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Bedding-parallel shear, thrusting and quartz vein formation in Witwatersrand quartzites

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Abstract—Evidence is presented which clearly demonstrates the presence of thrust faults in the gold-bearing sedimentary rocks of the Witwatersrand Supergroup. A package of these rocks subjected to shear strain allowed overlying beds on the northern margin of the Witwatersrand Basin to move outwards in a N–NW direction. Movement took place on ductile shear zones which were parallel to the bedding and often reveal excellent examples of ramp and duplex structures. It has also been established that syntectonic foliation planes were utilized as planes of shear in certain circumstances. Quantitative estimates of strain for the pile, which are of necessity minimum values, give $\gamma \approx 1$. Fluids, from which vein quartz formed, played a critical role in the shear plane movement and may have relieved a portion of the overburden load during deformation.

INTRODUCTION

The presence of major thrust faults within rocks belonging to the gold-bearing Witwatersrand Supergroup has been documented in recent years (McCarthy *et al.* 1982, Roering 1983, 1984) although reference to similar structures appeared earlier in the literature (e.g. Hendriks 1961, Winter 1964, Olivier 1965, Fripp & Gay, 1972). Roering (1983, 1984, 1986) has identified a major thrusting event on the northern margin of the Witwatersrand Basin which involved an imbricate stack of granitoids, greenstones and Witwatersrand sediments. This event was generally directed towards the north and was responsible for the transportation of sediments for several tens of km. The suggested mechanism of thrust faulting as well as the direction and magnitude of northward displacement have not readily been accepted by Witwatersrand geologists. In this paper we add new information in support of these proposals and also report on a detailed investigation of shear strain in the Main Bird quartzites within the Witwatersrand Supergroup. These rocks, previously regarded as relatively undeformed, contain excellent examples of bedding plane shear strain and ramp formation whereby individual strata are thrust towards the N and NW.

LOCATION AND STRATIGRAPHY

The stratigraphy of the Witwatersrand Basin was originally described by Mellor (1911) and consists of a thick sequence of quartzites, shales and conglomerates. Basin stratigraphy may be divided into a lower more argillaceous unit (West Rand Group), and an upper more arenaceous unit (Central Rand Group),which is characterized by quartzites and Au-bearing conglomerates.

The packet of Witwatersrand quartzites to be discussed crop out in a road-cut in the western suburbs of Johannesburg (Fig. 1) and consists largely of grey medium-grained quartzite (with minor conglomerate) and schist. The character of the rocks as well as their geographic position suggest that they belong to the Bird Reefs of the Central Rand Group.

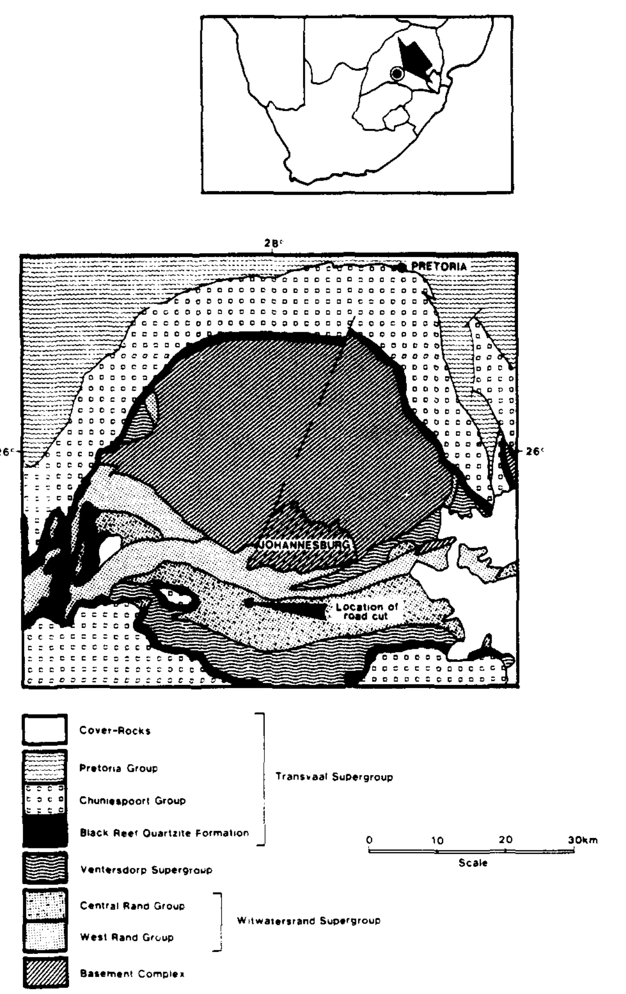

Fig. 1. Location of investigated area.

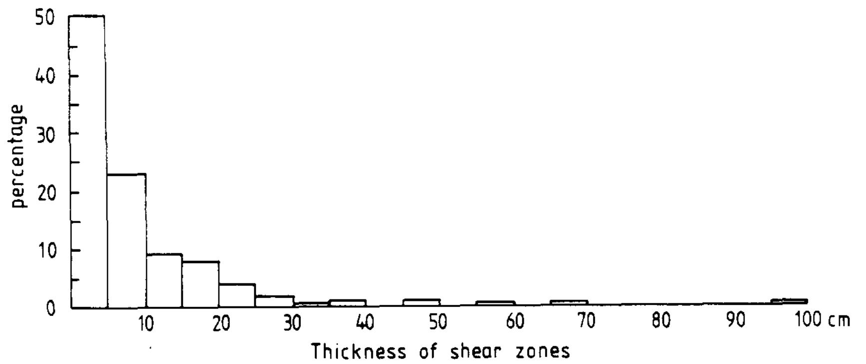

Fig. 2. Frequency diagram of the thickness of all shear zones in the road-cut exposure.

DESCRIPTION OF STRUCTURES

General

Conglomerates make an insignificant contribution to the total thickness of sediments and are developed towards the top of the exposed sequence. They have not been studied further. The massive quartzites reveal no distinctive signs of deformation, and individual beds have an average thickness of 75–150 cm.

Apart from the pronounced parallel layering, caused by the alternation of sedimentary strata, foliation is the most common fabric observed in the exposures. Foliation is preferentially developed in certain layers which initially had higher clay contents than adjacent layers. The layers in which the foliation is developed represent zones of ductile shear deformation parallel to the bedding planes. A frequency diagram of all shear zone thicknesses in the road-cut is shown in Fig. 2. The thicknesses of the foliated layers vary from several mm to 1 m. The orientation of foliation in these layers is systematically steeper than the bedding. The dips of the foliation and the bedding planes are towards the S and SSW, respectively.

Sigmoidal shear zones

At certain localities narrow curved shear zones develop in the stiffer quartzites adjacent to a ductile shear zone (Figs. 3a & b). These zones are clearly distinguished from layering in the surrounding pebble, grit and quartzite by their cross-cutting attitude. Furthermore, the fill of the shear zone contrasts sharply with the adjacent rock because of its very fine-grained nature and the presence of pyrophyllite grains oriented parallel to the shear plane. Grain size reduction of both quartz and the phyllosilicates is clearly seen in the shear zone under the microscope. The curvature of the zones is systematic with respect to the bedding planes. Where they form in the hangingwall of a shear zone their shape is concave upwards (Fig. 3a), while in the footwall they are convex-up (Figs. 3b & 5). Steeper inclinations are generally attained in grit and pebble bands while a more asymptotic or bedding-parallel orientation is attained in the phyllosilicate-rich units. Careful examination of the shear surfaces reveals a distinct mineral lineation in the direction of tectonic transport. Individual shear zones often occur together and branch systematically out of a larger bedding-parallel shear zone giving rise to a horsetail pattern. Where these narrow shear zones link across a sedimentary layer they are sigmoidal when the concave and convex zones meet in the middle of the layer (Fig. 3b). Otherwise they maintain their curved (listric) shape across the entire thickness of the layer (Figs. 3a & b). Locally, where an individual shear zone thickens to a width of approximately 1 cm, a distinct foliation inclined to the shear plane is developed, a further indicator that these structures are narrow ductile shear zones.

The angle between a narrow sigmoidal shear zone and the bedding plane increases from asymptotic at the margins of the stiffer quartzite layer to as much as 50° in the middle of the layer. Similarly oriented zones are also developed within less-deformed non-foliated relicts (fishes) in a strongly foliated ductile shear zone (Fig. 3c). The narrow shear zones always have the same orientation with respect to the direction of movement as determined by the attitude of the foliation (Fig. 3c).

It would appear from the field data that these narrow shear zones develop preferentially at the ends of a bedding-parallel shear zone or possibly along such zones when they lock at sites where further movement is inhibited.

The narrow shear zones are, therefore, considered to represent small-scale versions of step faults in a system of bedding-plane thrusts. The sigmoidal shape of such structures has been modelled by Mandl & Shippam (1981). These authors have shown that step faults would occur on surfaces parallel to slip lines with isogonal cycloid shapes in a plastic medium subjected to simple shear. The increase in angle between the step fault and the shear plane towards the middle of a layer is suggested by these authors to be controlled by variations of pore pressure within a frictional plastic material in a single layer. A decrease in angle is associated with an increase in pore pressure. This proposal is supported by field observations that bedding-parallel shear planes are generally restricted to the more phyllosilicate-rich horizons.

The narrow shear planes described in this section are considered to represent embryonic step faults which were also sites for ramps where thrusting has ensued.

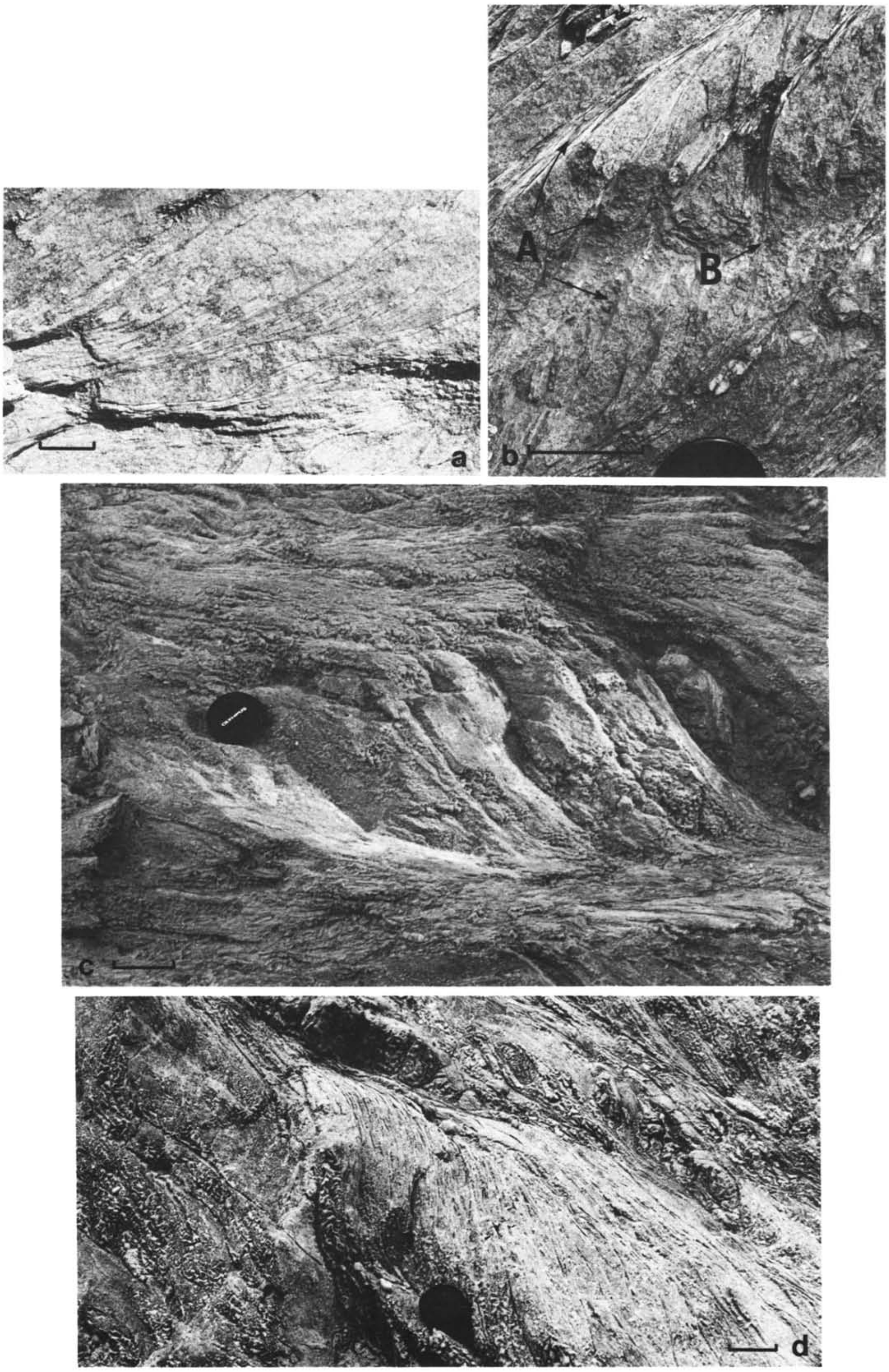

Fig. 3. (a) Horse-tail shear zones (darker concave-up lines) in relatively undeformed quartzite. (b) Two types of narrow shear zone: A—broadly convex-up zones; B—a sigmoidal zone. (c) A lens of non-foliated quartzite enclosed in a highly foliated (horizontal fabric) ductile shear zone. The stiffer relict is traversed by numerous parallel narrow shear zones that are oriented at an angle of 55° to the dominant foliation. Relative shear displacement is sinistral. (d) Foliated quartzite is situated behind and to the right of an inclined ramp of massive quartzite. Immediately adjacent to the ramp the foliation is oriented at 50° to the shear (bedding) plane. Further behind the ramp (i.e. towards the right of the photograph) the angle becomes flatter. Behind the ramp there is an anticlinal stack which developed from the thrusting of foliated material parallel to the foliation planes. Length of scale bars is 50 mm.

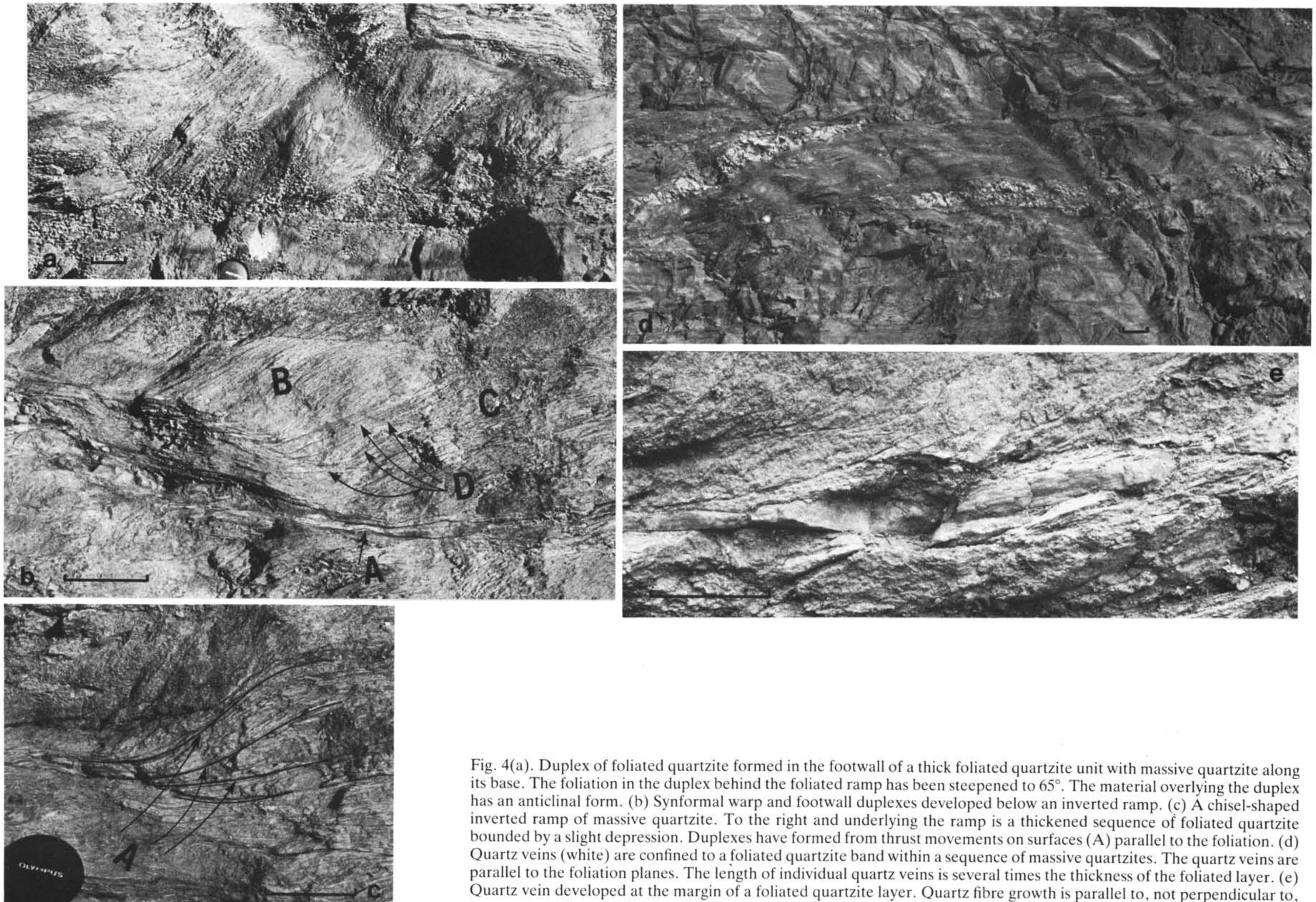

Fig. 4(a). Duplex of foliated quartzite formed in the footwall of a thick foliated quartzite unit with massive quartzite along its base. The foliation in the duplex behind the foliated ramp has been steepened to 65°. The material overlying the duplex has an anticlinal form. (b) Synformal warp and footwall duplexes developed below an inverted ramp. (c) A chisel-shaped inverted ramp of massive quartzite. To the right and underlying the ramp is a thickened sequence of foliated quartzite bounded by a slight depression. Duplexes have formed from thrust movements on surfaces (A) parallel to the foliation. (d) Quartz veins (white) are confined to a foliated quartzite band within a sequence of massive quartzites. The quartz veins are parallel to the foliation planes. The length of individual quartz veins is several times the thickness of the foliated layer. (e) Quartz vein developed at the margin of a foliated quartzite layer. Quartz fibre growth is parallel to, not perpendicular to, the vein. See text for full description and terminology. Length of scale bar is 50 mm in all cases.

Variation in the angle between the foliation and the shear zone

The angle between the foliation and the shear plane in a ductile shear zone should be less than 45°, assuming simple shear with no volume change (Ramsay 1980). In the area of study, the average angle is 26° (Fig. 6), although the variation is large. An angle of 60° has been measured in outcrop and values approaching 45° are shown in Fig. 6. It should also be emphasized that this angle can approach 0°, which is generally the case for the narrow shear zones less than 10 cm in width. These narrow shear zones (A in Fig. 6) in which the foliation is essentially parallel to the shear plane are often cross-cutting and post-date the foliation. They do, however, involve the same direction of shear as the wider zones and are therefore included in the overall deformation event.

While angles of foliation to shear zone of greater than 45° can be attributed to a superimposition of pure shear on simple shear acting in ductile shear zones (Coward 1976, Hudleston 1980), the increase in angle in the present investigation is closely related to ramp structures. Different types of ramp have been recognized and are distinguished from each other by the rock-type constituting the ramp, that is whether the ramp consists of foliated or non-foliated quartzite (Figs. 3d and 4a).

Figure 3(d) shows a good example of a non-foliated footwall ramp. The angle formed by the ramp and the bedding plane is 50°. The orientation of the foliation is essentially parallel with the ramp surface itself, while on the flat ahead of the ramp, the foliation defines a relatively small angle with the bedding. Behind the ramp the foliation maintains the 50° orientation for a short distance and then ultimately takes on the average angle of the foliation for the outcrop, which is 26°. There is also an indication of an anticlinal stack forming in the foliated quartzites behind the ramp. This implies that duplexes are forming in the foliated material behind the ramp and that sliding has possibly taken place on the foliation planes. The occurrence of steeper inclinations of the long axes of the strain ellipsoid behind a ramp has been admirably demonstrated by Sanderson (1982, fig. 17).

Figure 4(a) shows a duplex which has developed at the base of a foliated layer, which in turn is underlain by a massive non-foliated quartzite band. The anticline which has formed above the duplex is clearly defined by the orientation of the foliation. The foliation in the duplex is clearly steepened behind the ramp.

A related situation is illustrated in Figs. 4(b) & 4(c). The structures shown are geometrically identical to the previous examples but represent inverted facsimiles of them. That is, instead of an antiformal region developing above a ramp, a synformal depression has developed below the area of thrusting. This 'inversion' is geometrical, not stratigraphic. The two situations are distinguished by the position of the duplexes. In Figs. 3(d) & 4(a) the antiformal structure is formed by a process of duplex formation in the hangingwall above a footwall ramp. In Figs. 4(b) & (c), however, the synformal depression is caused by duplex formation in the footwall below a chisel-shaped inverted ramp. The major factor controlling the development of antiformal or synformal structures is the position of the more rigid layer: whether this was situated in the hangingwall or the footwall of the region where the duplexes were formed.

The synformal warp in Fig. 4(b) is defined by the narrow curved shear plane (A). Between this plane and the overlying massive quartzite layer there are two distinct domains. The chisel-shaped lighter coloured foliated portion (B) is geometrically similar to an inverted ramp with a thickened thrusted unit occurring to the right (C). In the thrusted unit there are darker lines parallel to the foliation which are thin high-strain zones separating narrow foliated slices from each other (D). The foliated slices are narrow duplexes. It is quite clear that the duplexes have been sheared past one another on planes which are parallel to the foliation. The orientation of the foliation with respect to the bedding is again steeper than normal in the region of footwall duplex formation.

A similar situation is seen in Fig. 4(c). Here, however, the footwall duplexes formed below massive and not foliated quartzite. The foliation again steepens in the thickened unit adjacent to the inverted ramp, and narrow shear zones (A) also delineate duplexes. A synclinal depression is developed at the base of the thickened unit and the narrow high-strain zones are parallel to the foliation.

Steepening of foliation is, therefore, related to a process of ramp formation. The controlling feature is the occurrence of a plane, inclined with respect to the bedding, along which thrusting takes place, and adjacent to which the orientation of the strain ellipsoid changes from that which it normally assumes with respect to the bedding planes (Sanderson 1982). It is important to note that the foliation planes themselves are utilized as shear planes in close proximity to the ramps.

Foliation and vein quartz

There is a clear relationship between the distributions of vein quartz and ductile shear zones (Figs. 4d and 5). The overwhelming majority of vein quartz lenses are spatially confined to such zones. Furthermore, no instance has been found where these bodies were injected into the adjacent non-foliated quartzites. Vein quartz occurs typically as lens-shaped bodies whose major and intermediate axes are always within or close to the foliation plane and/or bedding plane. Individual lenses can sometimes be connected by a thin film of vein-quartz material. The maximum length is several metres while the maximum thickness is 20 cm.

Fibre growth of quartz has been observed in some of the smaller lenses and is parallel with the foliation and also the postulated transport direction, which is the stretching direction (Fig. 4e). In larger lenses the fibre growth is confined to the outer portion or sometimes the outer skin only. Slickensides, caused by quartz growth on movement surfaces, developed a strong lineation of

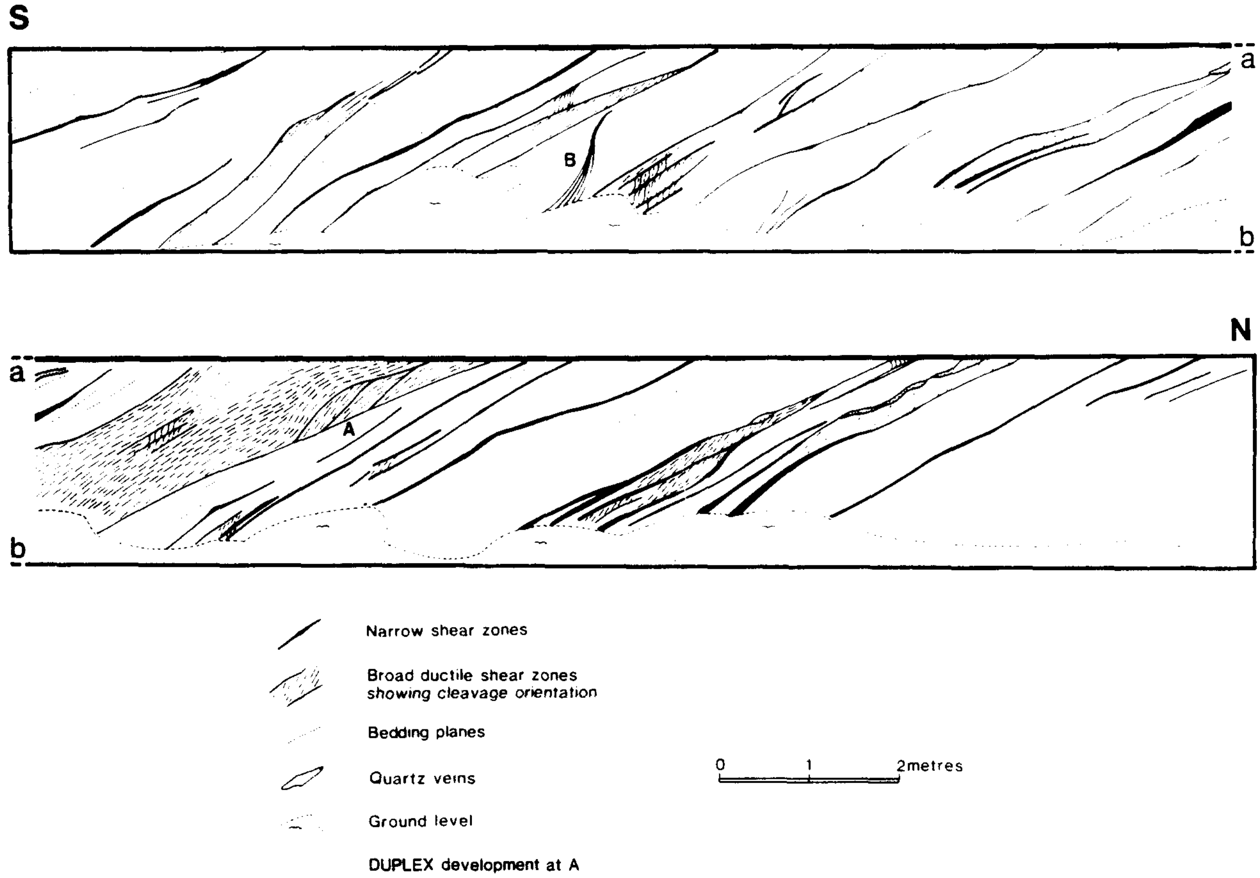

Fig. 5. Detailed section of the outcrop showing duplexes at A and sigmoidal shear fractures at B.

same orientation as the quartz fibres associated with the vein quartz lenses.

STRAIN QUANTIFICATION

Measurements of the following parameters could be made directly on the outcrop. (a) Thicknesses of foliated and non-foliated strata. Except in the vicinity of ramps, variations in thickness correspond to primary variations within the sedimentary pile. The schistose layers are ductile shear zones which are ideally parallel to the primary bedding but may be deflected from this orientation near ramp structures. (b) Orientation of the foliation and its angular relationship (θ') to the bedding planes. These were recorded in order to quantify shear strain (γ) (see terminology and symbols used by Ramsay 1980). (c) Lineations.

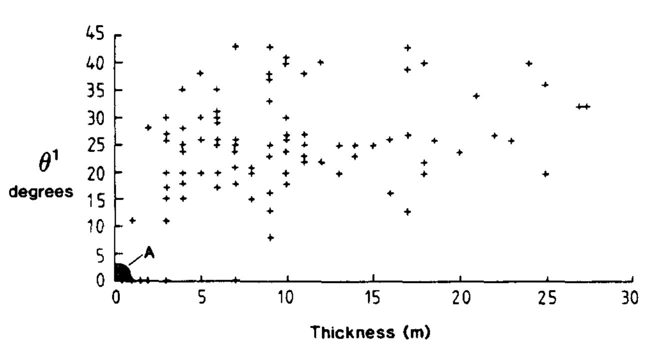

Fig. 6. Plot of the variation in the angle of the shear plane to the foliation (θ') against shear zone thickness. A curve fitted to the data would swing down towards area A in which many points are concentrated. Area A represents narrow shear zones in which foliation is parallel to the shear plane. If the population at A is disregarded the arithmetic mean of the remaining values of θ' is 26°.

In order to obtain an estimate of total strain integrated over the entire exposure, the road-cut was photographed and a mosaic was constructed from which the stratigraphic thicknesses could be calculated. The mosaic also provided a base section for geological and structural mapping (Fig. 5). However, data used for quantifying strain were obtained by making measurements on the outcrop itself. The outcrop was considered to represent a random sample line through a certain thickness of quartzites. The true width of every shear zone and every undeformed layer was determined at the point of intersection of these structures with a horizontal line. The angle between the bedding plane and the foliation was generally measured with a clino-rule in the plane of the outcrop. Where possible the orientations of bedding and foliation were measured and plotted to allow the angle between them to be read off a stereographic projection.

Strain estimate

The true thickness of sediments represented in the road-cut is 108.4 m. Good foliation inclined to the bedding is developed in 11.14 m of this, while 4.84 m is made up of thinner shear zones, generally 0.5–7 cm in width, within which the foliation is parallel to the shear

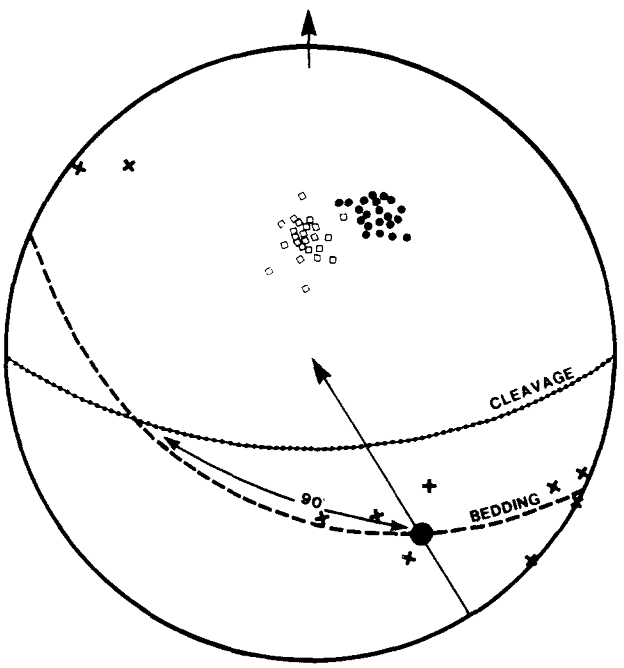

Fig. 7. Lower hemisphere projection of structural geological data. Dots are poles to bedding planes. Open squares are poles to cleavage planes. Crosses are lineations. Large dot is the constructed transport direction based on the average cleavage and bedding orientations.

zone or bedding planes. Ductile shear zones with foliation and thinner shear zones with foliation parallel to the bedding are included in the frequency diagram of Fig. 2. Clearly the frequency of shear zones increases with decreasing shear zone width: 51% of the shear zones are from 0 to 5 cm in thickness while 71% are less than 10 cm thick.

The arithmetic mean of the angle θ' between the shear zone and foliation plane is 26° when measured with a clino-rule in the plane of the exposed face. The average angle determined from the stereographic projection is 27° (Fig. 7) so that values measured in the plane of the road-cut are considered valid. Employing an average of 26° for θ' and applying this to an 11 m thickness of foliated quartzites gives an estimate of 17 m of shear displacement, corresponding to $\gamma = 1.55$. Another estimate of strain was made for the same 11 m of strata using the individual thicknesses of foliated quartzite layers and the corresponding values of θ' determined for each layer. Ninety-six layers of varying thickness were employed in this estimate. Using this second method, an estimate of total displacement of 19 m (i.e. $\gamma = 1.73$) was derived. The difference between the results of the two methods is only 10% and hardly affects the estimate of total shear displacement which must also incorporate the smaller zones.

The main problem in the estimate of strain hinges on the 5 m thickness of rock in which the foliation is essentially parallel to the shear plane. What value of θ' can be utilized for the calculations? A value of 5° is realistic as an upper bound, because larger angles would be clearly measurable. If θ' is taken as 5°, γ would be 11, equivalent to a displacement of 55 m for a stratigraphic thickness of 5 m. The total minimum displacement for the package is thus 55 m + 19 m = 74 m. If an average γ is calculated for the total pile of sediments investigated (108 m) a value of 0.7 is obtained.

The angle θ' could well be smaller than 5°, and γ would therefore be correspondingly larger. Just how much larger cannot be determined from the existing data. Since it is impossible to rigorously constrain the estimates of finite displacement it is proposed that a value of $\gamma = 1$ be accepted as a minimum for the entire thickness of sediments investigated, which corresponds to an average angle θ' of 3° for all the narrow shear zones.

DIRECTION OF TRANSPORT

The transport direction can be determined with a high degree of certainty from these outcrops. It is known for example that the ductile shear zones are parallel with the bedding planes. The average orientation of the bedding and the foliation have been plotted on the stereographic projection (Fig. 7). The transport vector lies at 90° to the line of intersection of these two planes within the bedding (or fault) plane and is oriented towards the NW. Rotation of the bedding to the horizontal hardly affects this direction. Taking these facts into consideration it is obvious that the upper layers have been thrust over the underlying layers in a NW direction.

Lineations have also been measured at certain localities and have been plotted on Fig. 7. The variation in direction of the plunge of the lineations is from S to SE and NW, corresponding fairly well to the direction determined above. The lineations are all of the quartz fibre type and represent two groups: the first developed as thin quartz films (slickensides) on bedding plane surfaces; the second group has been referred to in the discussion on vein quartz and foliation. In this group the fibres represent a stretching lineation of the larger vein quartz lenses.

The duplex structures of Figs. 3–5 are irrefutable evidence that the overlying strata moved up-dip, and clearly substantiate the fact that the strata were thrust towards the N and NW.

DISCUSSION AND CONCLUSIONS

It was mentioned that the estimates of strain are conservative. The greatest uncertainty in the estimate of strain is due to the narrow shear zones in which the foliation is parallel to the movement plane. Although representing only 5% of the total thickness of the sediments investigated, 71% of all shear zones are less than 10 cm in width. This means that the overwhelming majority of shear zones are narrow. The amount of shear strain taken up by these narrow zones cannot be rigorously established because of the inherent difficulty in measuring small angles.

Since the frequency of smaller shear zones increases on a log normal basis (Fig. 2) the question may also be raised as to the validity of the final estimate of shear strain. Microscopic shear zones and other fractures simply identified as bedding planes separating two distinct sedimentary layers have not been taken into consideration. It is possible that the number of such planes is large and that neglecting them has considerably influenced the accuracy of the shear strain estimates. Because of this the present estimate can only be considered as a lower limit.

The total thickness of sediments comprising the Witwatersrand Supergroup in the Central Rand area is 7.4 km (Truswell 1977, South African Committee for Stratigraphy (SACS) 1980). Of the succession, which consists essentially of quartzites, shales and conglomerates, the shales make up approximately 2 km. The present investigation reveals that certain essentially arenaceous zones have been subjected to simple shear. Although this deformation does not necessarily apply to all the arenaceous zones of the Supergroup it probably had a more dramatic effect on the larger shale units. This work indicates that a conservative estimate of the shear strain is in the order of $\gamma = 1$. Subjecting the entire 7.4 km thickness of sediments to an equivalent deformation would result in the uppermost members being transported in a northerly direction for distances of at least several kilometres. Such a conclusion would be in support of structural geological investigations done at Swartkops and in the basement granite and greenstones which form the 'floor' of the Witwatersrand Basin a few kilometres immediately north of the area described in this paper (Roering 1984, 1986). At Swartkops, lower Witwatersrand sediments, which can be traced for a distance of 3 km in the tectonic transport direction, have been subjected to a shortening of 6–7 km. The shortening across the exposed granite–greenstone terrane occurring immediately north of the border of the Witwatersrand basin has similarly been estimated to be several tens of km (Roering 1984). All the shortening can be accounted for by contractional faulting as displayed by the fact that the granite–greenstone terrane (the so-called Johannesburg Dome) is made up of an imbricate stack of granitoids, greenstones and Witwatersrand sediments (Roering 1986). The proposition that Witwatersrand sediments have been subjected to deformational events of a magnitude larger than has ever been contemplated before should now be worthy of consideration.

Deformation structures in the outcrop indicate that the angle between the foliation and the shear zone (bedding planes in this area) steepens adjacent to ramp structures. The foliation planes are themselves also utilized as shear planes in certain areas of duplex formation. Narrow shear zones are sometimes developed in the non-foliated quartzitic layers and have a distinctive curved (listric) or sigmoidal shape. These structures are embryonic step faults which are geometrically similar to those predicted by the theoretical models proposed by Mandl & Shippam (1981).

The association of tectonic veins and shear zones is well documented in the literature (e.g. Beach 1974, 1980, Kerrich 1977, Ramsay 1967, Ramsay & Graham, 1970). The general argument is that there is a direct mass transfer from areas of material loss to openings where material gain takes place. The losses are also commonly attributed to a process of pressure solution and fluids moving down a stress gradient to site of low pressure (Beach 1974, Kerrich 1977). Similarly the process of seismic pumping (see Sibson *et al.* 1975, Beach 1980) begins with an essentially brittle deformation in which fluids move from the surrounding rocks into a dilatant shear zone. When ductile deformation ensues the fluids can be driven out of this shear zone.

The above-cited examples clearly relate to openings in rock systems. Classically such openings will be caused by extensional fractures whose orientation is strictly controlled by the stress field, that is they tend to form at right angles to the minimum principal stress direction. This well-known orientation of veins cannot have been the case for the rocks in the road-cut investigated in this paper. Firstly, the veins are essentially parallel to the foliation plane, which is a plane of flattening. Secondly, the length of individual veins in many examples exceeds the thickness of the shear zone by a factor of up to 10. This latter observation discounts the possibility of the veins having initially been extensional veinlets which have subsequently been rotated into the plane of flattening. Lastly the quartz fibres are also parallel with the foliation and not at right angles to the plane of the veins. These factors, combined with the boudinaged nature of some of the quartz veins, indicate that they are essentially syntectonic.

The observations in the road-cut demonstrate, therefore, that fluids giving rise to quartz veins have not simply migrated to sites of lower pressure but rather to have moved to areas which are parallel with the foliation. Clearly these areas are not low-stress extensional openings which would be oriented more or less at right angles to the foliation. Another mechanism must be responsible for the formation of these quartz veins and it would appear that a filter-press type of action was more applicable to the quartz-bearing fluid phase, and for the concentrating mechanism. The fluid phase was also able to maintain the lithostatic loads at the time of deformation because it was not squeezed out of the shear zones into the adjacent non-foliated quartzites. The ductility of the shear zones would possibly have increased due to an increased presence of a fluid phase. The increased ductility would have then enhanced deformation rates. Furthermore the fluid phase would tend to reduce the effect of the overburden (Rubey & Hubbert 1959). The fluids from which the quartz formed in these shear zones therefore, enhanced bedding plane movement. If the bulk of the quartz were to have crystallized this would have had a braking effect on the movement. This mechanism may in fact have important implications in the gold mines where vein quartz material often occurs in the bedding planes, which by implication would mean that they also represent bedding plane faults.

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