Indentation pits: a product of incipient slip on joints with a mesotopography

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Abstract: The mechanism for structural damage during incipient slip on joints within the Melechov Granite, Czech Republic, changes with the misalignment of the joint's mesotopography, largely a plumose surface morphology. Prior to slip, the joint surfaces are well mated so that contact area is organized on a microscopic scale. During the first phase of slip, diffusion-mass transfer is the active deformation mechanism between the sliding surfaces of the joints, as indicated by the extensive growth of crystal-fibre lineations characteristic of slickenside surfaces. After slip of the order of 1 cm or more, the mesotopography becomes mismatched and the contact area is reorganized to form indentation pits aligned on the ridges of hackle plumes. Indentation pits, that are testimony to a brittle process, are generated by the excavation of Hertzian ring cracks that propagate under contact loading of a brittle substrate. The depth of the indentation pits increases with contact width, suggesting that indentation creep is active. Following indentation along Hertzian ring cracks the slip mechanism transforms to a frictional abrasion. The distribution of indentation track lengths is consistent with laboratory wear grooves generated during earthquake-like stick–slip sliding. The elliptical shape of the indentation pits indicates a gradual decrease in contact area, a process that is consistent with a slip-weakening mechanism during a stick–slip cycle.

Joints appear as early structures within many tectonic settings, in igneous rocks of convergent margins as well as in sedimentary rocks of extensional basins (e.g. Pollard & Aydin 1988). Because joints form early in the tectonic cycle, one presumes that there should have been ample opportunity for a shear traction to drive slip and subsequent overprinting by any of a number of processes reflecting frictional wear. Yet, joints persist even when host rocks have been subject to a complex tectonic history (Nickelsen 1979; Gray & Mitra 1993). In some tectonically complex areas, slip is difficult to detect even when it is clear that the joints were subject to a shear traction as a consequence of changes in the orientation of the remote stress field (Younes & Engelder 1999). On occasion, when joints do slip, there is no evidence for frictional wear on these incipient faults (Engelder *et al.* 2001; Silliphant *et al.* 2002). In other instances, frictional wear during slip on joints is seen in its most common manifestation, the slickenside surface (Hancock 1985). When joints of several sets are decorated with slickensides, they serve as a basis for fault-slip analyses to determine the orientation the regional stress field (Angelier 1979).

Frictional wear during the formation of lineations on slickenside surfaces includes both brittle and ductile processes (Wilson & Will 1990). Lineations on slickenside surfaces may consist of scratches, commonly called wear grooves, wear tracks or tool marks (e.g. Engelder 1974; Fleuty 1975; Hancock 1985; Doblas 1998). These, along with streaks and trails, are a manifestation of brittle wear processes (e.g. Tjia 1967). Ductile wear shows up as the removal of steps and minor elevations by pressure solution to form slickolites (Arthaud & Mattauer 1972; Davis & Reynolds 1996). In other instances, ductile wear leads to the formation of striations that more closely resemble experimentally deformed paraffin wax (Means 1987). There are also examples reported of crystal fibres growing to form lineations on the leeward side of small steps and asymmetric elevations (Durney & Ramsay 1973). The small steps and asymmetric elevations tend to cause fracture dilation upon slip and thus indicate frictional contact (Petit 1987).

Despite the large population of joints present during the tectonic cycle, instances of a combination of brittle and ductile wear processes operating either simultaneously or serially during slip on joint surfaces are either uncommon or difficult to recognize. There are several reasons for this result. First, a multiple-step tectonic process is required where the generation of an initial joint is followed by the reorientation of the stress field to subject that joint to a shear traction (Engelder *et al.* 2001). Stress field reorientation over geological time may be less common than presumed. Second, it does not take much slip before all evidence of the initial joint surface is removed by fault-related abrasion and the

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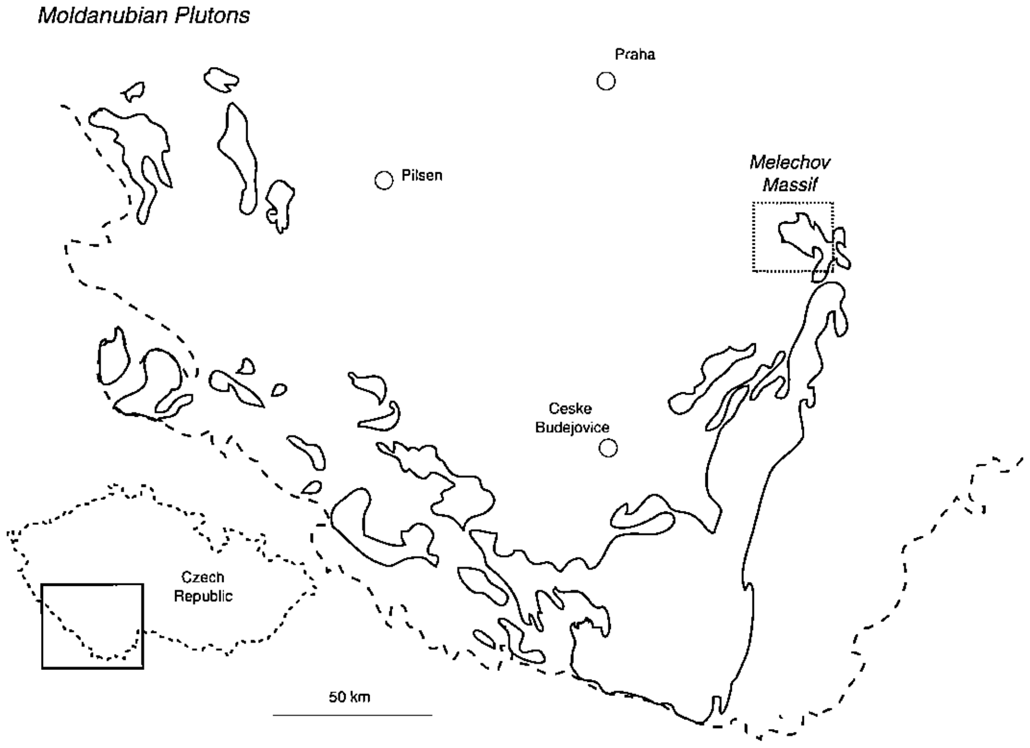

Fig. 1. Tectonic map of the Bohemian Massif showing the location of the Melechov Granite.

generation of fault gouge (Scholz 1987). Third, many faults start as en echelon cracks, hence bypassing the need for stress realignment after joint propagation (e.g. Martel *et al.* 1988). The purpose of this chapter is to describe the transition from ductile slip to abrasional wear on joints that have become incipient faults. The evolution of slickensides on these joint surfaces is of particular interest because the development of indentation pits provide clues about the evolution of rock friction during fault slip.

Rock friction and the mechanism for sliding of rock in the brittle regime is largely a reflection of the behaviour of contacts during abrasional wear. One model for frictional slip, particularly the earthquake-generating stick–slip mechanism, focuses on the locking and breaking of contacts during sliding (Byerlee 1967). Stick–slip requires that stationary contacts create a higher friction than that present during fault slip (Rabinowicz 1958). Stationary contacts develop a higher friction by a time-dependent behaviour arising from static fatigue under these contacts (Dieterich 1972; Scholz & Engelder 1976). An early explanation for stick–slip focuses on a model for which frictional contacts weaken with slip (Byerlee 1970). However, stick–slip oscillations are best explained if incipient slip during contact rupture is a velocity-weakening process (i.e. Ruina, 1983; Scholz 1998, 2002). Theories for stick–slip by velocity weakening are best tested in the laboratory using relatively clean joint surfaces where frictional abrasion is minimal (Marone 1998). Appropriate field examples demonstrating contact behaviour during stick–slip are far less common. While inferences from field observations are restricted to slip weakening, they are nevertheless instructive for understanding the evolution of friction in nature. An opportunity for a case study of natural contacts is found on joints that have slipped a small amount (<10 cm) within a granite of the Bohemian Massif, in the Czech Republic.

The geology of the Melechov Massif

The Bohemian Massif encompasses a large suite of outcrops within the Variscan (Devonian–Carboniferous) Orogen of Europe (Schulmann *et al.* 1994). Within the massif are NE-SW-trending Neo-Proterozoic blocks surrounding a high-grade orogenic root domain in the centre – the Moldanubian zone. The central part of the Moldanubian zone is intruded by a composite crustal batholith, the Central Moldanubian Pluton (Fig. 1). The Melechov Massif,

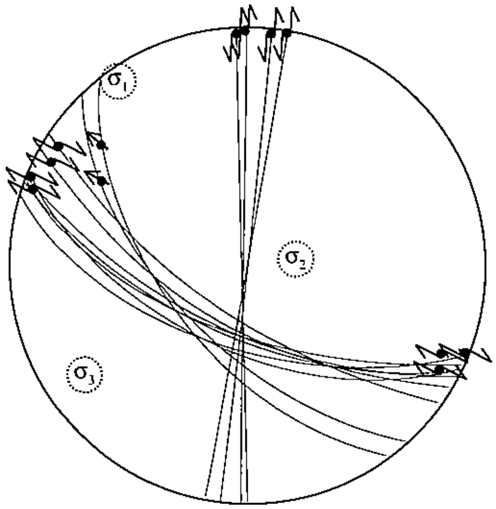

Fig. 2. Lower-hemisphere projection of joints within the Dolni Brezinka quarry of the Melechov Granite. Orientation of the principal stresses is based on the inverse method for fault-slip data.

Fig. 3. A joint surface within the Melechov Granite at the Dolni Brezinka quarry, Svetla, Czech Republic (joint surface A). Tracks of indentation pits can be seen running subvertically on this joint face (white arrows). This joint dips toward the camera (WSW) at 72°. Slip on the joint is subhorizontal with a dextral sense.

the subject of this study, is composed of a complex of granitic bodies separated from the northern edge of the Central Moldanubian Pluton by metamorphic rocks of the so-called monotonous series of the Moldanubian zone. The marginal parts of the Melechov Massif are built of fine- to medium-grained granites. The age of the granite established by the Rb–Sr method gave 303 ± 6 Ma (Scharbert & Vesela 1990). A fine- to medium-grained two-mica (biotite–muscovite) granite forms the rim of the entire massif. The central part of the massif is built of coarse-grained to porphyritic two-mica (biotite–muscovite) granite of the Melechov type. This pluton is of elliptical shape, elongated in the NNE–SSW direction.

The entire massif exhibits a concentric zoning with corresponding orientation of foliation in adjacent metamorphic rocks. Granites of the Melechov Massif to the west are enveloped by the rocks consisting of biotite and sillimanite–biotite paragneisses with cordierite, locally migmatized and containing bodies of marbles, calc-silicate rocks, amphibolites and quartzites. The northern and southern mantle of the massif is built of rocks of the Moldanubian monotonous series.

Fractures in the Melechov Granite

The Melechov Granite at the Dolni Brezinka quarry contains several fracture sets with two prominent sets, one striking at approximately 118° and dipping about 72° SSW and the other vertical set striking 5° (Fig. 2). Fibre lineations on the 118°-striking fracture set have a small rake (<5°) and steps on the fibres indicate slip of the hanging wall to the WNW (i.e. top or missing half of the joint surface in Figs 3 and 4 moved to the left giving a dextral sense of slip). The 005°-striking fracture set bears fibre lineation with a small rake (<5°) indicating sinistral displacement. Estimated principal maximum compressive stress calculated using an inverse method is subhorizontal and oriented NW–SE (Fig. 2).

The 118°-striking fractures are planar, parallel features, a pattern that is consistent with a joint set. Surfaces of these joints are decorated with brittle indentation pits or cavities a few centimetres in diameter and generally less than 0.5 centimetres deep (Fig. 3). Rather than being uniformly scattered on the joint surface, as is common for most fault surfaces displaying tool marks (i.e. Petit 1987), these indentation pits are aligned in a series of gently curving, concentric paths. Their concentric arrangement makes a pattern much like either the plumose morphology seen on joint surfaces in sedimentary rocks (Woodworth, 1896) or rib marks seen on the surfaces of joints found in granites elsewhere within the Czech Republic (i.e. Bankwitz & Bankwitz 1984; Bahat *et al.* 2003). Topography on plumose morphology is referred to as plume barbs (Bahat 1991) or hackle plumes (i.e. Kulander & Dean 1985). Because the tracks of indentation pits radiate along irregular paths rather than forming a series of concentric rings, we favour the hackle plume (i.e. plume barb) interpretation (Fig. 3).

The indentation pits follow along a mesotopography on the joint surface (Fig. 4). We used the term

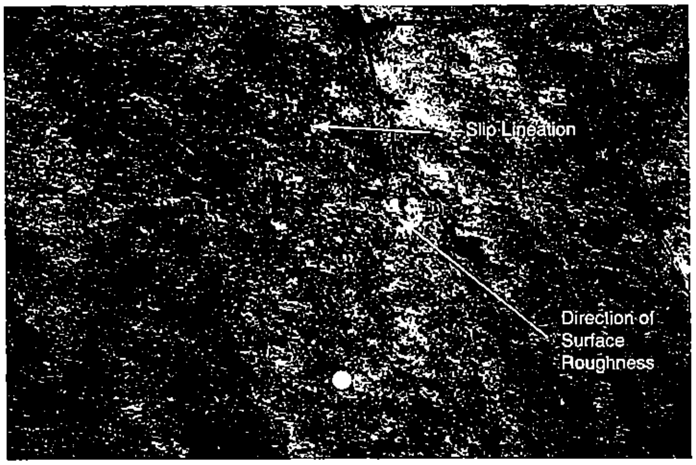

Fig. 4. Indentation pits within joint surface B in the Melechov Granite at the Dolni Brezinka quarry, Svetla, Czech Republic. The pits are elongated parallel to the slip lineation. A mesotopography (i.e. a surface roughness) in the form of a series of ridges sweeps to the upper left from the bottom of the photograph. The Czech coin is 23 mm in diameter.

mesotopography (amplitude on the order of 5 mm) to distinguish it from the microtopography (amplitude on the order of 10^{-2} mm) that may be found at the grain scale on a fresh joint surface. Microtopography may also have a grain that gives rise to a very fine plume pattern on a joint surface in sandstone (Bahat & Engelder 1984). This mesotopography has a trough to peak elevation of a few millimetres, as is common for the plumose morphology on other granites (Bankwitz & Bankwitz 1984).

Indentation pits

Indentation trails are best developed where the mesotopography is at a high angle to the slip lineations (Fig. 3). On some joints most indentation pits are approximately circular with a depth that often exceeds the amplitude of the mesotopography on the joint surfaces (Figs 5 and 6). On other joints indentation pits are elliptical with their long axis aligned parallel to crystal fibre lineations characteristic of slickensided surfaces (Fig. 7). Because the long axes of the elliptical indentations parallel the slickenside lineations, there is little doubt that the indentation pits are tool marks produced by frictional abrasion on the joint surface (Doblas 1998). Many of the indentation pits contain tension cracks that have the characteristic of chatter marks left by tools on fault surfaces or along glacially carved outcrops (Willis & Willis 1934; Tija 1967) (Figs 6 and 7). Such chatter marks are the manifestation of Hertzian ring cracks generated during asperity indentation (Lawn 1993). The deepest part of the pit is often at the back end of the pit (i.e. the right-hand side of the pits shown in Figs 6 and 7). Hence, the deepest portion of the pit is located at the trailing edge of the asperity that is responsible for the pit and concomitant elliptical groove, if present.

Three data were collected when documenting the geometry of individual indentation pits on three 118°-striking joints surfaces: length parallel to the crystal fiber lineation, width normal to the crystal fibre lineation and depth of the pit (Fig. 5). There are no offset markers on the joint surface so we have no independent indication of the magnitude of slip along these three joints. We assume that total slip distance is proportional to the sum of the length of the crystal fibre growth and the degree of ellipticity of the indentation pits. Those joints with more elliptical indentations are presumed to reflect a greater total slip distance.

The indentation pits show a gradual progression in excavation from a more or less circular hole to an elliptical cavity with a length (i.e. the dimension in the slip direction) nearly three times the width of the indentation. Each of the joints shows enough slip to have developed crystal fibre lineations, but for one the mode of the length/width ratio for various indentation pits was close to 1 (Fig. 8a). With the joint showing a mode close to 1, there is a range of length/width ratios for the indentation pits including a number of pits with a value of less than 1. We presume that this scatter in the data indicates that the contact areas responsible for the indentation pits were irregular in shape, with some having a longer dimension in a direction normal to the slip lineation. The fact that the mode is not centred on 1 but rather shifted to a value slightly higher than 1 indicates ongoing slip with the incipient excavation of a groove in the direction of slip. Of course, as slip progresses the mode for the length/width data increases from

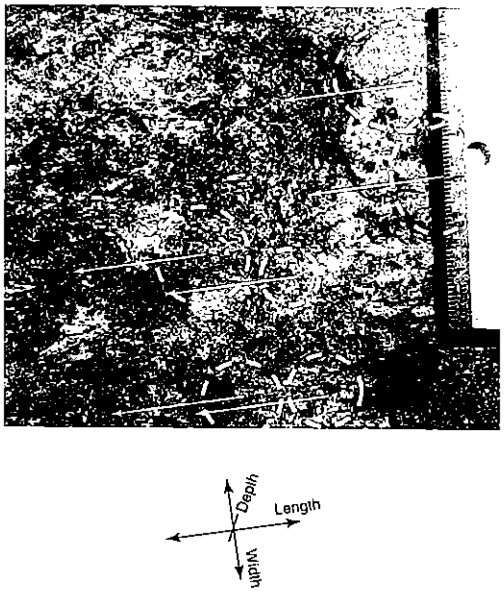

Fig. 5. Indentation pits on joint surface A. Arrows parallel the slip lineation as indicated by the orientation of crystal fibre growth. The arrows indicate the direction and distance of motion of the top (forward) surface during development of the crystal fibre growth. Hence, slip on the joint was subhorizontal with a dextral sense.

1.1 to 1.3 to 1.5, respectively (Figs 8a, b and c). By the time slip has generated a length/width mode of 1.5 there are no indentation pits with a length/width ratio <1. At this point excavation during slip has compensated for any irregularities in the shapes of the contact area.

Depth of excavation is a function of the size of the contact area, as indicated by the correlation between depth and width of the indentation pit (Fig. 9). Although the exact timing (i.e. syn-slip v. post-slip) for excavation of the indentation pits is unclear, the present depth of the indentation pits correlates with the depth of penetration of the initial ring cracks. Depth of excavation is, however, not a function of the amount of slip or length of the cut made by the contact, as indicated by the fact that pit depth is not a function of the length of the indentation pit but correlates very nicely with the width of the pit regardless of its ellipticity. Pit excavation can also be viewed in terms of a plot of length against width (Fig. 10): initial excavation plots with a slope of 1 (i.e. surface A). Of course, as excavation continues with slip, length increases without concomitant increase in either width or depth (i.e. surfaces C). This is somewhat contrary to the conventional view of tool marks that become progressively deeper as an asperity is dragged through a substrate (i.e. Engelder 1974; Doblas 1998).

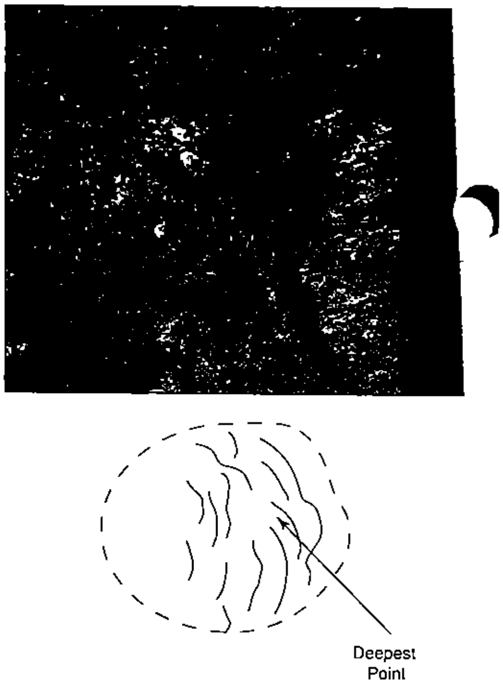

Fig. 6. Indentation pit on joint surface B. The drawing of the pit shows the location of Hertzian ring cracks in the back (bottom) block that developed as the top (forward) block moved to the left.

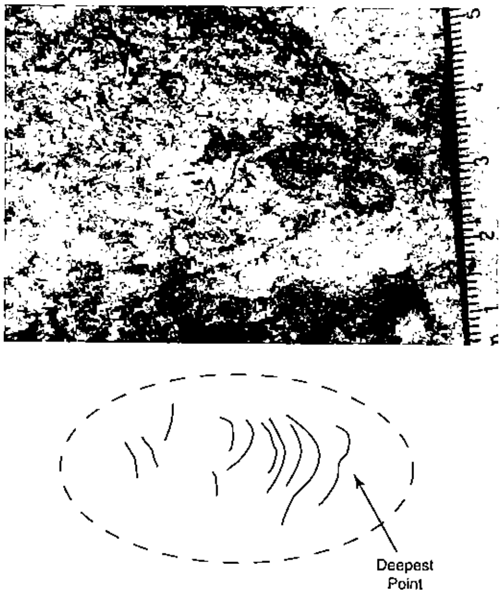

Fig. 7. Indentation pits on joint surface C. The drawing of the pit shows the location of Hertzian ring cracks in the back (bottom) block that developed as the top (forward) block moved to the left.

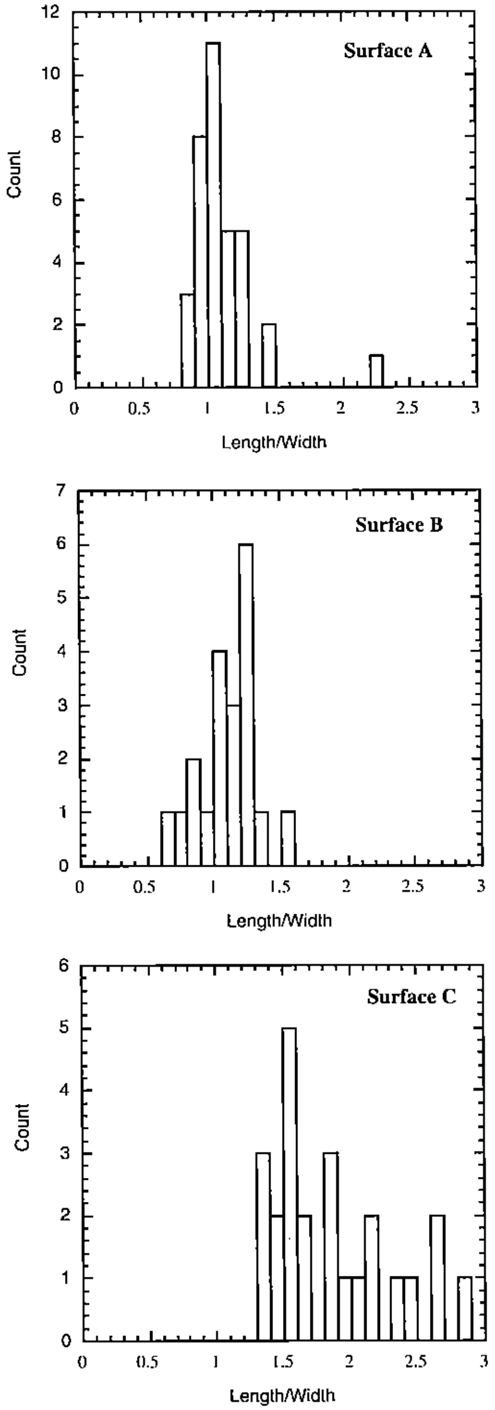

Fig. 8. Histogram for the ratio of length/width of the indentation pits in a joint-normal view of joint surfaces A, B and C, respectively. Length is defined as the dimension of the pit parallel to the slickenside lineation and width is the dimension normal to the slickenside lineation.

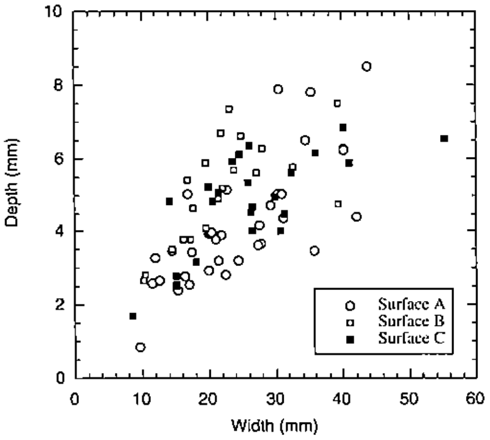

Fig. 9. Depth as a function of width of indentation pits on joint surfaces A, B and C, respectively.

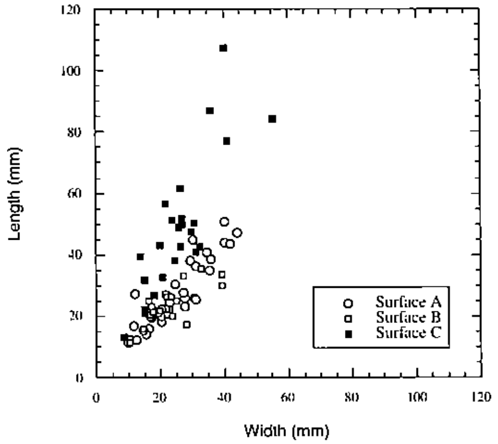

Fig. 10. Length as a function of width of indentation pits on joint surfaces A, B, and C respectively.

Discussion

Transition from ductile slip to abrasional wear

The indention pits cut off crystal fibre lineation, and crystal fibre lineation is never seen growing within indentation pits. This is direct evidence in favour of a transition in slip mechanism from ductile creep to abrasional wear. Initially, the joint surfaces are well matched so that the mesotopography associated with plume morphology is well mated. Contact points are small, probably on the grain scale or smaller, so that microtopography controls the slip mechanism. At this stage, crystal fibre growth accompanied slip.

Hence, we infer that as long as the joint surfaces were in reasonably good contact without contact stress being focused on the mesoscopic scale, creep by diffusion-mass transfer mechanism was responsible for ductile 'fault' slip. It may be that at the microscopic scale, point contact stress favoured pressure solution rather than brittle indentation. Abrasional wear by brittle indentation starts after some finite amount of 'fault' slip. The length of the crystal fibre lineation indicates that this slip may have been of the order of 1–3 cm (Fig. 5). At this stage during slip, surface contact reorganizes to support occasional mesoscopic contact areas.

Brittle indentation requires the appropriate contact area. In the literature on slickenside surfaces, such contact area comes from structures known as steps (Hancock 1985), slickenside roches moutonnées (Tjia 1967) or knobby elevations (Doblas 1998). Enough of the morphology of the original joints is visible in the Melechov Granite to infer that the tops of the plumose mesotopography on the joint surface account for the distribution of contact points. In particular, it is clear that once the joints had slipped 1–3 cm (i.e. the wavelength of the mesotopography on the joint surface) there is sufficient mismatch in the shape of the surfaces so that contact area was reorganized from the initial condition presented by the initially well-fitted joint surfaces.

In summary, crystal fibre lineation provides direct evidence that the joint surfaces slipped by a ductile mechanism prior to the generation of indentation pits. After slipping, the joints no longer fit in the nearly perfect match that would have been present just after joint propagation.

Brittle indentation

Once the mismatch between surfaces becomes sufficient, contact is localized. At this stage indentation pits seem to have originated under static contact points by Hertzian intentation (Lawn 1993). Cracks are driven into the substrate at the edge of local contact points. This is certainly consistent with the trailing end of the indentation pits being deepest following the initiation of slip. This heavy fracturing may have allowed for later excavation of the indentation pits by rapid erosion of the cracked contact area after the removal of the hanging-wall block. The indentation pits grow under an asperity indentation mechanism called indentation creep (Westbrook & Jorgensen 1968). Indention creep has the time-dependent effect that allows an increased penetration depth with time of loading (Scholz & Engelder 1976). As the surfaces close by indention creep, more points along the surface come in contact, leading to the linear distribution of indendation pit depths as a function of width (Fig. 9).

The size and shape of the contact area (i.e. the tops of the mesotopography on the plumose morphology) are reflected in the geometry of the indentation pits. The size of the contact areas was not uniform. The areas and vertical depth of the indentation pits scale with each other, and their size conforms with the mesotopography of the wall that has been removed. Finally, the mesoscopic contact points are, on average, initially circular in map view.

The indentation pits on two of the three joint surfaces (i.e. A and B) have a length/width ratio close to unity (Fig. 10). This behaviour suggests that once indentation creep was initiated following 1–3 cm of slip as indicated by the growth of fibre lineation, the joint surfaces locked before further slip. Indentation creep has the effect of raising the frictional resistance to slip. On surface C, additional slip is by an abrasional wear mechanism with indentation pits leaving a track of ring cracks (Fig. 7).

The elliptical indentation pits on joints of the Melechov Granite are similar to a group of tool marks called 'V' or crescentic markings (Doblas 1998). Commonly, the deepest part of the marking is found at the trailing edge of the excavation tool. These most closely resemble gouging/plucking markings, except that the excavation pits contain chatter marks and they tend not to be carrot-shaped features. Laboratory sliding friction experiments typically show carrot-shaped wear grooves, but the sharp end of these grooves point in the direction of motion of the surface in which the grooves lie (Engelder & Scholz 1976). This means that experimentally produced grooves get deeper at the leading edge of the excavation tool, whereas in this natural example the deepest edge of the pit is found at the trailing edge. Because of their shape, the elliptical excavation pits on joints in the Melechov Granite are thought to reflect slip weaking as frictional slip is reinitiated after a period of stationary contact.

Significance relative to stick–slip and microearthquake generation

To better understand the significance of the indentation pits on the joints of the Melechov Granite, we turn to the laboratory experiments where tool marks have been produced (e.g. Engelder 1974, 1976). Tool marks are produced on highly polished Westerly Granite when sliding takes place in compression above 30 MPa confining pressure on surfaces inclined at 35° to the cylinderical axis. Often slip is by earthquake-like stick–slip where tool marks are equal to or less than slip during individual stick–slip events. The normalized length distribution of tool marks in feldspar in the Westerly Granite experiments shows that the mode for these data is

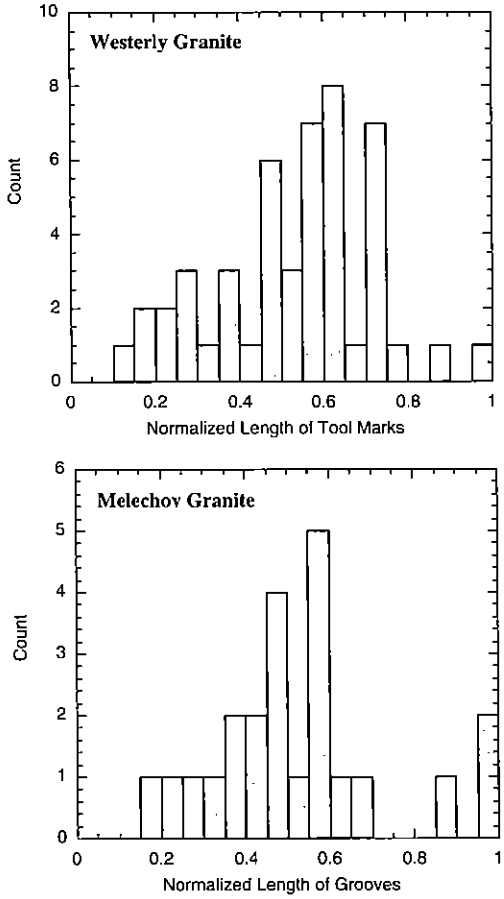

Fig. 11. Normalized length of tool marks developed during frictional wear on a polished surface of Westerly Granite (slip normalized by longest groove). Measurements taken on the large quartz grain in the upper portion of figure 5 in Engelder (1976). The normalized length of grooves developed during frictional wear on joint surface C in the Melechov Granite.

approximately the length of the slip event (Fig. 11) (see fig. 6 in Engelder 1976). This is true for both quartz cutting into feldspar and feldspar smears on quartz (see figs 7 and 8 in Engelder 1976). The length distribution data gradually increase to the mode and then fall off abruptly. In the experiments there are some tool marks that are longer than individual slip events, perhaps as an indication that some tools survive through more than one stick–slip event.

A plot of the normalized groove lengths on joint surface C of the Melechov Granite shows a similar distribution as that seen on the Westerly Granite (Fig. 11). This comparison ties the mechanism for frictional slip under brittle conditions in the field to the mechanism for frictional slip in the laboratory. One interpretation is that tool marks on surface C in the Melechov Granite were produced during one earthquake-like slip event. If this were the case, then we are looking at a surface that slipped stably as a ductile fault to produce crystal fibre lineations during early slip. This early stage of slip produces the mismatch of the joint surface and concomitant reorganization of contact area for the initiation of indention creep. During further evolution, joints in the Melechov Granite slipped by a very different mechanism, a brittle indentation. Regardless, the parallelism between the slip lineation and the long axis of the tool marks suggests that the orientation of the critically resolved shear stress did not change during the switch from sliding by ductile creep to brittle wear. Then, further slip on surface C was accompanied by a gradual decrease in width and depth of penetration of Hertzian cracks. This means that the contact area was gradually decreasing as slip reinitiated. Although the detailed reasons for the decrease in contact area are unknown, the decreasing depth of penetration is not consistent with a concomitant higher normal stress under contact areas. Hence, the frictional force decreases with additional slip, a characteristic that is consistent with a slip-weakening model. The slip distance during slip weakening is approximately 2.5 cm, as indicated by subtracting the width of the indentation pits on surface C from their length.

The Melechov joints may be a very small-scale model for the creeping portions of larger-scale crustal faults. Portions of the San Andreas fault zone are known to produce most of its slip aseismically while generating large numbers of microearthquakes that occur in streaks (e.g. Rubin *et al.* 1999). While not aligned in the direction of slip, it is clear that brittle slip on the Melechov joints is locally concentrated, particularly if each indentation pit is considered the hypocentre of a microearthquake. The analogy with a creeping fault is further strengthened by the well-developed fibre lineation that grows during aseismically slippage.

Conclusions

Joints in the Melechov Granite, in the Czech Republic, contain clear evidence for a transformation in slip mechanism during initial rock sliding. Early in the slip history of these joints, slip was by a diffusion-mass transfer that led to the growth of a crystal fibre lineation. This initial slip caused well-mated joint surfaces to become misaligned. With the misalignment, the contact area reorganized. With a reorganized contact area, indentation creep was initiation by penetration of Hertzian ring fractures, a brittle mechanism. Indentation creep lead to the generation of indentation pits that follow the meostopography of a plumose morphology on the joint surfaces. Further slip is accompanied by indentation creep under the reorganized contact points. The subsequent wear grooves are elliptical indention pits indicating slip of about 2.5 cm with the deep end of the indention pit near the trailing end of the pit, as would be expected for a slip-weakening friction model for stick–slip.

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