PERGAMON

Journal of Structural Geology 22 (2000) 1015–1025

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Coeval formation of cataclasite and pseudotachylyte in a Miocene forearc granodiorite, southern Kyushu, Japan

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Received 2 October 1998; accepted 10 March 2000

Abstract

Cataclastic rocks and pseudotachylytes are exposed along the Uchinoura shear zone, a normal fault zone cutting the middle Miocene (14 Ma) Osumi granodiorite in southern Kyushu, Japan. Cataclastic rocks include non-foliated clast-supported to matrix-supported cataclasite and foliated clast-supported cataclastic granodiorite. In these rocks, fracturing and comminution played a major role, but dissolution and recrystallization of quartz, and plastic deformation of quartz and biotite were also active processes, especially in foliated granodiorite. Two types of pseudotachylyte are distinguished: a foliated-type characterized by a planar arrangement of clasts and microlites, and a spherulitic-type characterized by clasts surrounded by microlite overgrowths. Both types are of melt origin, as attested by the presence of microlites and rounded or embayed clasts, and by the scarcity of biotite clasts. Unlike spherulitic-type pseudotachylyte, which solidified without being deformed, the foliated-type pseudotachylyte underwent flow before complete solidification. This deformation is thought to reflect post-seismic strain accommodation immediately following the main slip episode.

Kinematic indicators, which consist of Riedel-type secondary fractures branching on primary fractures, shear bands offsetting the foliation of foliated granodiorite, or asymmetrical porphyroclast systems within pseudotachylyte veins, show that all fault rocks were generated during N–S- to NW–SE-directed extensional deformation. Pseudotachylyte is closely associated both in time and space with cataclastic rocks, thus indicating that the behaviour of the Uchinoura fault zone alternated between comminution and frictional melting. Given the slow strain rates which characterize dissolution and recrystallization processes detected in cataclasites, the juxtaposition of pseudotachylytes and foliated cataclasites provides an example of aseismic and seismic displacements within the same shear zone.

1. Introduction

In the upper part of the brittle crust, pseudotachylytes are frequently found in close association with cataclasites (Philpotts, 1964; Francis, 1972; Sibson, 1975, 1977; Magloughlin, 1989, 1992; Magloughlin and Spray, 1992; Maddock, 1992; Swanson, 1992). This association can be accounted for by the fact that ultracomminution is a preliminary process efficient in facilitating subsequent melting. The possibility of a genetic link between cataclasites and pseudotachylytes is further supported by high-speed friction experiments, which clearly indicate that comminution and melting are related processes (Spray, 1987, 1995; Lin and Shimamoto, 1998).

We present an example of a cataclasite–foliated cataclasite–pseudotachylyte association from a normal fault zone in the Miocene Osumi granodiorite pluton exposed in Kyushu, SW Japan. Observations of field exposures, hand-sample sections and thin sections show that pseudotachylytes are closely associated both in time and space with cataclastic rocks, thus indicating that the fault zone behaviour alternated between comminution and frictional melting. We show that, in

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0191-8141/00/$ - see front matter
PII: S0191-8141(00)00021-3

addition to comminution, dissolution–recrystallization and plastic deformation were involved in the generation of cataclastic rocks. Dissolution–recrystallization is typical of slow, aseismic strain rates. This suggests that both seismic slip and aseismic creep occurred in the fault zone. Lastly, in some of the pseudotachylytes, we document a coaxial or non-coaxial flow of a not completely solidified material, which is interpreted as reflecting a post-seismic strain accommodation immediately following the main seismic slip episode.

2. Geological setting

The 50 × 15 km^2 Osumi granodiorite pluton is located at the southern end of the island of Kyushu approximately 170 km from the nearby Nankai subduction zone (Fig. 1). It intrudes Paleogene sedimentary rocks of the Shimanto belt and is covered by Quaternary volcanic or alluvial deposits (Oba, 1960; Nozawa and Ota, 1967). Radiometric dating of the granodiorite indicates a cooling from about 280°C (biotite K–Ar dating) to 110°C (apatite fission track dating) occurring between 15 and 12 Ma (Miller et al., 1962; Shibata, 1978; Miyachi, 1985). The main lithology is a medium-grained granodiorite, defined by quartz, plagioclase, orthoclase and biotite. Accessory minerals include garnet, cummingtonite, apatite, muscovite, spinel, chlorite, ilmenite and tourmaline. No magmatic or solid-state foliation could be recognized across the pluton. The granodiorite is cut by numerous aplite veins and, rarely, pegmatite veins. Felsite or microgranite intrusions are uncommon, but can locally become pervasive, especially in the vicinity of fault zones, as will be detailed later.

The Osumi pluton is cut by a series of ENE-trending faults that have been mapped in the eastern part of the body (Fig. 1; Nozawa and Ota, 1967; Fabbri et al., 1997a). Fault zones are well exposed along the southern coast of the study area where they typically

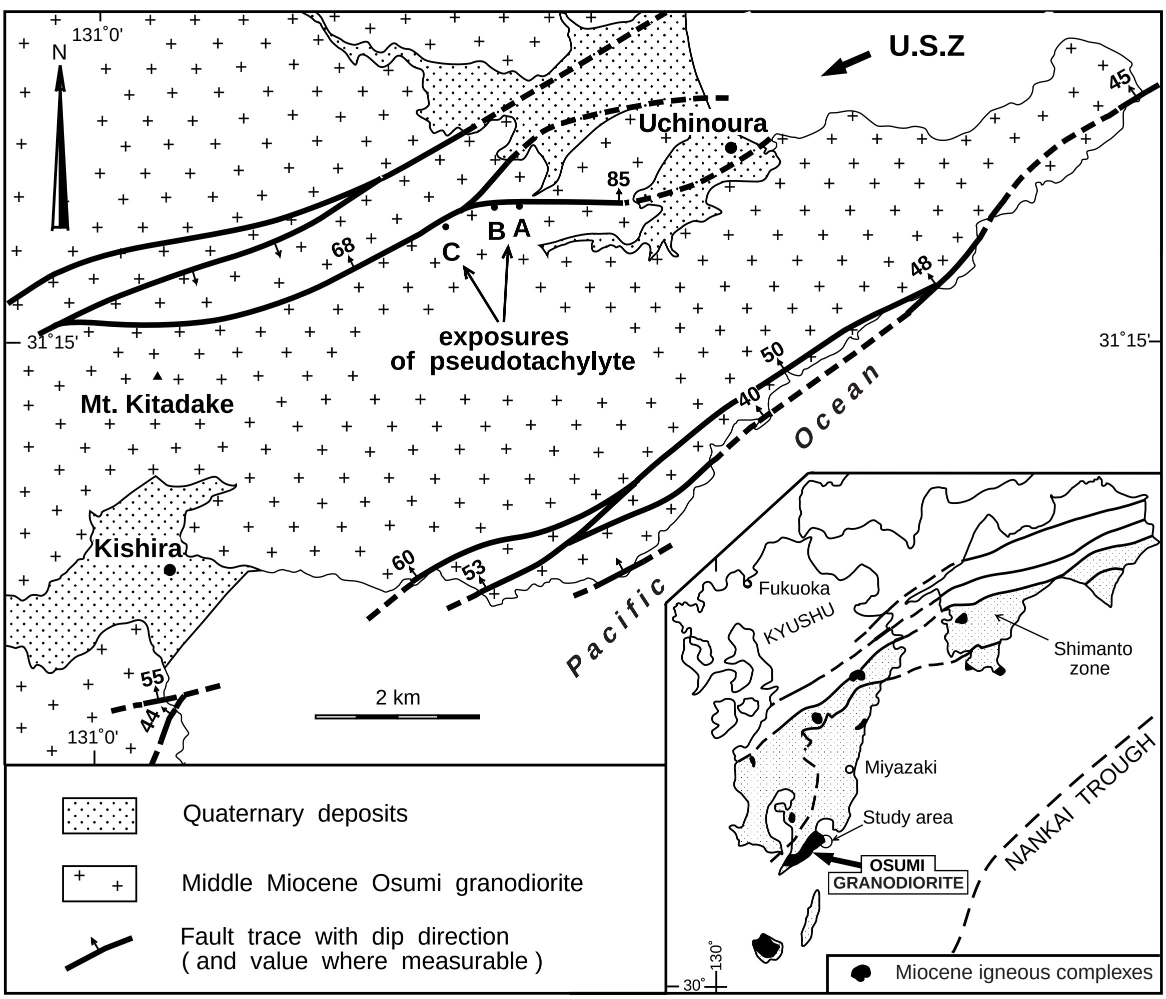

Fig. 1. Tectonic map of the eastern part of the Osumi batholith with location of pseudotachylyte occurrences. U.S.Z. is for Uchinoura shear zone. Insert: location of the Osumi batholith (black areas are exposures of Miocene igneous complexes in the Shimanto zone).

show strongly fractured and hydrothermally altered granodiorite encompassing decimetre- to metre-thick lenses or 'layers' of incohesive fault gouge or fault breccia (terminology after Sibson, 1977). Most slickensides dip 40–60° to the NNW and exhibit striations with rakes larger than 60°, indicative of dip-slip motion. The arrangement of secondary-branching oblique fractures on the planes (Petit, 1987) indicates a normal displacement. Horizontal striations indicative of strike-slip motion can be locally observed but remain incidental. Between Uchinoura and Mt Kitadake (Fig. 1), the Uchinoura shear zone consists of fault planes with minor, centimetre-thick lenses of cohesive cataclasite or breccia. Slickensides dip steeply to the NNW (60–85°) with dip-slip striation rakes larger than 60°. The arrangement of secondary fractures suggests a normal sense of displacement. The intact colour of the granodiorite testifies to the absence of any significant hydrothermal alteration. In the vicinity of the Uchinoura shear zone, pseudotachylyte veins were discovered at three adjacent localities (A, B and C, Fig. 1). Similarities in observable fault rocks and structural trends clearly indicate that the three localities belong to a unique pseudotachylyte-bearing zone lying immediately south of a north-dipping regional fault.

3. Outcrop and hand-sample observations

3.1. General features

At the three studied localities, the granodiorite, aplite veins and some of the microgranite dykes are faulted. Three types of fault-related rocks can be observed: non-foliated cataclasites, foliated cataclastic granodiorite, and pseudotachylytes. The most complete section across the Uchinoura shear zone is found at locality B (Fig. 2). A 1/10 scale sketch map of the most complex area (Fig. 3) was drawn by placing a string

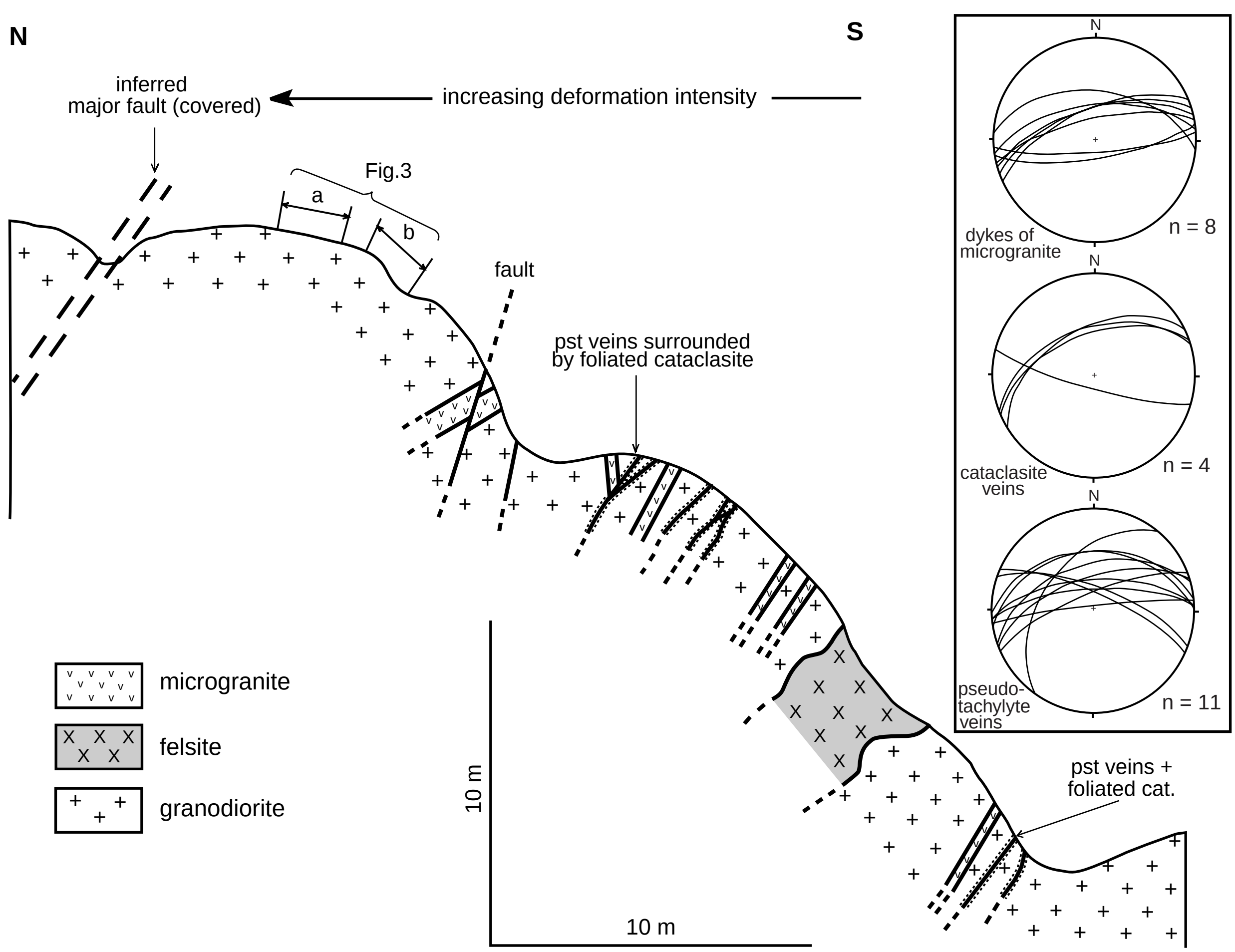

Fig. 2. Schematic cross-section of the Uchinoura shear zone at locality B showing the relationships between microgranite dykes, cataclasite zones and pseudotachylyte veins. Also indicated is the location of the sketches of Fig. 3. Right-side diagrams are lower-hemisphere equal-area projections of microgranite dyke boundary planes, pseudotachylyte veins and cataclasite zones.

grid directly on the gently to moderately inclined outcrop surface. Outcrop observations were completed by examination of oriented hand samples cut along vertical planes striking N–S or NW–SE, that is, parallel to the inferred motion plane of the fault zone as determined by Fabbri et al. (1997a,b). Typical deformation features observed on hand sample sections are depicted on Fig. 4.

3.2. Igneous veins and dykes

Aplite veins are typically 5-cm-thick, white aphanitic veins with poor lateral continuity, due to faulting. Vein attitudes are not easily measured and seem to be variable, especially where the veins are kinked (Fig. 3a). *Microgranite dykes* consist of a light green, aphanitic rock. Dyke thickness ranges from a few centimetres to about 1 m. Green to grey felsite intrusions can also be found. When planar, the boundaries of the dykes strike about E–W and dip N45°N–N85°S. Depending on the degree of deformation, two types of dykes can be distinguished. The undeformed type-I microgranite dykes show a good lateral extent, with thickness being constant over several metres, and are not faulted. Along the contact with the host granodiorite, the rock is whitish in colour on a 1- or 2-mm-thick chilled margin. At locality A, secondary dykelets emanating from an undeformed (type-I) microgranite dyke clearly cross-cut cataclastic veins, thus indicating that emplacement of type-I dykes post-dates faulting and cataclasis. At localities A and B, type-II microgranite dykes are faulted and locally sheared. No chilled margin can be recognized. Some pseudotachylyte veins or cataclasite zones cross-cut the deformed microgranite veins (Fig. 3b), and are therefore younger than the type-II microgranites.

3.3. Fault rocks

Fault rocks consist of pseudotachylyte, non-foliated cataclasite, and foliated cataclastic granodiorite. There is a clear strike-parallel variation in the relative proportion of pseudotachylyte and cataclasite along the Uchinoura shear zone: pseudotachylyte represents 10% of the fault rocks at locality A, 60% at locality B, 90% at locality C.

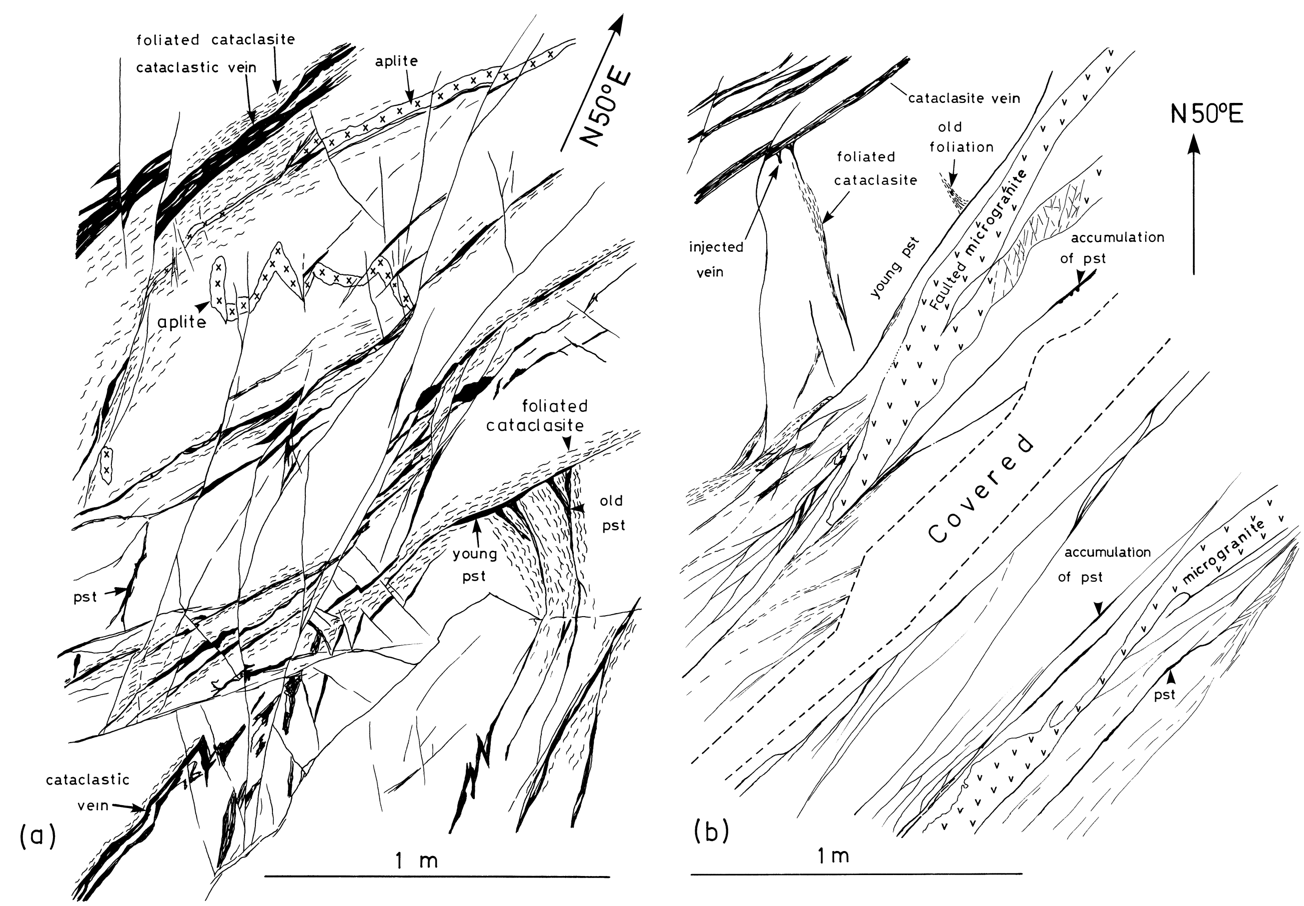

Fig. 3. Detailed maps of cataclasite zones and pseudotachylyte veins in the most deformed part of locality B. The sketched surfaces are slightly (a) or moderately (b) tilted towards the lower part of the sketches. 'pst' represents pseudotachylyte.

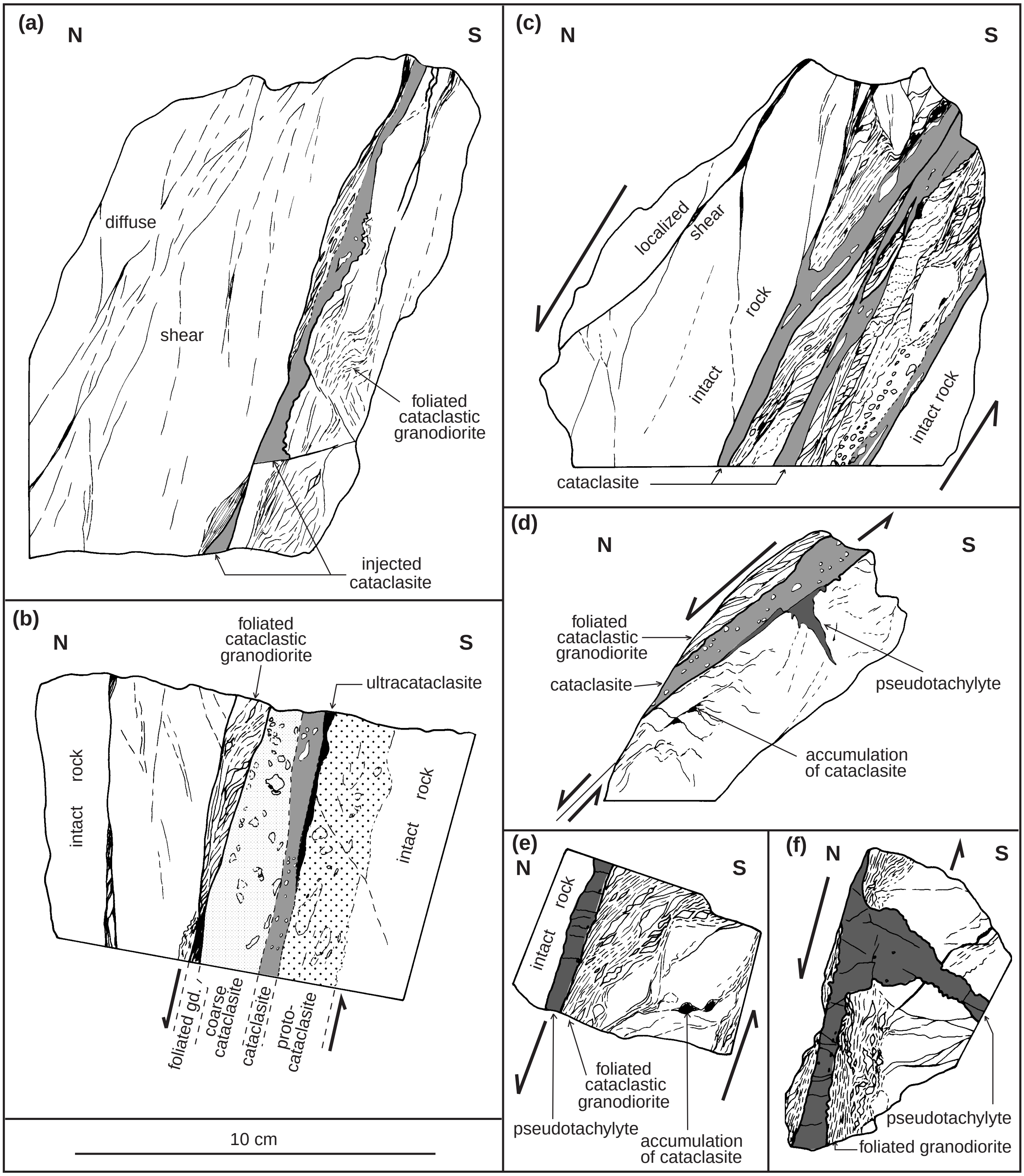

Fig. 4. Typical deformation features observed on N–S sections of hand samples from the Uchinoura shear zone. Scale bar (bottom left) is common to all sketches. (a) Cataclasite injected along a shear zone marked by foliated cataclasite (locality A). (b) Shear zone showing a juxtaposition of cataclasite–protocataclasite and foliated cataclasite. Note the progressive decrease in fragment size and of fragment-to-matrix abundance ratio when going to the central ultracataclasite layer (locality A). (c) Imbrication of cataclasite and foliated cataclasite (locality A). (d) Cataclasite vein truncating pre-existing pseudotachylyte (locality B). (e) Pseudotachylyte vein developed aside from foliated cataclastic granodiorite. The fine fractures inside the vein and perpendicular to the vein–host boundaries are interpreted as cooling joints (locality C). (f) Same as (e), but showing a secondary vein intruding the foliated wall rock.

Cataclasite is an indurated rock composed of a dark brown matrix and light-coloured sub-angular to rounded fragments of granodiorite. It forms either very thin (0.1–0.5 mm) dark films underlining isolated or anastomosing minor shear planes, or accumulates along more important (several metres long) shear planes. The thickness of such accumulations can reach 3 cm. The transition with the host rock can be sharp (cataclasite *veins*, Fig. 4a) or progressive (cataclasite *zones*, Fig. 4b, c and d). Where the transition is sharp, the cataclastic vein propagates along the foliation of pre-existing foliated cataclasite. Where the transition is progressive, the cataclasite zone can be bordered on both sides by coarser cataclasite or protocataclasite. The zones that show a lateral continuity of a few metres strike about E–W and dip between 40°N and 60°S. Minor zones show more scattered attitudes.

At first glance, *pseudotachylyte veins* (Fig. 4e and f) resemble cataclasite veins. However, the following features distinguish them from cataclasites: they are black and have a lustrous aspect; the vein thickness falls between 1 and 10 mm; included fragments are scarce, rounded, apparently monomineralic (quartz or feldspar), and their largest dimension never exceeds 1 mm; secondary, finger-shaped, branchings penetrate the host rock at high angles from the primary veins. Like the cataclasite veins, pseudotachylyte veins can be planar and extend laterally for several metres. The attitudes of pseudotachylyte veins are similar to those of cataclasite veins (e.g. Fig. 2, insert).

Foliated cataclastic granodiorite is commonly associated with pseudotachylyte veins and less frequently with cataclasite zones (Figs. 3 and 4). It can be found on both sides of the veins or zones, but is usually restricted to one side only (Fig. 4). The foliated granodiorite is characterized by the development of a foliation forming an angle ranging from 1° to 30° with the trace of the adjacent cataclasite or pseudotachylyte vein or layer. At the hand-sample scale, the foliation is defined by an alternation of dark biotite-rich layers and white quartz–feldspar-rich layers. The foliation can be offset by shear bands making small angles with the S planes. The foliation–shear band association indicates a normal sense of shear (Fig. 4).

Mutual relationships between the three types of fault rocks make clear the following points: (1) cataclasite veins or zones are concordant or almost concordant with adjacent foliated cataclastic granodiorite; (2) pseudotachylyte veins are either oblique (Fig. 4e) or parallel (Fig. 4f) to the foliation of the nearby foliated cataclastic granodiorite, but secondary veins commonly cut the foliation (Fig. 4f), indicating that the formation of the pseudotachylyte is after that of the foliated granodiorite; (3) at least one hand sample (Fig. 4d) shows that a cataclasite vein cross-cuts a pseudotachylyte. As will be discussed later, this last point shows that, in some instances, cataclasis can occur after pseudotachylyte generation.

3.4. Succession of tectonic events

From field and hand-sample observations, it may be inferred that the major episode of deformation in the Uchinoura shear zone occurred between the two stages of microgranite intrusion. The deformation episode itself includes at least three phases: (1) generation of foliated cataclastic granodiorite, cataclasite and pseudotachylyte; (2) kinking of aplite and cataclasite layers; (3) late faulting of pseudotachylyte veins and cataclasite layers.

At least two stages of pseudotachylyte generation can be distinguished. Indeed, at locality B (Fig. 3a), an older, N–S-trending pseudotachylyte and associated foliated cataclasite perpendicularly abuts against a younger, E–W-trending zone. The time gap between the two stages of generation cannot be estimated: it could be negligible (contemporaneous) or more substantial (two discrete events). Late faulting deformation consists of N40°E-trending right-lateral faults as observed in map view (Fig. 3a). Vertical sections of hand samples also show that cataclastic zones can be offset by sets of synthetic (R) or antithetic (R') fractures, the arrangement of which is compatible with a normal sense of shear.

4. Microstructures and deformation mechanisms

4.1. Cataclastic rocks

Non-foliated cataclastic rocks (Fig. 5a–d) encompass the whole spectrum between clast-supported protocataclasite (matrix $<10\%$ in proportion) and matrix-supported ultracataclasite (matrix $>90\%$ in proportion). Most of the clasts are derived from the host granodiorite, but can also come from microgranite or aplite. When passing from protocataclasite to ultracataclasite, there is a general decrease in clast size and clast-size heterogeneity, and a correlative increase of clast roundness and matrix abundance. This evolution reflects the increasing importance of cataclasis, which consists in microfracturing and microbrecciation of quartz and feldspar crystals, together with intergranular sliding and rotation of the resulting fragments. Besides mechanical cataclasis, diffusive mass transfer (DMT) also played a role in the genesis of cataclasite. Dissolution is indicated by stylolite-like surfaces crossing clasts of quartz (Fig. 5c) and, in some instances, the matrix. Recrystallization of the dissolved material probably occurred in the matrix, inside which small (largest dimension <10 μm) crystals of quartz are widespread. With increasing proportion of matrix ($>40\%$),

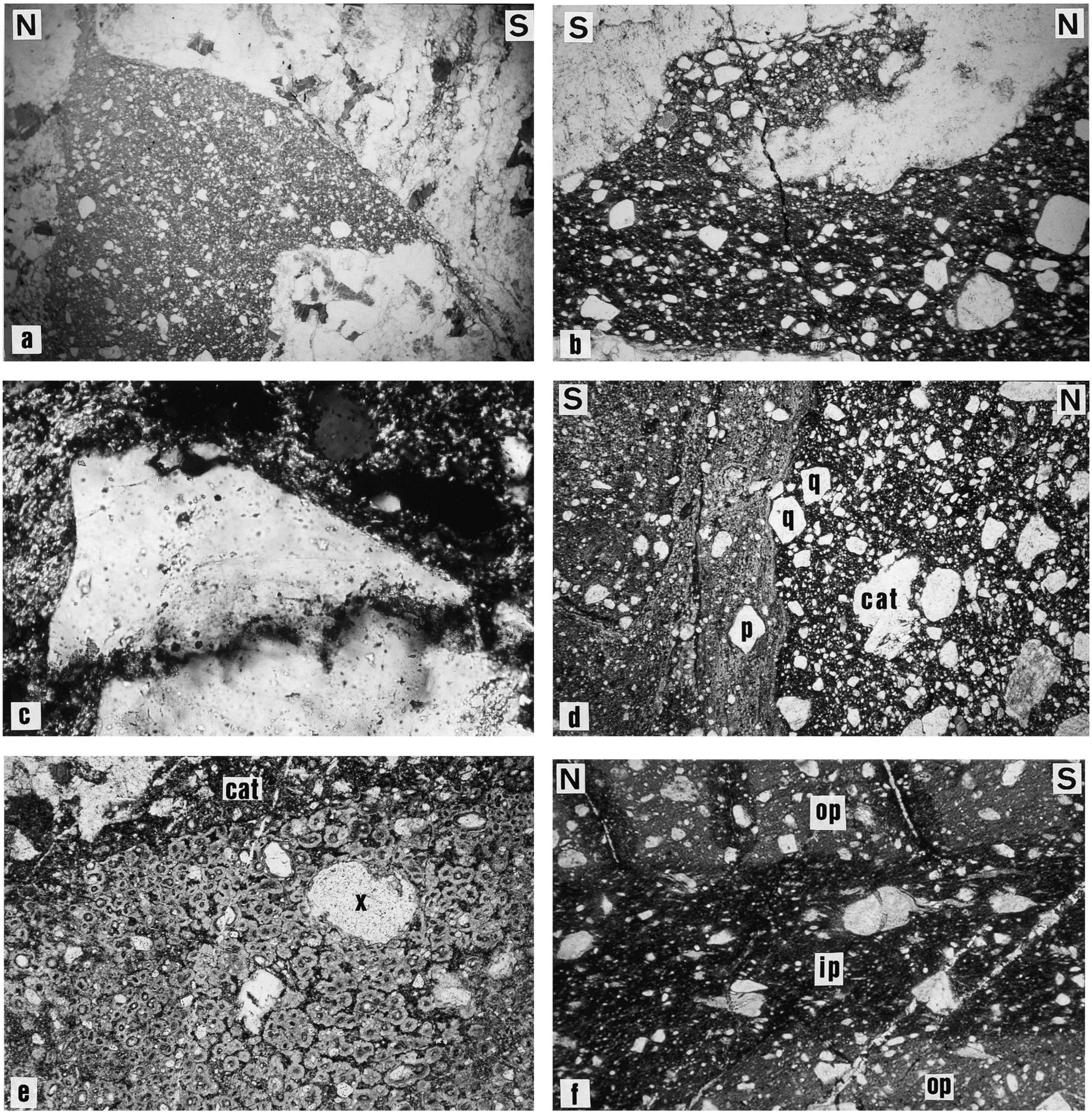

Fig. 5. Photomicrographs of cataclasites (a–d) and pseudotachylytes (e–f). Plane polarized light. Samples a, b and c are from locality A, the others are from locality B. (a) Abrupt termination of the cataclasite injection vein sketched in Fig. 4(a) (bottom). Width of photograph = 12 mm. (b) Detail of a cataclasite injection vein. The largest clasts consist of monocrystalline or polycrystalline quartz. Among the smallest clasts, plagioclase fragments are common. Width of photograph = 4 mm. (c) Partial dissolution of a quartz clast from a cataclasite zone. The dissolution surface separating the two parts of the clast is underlined by insoluble biotite and opaque minerals. Width of photograph = 0.4 mm. (d) Cataclasite (right side) injected along a previously injected pseudotachylyte (left side). The pseudotachylyte consists of a brown-coloured matrix containing well-rounded quartz or plagioclase clasts (average diameter 0.04 mm) and spherulites (average diameter 0.025 mm). In the injected cataclasite, the fragments are numerous, less rounded, and less sorted than in the pseudotachylyte. Abbreviations: q = quartz, p = plagioclase, cat = cataclastic granodiorite. Width of photograph = 4.8 mm. (e) Spherulitic-type pseudotachylyte injected through cataclastic material (cat). X is a plastically deformed polycrystalline quartz mosaic. The section is not oriented. Width of photograph = 1.5 mm. (f) Detail of the central part of the pseudotachylyte vein sketched on Fig. 6. The pseudotachylyte in the central and lower part of the photograph (new pseudotachylyte, or ip) was injected through an already solidified pseudotachylyte (old pseudotachylyte, or op). Two generations of quartz-filled tension gashes are visible: an old one, cutting the op and abutting against the ip, and the young one, cutting both op and ip. Note the recrystallized tails attached to clasts in the central part. Width of photograph = 2.5 mm.

the largest clasts show a tendency to be aligned with the general trend of nearby shear zones, thus indicating that some flow occurred in matrix-supported cataclasite.

Under the microscope, the foliated cataclastic granodiorite is defined by alternating thin dark layers of opaque minerals and biotite, and thicker light-coloured layers of quartz and feldspar. Biotite is highly strained: it is commonly kinked, split up into several fragments, or sigmoidally bent. The shear bands offsetting the foliation consist of mosaics of recrystallized quartz grains displaying a planar preferred orientation parallel to the general trend of the band. Between the mosaics, relict fragments of quartz or feldspar are locally preserved. With increasing strain intensity, usually when approaching a pseudotachylyte vein, the angle between the foliation and the shear bands decreases from 30° to about 10°, and the density of the shear bands increases drastically. The mechanisms of deformation which led to the formation of the foliated cataclastic granodiorite are the same as those operative in non-foliated cataclasites: faulting, cataclasis, and DMT processes. However, some differences can be noted. Firstly, DMT processes were more important throughout the foliated granodiorite. Indeed, the whole foliation can be interpreted as a dissolution sur-

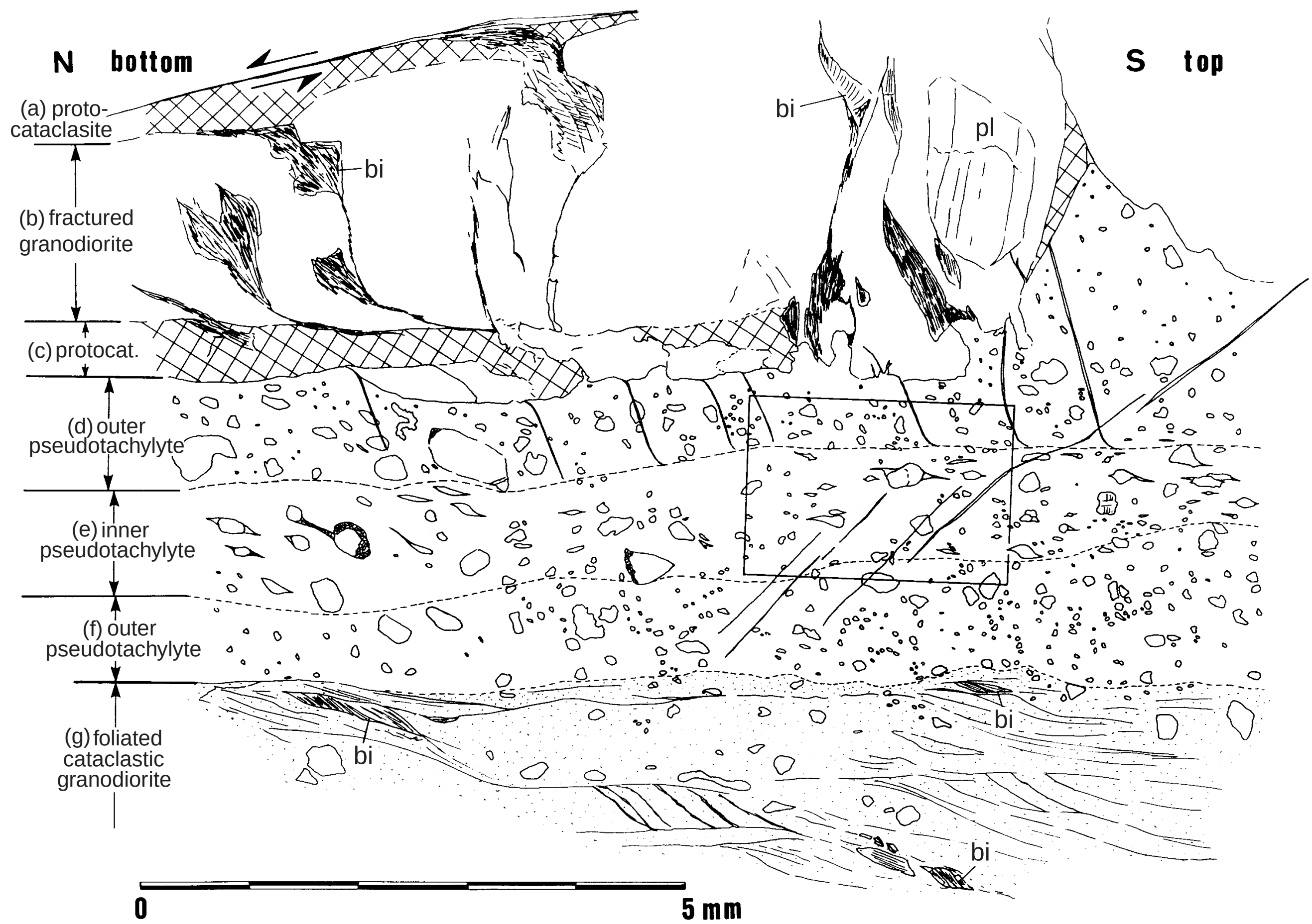

Fig. 6. Sketch of a thin section showing two stages of injection of pseudotachylyte between foliated cataclasite and non-foliated cataclastic granodiorite (partly drawn after photographs). Insert: photomicrograph (f) of Fig. 5. The following domains are distinguished. a: protocataclasite; b: fractured granodiorite; c: early-stage pseudotachylyte (op of Fig. 5f) cut by quartz-filled cooling joints almost perpendicular to the boundary with the adjacent granodiorite; d and e: late-stage pseudotachylyte (ip of Fig. 5f) intruded along the boundary between the old pseudotachylyte and foliated cataclastic granodiorite of domain f. The matrix of domain d pseudotachylyte is marked by a planar fabric parallel to the boundary between op and ip. The domain d is further characterized by the presence of quartz porphyroclast systems (clasts and recrystallized tails) and by plastically deformed sigmoidal quartz clasts. The planar fabric of the matrix of domain e pseudotachylyte is less pronounced than in domain d. Late-stage quartz-filled veins cutting obliquely domains c, d and e are interpreted as tension gashes. f: foliated cataclasite. Sense of shear criteria include top-to-the-left motion along synthetic, R-type, secondary fractures (domains a and b), deflection of early-stage cooling joints, asymmetric porphyroclast systems, sigmoidally deformed clasts (domain d), oblique tension gashes (domains c, d and e), sigmoidal biotites, deflection of S surfaces by C planes (domain f). All these criteria indicate a top-to-the-north normal sense of shear.

face (solution cleavage), the dark layers consisting in fact of residual accumulations of insoluble biotite and iron oxides. Newly recrystallized polygonal quartz grains or subgrains (diameter < 25 μm) surround larger quartz or feldspar crystals or fill the spaces along intragranular fractures, in a way similar to that described by Hippertt and Egydio-Silva (1996). Secondly, plastic deformation mechanisms also played a role in the genesis of the foliated cataclastic granodiorite. This can be deduced from the observation, common along the shear bands, of sigmoidally bent biotite crystals or elongated recrystallized quartz grains showing a pronounced undulatory extinction, as is observed along the shear bands.

4.2. Pseudotachylytes

Thin section observation shows that some of the dark veins cutting the granodiorite at the three studied localities are filled with a material that experienced melting (Figs. 5e–f and 6). This material, which corresponds to pseudotachylyte sensu stricto, is made of an orange-coloured matrix including clasts derived from undeformed or deformed granodiorite. Melting is attested by the presence of rounded or embayed clasts (Fig. 7a) and of microlites scattered in the matrix or surrounding clasts (Fig. 7b). Two categories of pseudotachylytes can be distinguished: foliated-type and spherulitic-type.

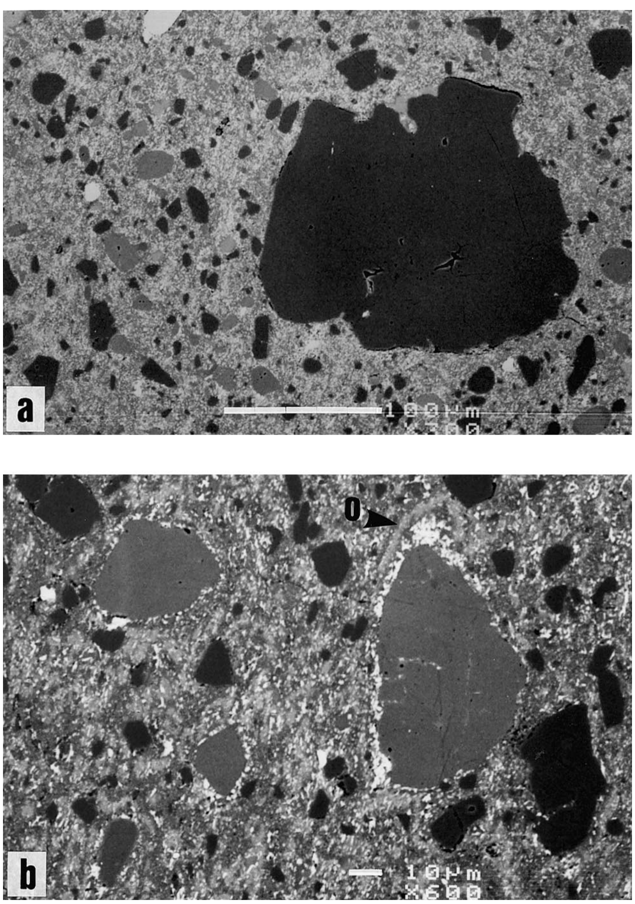

Fig. 7. Back-scattered electron images of planar-type pseudotachylytes. (a) Embayed quartz clast. Scale bar is 100 μm. (b) Microlite rim surrounding a well-rounded plagioclase clast. The microlites, which appear light-coloured in BSE mode, are probably mafic minerals (possibly biotite or amphibole). O denotes a more discrete outer rim made of very fine microlites. Scale bar is 10 μm.

Foliated-type pseudotachylyte is characterized by a finely foliated matrix with a proportion of clasts lower than 20%. The matrix consists of highly elongated, 50-μm-long or less, microlites of undetermined nature. The clasts consist of quartz, feldspar and rare biotite and opaque minerals. The foliation of the pseudotachylyte, which is parallel to the vein boundaries, is defined by the preferred orientation of the microlites and by the planar arrangement of elongated clasts. The foliation is usually more marked in the central part of the vein rather than near the margins. In some cases, the central part of the foliated-type pseudotachylyte veins gets a mylonitic aspect. Clasts are flattened or stretched, and are flanked by polycrystalline quartz tails (Figs. 5f and 6). Most quartz clasts are partly or completely replaced by a mosaic of grains with a strong undulatory extinction. The foliated texture, which is reminiscent of the microscopic fabric of ignimbrites, is evidence for the displacement of a viscous medium. The clasts and their tails display analogies with porphyroclast systems in mylonites (Passchier and Simpson, 1986). The clast-tail systems can be symmetrical, suggesting that the vein-filling material underwent pure shear deformation before complete solidification, or can be asymmetrical (Figs. 5f and 6), suggesting that the pseudotachylyte suffered from a non-coaxial shearing deformation. Where present, asymmetrical clast-tail systems are consistent with other criteria in the vein, or in the host rock, that indicate a top-to-the-north normal sense of shear (Fig. 6).

Spherulitic-type pseudotachylytes consist of zoned spherulites embedded in an amorphous matrix (Fig. 5e). The proportion of remaining clasts is lower than 10%. The spherulites are typically formed by a central, well-rounded clast surrounded by one or two aureoles of newly crystallized microlites. Where recognizable, the clasts are most commonly monocrystalline or polycrystalline quartz, rarely feldspar or cataclastic quartz–feldspar fragments. Biotite could not be found. The outer rim consists of a radially arranged set of thin and elongated microlites. Where present, the inner rim is a zone of needle-shaped microlites with radial or random arrangement. The strong relief of the microlites rules out the presence of quartz. On back-scattered electron images (Fig. 7b), the inner rim appears white, suggesting it could consist of a mafic mineral such as biotite or amphibole. Microlite clusters can also make up the nuclei of small-sized spherulites. In such cases, the clusters have fan or bow-tie shapes. Like the clast-nucleated spherulites, they are bordered by a rim of fine, radially arranged mineral. This similarity suggests that, in some cases, the clastic nucleus can be completely assimilated and replaced by microlites. A clear zonation can be observed in the thickest veins. It is defined by the alternation of 1- or 2-mm-thick layers of large (0.1 mm in average diameter) and small (0.02 mm in average diameter) spherulites. The margins of the veins are devoid of any spherulitic texture. Instead, tiny microlites (length <10 μm), having plumose or bow-tie shapes, punctuate an amorphous matrix in which very few clasts are visible.

5. Discussion

5.1. Evidence for melting and for post-seismic strain accommodation

The following observations, already reported by many authors (Sibson, 1975; Allen, 1979; Spray, 1987, 1992, 1993, 1995; Magloughlin, 1989, 1992; Maddock, 1992; Magloughlin and Spray, 1992; O'Hara, 1992; Lin, 1994, 1999) are indicative of a melt origin of the Uchinoura pseudotachylytes: (1) abundance of newly crystallized microlites, either scattered in the matrix (foliated-type pseudotachylyte or marginal parts of spherulitic-type pseudotachylyte veins) or clustered around clasts (spherulitic-type pseudotachylyte); (2) presence of rounded or embayed clasts; (3) scarcity of biotite clasts, reflecting the preferential destruction and assimilation of biotite (and of any hydrated ferromagnesian mineral as well) during melting. Thermodynamic calculations and experiments show that only displacements at seismic rates can produce melting along a fault plane and therefore generate pseudotachylytes (McKenzie and Brune, 1972; Sibson, 1973, 1975; Spray, 1987, 1993, 1995; Lin and Shimamoto, 1998). We conclude that, along the Uchinoura shear zone, friction during seismic slip provided the heat necessary to melt the granodiorite or granodiorite-derived cataclasite.

Even if both types of pseudotachylytes went through a melt stage, they did not undergo the same post-melting strain history. The spherulitic-type pseudotachylyte did not undergo any post-melting strain. The microlite overgrowths surrounding the clasts, which are undeformed, grew statically. On the contrary, the foliated-type pseudotachylytes underwent some flow, as shown by the preferred orientation of microlites and clasts. The flow took place when the pseudotachylyte was not completely solidified, since all the observed textures are concordant with the general fabric.

In most foliated-type pseudotachylytes from the Uchinoura shear zone, the preferred orientation of clasts and microlites is parallel to the vein boundaries and does not display any asymmetrical structure. This is indicative of coaxial flow. However, in some foliated-type pseudotachylytes, flow was non-coaxial, as shown by asymmetrical clast-tail systems. In the example depicted in Fig. 6, the non-coaxiality is observed only in the central part of the vein, whereas the marginal parts recorded only a coaxial strain. This shows that the non-coaxial shear occurred when the marginal parts of the vein were almost completely solidified, whereas the central part was still viscous. Complete solidification of a 10-mm-thick pseudotachylyte does not last more than a few seconds or minutes (Sibson, 1975). We thus interpret the non-coaxial shear as a post-seismic strain accommodation taking place during the few seconds or minutes following the main episode of seismic slip and pseudotachylyte generation.

5.2. Evidence for aseismic creep in the Uchinoura shear zone

Energy balance for mechanical cataclasis is less quantified than for pseudotachylyte, and there are no unambiguous criteria which could help in deciding whether a cataclastic rock formed during seismic or aseismic slip (e.g. Cowan, 1999). However, the importance of dissolution–recrystallization processes, whose effects are widely recognizable in the Uchinoura cataclastic rocks, especially the foliated granodiorite, advocates for deformational increments at aseismic rates. Indeed, diffusive mass transfer is typically a slow process acting at strain rates of about 10^{-14} s^{-1} (e.g. Shimizu, 1995; Gratier et al., 1999). We conclude that at least some stages of generation of foliated granodiorite and, to a lesser extent, of non-foliated cataclasite, took place under slow, aseismic rates.

6. Conclusions

The Uchinoura shear zone shows an intimate association between pseudotachylyte and cataclastic rocks. Whatever the scale of investigation (outcrop, hand sample, thin section), there is always a spatial association between pseudotachylytes and cataclastic rocks in the three studied localities. This association is also temporal, since mutual cross-cutting relationships between the two types of rocks can be observed: pseudotachylyte frequently cross-cuts foliated granodiorite or non-foliated cataclasite (Figs. 4f and 5e), but cataclasite can also cross-cut pseudotachylyte (Figs. 4d and 5d). This temporal and spatial association shows that frictional melting alternated with cataclasis. Since the cataclastic rocks were at least partly generated at slow rates, as pointed out by dissolution features, the Uchinoura shear zone provides an example where past seismic and aseismic deformations can be documented.

The Uchinoura shear zone pseudotachylytes also display deformational microstructures which were formed before complete solidification of the melt. Given the quite rapid rates of cooling estimated for pseudotachylytes, these microstructures were probably formed in a short time (a few seconds to a few minutes) after the main seismic episode. They can thus be interpreted as reflecting post-seismic strain accommodation.

Acknowledgements

We would like to thank T. Kano (Yamaguchi University), P. Gaviglio (UFC) and J.F. Gamond (LGIT, Grenoble) for discussions in the field, M. Faure (IUF, Orléans) for critically reading the manuscript, S. André and M. Boué for technical assistance at the University of Franche-Comté and M. Imrie for checking the English. Professors J.G. Spray and T.G. Blenkinsop provided helpful reviews. Fieldwork was supported by grants from Japanese Monbusho and French Ministere des Affaires Etrangeres to Fabbri.

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