ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

THRUST-MOVEMENT QUANTIFICATION AND QUARTZ-VEIN FORMATION IN WITWATERSRAND QUARTZITES

C. ROERING and C. A. SMIT

• INFORMATION CIRCULAR No. 186

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

THRUST-MOVEMENT QUANTIFICATION AND QUARTZ-VEIN FORMATION IN WITWATERSRAND QUARTZITES

by

C. ROERING and C.A. SMIT

(Department of Geology, Rand Afrikaans University, Johannesburg)

ECONOMIC GEOLOGY RESEARCH UNIT

INFORMATION CIRCULAR No. 186

October, 1986

THRUST-MOVEMENT QUANTIFICATION AND QUARTZ-VEIN FORMATION

IN WITWATERSRAND QUARTZITES

ABSTRACT

Evidence which clearly demonstrates the presence of thrust-faulting in the gold-bearing sediments of the Witwatersrand Supergroup is demonstrated. A package of sediments subjected to shear-strain allows overlying beds on the northern margin of the Witwatersrand Basin to move outwards in a northerly-to-northwesterly direction. Movement takes place on ductile-shear-zones which are parallel to the bedding and which often reveal excellent examples of ramp- and duplex- structures. Quantitative estimates of strain for the pile give a minimum value of $\gamma = 1$. The development of vein-quartz material plays a critical role in the shear-plane movements, and it may, in itself, act as a lubricant during deformation.

——— oOo ———

THRUST-MOVEMENT QUANTIFICATION AND QUARTZ-VEIN FORMATION IN WITWATERSRAND QUARTZITES

CONTENTS

oOo

Published by the Economic Geology Research Unit
University of the Witwatersrand
1 Jan Smuts Avenue
Johannesburg 2001

ISBN 0 85494 946 1

THRUST-MOVEMENT QUANTIFICATION AND QUARTZ-VEIN FORMATION IN WITWATERSRAND QUARTZITES

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 and 1984), although reference to similar structures had appeared earlier in the literature (e.g. Winter, 1964; Olivier, 1965; Hendriks, 1961; Fripp and Gay, 1972). Roering (1983, 1984) suggested that a major thrust-event, generally directed towards the north, was responsible for the transportation of sediments for several tens of kilometres. This event was identified on the northern margin of the Witwatersrand Basin. The suggested mechanism of thrust-faulting, as well as the direction and magnitude of northward displacement,have not been accepted readily by Witwatersrand geologists. This paper adds new information in support of the above proposals and also reports a detailed investigation of shear-strain in a group of the Main-Bird quartzites within the Witwatersrand Supergroup. These rocks, previously regarded as relatively undeformed, reveal excellent examples of bedding-plane shear-strain and ramp-formation, whereby individual strata are thrust towards the north and northwest.

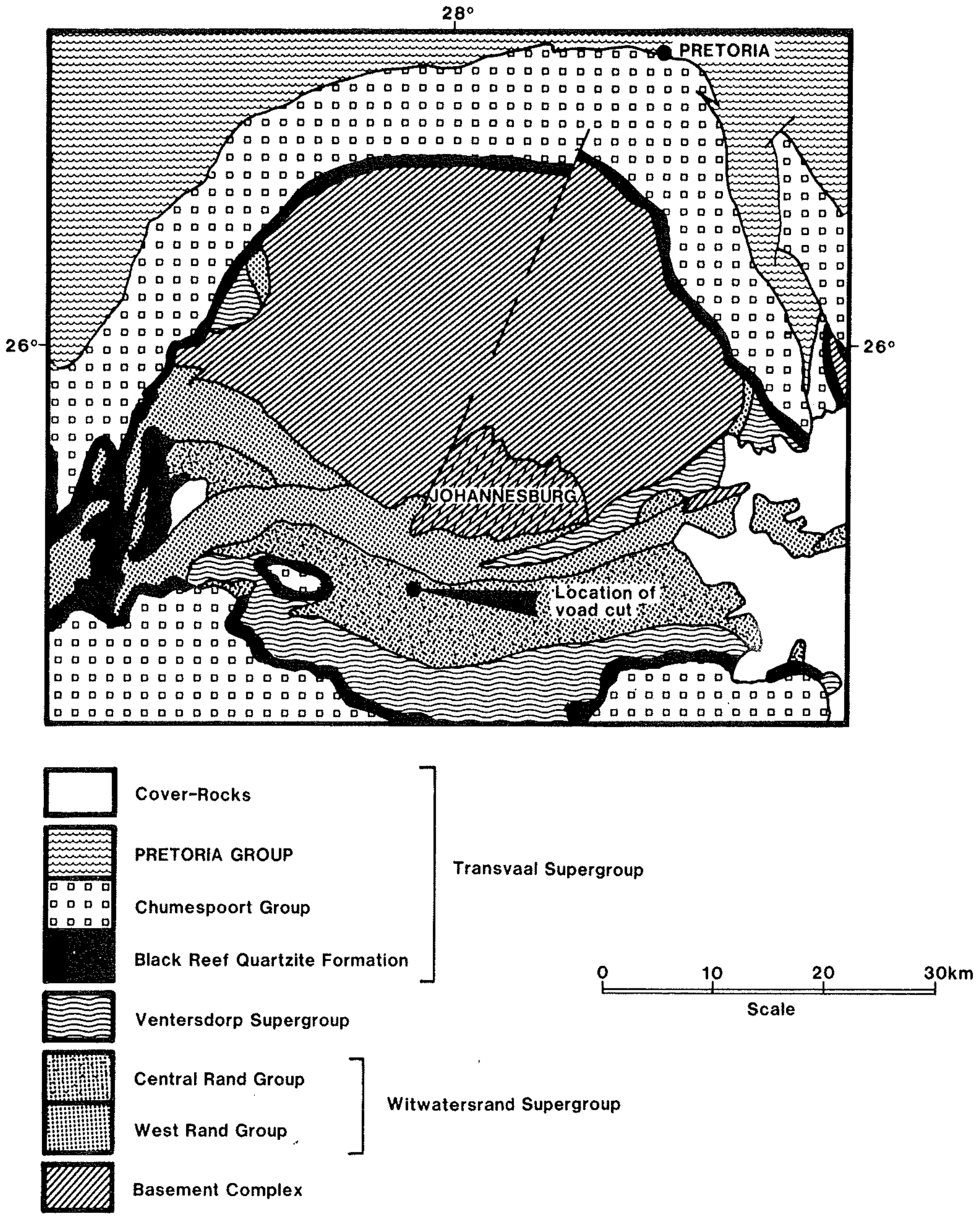
The stratigraphy of the Witwatersrand Basin was originally described by Mellor (1911) and consists of a thick sequence of shales, quartzites, and conglomerates. The main subdivision is into a lower, more argillaceous unit and an upper,more arenaceous unit which is characterized by quartzites and gold-bearing conglomerates. The only prominent argillaceous horizon in the upper unit is the Booysens Shale at the top of the Main-Bird assemblage.

The packet of Witwatersrand quartzites to be discussed crops 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 shale. The character of the rocks, as well as their geographic position, suggest that they belong to the Bird Reefs of the Central Rand Group.

DESCRIPTION OF STRUCTURES

General

The package of sediments and metamorphosed sediments identified in the road-cut consists of an alternation of quartzites, schists, and conglomerates. Conglomerates, which make an insignificant contribution to the total thickness of sediments, are developed towards the top of the exposed sequence and have not been studied further.



<u>*Figure 1*</u> : *A simplified geological map of the northern margin of the Witwatersrand Basin, near Johannesburg (after Borchers, 1961), showing the location of the road-cut.*

The massive quartzites reveal no distinctive signs of deformation and have an average thickness of 75-150 cm.

Apart from the pronounced parallel layering caused by the alternation of sedimentary strata, schistosity is the most common fabric observed in the exposures. Schistosity is preferentially developed in certain layers which, initially, had higher clay-contents relative to the adjacent layers. The layers in which the schistosity is developed represent zones of ductile-shear deformation and, therefore, are bedding-plane faults. A frequency-diagram of all the thicknesses determined in the road-cut is shown in Figure 2. The thickness of the schist layers varies from several mms to one metre. The fabric in the schist layers is systematically steeper than the bedding. The dip of the fabric and the bedding-planes is towards the south and southwest, respectively.

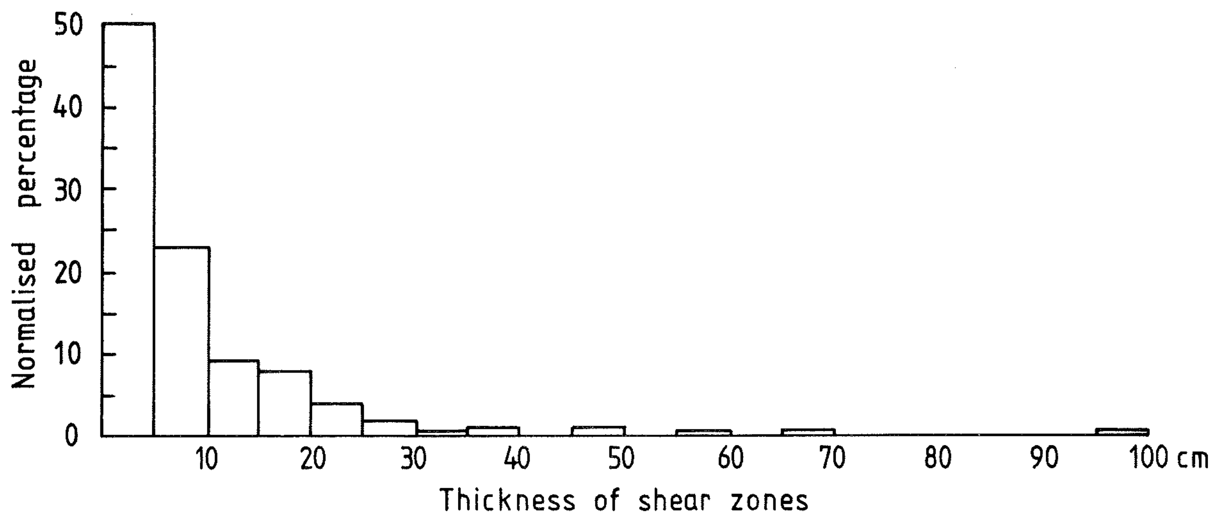


Figure 2 : *Frequency diagram of thicknesses of schistose horizons which, in fact, are ductile shear-zones parallel to the bedding.*

Fracture-Zones

At certain localities, curved fracture-zones develop in the more-brittle quartzites adjacent to a ductile-shear-zone (Figs. 3 and 4). Since individual fractures often occur together in zones, they can be described as small regions in which fracture-cleavage is developed. The curvature of the fractures is systematic, with respect to the shear-zones. When they form in the hangingwall of a shear-zone, their shape is concave upwards, while, in the footwall, they are convex in shape. Very often, the fractures are formed in those regions where a ductile-shear-zone ends, where they represent horse-tail fractures at the tip of a propagating shear-zone (Fig. 4). Such fracture-zones form the ideal sites, with increased simple-shear, for future ramps.

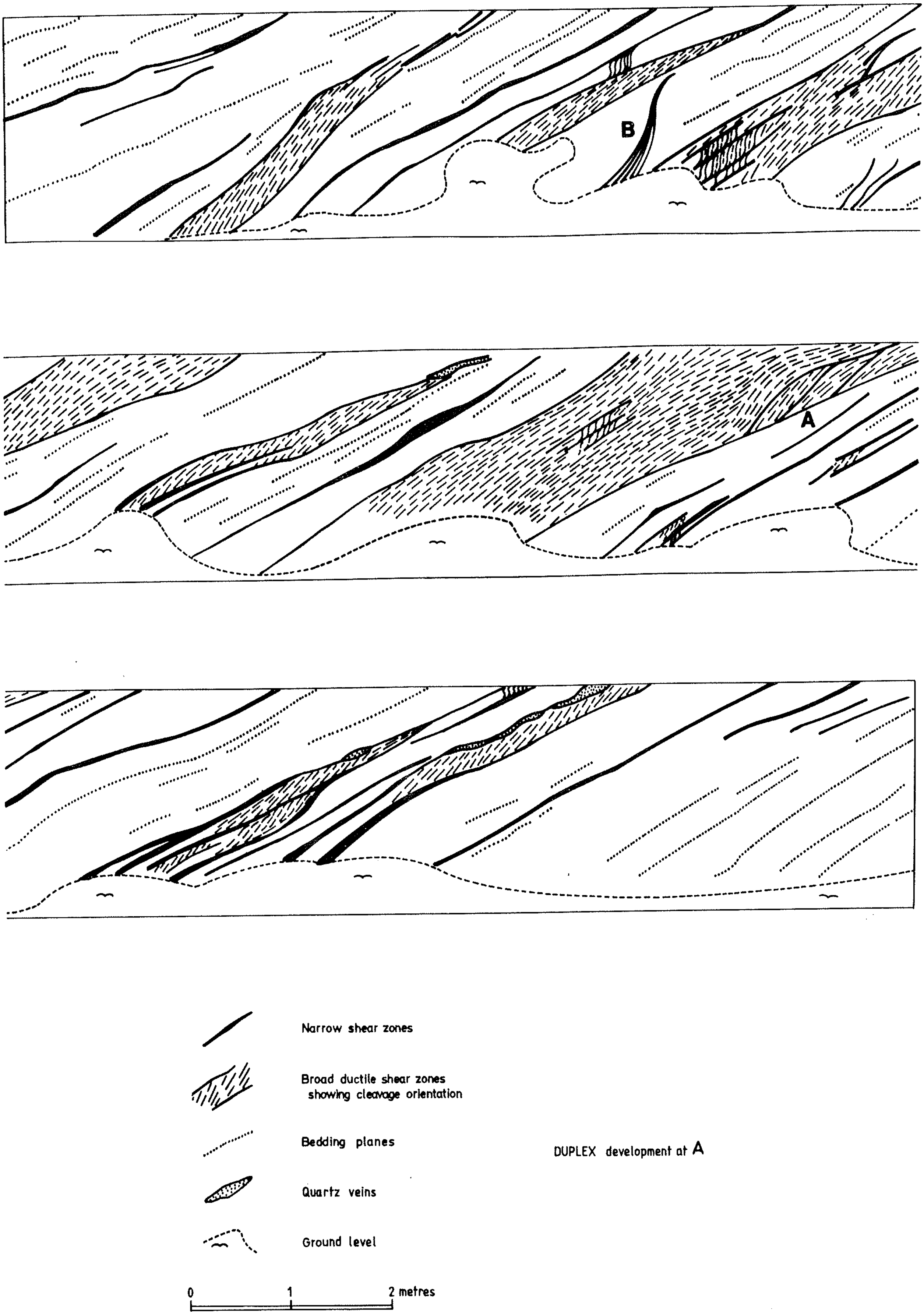


Figure 3 : *Detailed map of a portion of the road-cut. Position of duplexes is shown at Locality A. A fracture-zone is formed at Locality B, which could have generated into a ramp had the deformation continued. Note the long quartz-veins parallel to bedding at the right-hand side of the diagram.*

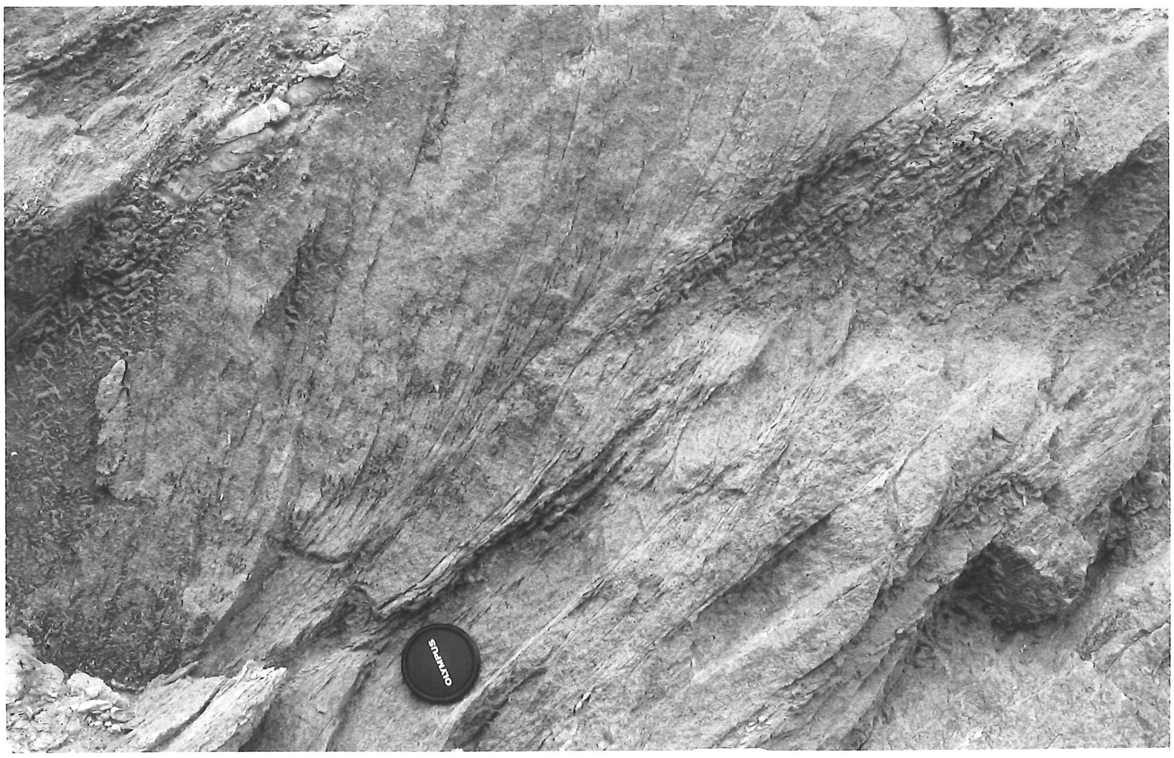


Figure 4 : *Series of concave fractures forming at the end of a shear-zone. The sheared and foliated quartzites terminate immediately to the left of the lens-cap. The fracture-zones have a similar appearance to cross-bedding in a massive quartzite, but are of tectonic origin. The fractures define an angle of 41° with the bedding. The lens-cap is 5cm in diameter.*

Variation in the Angle Between the Foliation and the Shear-Zone

The angle between the foliation and the shear-plane (i.e. bedding) in a ductile-shear-zone should be less than 45°. In this area, the average angle is 26° (Fig. 5). There is, however, a large variation in the angle. An angle of 60° has been measured in the outcrop, and values approaching 45° are shown in Figure 5. It should also be emphasized that this angle can approach 0°. The latter circumstance is generally applicable to the narrow shear-zones, less than 10cm in width, but can also be related to other processes that are discussed below. The narrow shear-zones, in which the foliation is essentially parallel to the shear-plane, are often cross-cutting and post-date the cleavage. They do, however, reveal the same direction of shear-strain and, therefore, are included in the overall deformation-event.

The steepening of the angle of schistosity to the shear-plane occurs in the immediate vicinity of the ramps. There are two types of ramps. Firstly, the ramp may consist of massive non-foliated quartzite (Fig. 6). The second type occurs within the foliated layer itself. In the latter case, the foliation-planes must behave as slip-planes, with concomitant development of duplexes (Figs. 7 and 8). Individual duplexes are difficult to identify because their boundaries are identical with the distorted foliation.

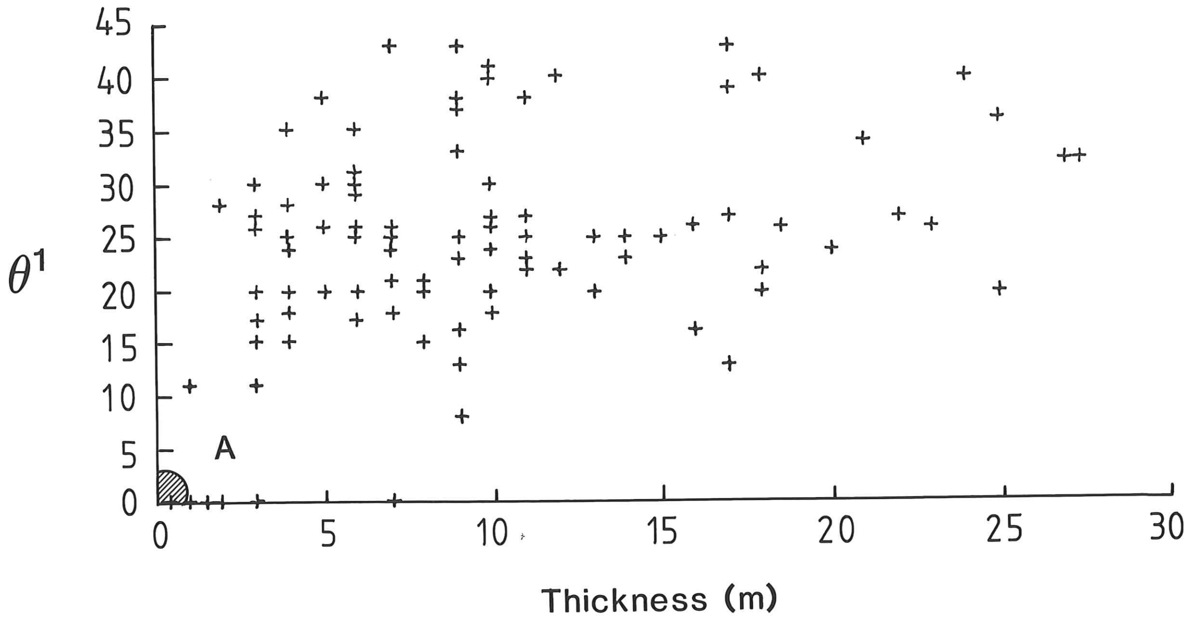
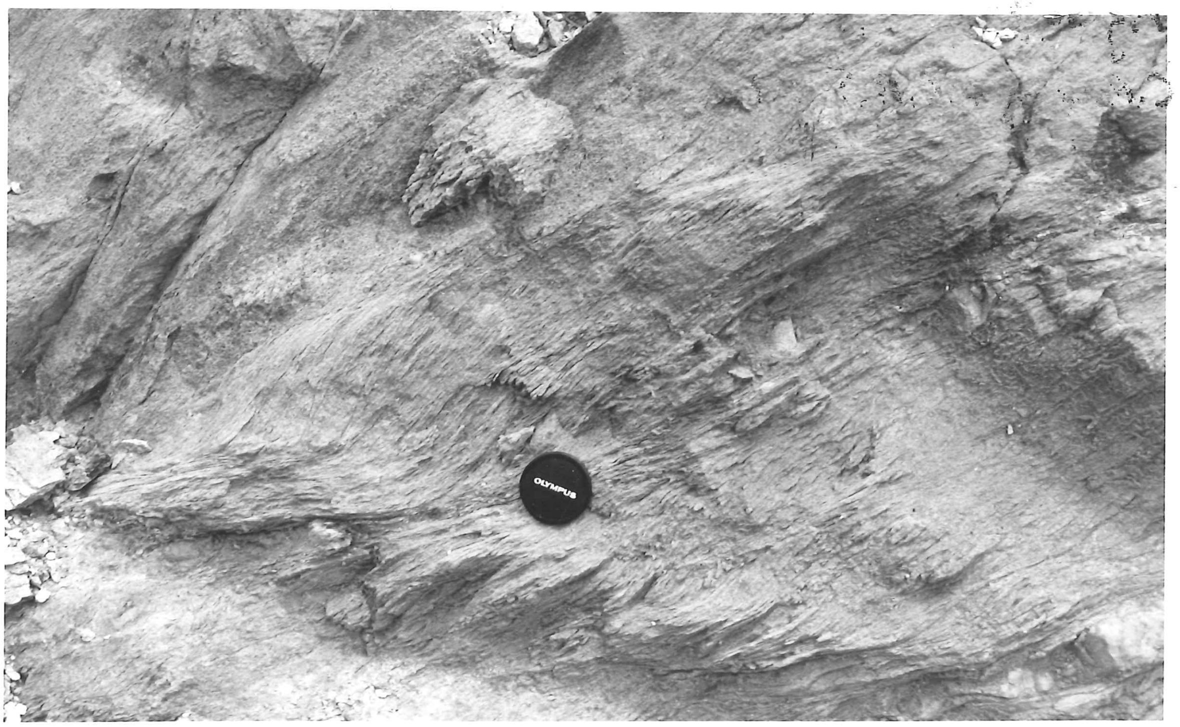


Figure 5 : *Variation in the angle between the foliation and shear-plane and the thickness of the ductile shear-zones.*

Figure 6 : *A massive quartzite ramp, behind which the foliated quartzite piles up so that the foliation-angle exceeds 45°. Note how the massive quartz-vein, occurring behind and ahead of the ramp above the flat, inhibits the amount of material that can be forced onto the ramp. The foliated material behind the ramp consists of a series of duplexes. The coin is 2,8cm in diameter.*

<u>Figure 7</u> : *The duplex on the left clearly reveals relative steepening of foliation, where the duplex lies adjacent to a ramp-surface. Note that the entire ramp of the massive overlying layer of schistose quartzite is made up of at least two larger duplexes (Fig.3, Locality A). The orientation of the foliation within the ramp itself can locally approach the plane of faulting, as does the foliation in the overlying layer of foliated quartzite. The duplex on the left is 40cm thick.*



<u>Figure 8</u> : *Steepening of foliation-angles to values larger than 45° behind a ramp. The ramp occurs immediately to the right of the lens-cap. The lens-cap is 5cm in diameter.*

The conditions which appear to be responsible for increasing the angle in excess of 26° are, firstly, the angle of the ramp itself and, secondly, a restriction which is imposed by a relatively-rigid layer overlying the ductile-shear-zone behind and ahead of the ramp. The ramp-angle, in general, does not greatly exceed 26°, although angles of up to 35° have been observed. Due to the influence of a relatively-stiff hangingwall-layer, a space problem developes immediately behind the ramp (Figs. 6 and 8). A thicker foliated unit is clearly being forced up into a narrower region on the flat ahead of the ramp. The material behind the ramp, as revealed by individual layers, thickens, and this causes the steepening of the foliation-angle. Furthermore, on the flat ahead of the ramp, the same foliation is almost parallel to the flat ramp-surface, and the layers are noticeably thinned. In Figure 8, the restriction imposed in the hangingwall is caused by a continuous quartzite layer, while, in Figure 6, it is imposed by a relatively-large vein-quartz lens which is parallel to the bedding.

There are several regions in and around the ramps and associated duplexes where the angle of the foliation is small and approaches parallelism with the shear-zone. This has already been demonstrated for the area on the flat immediately ahead of a non-foliated quartzitic ramp (Fig. 6).

Where the ramp and associated duplexes are composed of quartz-schist, the foliation within the ramp itself becomes flatter, with respect to the shear-zone (Figs. 7, 8, and 9). In Figure 8, the ramp-region occurs to the right of the lens-cap, and the foliation within the ramp is clearly almost parallel to the plane of movement. In Figure 9, the situation is more complex, as there are at least two duplexes in the immediate footwall of the massive schistose quartzite unit (Fig. 3, Locality A shows, in a simplified manner, the same features as in Fig. 9). In the quartz-schist on the right of the two duplexes, the foliation is almost parallel to the underlying bedding and then steepens to its normal angle on the right (Figs. 3 and 7). In all of the instances cited so far, the flattening of the foliation-angle within the ramps can be attributed to a relatively-large component of shear-strain's being transmitted to a narrow slice forming the ramp.

Another situation in which a flatly-orientated foliation is observed is in the basal region of a relatively-wide ductile-shear-zone (1m) which overrides the duplexes forming the ramp in Figure 7. Here, the foliation is parallel to, and merely follows, the shape of the footwall ramp. The parallelism is confined to a narrow zone adjacent to the fault-plane. The duplexes referred to in this example demonstrate, once more, a steepening of the foliation-planes behind a ramp, as described previously.

Foliation and Vein-Quartz

There is a clear relation between the distribution of vein-quartz and ductile-shear-zones (Figs. 3 and 9). The overwhelming majority of vein-quartz lenses are spatially confined to these zones. Furthermore, no instance has been found where these bodies inject into the adjacent, non-foliated quartzites. Vein-quartz occurs typically as lens-shaped bodies, the major and intermediate axes of which 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 20cm.

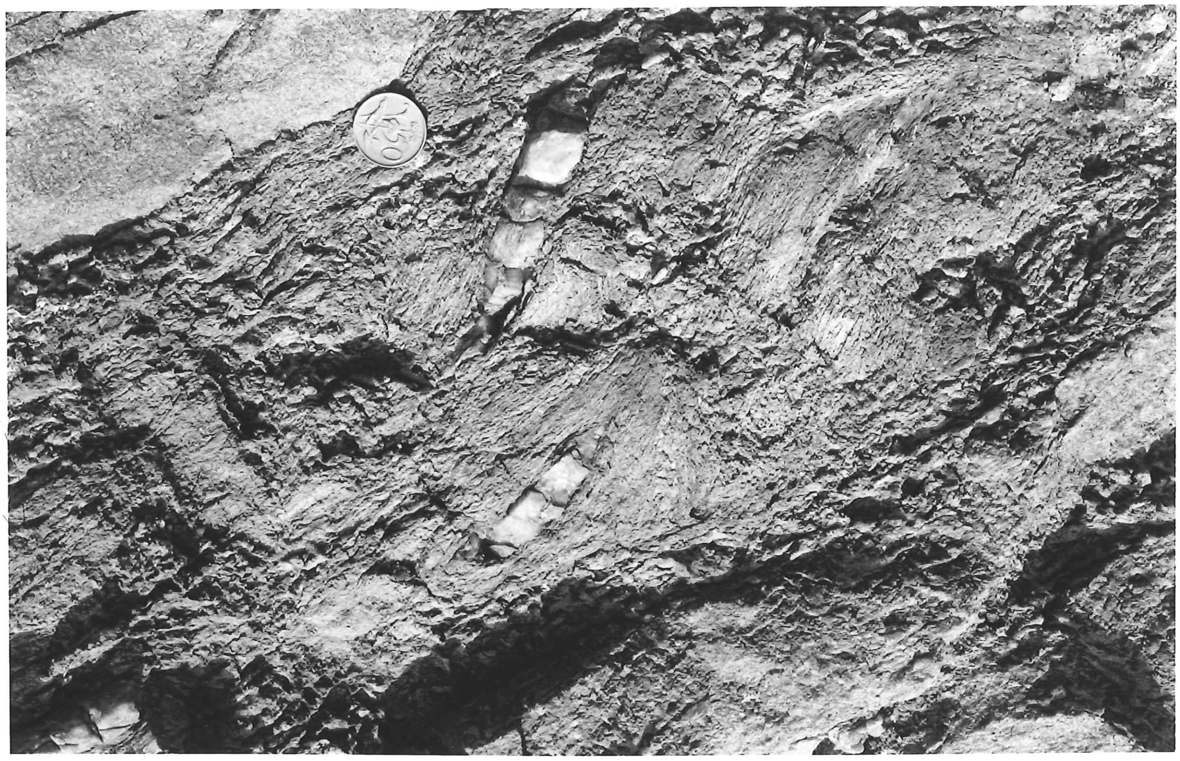


Figure 9 : *Lenses of vein-quartz parallel to the foliation in a ductile shear-zone. The coin is 2,8cm in diameter.*

Fibre-growth within quartz has been observed in some of the smaller lenses and is parallel to the foliation and also to the postulated transport-direction, which is the stretching direction (Fig. 10). In larger lenses, the fibre-growth is confined to the outer portion (Fig. 11) or, sometimes, the outer skin only. This mode of quartz-fibre orientation contrasts sharply with that of steeply-oriented lenses. The latter lenses are developed in certain non-foliated quartzitic layers, and the fibre-growth orientation is at right-angles to the long axes of the lenses, which, themselves, make a relatively-steep angle with the bedding-plane (Fig. 12). Although the fibre-growth orientation in shear zones is parallel to the long axes of the lenses, both situations indicate extension in essentially the same direction, i.e. at a relatively-small angle to, or parallel, to the bedding-planes. This latter group of quartz-lenses clearly represent tensile fractures which developed in the more-brittle, non-foliated quartzites. Slickensides, which are caused by quartz-growth on movement-surfaces, develop a strong lineation which also has the same orientation as the quartz-fibres associated with the vein-quartz lenses.

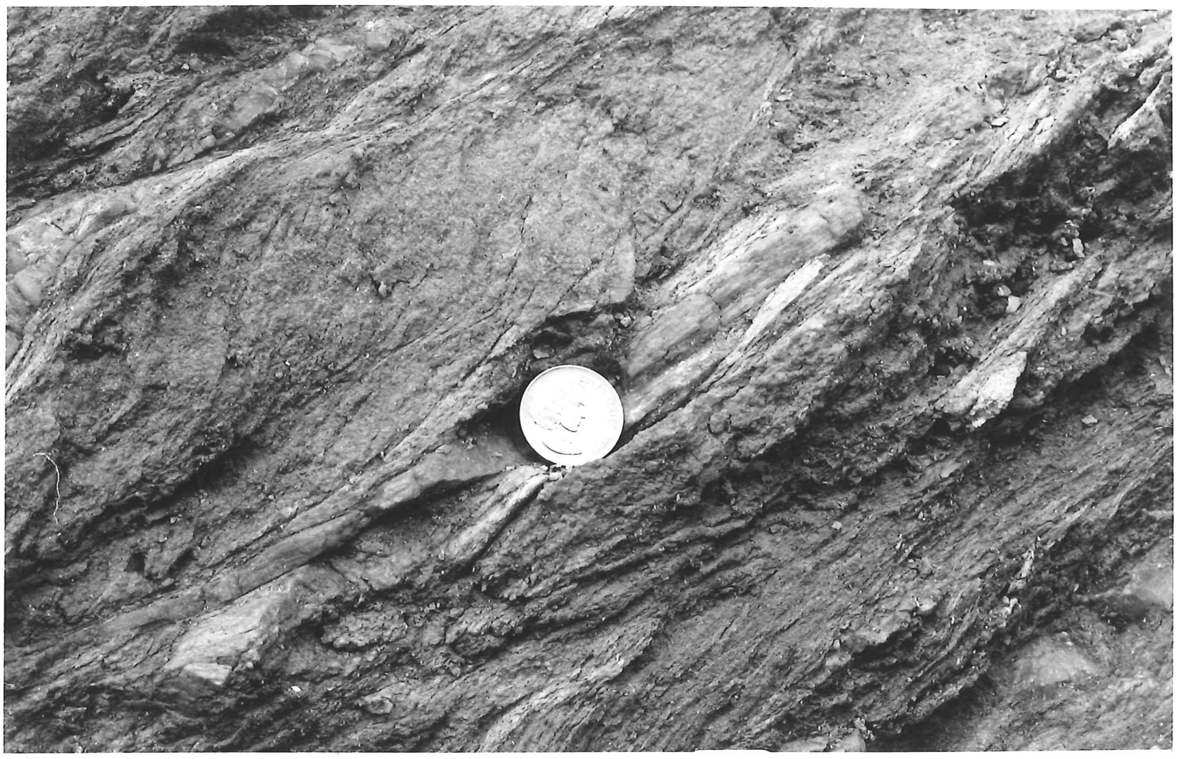


Figure 10 : Vein-quartz lying next to a coin. Quartz-fibres of the vein-quartz are parallel to the largest axis of the quartz-lenses and are parallel to the plane of shearing. The coin is 2,4cm in diameter.

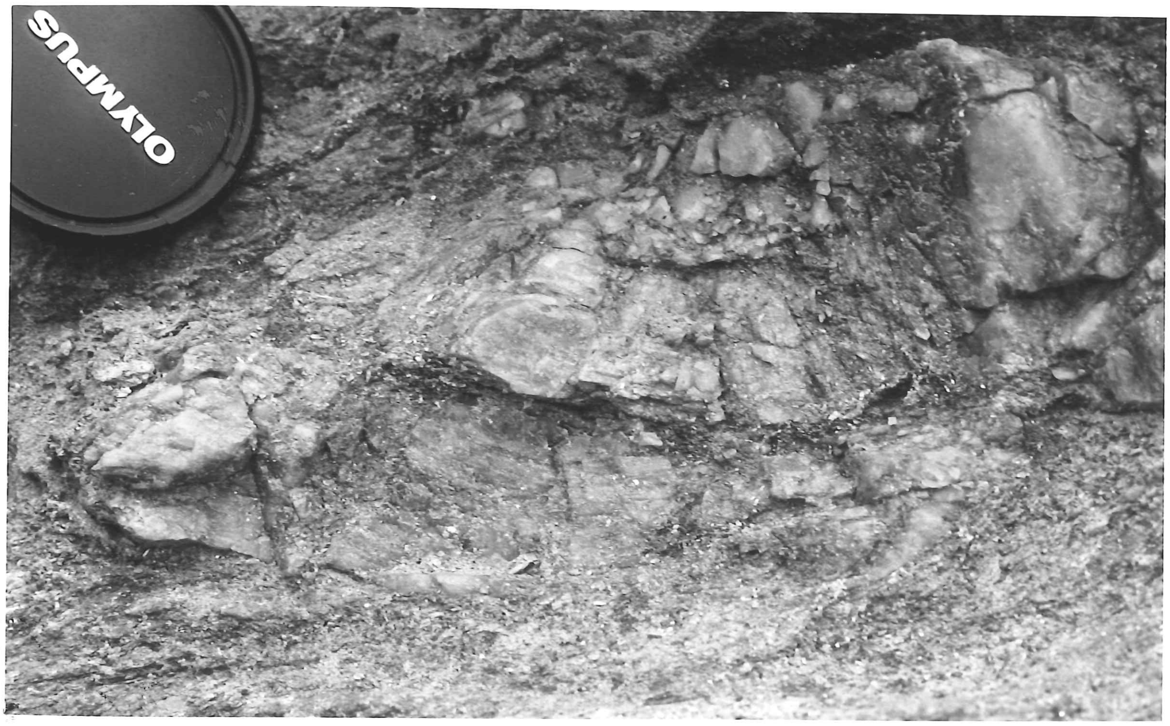


Figure 11 : Fibre-growth confined to the lower part of a quartz-vein. The fibre-growth is curved and follows the form of the quartz-boudins. The lens-cap is 5cm in diameter.

Figure 12 : *Quartz-vein belonging to a set of ladder-veins. Here, the fibre-direction is at right-angles to the long axis of the lenses. The lens cap is 5cm in diameter.*

STRAIN-QUANTIFICATION

Measurements of the following parameters could be made directly on the outcrop: (a) thicknesses of foliated and non-foliated strata; these thicknesses correspond with primary variations within the sedimentary pile; the schistose layers are ductile-shear-zones which are ideally parallel to the primary bedding, but which can change this orientation near ramp-structures; (b) orientation of the cleavage and its angular relation (θ) to the bedding-planes, in order to quantify the component of shear-strain (γ); terminology and symbols are those used by Ramsay (1980); (c) lineations; and (d) quantification of local shear-strain, employing the geometrical characteristics of duplex-structures, according to the method of Boyer and Elliot (1982).

In order to obtain the total integrated estimate of strain, based on the entire exposure, the road-cut was photographed, and a mosaic was constructed, from which the stratigraphic thickness could be calculated. The mosaic also provided a base-map for geological and structural mapping (Fig. 3). However, quantitative data used in this publication were obtained by making actual 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 cleavage-plane was generally measured, with a clino-rule, in the plane of the outcrop. Where possible, the actual orientation of the bedding-planes and cleavage-planes was measured and plotted stereographically, and the actual angle between bedding and cleavage was read off the stereographic projection. A photographic record was also made of many of the important small-scale structures which have a bearing on the interpretation of the strain-estimates.

STRAIN-ESTIMATE

The true thickness of sediments represented in the road-cut is 108,40m. Of this thickness, 11,14m reveals a good foliation inclined to the bedding, while 4,84m are made up of thinner shear-zones, generally 0,5cm to 7cm in width, within which the foliation is parallel to the shear-zone or bedding-planes. A frequency-diagram of ductile-shear-zones, with foliation and thinner shear-zones with foliation parallel to the bedding, is shown in Figure 2. Clearly, there is a tendency for the frequency of shear-zones to increase in number, with a corresponding decrease in width. Fifty per cent are from 0 to 5cm in thickness, while seventy-one per cent are less than 10cm in thickness.

The weighted average of the angle θ' between the shear-zone and foliation-plane is 26,24°, when measured with a clino-rule in the plane of the exposed face. The average angle determined from the stereographic projection is 27° (Fig. 13), so that values measured in the plane of the road-cutting can be considered valid. Employing an average of 26° for θ' and applying this to the 11,14m-thickness of foliated quartzites give an estimate of 17,25m of shear-displacement, i.e. $\gamma = 1,55$. Another estimate of strain was made for the same 11,14m, using the individual thicknesses of foliated quartzite and their corresponding values of θ'. as determined for each layer. Ninety-six layers of varying thickness and θ' were employed in this estimate. In this second estimate, a total displacement of 19,26m (i.e. $\gamma = 1,73$) was derived. The difference between the two methods is 10 per cent, and it will be shown that this value is only of academic interest and has hardly any effect on the estimate of total shear-displacement, which also incorporates the smaller zones.

The essence of the problem in the estimate of strain hinges around the 4,84m thickness of rock in which the foliation is parallel to the shear-plane. What value of θ' can be applied to these data? A value of 10° for θ' is unrealistic, because this is undoubtedly large enough to be measured physically in the field. A value of 5° and less is more realistic. If θ' is 5°, γ would be 11,34, which gives a displacement of 54,90m for a vertical thickness of 4,84m. The total minimum strain for the package is thus 54,90m + 19,26m = 74,16m. If γ is calculated for the total pile of 108,40m of sediments investigated, a value of 0,68 is obtained.

The angle, however, could well be smaller than 5°, and some justification has to be sought for using yet smaller values of θ' for the

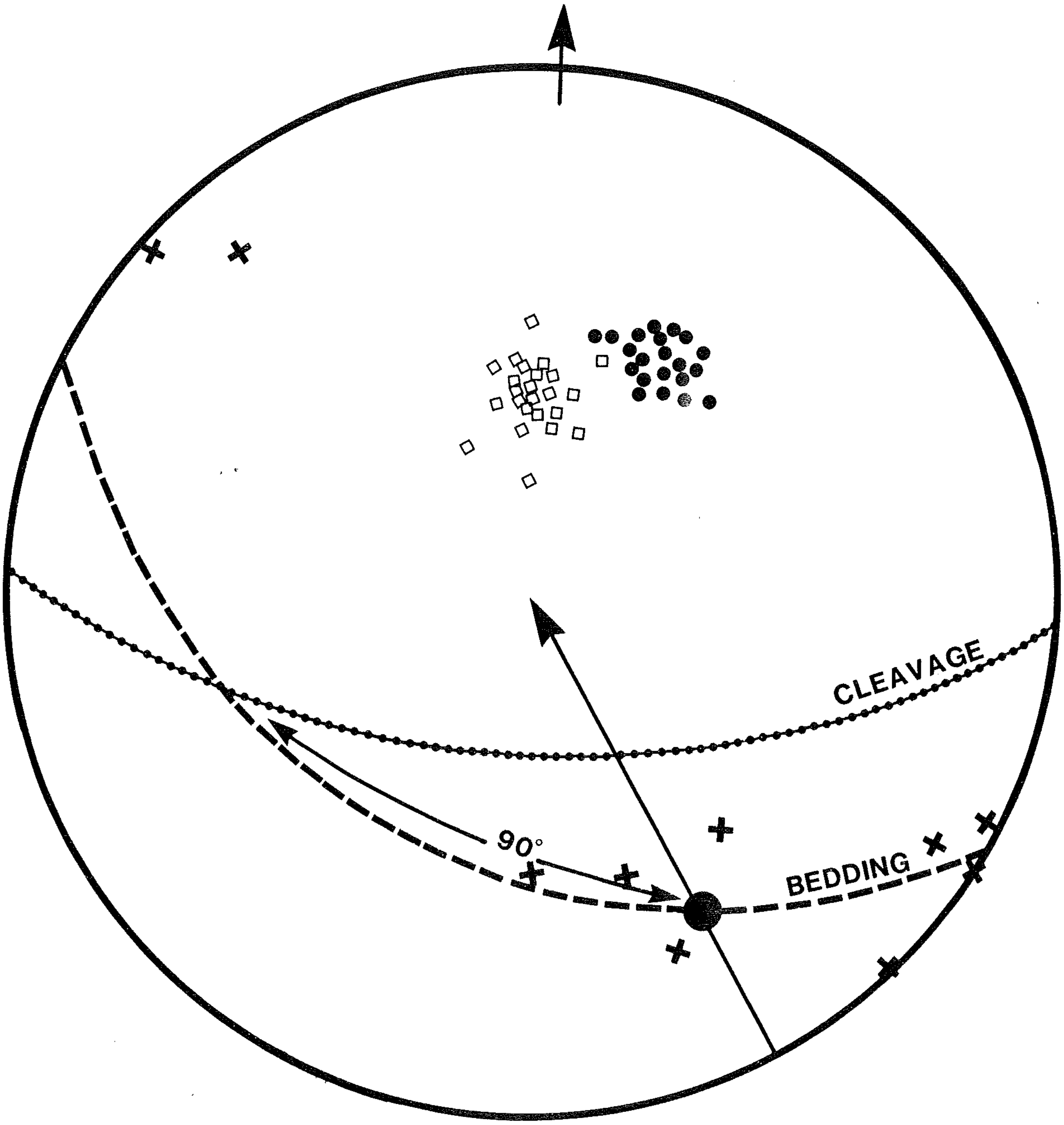


Figure 13 : *Stereographic projection of structural data from the road-cut. Circles are poles to bedding and squares are poles to cleavage. Since the bedding-planes are the fault-planes, the directed vector of movement is the arrow, i.e. upper layers move towards the northwest. The crosses represent lineations which define movement. They are developed on bedding- and foliation-planes, are slickensides, and are often formed by thin films of fibrous quartz in fault-planes.*

4,84m of thinner shear zones. One approach is to study the displacements on duplexes and apply this to the associated shear-zones. Figures 3 and 7 portray a series of duplexes which can be employed to establish the amount of shortening in the sequence of imbricated slices. Using the method proposed by Boyer and Elliot (1982), the amount of shortening experienced by the imbricated zone is at least 5,13m. This implies that the layer above the ramped duplexes has also moved an equal distance. The movement, however, is all taken up on a narrow shear-zone which is only 5cm in width. The average width of this zone is 5cm, and, therefore, γ has the value of approximately 100. This is about an order of magnitude greater than the 11,34-value obtained for $\theta' = 5°$, used in the previous estimate. If $\gamma = 100$ for the narrow shear-zones, the total displacement for the 108,40m pile of sediments would change dramatically, i.e. 19,26m + 484m = 503,26m. This would give an equivalent γ_τ of 4,64 for the pile.

Presumably the value of γ_τ is somewhere between the values that have been proposed. A more realistic value of γ_τ , therefore, would lie between 0,68 and 4,64. In support of this view is the observation that certain narrow shear-zones associated with duplexes have γ-values in the region of 20, which implies that the displacement for all these narrow shear-zones in the whole sequence would be 116,06m. This is equivalent to a γ-value of approximately 1 for the whole pile. Since it is impossible to rigorously constrain the finite displacement, it is proposed that the value of $\gamma = 1$ be accepted for the whole road-cut and be regarded as a minimum.

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, i.e. they are bedding-plane faults. The average orientation of the bedding-planes and the foliation-planes has been plotted on the stereographic projection (Fig. 13). The transport-vector, which occurs at 90° to the line of intersection of these two planes within the bedding- (or fault-) plane, is oriented towards the northwest. Rotation of the bedding to the horizontal hardly affects the northwest-movement trend. Taking these facts into consideration, it is obvious that the upper layers have been thrust over the underlying layers in a northwesterly direction.

Lineations have also been measured at certain localities and have been plotted on Figure 13. The variation in direction of the plunge of the lineations is from the south to southeast and northwest and corresponds to the direction determined above. These lineations are all of the quartz-fibre-type and represent two groups: (i) those developed in thin quartz-films (slickensides) on bedding-plane surfaces and (ii) those referred to in the discussion on vein-quartz and foliation, where the fibres represent a stretching-lineation of the larger vein-quartz lenses.

The duplex structures of Figure 7 are irrefutable examples of the fact that the overlying strata moved up-dip, which clearly substantiates the fact that the strata have been thrust up towards the north and northwest.

DISCUSSION AND CONCLUSIONS

It was mentioned that the estimates of strain are conservative. The greatest restriction in the estimate of strain hinges around the narrow shear-zones in which the foliation is parallel to the movement-plane. Although representing only 5 percent of the total thickness of the sediments investigated, seventy-one percent of all shear-zones are less than 10cm in width. This means that the overwhelming majority of shear-planes are narrow. The component of shear-strain for these narrow zones cannot be rigorously established. Variations of γ from 11,3 to 100 are realistic values that can be applied to certain examples. Because of the inherent difficulty in estimating γ and the fact that the deformation in the narrow shear-zones completely swamps the final estimates of strain, only minimal estimates can be given. Using a value of 20 for γ in the narrow shear-zones, the component of shear-strain for the entire section was found to have a value of 1.

Since the frequency of smaller fractures increases on a log-normal basis (Fig. 2), the question may also be raised as to the validity of the final estimate. Microscopically-sized 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 will increase exponentially and will have a considerable influence on the shear-strain estimates. Because of these reasons, 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 7,4km. Of the succession which consists essentially of shales, quartzites, and conglomerates (Truswell, 1977; S.A. Com. for Strat., 1980), the shale horizons are approximately 2km thick.

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 argillaceous units. This work indicates that a conservate estimate of the shear-strain is in the order of $\gamma = 1$. Considering the entire 7,4km-thickness of sediments as a whole and subjecting this whole pile to an equivalent deformation would result in the uppermost members having been transported for distances involving at least several kilometres. This would reinforce estimates made in similar rocks some 30km to the northwest of the road-cut (Roering, 1984). Furthermore, the type and geometry of deformation clearly indicates thrusting out of the Witwatersrand Basin, onto the granite basement.

The association of tectonic veins and shear-zones is well documented in the literature (e.g. Beach, 1974 and 1980; Kerrich, 1978; Ramsay, 1967; Ramsay and Graham, 1970; Roering, 1968). The general argument is that there is a direct mass transfer from areas of material-loss to openings where a material-gain takes place. The losses are also commonly attributed to a process of pressure-solution and to the fluids moving down a stress-gradient to sites of low pressure (Beach, 1974; Kerrich, 1978). Similarly, the process of seismic pumping (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 the shear-zone.

These examples clearly relate to openings in rock-systems. Classically, such openings will be caused by tensile fractures which have stringent limits to their orientation with respect to a stress-field, i.e. they tend to orientate themselves into the $\delta_1 - \delta_2$-plane and are at right-angles to the minimum-stress-component-direction. This well-known orientation of veins cannot be applied to the road-cut investigated in this paper. Firstly, the veins are essentially parallel to the schistosity-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 veins having initially being tensile veinlets which subsequently were rotated into the plane of flattening. Lastly, the quartz-fibre-growth-orientation is also parallel to the schistosity and is 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 in age. Migration of the vein-quartz material, therefore, has not simply been to sites of lower pressure but to bands or zones parallel to the foliation. This material could not have migrated to sites of lower stress. It would appear that a filter-press-type of action was more applicable to the quartz-bearing fluid-phase and was responsible for the concentrating mechanism. The fluid-phase was also able to maintain the lithostatic load at the time of deformation, because it was not squeezed out of the shear-zones.

The ductility of the shear-zones would possibly have increased, due to an increased presence of a fluid-phase. The increased ductility would then have enhanced higher deformation-rates. Furthermore, the fluid-phase would have tended to reduce the effect of the overburden (Hubbert and Rubey, 1959). The quartz-vein material in these shear-zones was thus the 'lubricant' for 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 represent bedding-plane faults.

The quartz-bearing fluids could also have played a dominant role in controlling the amount of shear-strain.

ACKNOWLEDGEMENTS

Professor D.A. Pretorius is thanked for initiating these structural studies of the Witwatersrand rocks. The authors would also like to thank Gold Fields of South Africa for financial support. Professor M. Coward made very useful comments when he visited this outcrop with the authors in 1984.

REFERENCES

Beach, A. (1974). A Geological Investigation of Pressure Solution and the Formation of Veins in a Deformed Greywacke. Contr. Mineral. and Petrol., 46, 61-68.

Beach, A. (1980). Retrogressive Metamorphism Processes in Shear Zones with Special Reference to the Lewisian Complex. J. Struct. Geol., 2, 257-263.

Borchers, R. (1961). Exploration of the Witwatersrand System and Its Extensions. Proc. Geol. Soc. S. Afr., 64, 67-98.

Boyer, S.E., and Elliot, D. (1982). Thrust Systems. Bull. Amer. Ass. of Petroleum Geologists, 66, 1196-1230.

Fripp, R.E.P., and Gay, N.C. (1972). Some Structural Aspects of the Hospital Hill Series on the North-Central Margin of the Witwatersrand Basin. Trans. Geol. Soc. S. Afr., 75, 187-196.

Hendriks, L.P. (1961). Die Voor-Transvaalse Gesteentes op Swartkop 82 en Omstreke, Noord van Krugersdorp, Transvaal. Unpubl. M.Sc. Thesis, Univ. of Pretoria, Pretoria, 76pp.

Hubbert, M.K., and Rubey, W.W. (1959). Role of Fluid Pressure in Mechanics of Overthrust Faulting. Geol. Soc. Amer. Bull., 70. 115-166.

Kerrich, R. (1978). An Historical Review and Synthesis of Research on Pressure Solution. Zbl. Geol. Palaeont., Teil I,H 5/6, 512-550.

McCarthy, T.S., Cadle, A.B., and Horrocks, P. (1982). Thrust Faulting in Witwatersrand Rocks at Langerman's Kop, Johannesburg. Trans. Geol. Soc. S. Afr., 85, 189-201.

Mellor, E.T. (1911). The Normal Section of the Lower Witwatersrand System on the Central Rand, and Its Connection with the West Rand Sections. Trans. Geol. Soc. S. Afr., 14, 99-113.

Olivier, H.J. (1965). The Tectonics of the Upper Division of the Witwatersrand System in the Loraine Area of the Orange Free State Gold Field. Trans. Geol. Soc. S. Afr., 68, 143-175.

Ramsay, J.G. (1967). Folding and Fracturing of Rocks. McGraw-Hill, New York.

Ramsay, J.G. (1980). Shear Zone Geometry: a Review. J. Struct. Geol., 2, 83-99.

Ramsay, J.G., and Graham, R.H. (1970). Strain Variation in Shear Belts. Can. J. Earth Sci., 7, 786-813.

Roering, C. (1968). The Tectonics of the West Rand Syncline: a Field Study of Brittle Failure in the Witwatersrand Basin. Inform. Circ., 48, Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg, 48pp.

Roering, C. (1983). The Witwatersrand Supergroup at Swartkops: a Re-examination of the Structural geology. Inform. Circ. 163, Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg, 36pp.

Roering, C. (1984). The Witwatersrand Supergroup at Swartkops: a re-examination of the Structural Geology. Trans. Geol. Soc. S. Afr., 87, 87-99.

Sibson, R.H., Moore, J. McM., and Rankin, A.H. (1975). Seismic Pumping: a Hydrothermal Fluid Transport Mechanism. J. Geol. Soc. Lond., 131, 653-659.

South African Committee for Stratigraphy (Sacs) (1980). Stratigraphy of South Africa - Part 1 (Comp. L.E. Kent): Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and The Republics of Bophuthatswana, Transkei and Venda. Handb. 8, Geol. Surv. S. Afr.

Truswell, J.F. (1977). The Geological Evolution of South Africa. Purnell, London, 218pp.

Winter, H.D. (1964). The Geology of the Virginia Section of the Orange Free State Gold Fields. in S.A. Haughton (ed.), The Geology of Some Ore deposits in Southern Africa, Volume I. Geol. Soc. S. Afr., Johannesburg, 507-548.

——— oOo ———