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Sheath-fold-like structures in pseudotachylytes

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Abstract—Sheath-fold-like structures in pseudotachylyte samples from a gold mine in the Witwatersrand Basin (South Africa) are explained by injections of frictionally produced silicate melt within the shear zone due to the formation of high and low pressure zones. If the shear zone geometry is known, the orientation of the fold closures can be used to determine the direction and the movement sense. However, if it is not possible to establish the shear zone geometry, only the azimuth of movement can be estimated from the orientation of the sheath-fold-like folds. The flow banding in these fault rocks is indicative of laminar flow, which suggests a low Reynold's number.

INTRODUCTION

IT IS generally accepted today that pseudotachylytes may result from processes associated with seismic faulting at relatively high strain rates (e.g. Sibson 1975). Pseudotachylyte is commonly regarded as the product of frictional melting (Sibson 1975, Maddock 1983, 1986, Spray 1987). Though Sibson (1975) suggested that the absence of high fluid pressure is critical in pseudotachylyte formation, Killick (1990) has shown that friction melts may form under wet conditions during high-speed drilling. This has possible implications for pseudotachylyte formation.

Pseudotachylytes are relatively common fault rocks in the region of the Vredefort Dome and the mines of the Witwatersrand Goldfield (Shand 1916, Killick *et al.* 1988, Killick & Reimold 1990). Several different pseudotachylyte-forming events have been distinguished in this area (Killick & Reimold 1990) and pseudotachylyte formation has been related to faulting at relatively shallow levels in the Earth's crust (Reimold *et al.* 1990). The faulting may partly be the result of a meteorite impact (Dietz 1961, Schwarzman *et al.* 1983).

Relatively little is known about the geometrical behaviour of pseudotachylyte melt during fault movement. Flow banding and internal folding are common features, and by examining these structures certain insights into the deformational behaviour can be obtained. In this paper we describe two pseudotachylyte occurrences of different ages from a gold mine in the Witwatersrand Basin which reveal internal structures that can be geometrically related to fault movements.

REGIONAL GEOLOGY

The investigated pseudotachylyte sample was collected from a bedding-plane fault in the Kloof Gold Mine, which is located about 50 km southwest of Johannesburg, South Africa (Fig. 1). The Kloof Gold Mine is one of a series of mines along the so called "West Wits Line", the geology of which has been described in detail by Engelbrecht *et al.* (1986). The uppermost part of the stratigraphy in the study area consists of sedimentary rocks of the Transvaal Sequence that dip at a shallow angle toward the southeast. They lie unconformably on

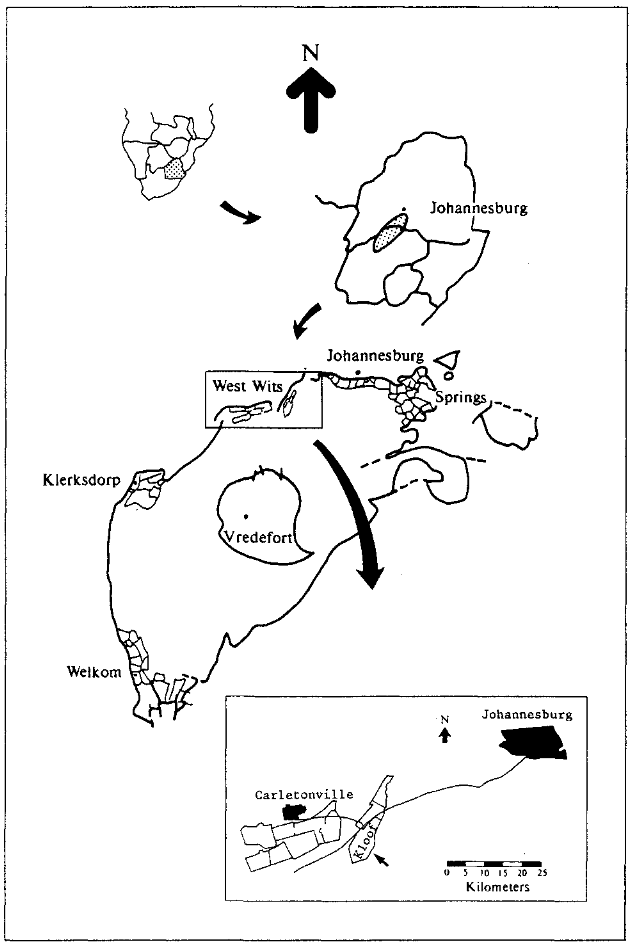

Fig. 1. Locality of the study area within South Africa.

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the mafic lavas of the Ventersdorp Supergroup. The latter are not exposed at the surface, but underground it can be seen that they conformably overlie the Ventersdorp Conglomerate Formation which, in the Kloof Gold Mine, is defined by the economically important Ventersdorp Contact Reef (VCR), a mineralized quartz conglomerate–quartzite sequence. The VCR, which dips at 30–35° toward the southeast, lies unconformably on the Booysens Shale and the Elsburg Quartzite Formations of the Witwatersrand Supergroup, which dip approximately 40° in the same direction. The pseudotachylyte vein described in this paper developed along the contact between the VCR and the overlying Ventersdorp lavas (Fig. 2).

Recent studies in the Kloof Gold Mine (Berlenbach & Roering 1990) and adjoining mines (Bevelander 1988, Killick *et al.* 1988, van Coller 1988) have shown that bedding-plane faults play a major role in the tectonic history of this area. The contact between the VCR and the overlying Ventersdorp Supergroup is commonly found associated with bedding-plane movements (Bevelander 1988, Killick *et al.* 1988, Berlenbach & Roering 1990). Pseudotachylyte occurrences have been previously described from this contact, and were related to a northerly- to westerly-directed thrust movement (Killick *et al.* 1988).

At the Kloof Gold Mine three distinct tectonic events are manifested on bedding-planes. The earliest major event which is bedding-plane related, is characterized by normal listric faults along which gravity sliding toward the southeast took place (Berlenbach & Roering 1990). The age of faulting is probably Middle Ventersdorp (approximately 2700 Ma, Roering *et al.* 1990). These normal faults do, however, truncate older strike-slip faults which are partly associated with pseudotachylyte veins.

The extensional period of deformation was followed by a compressional event of NW-directed thrust faulting (i.e. 'out-of-the basin'). The thrust faults have ramp–flat symmetries and partly gave rise to duplication of the VCR (Berlenbach & Roering 1990, and work in preparation). Ramps commonly formed in the VCR horizon and in the Ventersdorp Lava while the flats formed in

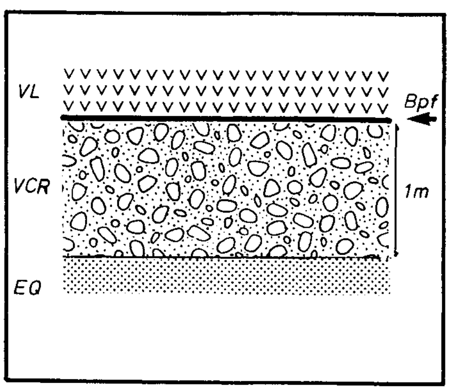

Fig. 2. Location of pseudotachylyte vein. The sample was taken from a bedding-plane fault (Bpf) in the contact between the Ventersdorp Contact Reef (VCR) and the Ventersdorp Lava (VL). The Elsburg Quartzite (EQ) underlies the VCR.

the Booysens Shale Formation and along the contact between the VCR and the Ventersdorp Supergroup. Where faulting took place along the latter, quartz veins, fault breccia, cataclasites, mylonites and pseudotachylytes were observed, indicating a complex structural history (Berlenbach in preparation). Significant thrusting 'out-of-the basin' of pre-Transvaal age (approximately 2500 Ma) has also been identified on the northern margin of the Witwatersrand Basin (Roering 1984, Roering *et al.* 1990).

A later compressional event with associated NE-verging thrust faults has also been identified in the Kloof Gold Mine. This thrust event resulted in a reactivation of the older bedding-plane faults (Berlenbach & Roering 1990, and work in preparation). Regional metamorphism in the Witwatersrand Basin did not exceed greenschist facies with temperatures below 400°C (Wallmach 1991).

SAMPLE PREPARATION

The sample was obtained from an underground mining stope-face (35 level, 53 longwall). The pseudotachylyte vein is persistent at this locality and has a maximum thickness of approximately 5 cm. Slickenfibres are well developed at the margins of the sample and have a NW–SE azimuth, parallel to the trend of the sheath-fold-like structures. The lower surface of the pseudotachylyte sample is essentially planar and represents the bottom shear zone margin. The upper part of the sample consists of Ventersdorp Lava. The contact between the latter and the pseudotachylyte is well preserved and constitutes the upper shear zone margin.

The specimen was first cut orthogonal to the foliation and parallel to the slickenfibres to identify structures that might have developed due to a shear movement (Fig. 3). Additional slices were cut at right angles to this plane, i.e. perpendicular to the movement vector (Figs. 4a & b). The slices were photographed and flow banding patterns and the upper shear zone margin were mapped. *X*, *Y* and *Z* co-ordinates of the upper shear zone contact were determined and a block diagram was constructed using a suitable computer program. Thin sections of the pseudotachylyte, which were cut parallel to the slickenfibres and orthogonal to the movement plane, were studied with a microscope.

PETROGRAPHIC INVESTIGATIONS

The pseudotachylyte displays light and dark grey layers which form a very well developed flow banding (Figs. 3a & b). The latter is distinctly folded, with an axial plane approximately in the middle of the layer and parallel to the fault plane. Under the microscope the bands are actually of light and dark brown material (Fig. 5). Toward the shear zone margin the pseudotachylyte grades into a cataclasite with pseudotachylyte material filling the space between the clasts. There are no cross-

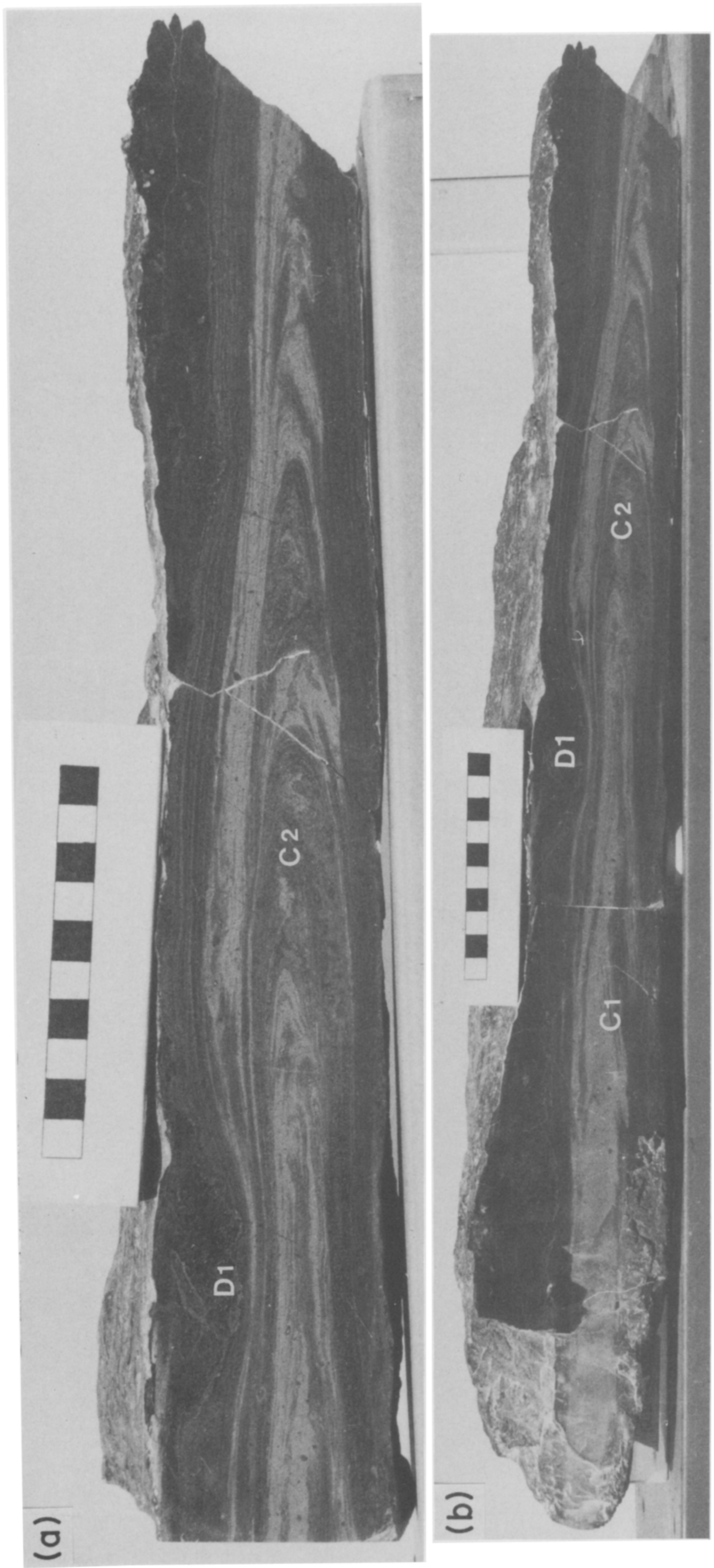

Fig. 3. Section through pseudotachylyte, parallel to the slickenfibres. A depression (D1) divides the pseudotachylyte into two chambers, C1 and C2 (a). While the flow banding is only poorly developed in C1, it is well defined in C2 (b). Scales in centimetres.

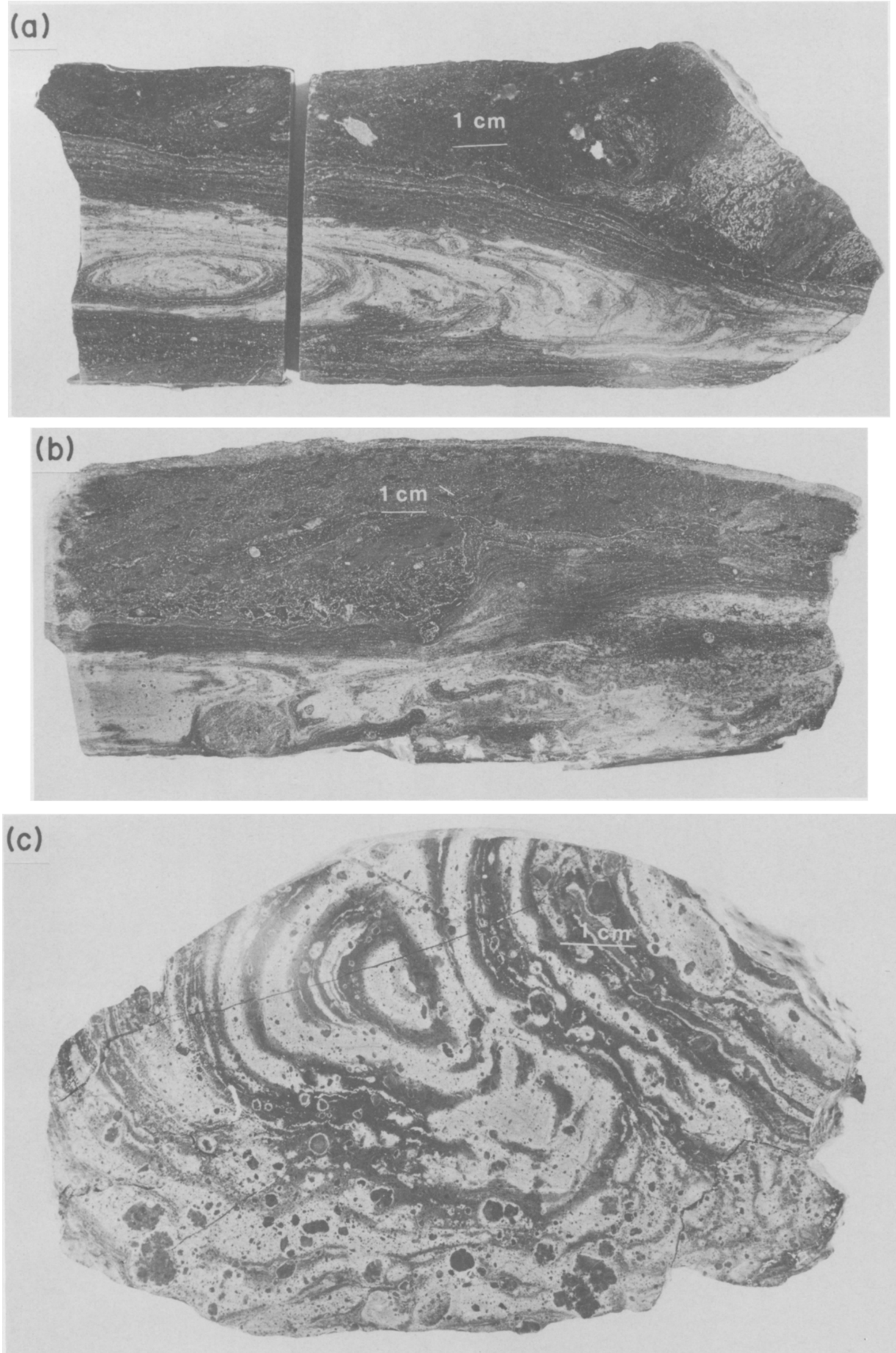

Fig. 4. Sections through pseudotachylyte samples, perpendicular to slickenfibres. (a) The 'eye' in a section perpendicular to the isoclinal 'fold' at the right-hand side of Fig. 3(a) resembles sheath folds, but is formed here by pseudotachylyte injection. (b) Irregular distribution of flow banding in a section perpendicular to the left part of Fig. 3(a). (c) 'Eye' in a pseudotachylyte which formed perpendicular to the movement direction of a strike-slip fault on Kloof Gold Mine.

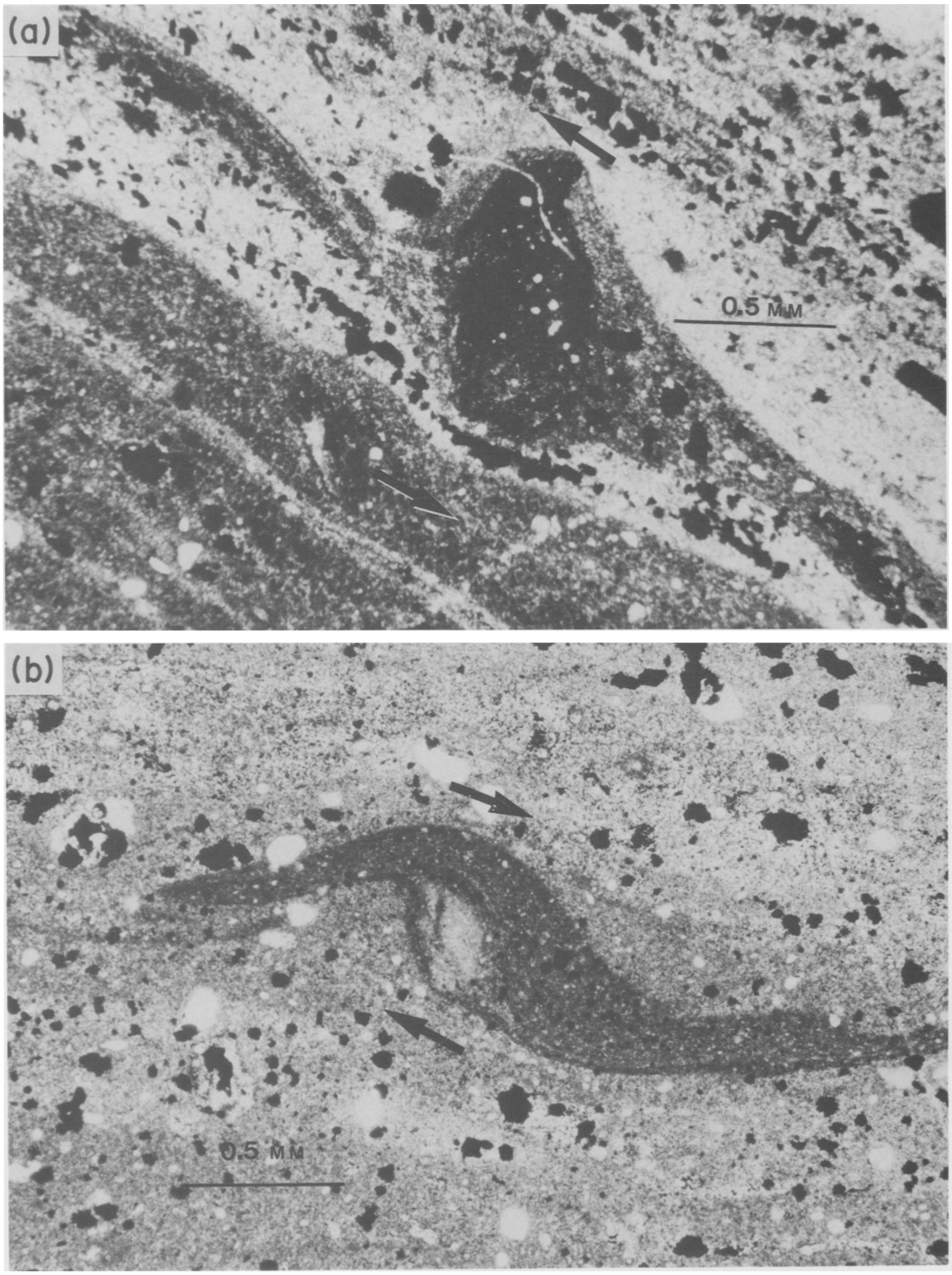

Fig. 5. Thin sections of pseudotachylyte. The sharp contact between dark and white bands in (a) (crossed nicols) is interpreted as having formed by silicate liquid immiscibility. The white bands brighten in a 45° position, indicating oriented microlites as devitrification products. Microfolds at the edge of inclusions indicate left-lateral shear sense in (a) and right-lateral shear sense in (b); plane polarized light.

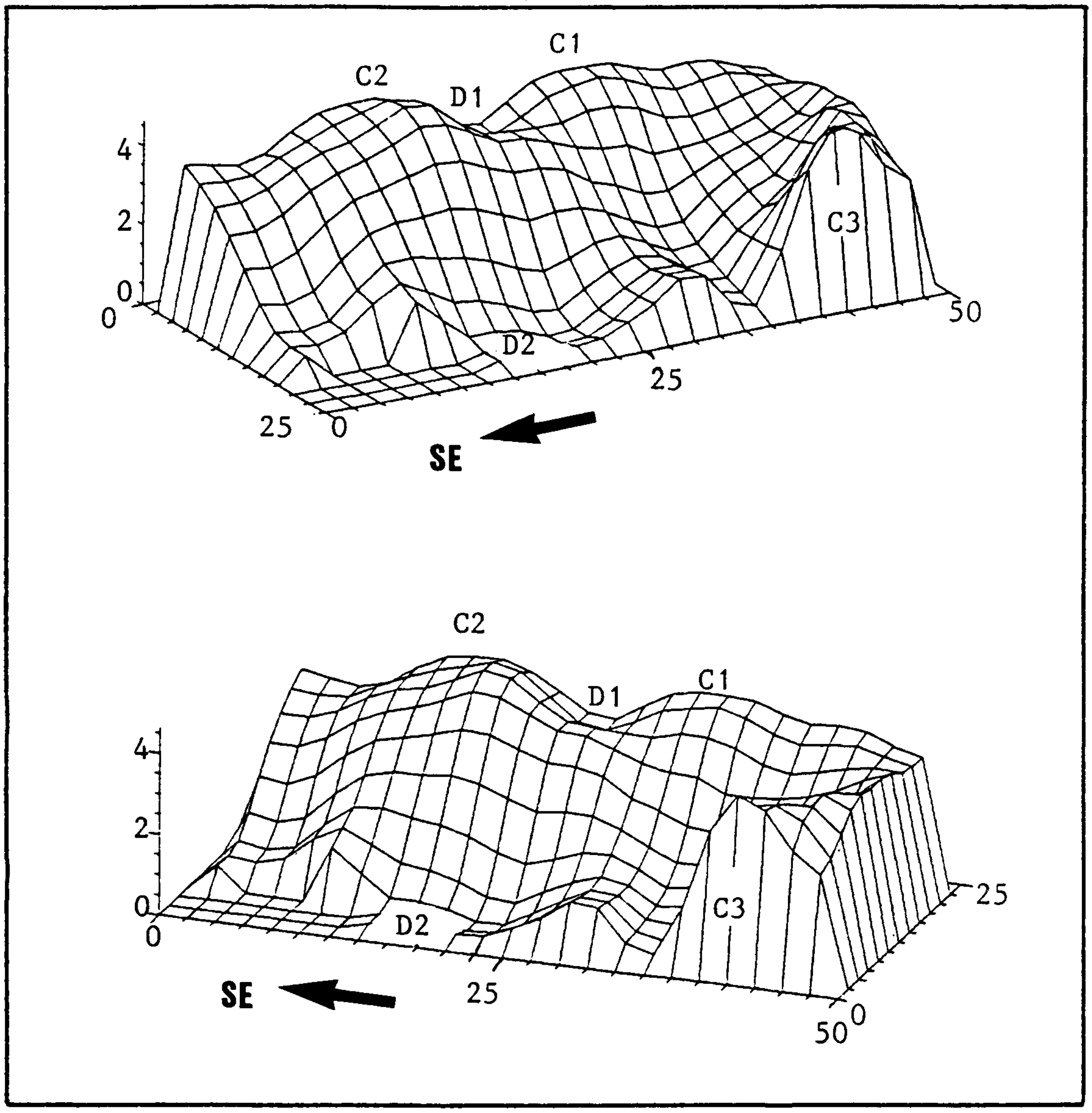

Fig. 6. Two views of the top surface of the pseudotachylyte vein. The complex morphology is defined by topographic highs and lows. The shear zone narrows toward the northeast (D2). A depression (D1) divides this part of the shear zone into two chambers, C1 and C2. Sheath fold-like structures formed in C2. C3 formed perpendicular to the main ridge. Note that direction of view in this figure is opposite that of Fig. 3. Data are smoothed and the vertical scale is exaggerated. Scales in centimetres.

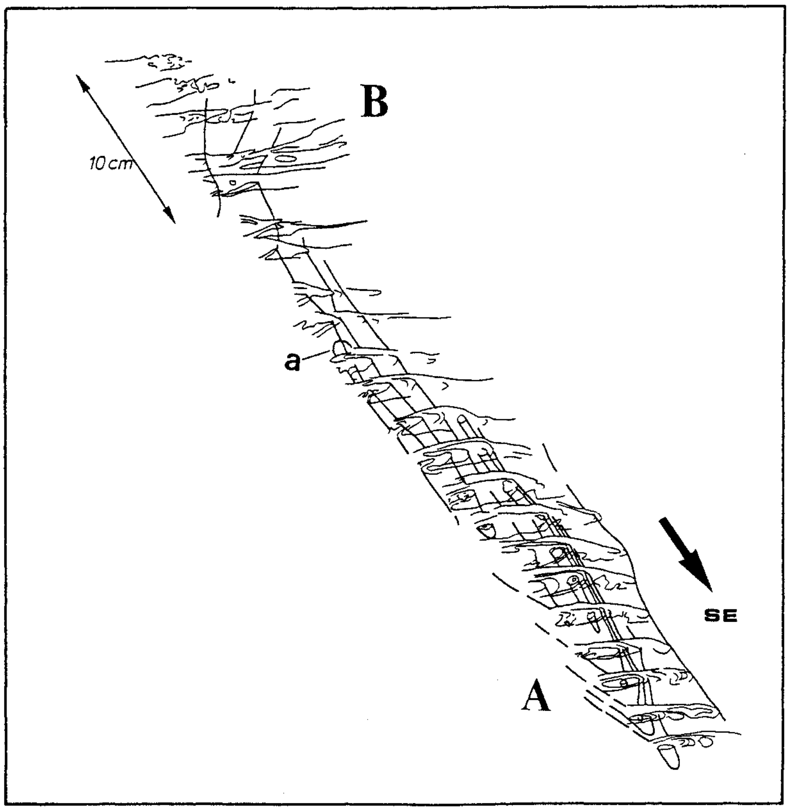

Fig. 7. Serial sections showing the distribution of flow banding. The flow bands form 'folds' with their hinge lines strongly curved in the fold axial planes in the southeastern part of the diagram (A). In the northwestern part the flow banding does not reveal a preferred orientation (B). All 'folds' close toward southeast, except fold (a) which closes towards the northwest. For greater clarity the distance between the sections was doubled.

cutting relationships between the cataclasite and the pseudotachylyte, suggesting that the two components may be related. Small cross-cutting quartz-filled extension gashes are an indication of later movements. The inclusions in the pseudotachylyte are derived from the shear zone margins. Fragments of the overlying basalts are mostly rounded, while quartz and pyrite crystals are subrounded to angular. The maximum diameter of the fragments is 0.5 cm, while most are of submicroscopic size. The bands are divided by sharp contacts and show hardly any mixing. In contrast with the darker bands, the lighter coloured bands show a brightening in the 45° position under crossed nicols, suggesting oriented microlites, probably formed by devitrification or recrystallization of a cryptocrystalline groundmass. X-ray diffraction studies of the pseudotachylyte indicate the presence of muscovite and chlorite.

RELATION BETWEEN SHEAR ZONE SYMMETRY AND FLOW BANDING

Using the sections in Figs. 3 and 4, block diagrams of the upper contact of the shear zone have been constructed in Fig. 6. The complex shape of this contact is characterized by two topographic highs (with respect to the pseudotachylyte vein) on a ridge which has a depression (D1) approximately in the middle of it. This depression divides the ridge into two 'chambers' (C1 and C2). At C3 (Fig. 6) the specimen ends in a ridge almost at right-angles to the main ridge, forming a third chamber. The shear zone narrows toward D2. Where preserved, the lower shear zone margin is essentially planar. The flow banding is generally oriented subparallel to the shear zone margins (UM and LM in Fig. 8 described later). The banding closes toward C2 (Fig. 3) where it forms isoclinal fold closures. In regard to the shear zone symmetry, the flow banding is much better developed toward the right of the depression (D1). Folding is particularly well developed here.

All fold closures reveal a systematic pattern, with a similar fold style geometry. It must be realized however, that the profiles are not necessarily at right angles to the fold axis. Sections orthogonal to the fold axial plane of the fold closures and normal to the slickenfibre lineation reveal perfect eye-shaped closures of the banding with the implication that the three-dimensional fold geometry is that of sheath folds (Fig. 4a). No sheath-fold-like structures could be identified in C2 (Figs. 3 and 4b).

A three-dimensional diagram of the flow banding was constructed from all of the sections cut through the pseudotachylyte sample (Fig. 7). The cross-cutting lines connect the data between sections and accentuate the form of the sheath-fold-like structures. The hinge lines are strongly curved in the plane of the axial surface and are subparallel over most of the sample. In the region where the sheaths end at a point, the parallel fold axes turn sharply over a very short distance. Smaller folds are enveloped by larger folds. Most of the folds are open toward the top left-hand corner of Fig. 7. Only one fold

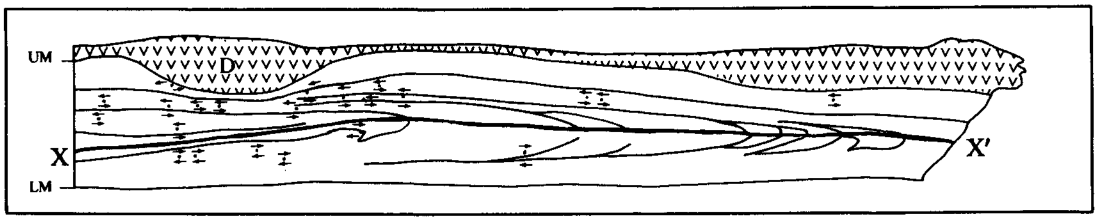

Fig. 8. Section parallel to the 'fold axial' trace, identical with Fig. 3(b). Thin black lines indicate flow banding. Points represent rotated fragments with rotation sense indicated (arrows). Fragments below trace X–X′ indicate a dextral sense of movement while those above this trace a sinistral one. Note the high concentration of rotated fragments in the vicinity of the depression (D). Upper (UM) and lower (LM) shear zone margins are marked.

(a in Fig. 7) closes in the opposite direction. However, this fold displays the same orientation as the other folds. Whereas the flow banding in the front lower right-hand part of the diagram is systematic it tends to become more disturbed and chaotic toward the top left-hand corner.

The relationships between the geometry of the flow banding, shear zone and slickenfibre orientation suggest that the internal structures in the pseudotachylyte were caused by the fault movement. It is thus necessary to investigate how the pseudotachylyte has flowed within the shear zone. To determine the sense of movement at any given point, rotated fragments and associated pressure shadows and microfolds were used (Simpson & Schmid 1983). The sense of rotation of 22 inclusions in the pseudotachylyte were determined from thin sections and plotted onto a section of the pseudotachylyte that is at right angles to the fault plane and the banding and parallel to the slickenfibres (Fig. 8). Examples of rotated inclusions with microfolds are shown in Fig. 5. Although the overall displacement along the bedding-plane fault took place by simple shear, the pattern of rotated fragments indicates an opposite shear direction above and below the line X–X′ (corresponding with the fold axial trace) (Fig. 8). Therefore the sheath-fold-like structures in the pseudotachylyte are not constant with uniform simple shear, unlike the experimentally formed sheath folds described by Cobbold & Quinquis (1980). However, the movement pattern is systematic: rotated fragments above line X–X′ show an anticlockwise sense of rotation, while those under this line reveal a clockwise rotation. This finding suggests that the pseudotachylyte was injected into the shear zone along the trace X–X′. The velocity of the injected fluid was highest along the middle part of the shear zone and decreased toward the shear zone margins due to boundary effects. This caused the opposite sense of rotation of fragments on either side of the trace X–X′.

The injection of the pseudotachylyte into C2 may be best explained by a left-lateral sense of movement (Fig. 9). Due to the narrowing of the shear zone at D, this sense of movement would generate an area of relatively low pressure in C2, assuming an upstepping of the lower shear zone margin at S. As a result, the pseudotachylyte was injected into C2.

There are several implications of this observation. Firstly, it is the shape of the chamber which is formed by the relative shear movement that determines where the melt will be injected. The direction of the injection

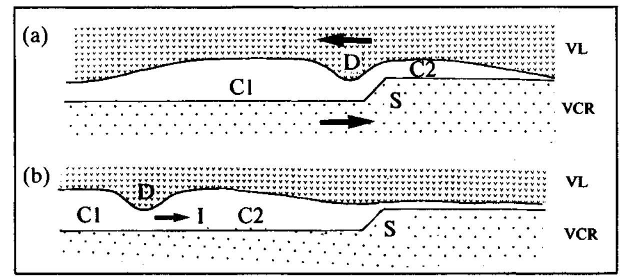

Fig. 9. Proposed shear zone morphology which is responsible for the pseudotachylyte injection during faulting at the VL–VCR contact. The depression (D) divides the shear zone in two 'chambers', C1 and C2. A left-lateral movement (a) would produce a low pressure in C2 under the assumption of a narrowing of the lower shear zone margin at S. As a result pseudotachylyte material would be injected (I) into C2 (b). VL is Ventersdorp Lava, VCR is Ventersdorp Contact Reef.

parallel to the movement direction of the shear zone implies that the chamber is relatively closed in three directions, thus allowing the melt to infuse only from one side. Secondly, the irregular shape of the chamber will also determine which are sites of turbulence. The turbulent areas will be those localities where there is a change in pressure gradient; generally where necking in the shear zone occurs. Non-turbulent flow will ultimately be achieved in those chambers where the shape remains more or less constant and where the viscosity and deformation rate are suitable (see below).

RELATION BETWEEN FLOW BANDING AND LAMINAR FLOW

The observed textures appear to be indicative of fluids. The well developed flow banding in C2 is indicative of laminar flow and therefore the Reynolds number (Re) of the melt must be below the critical Reynolds number Re_{cr} which marks the transition to turbulent flow. For most conditions, Re_{cr} is between 2000 and 2300 (Kreider 1985). A simple calculation shows that the Reynolds number of the pseudotachylyte melt lies well below this critical value. Re is given by (e.g. Kreider 1985)

$$Re = \frac{\rho\, v\, D}{\mu},$$

where ρ is the fluid density, v is the fluid velocity, D is the diameter of the conduit and μ is the fluid viscosity. The Reynolds number Re can be estimated assuming the following values. The density of the fluid is slightly less than the density of the solidified melt, say 2.6 g cm^{-3}. The maximum thickness of the shear zone at chamber 2, D, is 5 cm and the maximum velocity of the fluid corresponds with the dislocation velocity of the fault. For seismic events a velocity of 50 cm s^{-1} is assumed (Ambraseys 1969, Sibson 1975). The viscosity of the pseudotachylyte melt is roughly estimated at 10^3 P, which corresponds to the viscosity of a basaltic andesite at 1100°C and 1 bar (Scarfe 1973, Sibson 1975). With these values Re calculates to

$$\mathrm{Re} = \frac{2.6\,[\mathrm{g\,cm^{-3}}] \times 50\,[\mathrm{cm\,s^{-1}}] \times 5\,[\mathrm{cm}]}{10^3\,\mathrm{P}}$$

$$= 0.65.$$

The often observed flow banding in pseudotachylyte therefore likely corresponds to a low Reynolds number. While this is a very rough estimate, the constants employed yield a maximum estimate, and further, the estimated value for Re is orders of magnitude below $\mathrm{Re_{cr}}$. Considering the uncertain viscosity of the pseudotachylyte melt (temperature and percentage of volatiles at the time of faulting are not known) a viscosity which lies below the estimated value by an order of 3 would not change the significance of the calculation. All the relationship actually reveals is that laminar flow will take place in pseudotachylytes using realistic values for the viscosity and displacement velocity on the fault zone. This is to be expected from viscous silicate melts responding to geological deformational rates.

Figure 4(c) shows an 'eye' in a section cut perpendicular to the movement direction of a left-lateral strike-slip fault in the VCR horizon from another locality on the Kloof Gold Mine. The fault is truncated by a bedding-plane fault in the contact VCR–Ventersdorp Lava along which thrusting towards the northwest occurred. The sample shows dark and light flow bands which form a sheath-fold-like structure. The movement direction which is indicated by this eye is subparallel to slickenfibres on the fault plane. Although the shear zone symmetry is not known, the eye can be used to estimate the azimuth of movement. This confirms the presence of these structures in pseudotachylyte from another fault plane which was generated at a different time and a different stress field from the example described above.

CONCLUSIONS

(1) The commonly observed flow banding in pseudotachylytes is indicative of laminar flow of fluids with low Reynolds numbers. Textural relationships in the pseudotachylyte show evidence for the presence of a melt.

(2) It is suggested that sheath-fold-like structures in pseudotachylytes can develop as a result of injections of pseudotachylyte melt. The latter are related to irregularities in the shape of the bounding surfaces of the fault. The pseudotachylyte within these surfaces responds also very sensitively to the creation of relatively high and low fluid pressure areas within the shear zone. The sheath-fold-like structures can be used to give the azimuth of the movement of the fault, but not necessarily the sense of movement. Other parameters must be used to determine the movement sense.

(3) The formation of a pseudotachylyte along a bedding-plane fault along the contact between the VCR and the Ventersdorp Supergroup can be explained by NW-directed thrust fault movement. This conclusion is consistent with the direction of thrusting observed in the study area (Berlenbach & Roering 1990).

(4) Sheath fold geometry is not confined to this locality alone.

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