Geometric aspects of synkinematic granite intrusion into a ductile shear zone – an example from the Yunmengshan core complex, northern China

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Abstract: The Cretaceous Yungmengshan core complex in northern China contains a large syntectonic granodiorite batholith that intrudes a slightly older diorite intrusion. A major gently dipping ductile décollement shear zone is developed along the contact of the diorite and granodiorite. The shear zone is invaded by a large volume of granitic and pegmatite veins associated with the main granodiorite batholith during activity of the shear zone under high-grade metamorphic conditions. Progressively older veins are more strongly deformed into tight cylindrical fold structures rotated into parallelism with the lineation and foliation in the shear zone. Parallelism of veins to the foliation is partly due to this rotation, but also to foliation-parallel injection of younger syntectonic pegmatite veins. Several small-scale structures have been recognized that allow distinction of solid-state deformation of veins. Granite veins do not extend much above the ductile shear zone that seems to act as a lid and an effective depository to intruding granite veins from the underlying batholith. There was considerable volume increase in the footwall and lower part of the shear zone by vein intrusion.

Gently dipping ductile shear zones are a common feature of many continental metamorphic core complexes throughout the world, for example in the Basin and Range (Reynolds & Lister 1987; Fletcher & Bartley 1994; Foster & Fanning 1997; Foster *et al.* 2001), Algeria (Caby *et al.* 2001), New Guinea (Baldwin *et al.* 1993) and in the Aegean Sea (Lister *et al.* 1984; Walcott & White 1998; Pe-Piper *et al.* 2002). The shear zones are thought to accommodate most of the crustal-scale extension that is typical for the development of such core complexes. Core complexes are also commonly associated with the intrusion of granitoid plutons and associated rhyolitic volcanism (e.g. Caby *et al.* 2001; Foster *et al.* 2001; Pe-Piper *et al.* 2002). Many granitoid intrusions in core complexes can be shown to have intruded during active deformation of the ductile shear zones of the complex (Caby *et al.* 2001; Foster *et al.* 2001; Pe-Piper *et al.* 2002). In such cases, parts of a pluton may cut mylonitic rocks, while other parts are mylonitized with the same orientation of mylonitic structures as in the truncated older parts, and this is used as evidence of syntectonic intrusion.

In the Yunmengshan of northern China, a Cretaceous core complex developed in Archaean basement and Proterozoic metasediments at the northern rim of the North China Craton (Fig. 1) (Davis *et al.* 1996). The core complex is centred on a granodiorite batholith, which is truncated at the northern, eastern and southern sides by brittle and ductile shear-zone segments. The segments dip gently away from the granodiorite batholith towards the north, east and south (Figs 1 and 2). Mapping by Davis *et al.* (1996) has shown that, although these shear-zone segments are of different metamorphic grade and presumably of different age in different parts of the pluton, they share a common orientation of stretching lineations. They are therefore inferred to have formed as part of one tectonic shear-zone system that acted as a major décollement of the core complex. Its present variation in dip direction and dip is probably due to folding over the developing core complex, a feature also observed in many other complexes (e.g. Fletcher & Bartley 1994).

Along the NE side of the core complex, the Yunmengshan granodiorite is bordered by metadioritic rocks and the contact is affected by a ductile shear zone, the Sihetang shear zone discussed in this paper (Fig. 2). The metadiorites are intrusive into Proterozoic metasediments (Fig. 2) (Miyun metadiorite; Davis *et al.* 1996),

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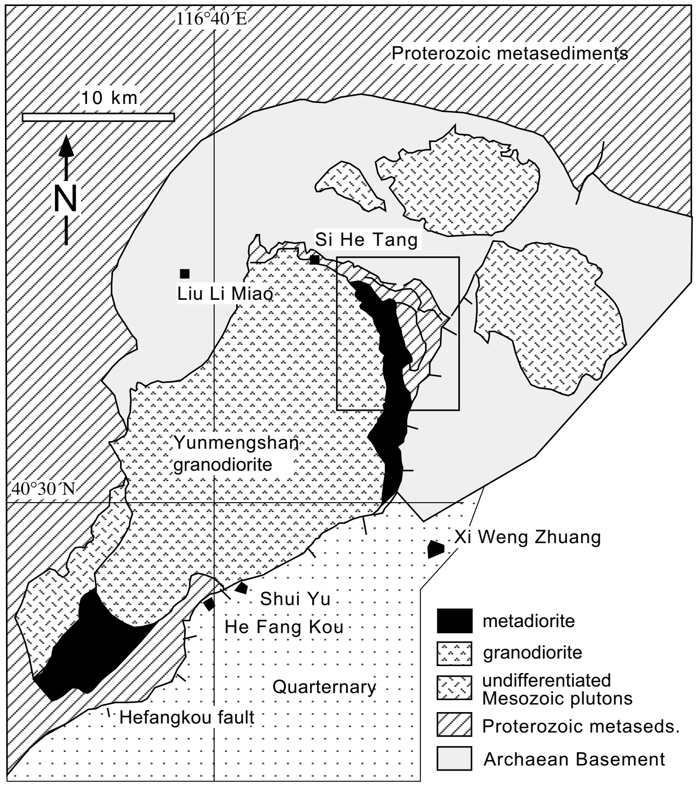

Fig. 1. General map of the Yunmengshan granodiorite core complex, after Davis *et al.* (1996). H, Hefangkou; L, Liulimiao; X, Xiwengzhuang.

but the intrusive contact is rarely exposed and is marked by a Mesozoic brittle thrust fault in most places (Fig. 2). This fault post-dates intrusion of the diorite and granodiorite, and seems to post-date and cut the Sihetang ductile shear zone. The thrust and the Sihetang shear zone are cut in the SE by the brittle Hefangkou normal fault (Fig. 1).

The Sihetang shear zone is an amphibolite facies ductile shear zone with a thickness of 20–50 m (Fig. 2) (Davis *et al.* 1996). The shear zone is centred on the contact between the meta-diorite and the granodiorite, and has strongly mylonitized the igneous rocks. Despite the presence of the shear zone, it is clear that the contact between the granite and granodiorite of the Yunmengshan batholith and the Miyun meta-diorite was intrusive: xenoliths of metadiorite occur in the granite, and granite veins intrude the metadiorite. The metadiorite therefore predates the granitic phases. Dating of both units has given concordant U–Pb zircon ages of 159 ± 2 Ma for the Miyun metadiorite and ages between 151 and 127 Ma for the Yunmengshan granodiorite (Davis *et al.* 1996).

Although the main body of the granodiorite is deformed by the Sihetang shear zone, there is a large volume of granite dykes that show different stages of deformation, and a decrease in deformation intensity with a decrease in relative age within the shear zone, based on cross-cutting relations. This suggests that the shear zone was active while intrusive material was added from lower levels of the granodiorite pluton. The Sihetang shear zone is not affected by late brittle deformation and forms a flat ‘roof’ to the batholith. It is only invaded by minor veins, although these represent a considerable volume of material. Some work has been published on synkinematic intrusion of granite veins into ductile shear zones (Zurbriggen *et al.* 1998; Pawley *et al.* 2002), but three-dimensional (3D) control on geometry is limited in these studies. The excellent outcrop condition and the sharp colour contrast between the metadiorite and the leucocratic veins in the Sihetang shear zone

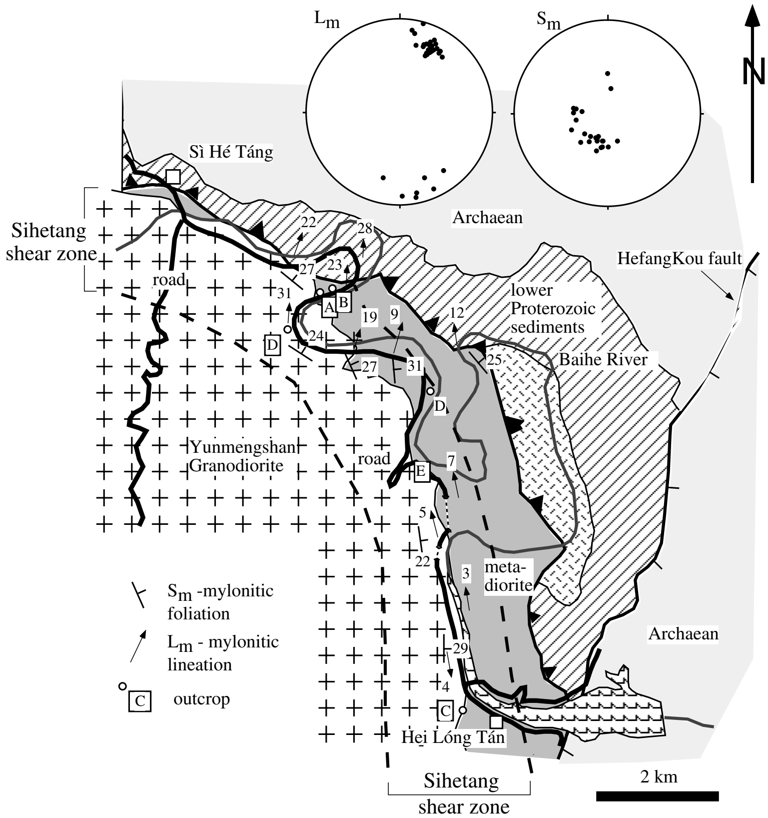

Fig. 2. Schematic map of the NE Yunmengshan granodiorite with the approximate position of the Sihetang shear zone, after Davis *et al.* (1996). Orientation of the mylonitic foliation (S_m) and lineation (L_m) measured in this study in this part of the shear zone is shown as inset stereograms.

allow a closer look at the internal structure of this type of ductile shear zone.

Host rock lithology

The Miyun metadiorite (Davis *et al.* 1996) consists of hornblende, plagioclase, biotite and quartz. It is metaluminous, alkaline to calc-alkaline–tholeiitic in composition with xenoliths rich in hornblende and garnet (Davis *et al.* 1996). Locally, evidence exists for several pulses of dioritic magma with different amount of dark minerals. The grain size is uniform at 0.5–3 mm, and phenocrysts of plagioclase are rare. Where the metadiorite is deformed, it shows weak banding indicating that originally some variation in composition may have been present.

The Yunmengshan batholith away from the shear zone is composed of granodiorite with few granite and pegmatite veins. The granodiorite outside the contact zone is coarse grained, with plagioclase grains up to 1 cm in diameter and relatively biotite-rich. In the top of the batholith close to the contact with the Miyun metadiorite, the batholith contains several generations of granite veins with xenoliths or blocks of granodiorite and late pegmatite and microgranite veins.

Sihetang shear zone

The Sihetang shear zone at the contact of the granodiorite and metadiorite has a single, penetrative foliation and a well-developed object lineation (terminology as in Piazolo & Passchier 2002) in both the granodiorite and the metadiorite (Fig. 3b). Strain seems to be highest along the contact of both units, and a mylonitic foliation and lineation is visible over at least 15 km along the contact (Fig. 2) (Davis *et al.* 1996). The main foliation consists of a preferred orientation of hornblende, biotite and of xenoliths in

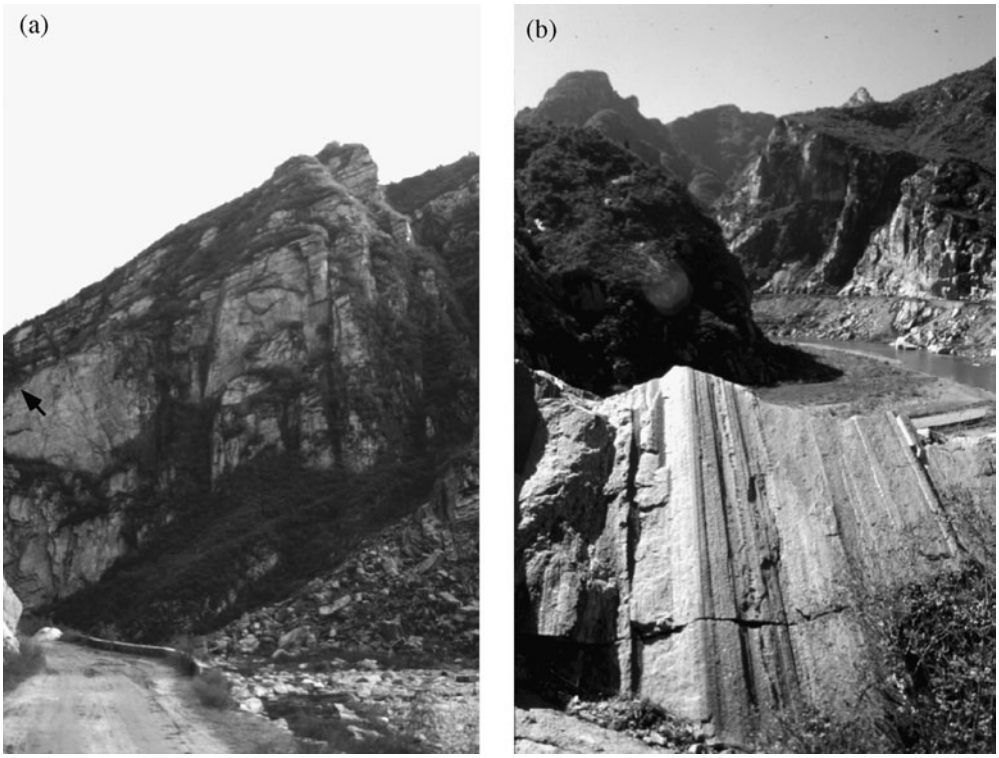

Fig. 3. (**a**) General structure of the Sihetang shear zone in outcrop C of Figure 2, looking west. The shear zone is developed in metadiorite with numerous veins on top of undeformed granodiorite. The contact between the granodiorite and the overlying metadiorite is indicated with an arrow. Deformed granite and pegmatite veins lie at a small angle to the contact in the metadiorite. The rock face lies at a small angle to the mylonitic lineation. The height of outcrop is approximately 50 m. (**b**) View from the core of the Sihetang shear zone in outcrop A of Figure 2, looking towards the south and the undeformed granodiorite. The outcrop in the foreground shows the strong N–S-trending object lineation characteristic of the deformed metadiorite.

the metadiorite, and a shape fabric of aggregates of recrystallized quartz, feldspar and biotite in the granodiorite. No magmatic foliation is visible in the granodiorite or metadiorite and dykes are undeformed away from the Sihetang shear zone.

In thin section, the deformed metadiorite consists of equigranular plagioclase, hornblende, biotite and quartz with minor sphene and zircon. Hornblende and biotite occur as clusters of euhedral or subhedral grains with a strong preferred orientation defining a foliation. Feldspar grains are commonly slightly elongate parallel to this foliation. Biotite, plagioclase and hornblende crystals are usually unzoned and strain-free. Albite twins in most plagioclase grains are straight and transect the whole grain, although some plagioclase grains show weak undulous extinction and tapering deformation albite twins. Quartz crystals show weak undulous extinction and elongate subgrains. Interphase boundaries and grain boundaries are mostly gently curving, but some boundaries, especially between quartz crystals, are lobate. The lack of small subgrains and new grains around old quartz crystals, and the lobate grain and interphase boundaries indicate the activity of high-temperature grain-boundary migration recrystallization in quartz above 500 °C (Stipp *et al.* 2002). However, chessboard-subgrain structures in quartz (Stipp *et al.* 2002) are lacking and all subgrains are of elongate prismatic type. The euhedral or subhedral shape of biotite and hornblende, and the gently curved boundaries of plagioclase grains indicate grain-boundary migration and grain-boundary area-reduction processes (Passchier & Trouw 1996).

The deformed granodiorite and the granite veins have a similar quartz–feldspar microstructure as the metadiorite and in many cases a strong preferred orientation of euhedral–subhedral biotite. Quartz occurs in ribbons 0.5–1 mm wide and up to 8 mm long in granite veins. Myrmekite growth is common. However, in the less deformed parts of the granodiorite, and in the younger, little deformed granite and pegmatite veins, some plagioclase grains show zoning that is probably a relict of the magmatic fabric. Such plagioclase grains are surrounded by a mantle of smaller grains inferred to have formed by recrystallization. These recrystallized grains have a diameter of 0.05–1 mm.

Relicts of magmatic microstructures are rare in the Sihetang shear zone. Although some of the microstructures observed above are also observed in undeformed igneous rocks, the most typical features such as feldspar synneusis, euhedral faces on plagioclase to quartz, zoning and truncated growth twins in plagioclase, and wedge- or corridor-shaped quartz grains between euhedral feldspar grains (Paterson *et al.* 1989, 1998) are missing in the oldest veins and in the metadiorite; they are present as relict in the youngest, weakly deformed veins.

The object lineation is a hornblende grain lineation in the metadiorite, and an aggregate lineation of quartz and feldspar in the granodiorite (Fig. 3b). The orientation of the foliation and lineation is remarkably constant within the shear zone. A deflection of the foliation is only visible close to veins or other features: in all other places it is straight (Fig. 3). Although most structures in the shear zone are symmetric in sections parallel to the lineation, local metre-scale ductile shear bands, shear-band boudins (Goscombe & Passchier 2001) and asymmetric σ-shaped feldspar porphyroclasts indicate S-directed transport of the hanging wall for at least part of the deformation history. Some shear bands have tension gashes filled with pegmatite that give the same shear sense. In a marble horizon within the metasediments overlying the metadiorite, asymmetric boudins, some with the geometry of delta objects and up to 50 cm in diameter, indicate top-to-the-south displacement as well.

The stability of hornblende, biotite, plagioclase and garnet in the samples, and the evidence for high-temperature grain-boundary migration in quartz and of grain-boundary area reduction in other minerals, indicate that deformation took place under amphibolite facies conditions. Migmatic veins are absent in the metadiorite, and no structures indicative of local melting or melt accumulation were seen; all veins are formed by intrusion from outside the observed outcrops.

An attempt was made to use amphibole–plagioclase thermometry on five samples from the metadiorite in the shear zone (Holland & Blundy 1994) to determine the temperature of deformation more precisely. All samples show the quartz-bearing mineral assemblage (amphibole–plagioclase–K-feldspar–quartz–biotite $\pm$ titanite) and thus both the edenite–tremolite and edenite–richterite calibrations can be used. The composition of amphiboles in all samples varies around the junction edenite–magnesiohastingsite–magnesiohornblende and the anorthite content of plagioclases is in the range of 17–28%. For all five studied samples, both calibrations gave similar but surprisingly high average temperatures of 662–722 °C (Table 1: standard deviation of *c.* $\pm$15 °C) in the range of pressures between 6 and 12 kbar. As no partial melt structures were observed in the shear zone, such high temperatures could be due to non-equilibration of magmatic hornblende in the samples.

Main contact of granodiorite batholith and metadiorite

We investigated the geometry of structures in the shear zone in some detail in a number of well-exposed road cuts along the main road from Hei Long Tan to Si He Tang (Fig. 2).

Table 1. *Average temperature estimates (including standard deviations) for studied samples**

Sample	Number of Am–Pl pairs	Average T ($P = 6$ kbar) ed–tr (°C)	SD (°C)	Average T ($P = 12$ kbar) ed–tr (°C)	SD (°C)	Average T ($P = 6$ kbar) ed–ri (°C)	SD (°C)	Average T ($P = 12$ kbar) ed–ri (°C)	SD (°C)
MY 18	13	694	15	657	16	667	15	692	16
MY 30	29	697	14	662	12	668	13	694	12
MY 38	16	710	16	676	14	682	13	710	13
MY 49	23	717	12	689	9	691	10	722	8
MY 7	17	691	19	663	20	669	15	699	16

*The temperatures were calculated using the amphibole–plagioclase thermometer of Holland & Blundy (1994). Abbreviations: ed–tr, edenite–tremolite calibration; ed–ri, edenite–richterite calibration.

In all localities, the contact between the dark metadiorite and light-coloured granodiorite rocks of the Yunmengshan batholith is sharp and dipping parallel to the main foliation, S_m (Figs 2 and 3). The granodiorite has only a few inclusions of metadiorite, but the latter is invaded by a large number of granite and pegmatite veins in a zone 50–100 m wide parallel to the contact (Fig. 3a). Up to 40% vol. of the rock can be made up of such veins. Higher up in the metadiorite, the veins are uncommon. The Proterozoic marbles and quartzite overlying the metadiorite (Fig. 2) contain occasional veins of metadiorite and granite, and the granite veins in all cases cut metadiorite veins, even in these metasediments. In the top of the Yunmengshan granodiorite batholith a metre-scale xenolith of alternating marble and quartzite was intruded by a diorite vein; all three units are cut off by the surrounding granite.

Nature of the veins

The veins intruding the metadiorite are richer in SiO_2 than the parent granodiorite and consist of several types of medium-to coarse-grained granite, alkali-granite and pegmatite. The veins range in thickness from 1 mm to several metres,

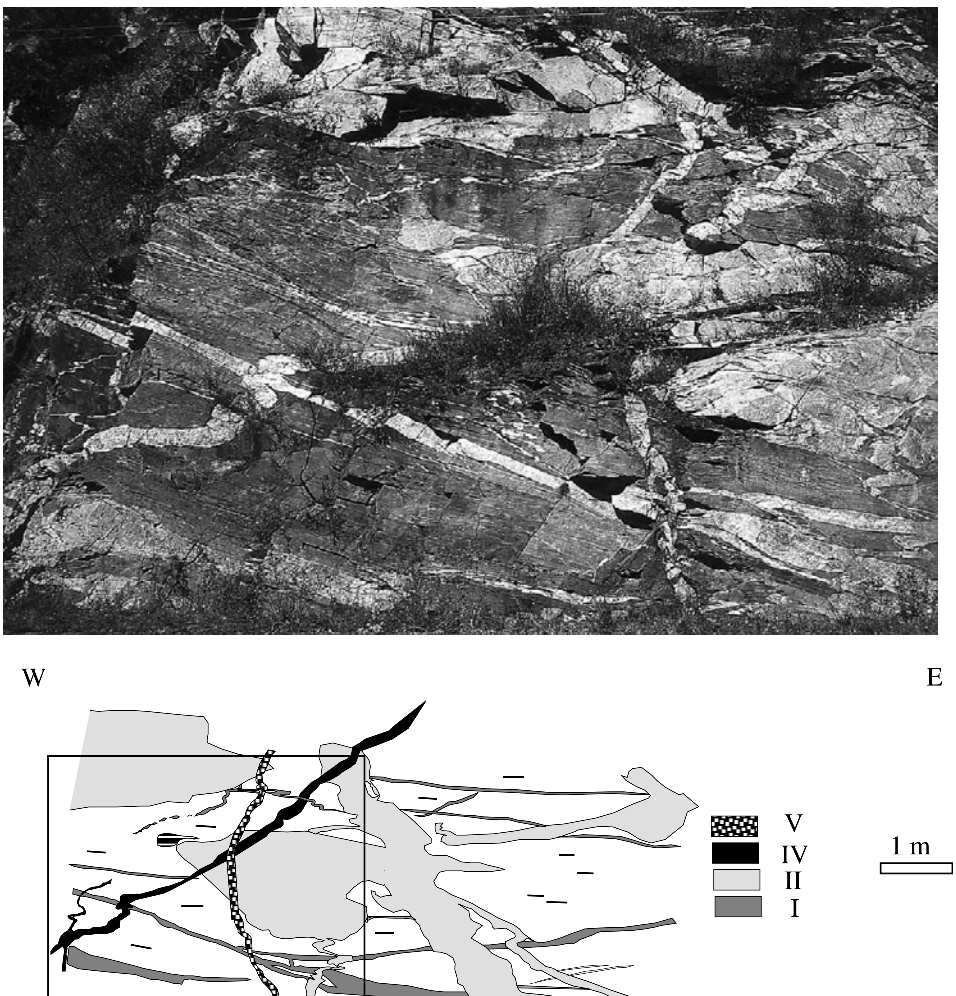

Fig. 4. Part of outcrop A in Figure 2 looking north, seen from the outcrop in Figure 3b. The age relationship of dykes visible in the photograph (I–V) is given in the sketch. Relatively younger veins are less folded and boudinaged, and at a higher angle to the mylonitic foliation than older veins.

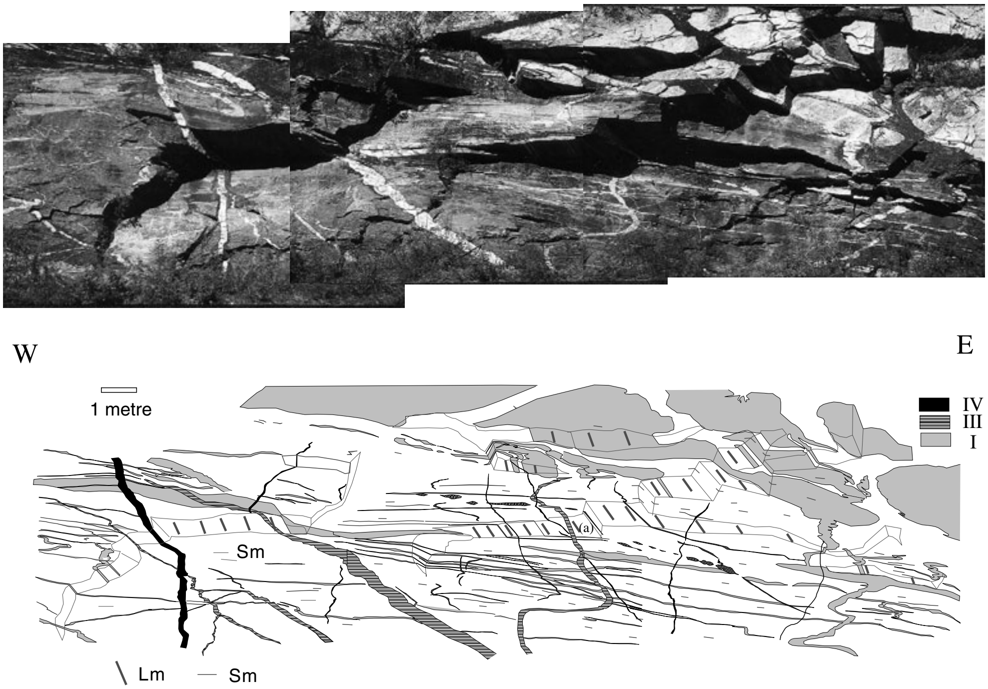

Fig. 5. Composite image of outcrop B in Figure 2 looking north. The age relationship of dykes visible in the photograph is given in the sketch. Relatively younger veins are less folded and boudinaged and at a higher angle to the mylonitic foliation than older veins. In the centre of the drawing (a) shows the site of Figure 6a.

have sharp boundaries and their relative age can be established by cross-cutting relations (Figs 4 and 5). All veins, even the oldest ones, show signs that they intruded the metadiorite after a foliation was established. This can be seen from the fact that parts of the contact or branches of the veins follow S_m (Figs 4–6c & f). Progressively younger veins were systematically subject to less deformation, but even the youngest veins recognized in the shear zone are slightly deformed. All veins in the shear zone are therefore synkinematic.

A sequence of veins can be recognized in every outcrop, suggesting that intrusion was phased, but this is not convertible from outcrop to outcrop, and they are not all separable by their bulk chemistry. There is a weak tendency for earlier veins to be granitic and medium grained, while later veins are more commonly pegmatitic, more alkaline and more coarse grained. However, exceptions to this trend are common. Flow structures have not been preserved in any veins.

Geometry of the veins

The geometry of the deformed veins has been studied in a number of fresh road cuts and cliffs of different orientation along the main Baihe River, as indicated in Figure 2. The geometry of the deformed veins is dramatically different on outcrop surfaces of different orientation. The outcrops A and B shown in Figures 4 and 5 are the most important data source for the vein network. The general characteristics are as follows.

Rock faces normal to L_m and S_m

On surfaces normal to the lineation, a complex network of veins of different colour, grain size and composition is visible (Figs 4 and 5). Cross-cutting relationships show that the oldest veins (I) are granite and alkali-granite veins subparallel to the foliation, branching at small angles into ladder- or irregular-shaped networks, usually with one set of branches parallel to S_m. These are followed by several generations of grey and red granite, and pegmatite veins (II–V), with increasing steepness towards the foliation in the metadiorite, although some branches of each system tend to be parallel to S_m. The youngest, little or undeformed veins (IV and V) are pegmatites or granite veins at a high angle to

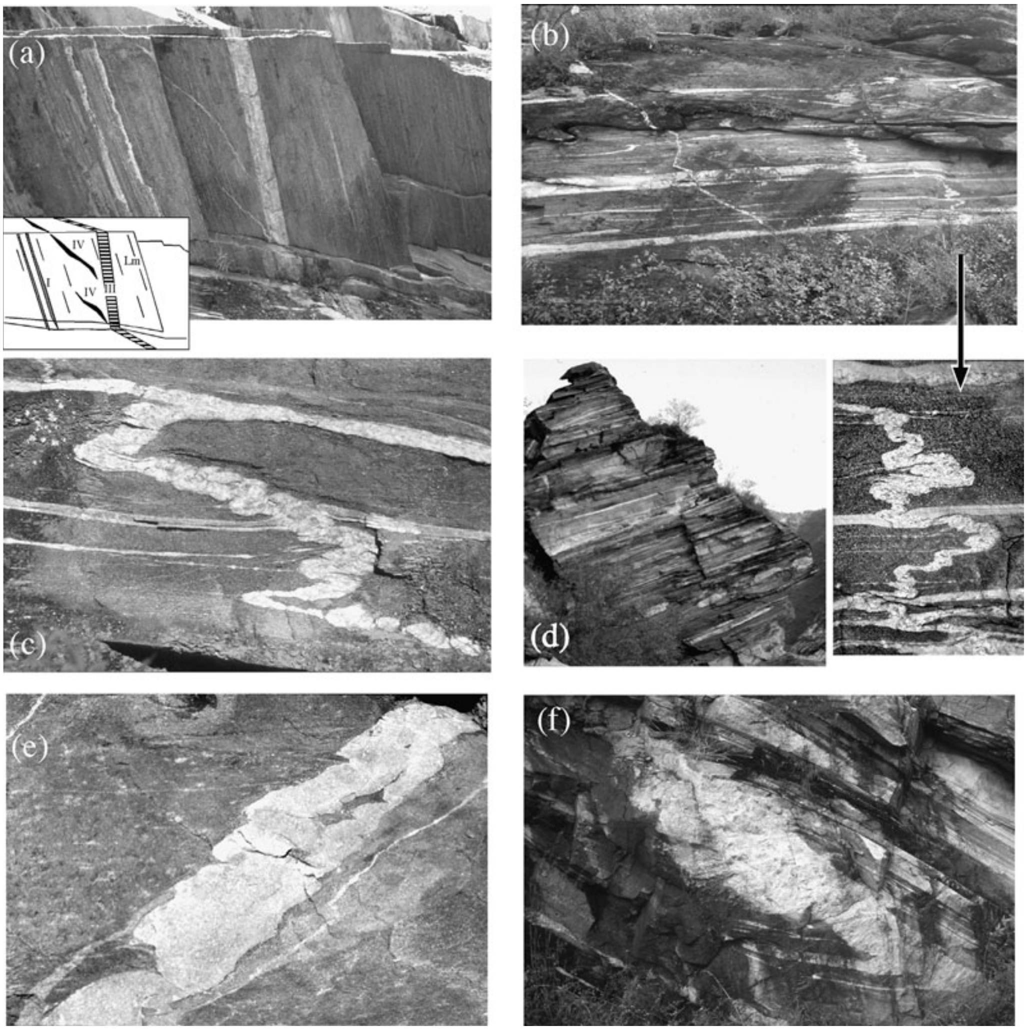

Fig. 6. (**a**) Lower part of an S_m-surface in metadiorite in outcrop B of Figure 5 showing strong object lineations and three types of veins of generations I, III and IV. Younger veins are more oblique to L_m than older veins. The width of the view is 1 m; (**b**) outcrop E normal to L_m looking south. Three sets of deformed veins of different age lie in the metadiorite; the oldest ones are horizontal parallel to S_m; the next generation is tightly folded (at right), the last generation is gently folded (on the left). The width of the view is 3 m. An enlargement of the tightly folded vein is given below (b). (**c**) Detail of a deformed vein of generation I with tight folding and a junction structure (Fig. 8a). Outcrop E of Figure 2. The width of the view is 1 m; (**d**) view of outcrop B in a section parallel to L_m and normal to S_m. All veins are subparallel or at a small angle to S_m. One vein is boudinaged. The width of the view is 4 m; (**e**) cuspate–lobate folding in a vein of generation I in outcrop A (Fig. 4). The width of the view is 1.5 m; (**f**) feeder vein in pegmatite with a large number of minor veins branching off into the metadiorite parallel to S_m. Flanking folds have developed in the branching veinlets in the rim of the feeder vein and show that the angle between the feeder and branching veins has decreased considerably. The width of the view is about 5 m.

the foliation. The hornblende–biotite foliation in the metadiorite continues into the veins as a shape or biotite foliation. Veins that lie at a low angle to S_m are either straight with a variable thickness or show pinch-and-swell or boudinage (Figs 4–6c & d). The straight nature of some veins may be an original intrusive feature as seen from steps in the contact. Veins in steeper orientation are commonly folded (Figs 4–6b & c). The scale and nature of the folds depends on thickness and composition of the vein. Older veins have tighter folds, with thin limbs and massive hinges (Fig. 6b, inset), more intense internal foliation and better developed boudin structures than younger veins (Figs 4 and 5). Some veins seem to have been shortened without being folded, as seen from adjacent parallel veins of a different composition but with tight folding. Other wide veins show cuspate–lobate folding in the contact, cusps pointing towards the granitic vein in all cases (Fig. 6e). Where cusps are not opposite lobes, these features could also be described as mullions (Fig. 6e). Thin branches from the same vein show open–tight parallel or similar folding. In most cases, the fold axis is at a small angle to the lineation in the rock. There are also rare examples of round- or ring-shaped vein segments in outcrops normal to L_m. These could be parts of sheath-fold-like structures in the veins (Fig. 5, left-hand side centre).

Rock faces parallel to L_m and normal to S_m

On surfaces parallel to the lineation and normal to the foliation (Fig. 6d), the geometry of the veins is dramatically different, and if both surfaces had not been observed as part of one outcrop they could be taken for non-related features (compare Figs 4–6d). In surfaces parallel to L_m, the veins are nearly all parallel (Fig. 6d). If outcrops are large enough, veins can be seen to be cross-cutting at very low angles below 10° (Fig. 6d, top). Deformed medium-grained veins are mostly straight and planar, and may have a weak internal shape fabric parallel to the hornblende foliation in the metadiorite. Veins are straight or show minor pinch-and-swell and occasionally boudinage on the metre–10 m scale (Fig. 6d, bottom). There is only one set of late pegmatite veins that are folded, and which lie at a high angle to L_m and S_m. These are the only veins that are visible on faces parallel to L_m which are prominently oblique.

Rock faces parallel to S_m

On surfaces parallel to S_m, the lineation L_m is prominently present (Figs 3b and 6a). On these outcrop surfaces, most veins are straight and subparallel to the lineation, but there is a clear relation between the angle of vein intersection with S_m and L_m, and vein age. Figure 5 shows a road cut normal to L_m on which at least three generations of granite and pegmatite veins can be clearly distinguished by their cross-cutting relations. The younger veins are progressively more oblique to S_m and less intensely folded and boudinaged. The same veins can be followed in this outcrop to surfaces parallel to S_m, on which the angle between vein intersection and L_m can be observed (Fig. 6a). The oldest veins are subparallel to L_m, the second generation makes an angle of 2–6°, while the last weakly deformed generation of pegmatite veins is oblique, 30–50° to L_m (Figs 5 and 6a).

Three-dimensional vein geometry

The overall 3D geometry of the veins as reconstructed from the outcrops described above is a system of straight cylindrical folds intersecting subparallel to L_m (Fig. 7a). The oldest veins are generally most strongly folded and boudinaged, and the fold axes make the smallest angle with

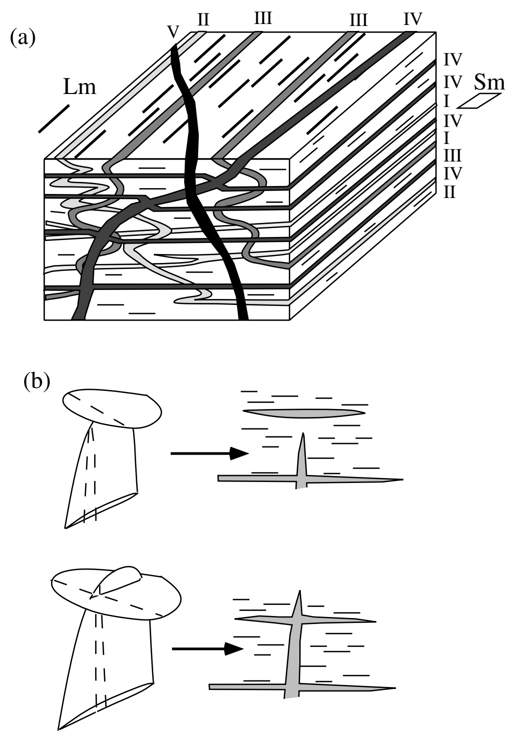

Fig. 7. (**a**) Schematic block diagram showing the 3D interpretation of vein geometry in the shear zone. Older veins (light colours) are more deformed than young veins (dark colours). Older veins are cylindrical and folded parallel to L_m; younger veins are less folded and more oblique to L_m. The dark vein IV is a feeder dyke with foliation-parallel injection veins. Roman numbers refer to vein generation; (**b**) explanation for foliation-parallel injection veins which branch from a feeder dyke on both sides; originally each foliation-parallel dyke spreads out from a tip of the feeder, but is subsequently cut by the expanding and propagating feeder dyke itself.

L_m. As a result, these veins appear as banded structures in sections parallel to L_m, and are tightly folded and boudinaged on sections normal to L_m. In most types of veins, boudins occur as strips parallel to L_m, and are therefore only visible in sections normal to L_m (Fig. 5). In some outcrops boudins occur that have a disk-shape, and are visible on surfaces normal and parallel to L_m. With decreasing age of veins, the tightness of folds in the veins decreases, and the angle between the fold axis and L_m increases (Figs 4–6b). The youngest pegmatite and granite veins can have orientations oblique or even normal to L_m.

Feeder veins

The parallelism of some of the granite and pegmatite veins to S_m is not only due to deformation, but partly an original intrusive feature. Although this is not always easy to show for the more deformed veins, the younger, less deformed veins clearly show evidence for intrusion parallel to S_m, such as foliation-parallel jogs in the veins (Fig. 8h), and rectangular xenoliths of the wallrock with sides parallel to the foliation in the xenolith. A number of feeder veins have been found that are connected to swarms of foliation-parallel veins, mainly of late pegmatite and granite veins (Fig. 6f). Feeder veins are between 0.3 and 2 m wide, and intrude highly oblique to S_m, although sideward jogs parallel to S_m of a few metres long and much thinner vein segments have been observed. In all cases these feeder veins show bristling sets of minor veins, 0.1–0.5 m thick, branching off the main vein parallel to S_m (Figs 6f and 7a). Owing to deformation, the angle between the feeder veins and the offshoots has in many cases been reduced, in some instances to less than 30°. The original steep orientation of the feeder veins can still be recognized by the presence of flanking folds (Passchier 2001) in the rim of the feeder veins (Fig. 6f). The amplitude of these flanking folds is never more than the diameter of the feeder vein. In most cases, the feeder veins are strongly affected by cuspate–lobate folding or mullion formation in the contact, and, in some cases, by 10 m scale open folding of the whole vein. In 3D the feeder veins are most commonly at a small angle to L_m. However, this applies to the most deformed examples, and other less deformed veins also occur oblique or even orthogonal to L_m. The fold axes in such veins are equally normal or oblique to L_m, the only examples of folds with this orientation in the Sihetang shear zone.

An interesting feature of the feeder veins is that there is usually only a single feeder vein without oblique branches or neighbours of similar nature. No examples were seen of veins parallel to S_m that are connected to more than one feeder. This is doubtlessly partly due to the limited size of the outcrops, but also shows that few feeder dykes are needed to produce the observed dyke swarms.

Many offshoots on the feeder dykes occur exactly opposite each other, i.e. they branch out from the feeder in two directions from the same point (Fig. 6f). This may give information on the nature of vein growth. If the feeder forms first and the branches later, there would be no reason for veins to branch off at the same site, unless there is a specific layer of lithological break that they follow. This does not seem to be the case here. A possible explanation is that the feeders and branching veins grow upwards and sideways at the same time (Fig. 7b).

Structures indicative of deformation in planar veins

Deformation of veins in granitoid rocks leads to folding and boudinage of the veins if these have a rheology significantly different from that of the host rock. However, a specific problem in deformed granitoid rocks is that veins and host rock have in many cases similar composition and grain size. As a result, veins act as passive markers and deformation leads to homogeneous thinning or thickening and change in angle between veins, and shape fabrics are commonly the only visible evidence of deformation. In such cases, some other more subtle structures may be useful to recognize vein deformation in the field. Several of these have been recognized in the Sihetang shear zone and are listed below. They may also be useful in other, similar settings.

Junction structure

Where an older vein is cut by a younger one some veins show significant thickening of the older vein towards the younger one (Figs 6c and 8a). In many cases, the younger vein is also thickened. This structure may form when the younger vein is oblique to the shortening direction and deforms by folding while the older one deforms by homogeneous thinning; where both veins are in contact, the thinning vein is hampered in its deformation by the presence of the younger one, and reveals the minimum original thickness of the older vein.

Vein refraction structure

Where two veins cross-cut obliquely, or at right angles, they may be deformed together so that

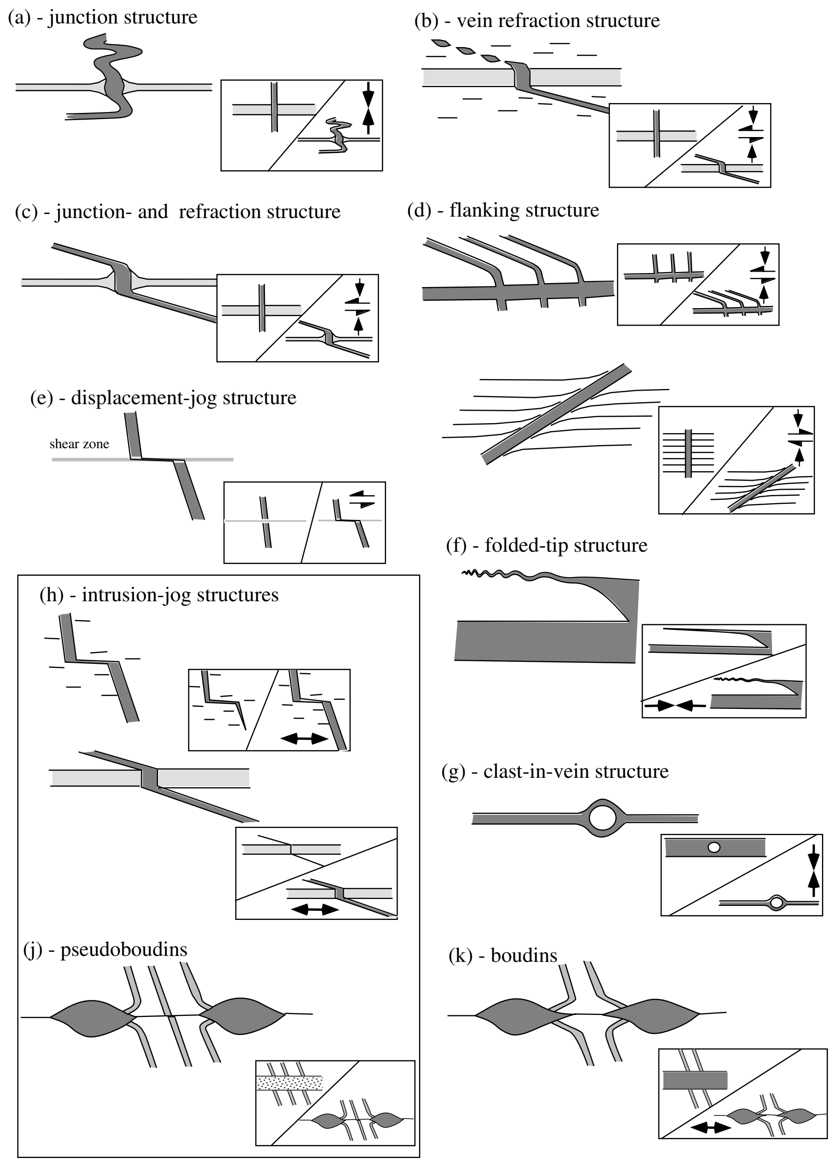

Fig. 8. Several types of mesostructures recognized in the Sihetang shear zone that can be used to recognize solid-state ductile deformation of intrusive dykes. Inset boxes show inferred mode of development, and arrows show whether the structure is associated with shortening, shear or extension. Intrusion-jog structures and pseudoboudins form by intrusion, not solid-state deformation and are therefore shown in a separate box. (**a**) Junction structure – an older, cross-cut vein widens towards the younger vein. As the younger vein is folded, this must be due to thinning of the older vein; (**b**) vein refraction structure – a younger vein has a jog where it cuts the older vein. This is due to relative rotation of both veins where the intersection domain is protected by the more rigid older vein; (**c**) combination of (b) and (c); (**d**) two types of flanking structure with deflection of veins close to a feeder dyke (top) or single dyke (bottom); (**e**) displacement jog structure due to offset; (**f**) folded tip structure. Thin branches of a dyke show folding, but wider parts are shortened more homogeneously. (**g**) Clast-in-vein structure – a large monocrystal of feldspar lies in a thinner vein due to deformation and thinning of the vein during or after intrusion; (**h**) intrusion jog structure due to jogged geometry of the original fracture before opening. This can have similar geometry as (b) or (e), but has undeformed material in the jog; (**j**) pseudoboudins, which can have older veins in the gap between the boudins, running up to the suture separating them. These structures form by collapse or inflation of a vein without vein-parallel extension; (**k**) solid-state boudins formed by extension of a vein; here, older veins cannot touch the suture between the veins but are linked to the boudins.

the intersection region is homogeneously flattened. However, if the older vein deforms less than the host rock, the intersection region preserves the original high angle to some extend. This leads to a sharp jog in the younger vein where it crosses the older one (Fig. 8b). This kind of structure is commonly observed in shear zones if older veins are subparallel to the flow plane. In many cases the younger vein is thicker in the junction area than in the wallrock as it is less deformed. Vein refraction structures can be confused with *intrusion jogs* formed during intrusion of a vein (Fig. 8h), but refraction structures have deformed and in some cases boudinaged limbs, can be oblique to the foliation in the wallrock and have less sharp hinges at the edge of the older vein (Fig. 8b).

Vein refraction structures may combine with junction structures (Fig. 8c). This kind of structure forms if the intersection area or the entire older vein has a higher competency contrast to the matrix than the younger vein. In the area investigated, this kind of structure only occurs around the youngest, least deformed pegmatite veins. This may be due to a decrease in temperature during late stages of the deformation.

Flanking structures

Some veins show rims of deviating orientation of the foliation or veins in the wallrock along the long axis of the vein (Figs 6f and 8d). Such structures were described by Passchier (2001) as flanking structures. Two types have been described, with either steepening or flattening of elements towards the central vein. In the area investigated here, both types have been observed. Veins branching from a feeder dyke are commonly developed as steepening flanking folds (Fig. 6f). Some veins in metadiorite have a rim of biotite–plagioclase where the hornblende has been transformed to biotite. In these biotite rims, the foliation flattens towards the vein (Fig. 8d, lower part). Such structures can form by either dextral or sinistral rotation of the vein with respect to the foliation (Graseman *et al.* 2003).

Displacement jogs

Some veins show sharp, angular jogs in the vein with a short segment parallel or at a low angle to S_m (Fig. 8e) that can form by localized shear flow, displacing the vein. However, this kind of structure is very similar to some intrusion jogs (Fig. 8h). It is not easy to distinguish both types, but presence or absence of deformation features in the jog is decisive. In the studies area, the intrusion jog type is most common.

Folded-tip structures

Some veins oblique to S_m may seem undeformed with straight sharp contacts that cut S_m. However, where thin side veins branch off such veins their tips may show folding where the large veins do not (Fig. 8f). This type of feature has already been recognized by Ramsay & Huber (1983) and is due to the dependence of fold wavelength on vein thickness (Biot 1961).

Solid-state boudins

Although the recognition of solid-state boudinage may seems trivial, Bons *et al.* (2004) demonstrated the existence of pseudoboudin structures in intrusive veins with a very similar geometry to boudins. Pseudoboudin structures (Fig. 8j) form by collapse or inflation of parts of a vein when it is still magma-filled. The resulting structure has a geometry very similar to solid-state boudins, with one major exception; older veins can pass up to a suture line separating pseudoboudins (Fig. 8j), but in solid-state boudins, all older veins must be connected to the boudins themselves and cannot be joined to the suture line (Fig. 8k).

Clast-in-vein structures

Some narrow veins parallel to S_m show no macroscopic signs of deformation but contain local porphyroclasts that consist of a large single grain of feldspar with a diameter exceeding the thickness of the vein and larger than any feldspar grain in the matrix (Fig. 8g). This structure is particularly common in thin branches of pegmatite veins. Such *clast-in-vein structures* are similar in geometry to mantled clasts, but represent a much smaller strain and are not diagnostic of solid-state deformation; they may have formed during vein intrusion or by later deformation. A magma-filled vein with large phenocrysts of feldspar may have collapsed by migration of the magma while few phenocrysts were left behind, which became compressed between the vein walls. Alternatively, during deformation the vein may have been stretched and thinned but, because of small rheology contrast, no other features formed. The large feldspar crystals, however, were not much reduced in size and show that the vein was initially much wider.

Discussion

Deformation described above is not due to normal movement on the Hefangkau fault zone (Fig. 1), as that zone has in general greenschist facies or lower grade fabric. Early deformation in amphibolite facies in the Sihetang shear zone has been by non-coaxial flow induced by S-directed transport of the hanging wall. This is in the same direction as thrusting on the brittle fault in the hanging wall, but thrust geometry in the present orientation may well have been a normal shear zone at an earlier time, tilted by folding of the entire shear zone over the batholith (cf. Passchier 1984).

Intrusion geometry

One of the most conspicuous properties of the Sihetang shear zone is the dominant parallelism of old, strongly deformed veins and L_m, and the gradual increase in obliqueness of veins to L_m with decreasing age (Fig. 6a). The shear-zone fabric indicates strong ductile extension in a N–S direction, a relative transport of the hanging wall to the south and vertical shortening in the shear zone. If the shear zone operated by simple shear or another monoclinic flow type (Passchier 1998) veins should have opened at right angles to the lineation, as shown in Figure 9a. However, even at very high strain it is impossible to rotate deformed veins into parallelism with the lineation in homogeneous monoclinic flow (Fig. 9a). A possible explanation for the observed structure could be orthogonal intrusion followed by *inhomogeneous* monoclinic flow, where some parts of the shear zone move faster than others (Fig. 9b). In fact, flow in the shear zone is locally triclinic in that case (Jiang & Williams 1998). This would rotate veins into the observed orientation, but it requires very high strain gradients in the mylonite. A third possibility is that veins already intruded oblique or even at a small angle to the lineation and were rotated in some type of monoclinic flow (Fig. 9c). There are strong indications for this scenario as late pegmatite veins are mostly observed in orientations oblique but not orthogonal to lineation, L (Fig. 6a).

In a simple model, a ductile shear zone operates by a stress field that is symmetrically arranged with respect to the resulting fabric elements and remains unchanged in orientation with respect to the wallrock during the development of the shear-zone fabric. An explanation for initial oblique intrusion of veins into such a simple shear zone could be that veins intrude from the solidified top of the underlying batholith upwards. If the stress field in the underlying batholith differs in orientation from that in the shear zone, the upwards intruding vein tips could simply copy the orientation of veins in the batholith into the shear zone. It is more likely, however, that a propagating vein tip would twist to adapt to the stress field in the shear zone.

A second possibility is that veins intrude as a conjugate set oblique to the principal stress directions in the shear zone. In that case they would have a shear component, i.e. they would not open normal to the plane of the vein. No displacement was observed along the veins except on a pegmatite vein but this applies to outcrop faces normal to L_m. On outcrop faces parallel to L_m and normal to S_m (Fig. 6d) strain is too high to make definite statements, and outcrops parallel

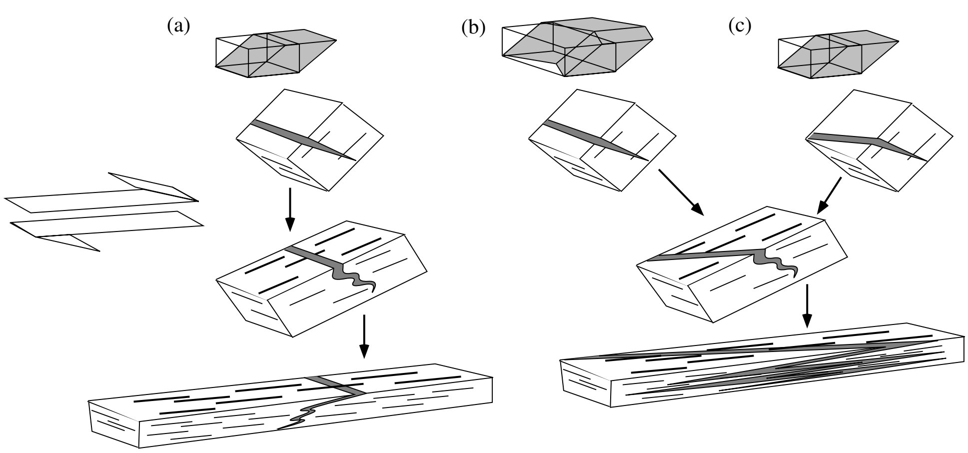

Fig. 9. (**a**) The present geometry of veins in the shear zone cannot be explained by deformation of veins originally orthogonal to the extension direction in simple shear; they would remain orthogonal. It can be explained if: (**b**) they were orthogonal but deformed in inhomogeneous monoclinic or triclinic flow; or (**c**) they intruded originally oblique to the extension direction. The latter seems to apply in the Sihetang shear zone.

to S_m (Figs 3b and 6a) are small and relatively rare. This type of oblique intrusion of veins would imply that some extension is possible in the plane of the foliation normal to the lineation, and that flow in the shear zone was not by plane strain.

Finally, the assumption of invariable orientation of stress in a developing ductile shear zone may be wrong. Mylonitic deformation is slow, and intrusion of a vein into the zone must be many orders of magnitude faster than the ductile flow. It might be that on the timescale of vein intrusion and on the outcrop-scale stress orientation changes periodically, but that the net result on the ductile fabric gives rise to a 'mean' orientation of stress averaged over the time it takes for the shear zone to develop. During vein intrusion, stress axes could have been significantly oblique to this 'mean' orientation and give rise to oblique vein intrusion, even in tension. In this case, the veins would give a unique insight in the variability of stress orientation throughout the active life of a ductile shear zone.

Shear-zone model

Gently dipping ductile shear zones in core complexes can operate by a variety of flow types. If volume is to be conserved, the simplest possible model is one of simple shear (Fig. 10a). However, if the wallrock is relatively hot, it is also possible that it stretches coaxially while conserving volume in the shear zone (Fig. 10b).

The Sihetang shear zone is also unusual as it cannot have conserved volume. It is clear from field observations that, during the process of deformation, 20–40% vol. of granitic material has been added to the shear zone in the form of dykes. This can simply be established from the surface area of vein material in Figures 4 and 5, and extrapolated to volume due to the cylindrical nature of the folds. The presence of folds, boudins and clast-in-vein structures shows that considerable vertical shorting occurred in the zone during magma emplacement. We have seen above that dykes seem to intrude oblique to S_m and L_m, although numerous branches intruded parallel to S_m. There is in principle no space problem normal to S_m, as the shear zone is gently dipping and the roof of the batholith may simply be uplifted.

The metadioritic rock of the hanging wall away from the Sihetang shear zone has only a weak deformation fabric, and it therefore seems likely that the top of the zone deformed by a regime close to plane strain simple shear. In this case, the rotation of the veins must be entirely due to plane strain non-coaxial progressive deformation, although a gradient of deviation from plane strain

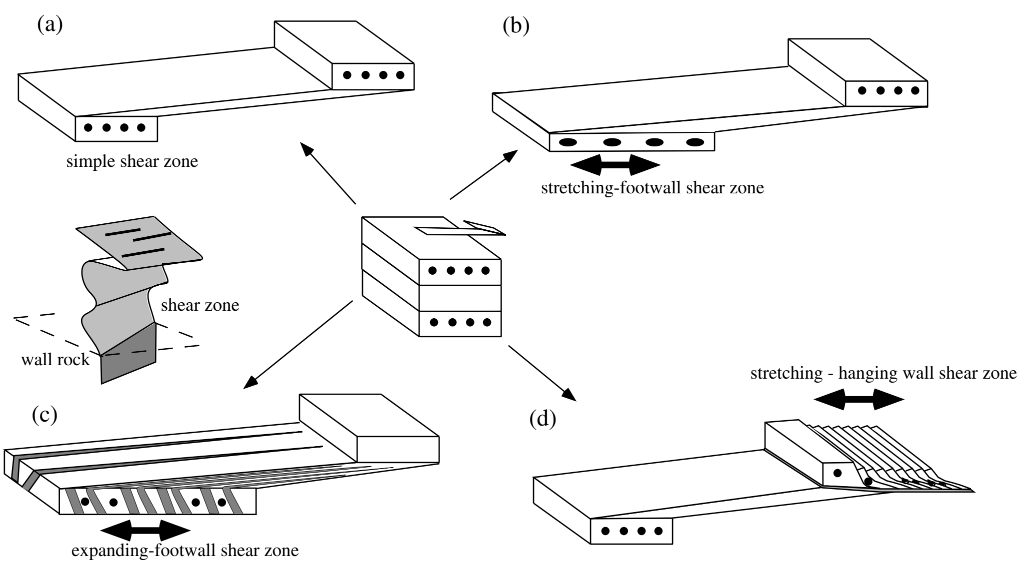

Fig. 10. Possible modes of deformation in a gently dipping ductile shear zone over a core complex: (**a**) simple shear; (**b**) volume-constant homogeneous ductile extension of the footwall and volume constant flow with a vorticity gradient in the shear zone; (**c**) volume increase in the footwall and shear zone by vein intrusion; (**d**) volume-constant brittle extension in the hanging wall, separated from an older simple shear ductile fabric in the footwall by a cataclasite zone. The Sihetang shear zone is of type (c). Inset in (c) shows deformation and rotation of a vein in the shear zone.

towards the footwall cannot be excluded. It may be that veins are injected one by one oblique to L_m and that flow is in reality not plane strain, but has a shortening component parallel to the rotation axis. Such a flow regime would cause a stronger rotation of veins towards parallelism with the lineation than in simple shear.

A strong mylonitic fabric with good planar and linear shape fabric developed in the metadiorite, but also in the top of the granodiorite batholith. Apparently, this part of the batholith was already in a solid state when the shear zone was active. The density of intruded granite veins rapidly decreases upwards from the contact between the metadiorite and the granodiorite. Few veins are found in the shear zone in the metadiorite at more than 50 m away from the contact, nor in the less deformed and undeformed metadiorite in the hanging wall. The mylonite zone seems to form an effective lid on the batholith, preventing the escape of magma to higher levels. It could be that the veins have difficulty transecting the highly anisotropic mylonite zone, and that most of the magma travelling up the veins is injected in sheets parallel to the foliation. The dominantly folded nature of older veins suggests, however, that they intruded oblique to the foliation in the shear zone. The most likely model for the development of the observed structures is that veins intruded from the granodiorite batholith into the active shear zone in a extensional setting, and were subsequently deformed. If the hanging wall is rigid, this can only occur by extension of the footwall to accommodate vein intrusion contemporaneous with relative N–S displacement of footwall and hanging wall along the shear zone (Fig. 10c). Stretching of the footwall rocks would be most effective if it was at a small angle to the shear direction in the shear zone. Such stretching of the footwall could also be accommodated by ductile pure shear in the footwall, and in that case the shear zone would be thinning (Fig. 10b). As there is no ductile deformation fabric in the granodiorite underlying the Sihetang shear zone, we can exclude this possibility.

The picture emerging from the shear zone is therefore one with simple shear in the top, and general non-coaxial flow with volume increase and stretching by vein intrusion towards the footwall. This type of shear zone could be referred to as an *expanding-footwall shear zone* (Fig. 10c). Interestingly, this is not the kind of shear zone that is commonly described from metamorphic core complexes. Usually, a brittle fault zone is overlying and reworking older mylonites, with a hanging wall consisting of brittle fault blocks (Fig. 10d) (Armstrong 1982). In many such cases, it is apparently the footwall that was rigid during brittle deformation. If other core complexes have evolved in a similar way to the Yunmengshan, with a stage of abundant vein intrusion, the décollement shear zone of the complex may show a change from ductile and intrusion-related expanding-footwall geometry, to brittle extending hanging wall behaviour, or possibly more complex transitions.

Conclusions

- The Sihetang shear zone operated under amphibolite facies metamorphic conditions in the absence of partial melting.
- A large number of granitic veins, up to 40% of the rock volume, intruded during mylonitic deformation in the shear zone.
- Veins parallel to the foliation form both by high strain and by foliation-parallel intrusion from feeder dykes.
- Veins seem to have intruded oblique but not orthogonal to the mylonitic lineation L_m.
- Deformed veins form a complex 3D network of late oblique structures and older progressively more deformed, folded veins that trend to parallelism with the lineation.
- The shear zone seems to have acted as a repository for the vein material; few veins breach the roof of the shear zone into overlying host rock material that is of identical composition, but less deformed.
- Deformation in the shear zone must have deviated significantly from simple shear because of the volume increase involved with granite vein intrusion. Most likely is a model with an expanding footwall. This is geometrically the opposite to brittle hanging wall extension in core complexes with a brittle overprint on the ductile shear zone.

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