chemical bonds in the material body. But the creation of a new crack area requires an investment in a different kind of energy, the 'surface energy', which relates to bond breaking in the new area. Accordingly, the crack grows and its area increases if the release of strain energy equals or is greater than the consumed surface energy (Griffith, 1920). It can be shown that often the crack growth results in an excess of energy, which is associated with the increase in the rate (per crack distance not per time) of energy release. This excess energy is expected to occur as kinetic energy which now relates to both crack dimension (length) and crack velocity (Mott, 1948). However, experimental investigations show that crack velocities do not reach their ultimate theoretical, Rayleigh wave speed.

According to Sharon et al. (1995), as the velocity of the primary crack initially increases, the energy released from the potential energy stored in the material is channeled into creating two new crack surfaces by lengthening the crack. However, at V_c there is an onset of branching, the energy flowing into the tip of the crack is now divided between the primary crack and the secondary cracks. Thus, less energy is directed into the primary crack and its velocity decreases. The secondary cracks, which compete with the primary crack, have a finite lifetime, presumably because the primary crack can 'outrun' them and screen the secondary cracks from the surrounding stress field. The branch cracks then die and the energy that had been diverted from the primary returns to its initial roll, speeding up the primary crack until, once again, the scenario repeats itself.

5. Intermittent dynamic and quasi-static fracture propagation of the trefoil joint

The fracture principles derived by Sharon et al. (1995) and related papers mentioned above, can help us explain the present observations (Fig. 3). The mirror of the trefoil joint propagated downward and en échelon segmentation occurred at its boundary. The intense en échelon segmentation into multiple new surfaces, played the role of the secondary cracks in the scenario shown by Sharon et al. (1995). The energy dissipation that occurred by creating the segment (tensile and shear) surfaces was associated with a reduction in fracture velocity, as also observed by Müller and Dahm (2000).

The remote stresses operating on the trefoil joint did not subside. Therefore, continued tension resulted in the creation of a new, 'secondary mirror' that propagated in the same downward direction, as shown by its downward facing convex boundary. The increase in length of the secondary mirror was associated with increasing its fracture velocity, in analogy to the above-mentioned fracture principles (Sharon et al., 1995). The formation of mirrors under mode I seems to be invariably associated with rapid fracture (e.g. Kerkhof, 1975).

6. The formation of the trefoil joint under mixed modes operation

Couplings of velocity decrease with the increase in new fracture surface area were observed both under quasi-static conditions (Müller and Dahm, 2000) and through dynamic ranges (Sharon et al., 1995). What are the differences between the two?

Sommer (1967, 1969) simulated en échelon segmentation on the fracture surfaces of circular glass rods loaded in tension by the superposition of a small amount of torsion, creating conditions of increasing mode III/mode I ratios. On the other hand, high K_I/K_{III} ratio (the stress intensity factors of the opening and tearing modes, respectively) increased crack velocity, leading to crack branching. Bank-Sills and Schur (1989) showed the inherent tendency of increasing mode III/mode I ratios from the center of metallic plates towards their boundaries and Bahat (1997) reported that the latter tendency occurred also in sub-horizontal chalk beds.

All these experimental and field observations match into the following scenario of the trefoil joint growth. The primary joint propagated both laterally and downwards under conditions of increasing K_I magnitudes and very low K_{III}/K_I ratios to the mirror boundary at which an abrupt increase in the mode K_{III}/mode K_I ratio occurred, leading to the breakdown into en échelon cracks (Cooke and Pollard, 1996). This was linked with an energy dissipation on many new crack surfaces and a reduction in crack velocity. The crack speed reduction was probably associated with friction and interlocking interferences along the fracture surfaces, known as the 'mode III crack closure' (Tschegg, 1983). Crack speed reduction can be very substantial under these conditions: en échelon cracks have been observed in borosilicate glass after application of stress with an intensity factor less than the fatigue limit, at very low crack velocities (Wiederhorn and Johnson, 1973, fig. 5). As mentioned above, recent experiments on rupture velocities in starch show similar results (Müller and Dahm, 2000). The second mirror reflects resumed conditions of increasing K_I magnitudes. Hence, the branching processes described by Sharon et al. (1995) relate to crack velocity oscillations under very high K_I/K_{III} ratios due to remote forces, whereas the experiments conducted by Müller and Dahm (2000) took place under local increasing K_{III}/K_I ratios.

7. Conclusions

The present study introduces a new fractographic feature that relates to a fringe of a fracture cutting granite (that we term a trefoil joint) in the Borsov quarry from the Bohemian Massif in central Europe. The fringe exhibits some six segments that merged into one step that displays a tensile, 'secondary' mirror plane. This tensile step differs from known fractographies in sedimentary rocks, where mirrors and other tensile fracture markings occur on en échelon segments but are absent on steps. Hence, the primary mirror of the trefoil joint was segmented into a fringe that then continued to fracture into a secondary mirror that also was segmented into a secondary fringe.

It is interpreted that the trefoil joint propagated to the mirror boundary under conditions of increasing K_I magnitudes and very low K_{III}/K_I ratios where an abrupt increase in the mode III/mode I ratio occurred leading to the breakdown into en échelon cracks. This cycle was repeated on the secondary mirror and associated secondary fringe.

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References

Abraham, F., Brobeck, D., Rafey, R.A., Rudge, W.E., 1994. Instability dynamics of fracture: a computer simulation investigation. Physical Review Letters 73, 272–275.

Bahat, D., 1991. Tectonofractography. Springer-Verlag, Heidelberg.

Bahat, D., 1997. Mechanisms of dilatant en échelon crack formation in jointed layered chalks. Journal of Structural Geology 19, 1375–1392.

Bahat, D., 1998. Quantitative tectonofractography—an appraisal. In: Rossmanith, H.P. (Ed.). Mechanics of Jointed and Faulted Rock, MJFR-3, Vienna, Austria. Balkema, Rotterdam, pp. 59–67.

Bank-Sills, L., Schur, D., 1989. On the influence of crack plane orientation in fatigue crack propagation and catastrophic failure. American Society for Testing and Materials, Standard Technical Publication 1020, 497–513.

Benes, K., 1971. Structure of plutonic bodies in the Bohemian Massif. Upper Mantle Project (UMP), Final Report—Geology, Praha, pp. 111–119.

Cooke, M.L., Pollard, D.D., 1996. Fracture propagation paths under mixed mode loading within rectangular blocks of polymethyl methacrylate. Journal of Geophysical Research 101, 3387–3400.

Dallmeyer, R.D., Franke, W., Weber, K., 1995. Pre-Permian Geology of Central and Western Europe. Springer-Verlag, New York.

Griffith, A.A., 1920. The phenomena of rupture and flow in solids. Philosophical Transactions of the Royal Society, London, Ser. A 221, 163–198.

Johnson, J.W., Holloway, D.G., 1966. On the shape and size of the fracture zones on glass fracture surfaces. Philosophical Magazine 14, 731–743.

Kerkhof, F., 1975. Bruchmechanische analyse von schadensfallen an glasern. Glastechnische Berichte 48, 112–124.

Kulander, B.R., Barton, C.C., Dean, S.C., 1979. The application of fractography to core and outcrop fracture investigations. Report METC/SP-79/3 to U.S.D.O.E. Morgantown Energy Technology Center, Morgantown, WV.

Lawn, B.R., Wilshaw, T.R., 1975. Fracture of Brittle Solids. Cambridge University Press, London.

Marder, M., Liu, X., 1993. Instability in lattice fracture. Physical Review Letters 71, 2417–2420.

Matte, Ph., Maluski, H., Rajlich, P., Franke, W., 1990. Terrane boundaries in the Bohemian Massif: result of large-scale Variscan shearing. Tectonophysics 177, 151–170.

Mott, N.F., 1948. Brittle fracture in mild steel plates. Engineering 165, 16.

Müller, G., Dahm, T., 2000. Fracture morphology of tensile cracks and rupture velocity. Journal of Geophysical Research 105, 723–738.

Sharon, E., Fineberg, J., 1999. Confirming the continuum theory of dynamic brittle fracture for fast cracks. Nature 397, 333–335.

Sharon, E., Gross, S.P., Fineberg, J., 1995. Local crack branching as a mechanism for instability in dynamic fracture. Physical Review Letters 74, 5096–5099.

Sommer, E., 1967. Das bruchverhalten von rundstaben aus glas im manteldruckversuch mit uberlagerte zugspannung. Glastechnische Berichte 40, 304–307.

Sommer, E., 1969. Formation of fracture 'lances' in glass. Engineering Fracture Mechanics 1, 539–546.

Tipper, C.F., 1957. The study of fracture surface markings. Journal of Iron Steel Industry 185, 4–9.

Tschegg, E.K., 1983. Mode 3 and mode 1 fatigue crack propagation behaviour under torsional loading. Journal of Materials Science 18, 1604–1614.

Wiederhorn, S.M., Johnson, H., 1973. Effect of electrolyte pH on crack propagation in glass. Journal of the American Ceramic Society 56, 192–197.

Yoffe, E.H., 1951. The moving Griffith crack. Philosophical Magazine 42, 739–750.