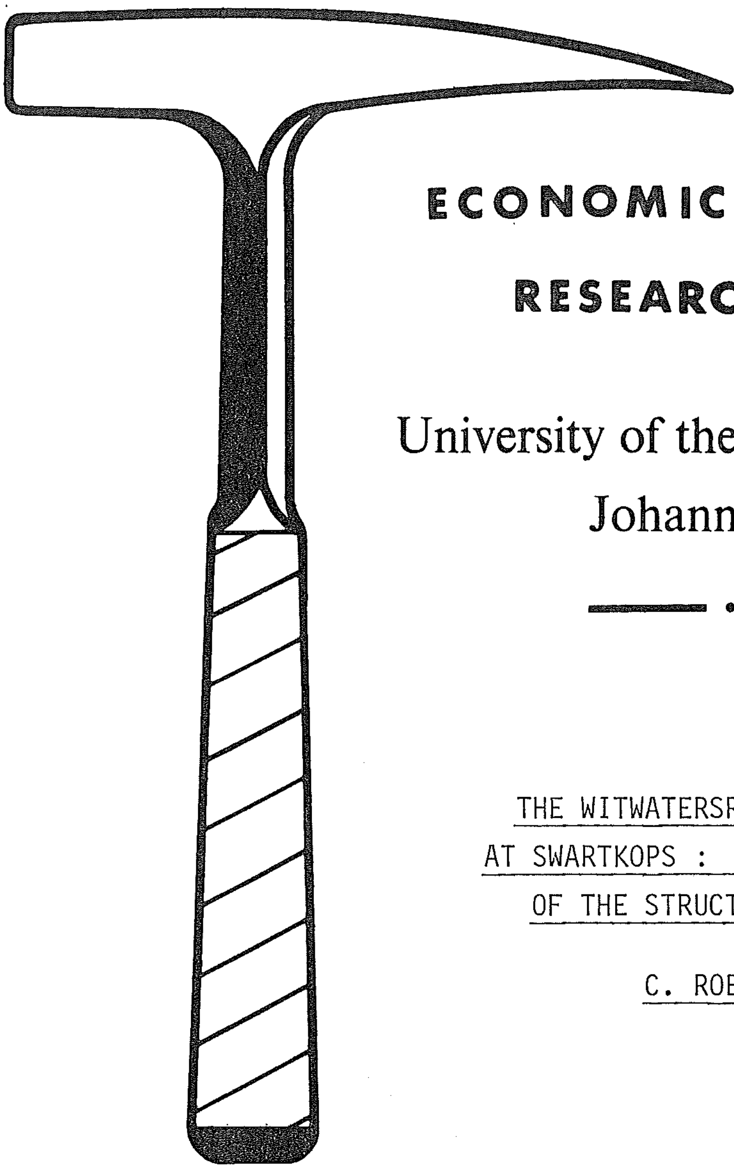


ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

THE WITWATERSRAND SUPERGROUP AT SWARTKOPS : A RE-EXAMINATION OF THE STRUCTURAL GEOLOGY

C. ROERING

INFORMATION CIRCULAR No. 163

UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG

THE WITWATERSRAND SUPERGROUP AT SWARTKOPS : A RE-EXAMINATION OF THE STRUCTURAL GEOLOGY

by

C. ROERING

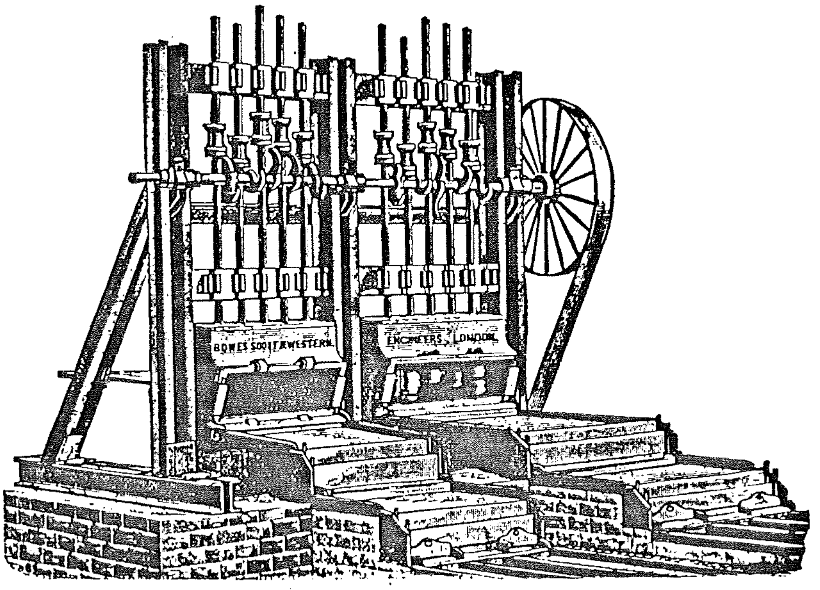
(Professor of Geology, Rand Afrikaans University, Johannesburg, and Visiting Research Professor, Economic Geology Research Unit)

ECONOMIC GEOLOGY RESEARCH UNIT

INFORMATION CIRCULAR No. 163

September, 1983

1886–1986



A CONTRIBUTION TO THE CELEBRATION OF THE CENTENARY OF THE DISCOVERY OF THE WITWATERSRAND GOLDFIELDS

THE WITWATERSRAND SUPERGROUP AT SWARTKOPS : A RE-EXAMINATION OF THE STRUCTURAL GEOLOGY

ABSTRACT

The structural geology of the West Rand Group at Swartkops, situated 10 km to the north of Krugersdorp, has been re-investigated. Palinspastic reconstructions of the geology reveal that stratigraphic thicknesses of various formations and members are less than the values obtained from the Central and West Rand. These differences can be accounted for, in part, by tectonic thinning associated with nappe- and thrust-formation. The structure of the area can best be accounted for by means of a system of thrust faults, as was suggested by Hendriks (1961). The general vergence of the system is towards the north. A uniformly-oriented fabric is associated with this deformation and is a result of a simple shear strain. The fabric has an east-west orientation and dips towards the south at 30°, indicating that the overlying layers, or thrust slices, have moved in a northerly direction. A large fold-axis and other lineations are orientated in a north-south direction and lie in the fabric plane, indicating that both pre- and syn-deformational linear structures tend to orient themselves in the direction of the tectonic transport. Tensile phenomena, revealed by boudins, foliation boudins, and quartz veins, are orientated in a dominantly east-west direction. The combined data are suggestive of a tectonic movement which was directed from the south towards the north. Observations in the rocks surrounding Swartkops indicate that this deformational period also involved successions which are currently correlated with the Ventersdorp Supergroup,but did not affect the Transvaal Supergroup. Estimates of strain suggest shortening of, at least, 6-7 km. If the same degree of shortening were applied to the entire area from Swartkops, through the Witwatersrand outcrops at Honingklip, to the West Rand Syncline, a contraction of 40 km would be involved. These estimates of strain are much greater than have been considered previously as applicable to Witwatersrand rocks.

———— oOo ————

THE WITWATERSRAND SUPERGROUP AT SWARTKOPS : A RE-EXAMINATION OF THE STRUCTURAL GEOLOGY

CONTENTS

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

ISBN 0 85494 794 9

THE WITWATERSRAND SUPERGROUP AT SWARTKOPS : A RE-EXAMINATION OF THE STRUCTURAL GEOLOGY

GENERAL

Sediments belonging to the Hospital Hill Subgroup of the Witwatersrand Supergroup occur on granitic and related greenstone rocks of the Johannesburg granite dome at Swartkops which is situated 10 km to the north of Krugersdorp. The origin and disposition of these rocks have been a point of contention among geologists for many decades. Although Swartkops probably represents one of the most intensively mapped areas in Southern Africa, as a result of its convenient situation with respect to students at three universities, no completely satisfactory explanation has so far appeared to account for the location and structure of these rocks.

Renewed interest by the gold-mining industry in all aspects of Witwatersrand geology dictated that another attempt to clarify the problems associated with this area was justified. Clearly, the detailed geology of such a small area can contribute to a few limited aspects only of the geology of the Witwatersrand Supergroup. Therefore, the entire Witwatersrand outcrop area, from Klerksdorp to Heidelberg, is being systematically remapped, as part of a larger study of the structure of the Witwatersrand Basin, which is being undertaken by the Economic Geology Research Unit.

PREVIOUS WORK

According to Hall and Humphrey (1906), the earliest published reference to the geology of Swartkops was by Draper, in 1899, who described the rocks as a 'hill of Witwatersrand Beds'. Hall and Humphrey (1906) started a controversy, during the pioneering days of Witwatersrand geology, by correlating the sedimentary rocks, and particularly the 'ironstone rock', with 'calico' and 'Swaziland rocks' found at 'other districts in the Transvaal'. They also stated that the strike of the 'hilly ground is nearly true north and south' and that there was no structural relationship between the 'base of the Witwatersrand Series and the Swartkops beds'. The difference in strike between these two 'formations' was suggested to be 80°. Banding was observed in an amphibolite schist and a dioritic rock in the granites, close to the base of the sediments, and was found to be parallel to that of the overlying rocks. These observations led them to believe that the granites were intrusive into the sediments and had themselves become 'modified' close to the contact. The same two authors made reference to Hatch's (1905) second edition of the geological map of the Transvaal, in which the 'Swartkops sediments' were included as a 'northerly extension of the Lower Witwatersrand Beds' and conceded that the lithology 'bears some resemblance to the quartzites and shales of the Hospital Hill Series'. In drawing their final conclusion about the correct correlation of the 'Swartkops sediments', they did not concur with the interpretation that Molengraaff (1902) (see also Hall and Humphrey, 1906) had made in correlating the 'Barberton Series' with the 'Witwatersrand Beds'. At that stage in the development of South African stratigraphy, it had been established that the 'Barberton Beds' were more 'ancient than the Old Granite', and, therefore, had been reclassified as belonging to the 'Swaziland Series'. This led Hall and Humphrey (1906) to the ultimate conclusion that the sediments at Swartkops also belonged to the 'Swaziland Series'.

Later, in 1908, Corstorphine and Jorissen stated that the stratigraphy of Swartkops had already been dealt with by Hall in his annual report to the Geological Survey in 1905, as well as in the paper referred to above. These two authors also reported that the Director of the Transvaal Geological Survey, Mr. Kynaston, 'confirmed' the results of Hall and Humphrey in his report of 1906 and 'presented to the world in Sheet 1 of the official map of the country' supporting evidence of the pre-granite age of these rocks. In this regard, it is important to record that Kynaston (1906) mentioned that two smaller patches of similar rock-types occurred on the nearby farm of Honingklip 178 IQ.

Corstorphine and Jorissen (1908) provided a systematic description of the rocks at Swartkops and recognized all the marker-horizons of the 'Lower Witwatersrand Beds'. They emphasized that these rocks could be correlated in detail with those found in the Witwatersrand to the south. Swaziland rocks were identified in the surrounding granites, including the amphibolitic schists previously referred to by Hall and Humphrey (1906). The banding in these rocks, parallel to the bedding of the 'Witwatersrand Beds', by no means signified conformity between the two formations, but that both had been affected by the same series of earth movements. They were also the first to recognize evidence of thrusting and reported the presence of 'crush-breccias'. The intensity of thrusting was suggested to increase towards the south, and the movement was implied to be from the west towards the east. Finally, they argued that the rocks at Swartkops were not 'torn off' from the Witwatersrand successions towards the south, but that they had been continuous initially and that subsequently they had been affected by the folding and erosion which stripped off the intervening Witwatersrand cover.

The most significant contribution to the understanding of the structural geology at Swartkops appeared very much later, when Hendriks (1961) recognized the folded nature of the rocks belonging to the Witwatersrand Supergroup. In profiles and diagrams of the structure, he depicted a relatively open fold which plunges towards the south. The southern portion of the fold, in which numerous thrust faults are found, was indicated to be the more complex area. His detailed map showed the presence of numerous thrust faults which appear to be oriented fairly close to the bedding-planes. In his diagram of the overall structure, however, a major thrust fault intersects the bedding almost orthogonally. A very significant observation made by Hendriks (1961) was his portrayal of a thrust fault at the basal contact of the Ventersdorp Supergroup with the other rock-types in the area. At the base, he discovered a white-to-greenish, deformed rock which was interpreted as being a sheared felsitic lava. The Ventersdorp rocks, therefore, were considered to be in the form of a thrust sheet which had been transported essentially from the west to the east. Hendriks (1961) also attributed the deformation of the underlying West Rand Group to the movement of the thrust sheet. These early references to alpine-like deformation close to Johannesburg subsequently were ignored for more than two decades.

In an unpublished map of the Swartkop-Crocodile River area, by E.J. Poole, J.R. McIver, and D.J. French (1968), virtually all the rocks belonging to the Witwatersrand Supergroup, which occur on the high hill to the south of Blaubankspruit, are shown as being overturned. Mapping north of this spruit showed that one of the Hospital Hill quartzites is overturned. In the southern area, overturning was postulated from bedding-plane-cleavage relationships in the shales. Such an interpretation is not necessarily valid where superimposed folds or fabrics are developed from fault movements.

STRATIGRAPHY

(a) General

The most important mechanisms of deformation within the Swartkops area are thrust faulting and nappe formation. Each nappe contains certain lithologic units, the actual relationship with members of an adjacent nappe of which is fault-controlled. One of the major contributing factors to the solution of the structural geology lies in the fact that the Hospital Hill Subgroup is well endowed with distinctive marker horizons. The preservation of sedimentary structures within the quartzites has been an equally valuable contribution to the investigation of a highly-deformed area. Little attention was paid to the rocks belonging to the Johannesburg granite dome, the Muldersdrif and Roodekrans complexes, and the Ventersdorp Supergroup. The stratigraphy that is discussed is concerned with those formations which belong to the Hospital Hill Subgroup of the West Rand Group.

(b) Orange Grove Quartzite Formation

No outcrop has yet been found that provides a clear exposure of the original sedimentary contact between the rocks belonging to the Witwatersrand Supergroup and the underlying Archean granites and associated greenstones. The nature of this contact has therefore been deciphered from scattered, discontinuous outcrops.

The lowermost rocks, which lie beneath the typical Orange Grove Quartzites, are all characterized by a deep brownish-red colour which is attributed to the abundance of iron oxides. These basal rocks are relatively coarse-grained grits which, themselves, often form the groundmass to matrix-supported conglomerates. In such conglomerates, the pebbles consist almost entirely of white vein-quartz and are 1-6 cm in diameter (Figure 1). The pebble-size increases towards the base, and diameters up to 8 cm have been recorded. Below this coarser conglomerate, the rock becomes strongly deformed, and the pebbles are flattened. A schistose rock is then developed which contains elongated fragments of both quartz and granitic material. It is uncertain whether the granite inclusions indicate the schist to be a tectonic breccia, developed on a fault-plane, or whether the rocks were originally conglomerates with granitic pebbles, deformed near a fault-plane. The thickness of the whole group of iron-rich basal sediments is estimated at 4-5 m.

Figure 1 : *Basal vein-quartz conglomerate underlying the typical quartzites and conglomerates of the Orange Grove Quartzite Formation.*

Figure 5 : *Quartz schist, within which quartz grains of metamorphic origin (A) have formed. (A five-cent coin is situated in the upper, right-hand corner).*

Figure 6 : *A southward view of the Parktown Shale Formation (grass-covered foreground) which dips gently towards the right and which is overlain by the lowermost quartzitic-and-conglomeratic member of the Orange Grove Quartzite Formation (bush-covered koppie). The whitish-coloured layer in the foreground is the Ripple-marked Quartzite. The Contorted Bed occurs just below the Orange Grove Quartzite hill.*

FIGURE 1

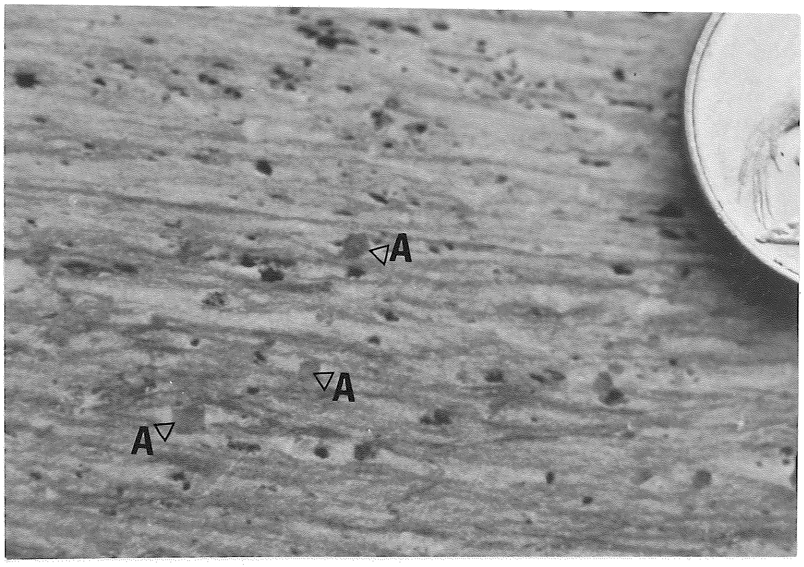


FIGURE 5

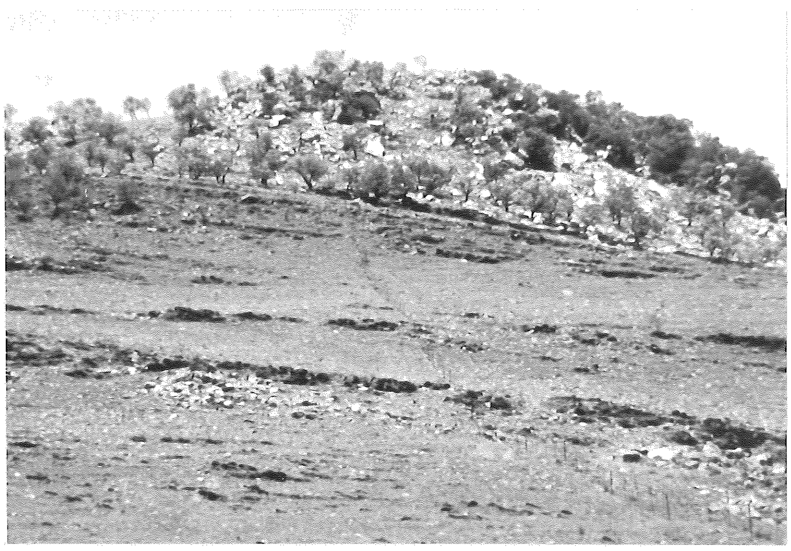


FIGURE 6

Overlying these rocks is a 10-m-thick quartzite zone, above which the conglomerate horizons are developed. There are three or four conglomerate-rich zones which may interlink with each other along strike. Individual zones are up to 4 m in thickness and contain thinner quartzitic lenses which separate discrete conglomerate bands. The conglomerates are extremely well-sorted, with relatively small pebbles, 0,25-1,5 cm in diameter. Planar cross-bedded units, typically 15-30 cm in thickness, occur within the quartzites that are developed between the conglomerate zones.

The other rocks belonging to this formation are typically light orange-brown quartzites in which several argillaceous members occur. In places, the shales are tectonically important because they acted as fault-planes along which considerable movement took place. Under such conditions, the rocks are not true shales but phyllonites, or even schists. One of the most difficult mapping problems encountered in the area was to decide whether a 'shale' horizon represents a plane of significant tectonic movement or not. At least three distinct shale horizons have been identified, but the actual thicknesses are not known, due to the effects of tectonism. They are estimated as being 2-5 m thick. The uppermost quartzites, which are considered to underlie the Parktown Shales, are characteristically pure, massive, and glassy, only rarely displaying sedimentary structures.

A total thickness of 110 m for the Orange Grove Quartzite Formation has been derived from palinspastic reconstructions of the structure. This value compares favourably with the estimate of 91 m obtained previously by Hendriks (1961), but differs markedly from the 220 m measured by Watchorn (1981) at Witpoortjie.

(c) Parktown Shale Formation

The dominantly shaly rocks of this formation show many signs of intensive deformation :

- (i) penetrative cleavage;
- (ii) local folding;
- (iii) sliding movement along fabric planes; and
- (iv) mobilization into pseudo-tachylite.

Rocks which contain all these signs of strain are not typical shales, but phyllonites which locally grade into schists, mylonites, and pseudo-tachylites. Despite these structural disturbances, a stratigraphy can still be recognized.

The Water Tower Shale Member is the lowermost marker in the Formation and is essentially a magnetic quartzite which, on weathered surfaces, gives rise to typical snuff-box texture. This unit is 1-3 m thick. Sediments belonging to the Ripple-marked Quartzite define the next prominent marker bed. Deformation of these rocks gives rise to large variations in thickness, but a possibly true value is 2 m. The Speckled Bed is also present, but is not nearly as continuous as the Ripple-marked Quartzite. It generally occurs as isolated lenses, not more than 0,5 m in thickness. Where it is best developed it is 1,0 m wide and has a characteristic speckled appearance, due to its arkosic composition. The Contorted Bed is also an exceptionally useful and relatively persistent marker horizon in this area. Alternating magnetic shale and chert bands, often highly contorted, give this rock its well-known appearance.

If the stratigraphic thickness from the Water Tower Shale Member to the Contorted Bed, as determined from reconstructed sections, is compared with values given by Mellor (1917) for the Central Rand, the agreement is surprisingly good at 280 m. However, the shales occurring stratigraphically below the Water Tower Shale Member and above the Contorted Bed have been estimated at 70 m in each case, and these thicknesses contrast with those of 100 m and 400 m, respectively, as determined by Mellor (1917). These significant differences could have either tectonic or depositional implications. Either the shales have been reduced in thickness by deformation, or variable amounts of sediment were deposited in the two different areas. It may be noteworthy that the reduced stratigraphic thicknesses are, in the main, limited to those areas where the Parktown Shales are in contact with, or relatively close to, competent quartzites belonging to the Orange Grove Quartzite or Brixton formations. When the entire thickness of 420 m of the Parktown Shale Formation at Swartkops is compared with approximately 800 m obtained for the Central Rand (Mellor, 1917), discernible differences exist in those units located at the stratigraphically-lowermost and -uppermost shales lying in contact with massive quartzites. These contact zones are also observable sites of conspicuous bedding-plane movement, which could account for an important amount of stratigraphic thinning.

(d) *Brixton Formation*

The Brixton Formation is largely confined to the central and southern portions of the map-area. Quartzites and shales belonging to this formation have suffered intense deformation due largely to the effect of faulting which produced a micro-breccia.

The lowermost quartzites, which have a faulted contact with the Parktown Shales, are whitish in colour, but frequently have a greenish tinge, due to the presence of fuchsite (Frankel, 1939). Trough cross-laminae are frequently observed in these rocks. A conglomerate band, 30-50 cm in width, occurs towards the base, and its absence often can clearly be accounted for by faulting near to the Parktown Shale contact. The conglomerate, with pebbles generally 1-2 cm in diameter, is matrix-supported and is relatively free of any iron-bearing minerals. Shale horizons also occur in these dominantly-quartzitic members. The shales are characteristically red in colour and differ from the dark grey shales belonging to the Orange Grove Quartzite Formation. The interbedded 'shale' horizons are also planes of movement and, in some instances, completely transgress the larger quartzitic members, splitting them into gigantic tectonic breccias.

Quartzites belonging to this Formation occur as an isoclinal fold. Thickness determinations show the lower fold limb to be 113 m, while the upper overturned fold limb is 170 m. This difference is also due to faulting on planes which are generally parallel to the bedding. Both of these values should be compared with 250 m for the Krugersdorp area (Mellor, 1917). There is, therefore, a suggestion of stratigraphic thinning at Swartkops, and a certain proportion of this could be accounted for by structural deformation.

STRUCTURAL GEOLOGY

(a) Main Structures

1. General

Because of the limitations imposed by the distribution of outcrops and the inherent nature of the structures occurring within the area, the region mapped can be subdivided into three separate domains (see Figure 2). Each domain has its own specific structural geological characteristics.

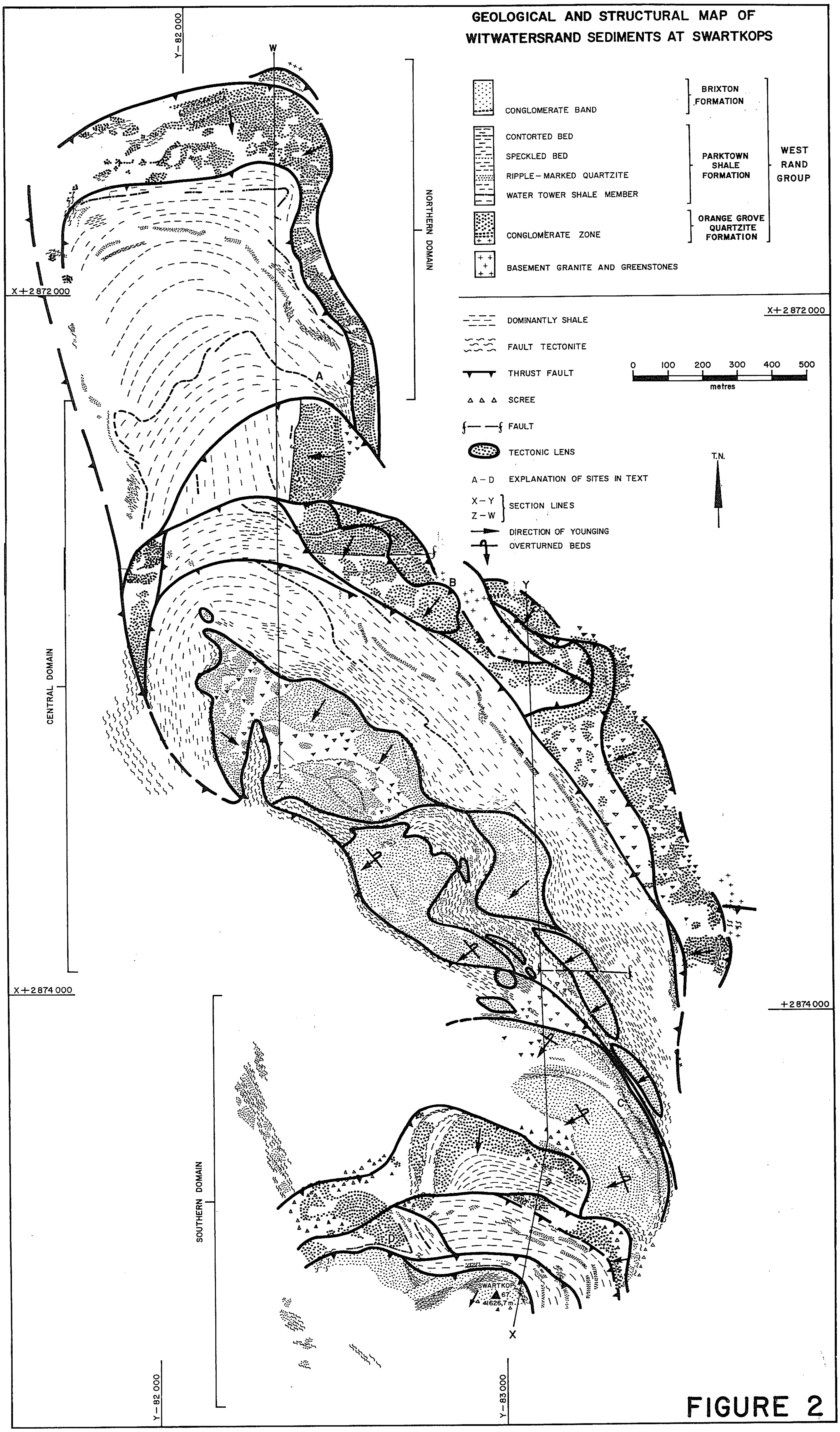
2. Northern Domain

The distribution of Orange Grove Quartzites and a relatively complete Parktown Shale Formation, with its associated marker horizons, demonstrates that this domain is, structurally, the least complex at Swartkops. Several important phenomena are developed, which relate to the overall mechanics of deformation of the region, as a whole.

Possibly, the most obvious structural feature is the folded nature of the sediments belonging to the Orange Grove Quartzite and Parktown Shale formations. The quartzites forming the western limb of the fold are so highly deformed that the original depositional fabrics are eliminated, and the orientation of the strata cannot be determined. However, the attitude of bedding-planes in the remainder of the area indicates that the fold is relatively open, with a saucer-like profile which plunges to the south (see Figure 3). It can also be observed in Figures 2 and 3 that the marker-units of the Parktown Shale Formation maintain the same basic arcuate pattern as the underlying Orange Grove Quartzites. The actual contact between the two basal formations of the West Rand Group is a fault-plane. This can be established by examining the behaviour of the Water Tower Shale Member with respect to the Orange Grove Quartzites. On the eastern fold-limb, the Water Tower Shale Member occurs next to the Orange Grove Quartzites, while in the north it is separated from them by shales. Further supporting evidence of the proposed fault-plane is provided by the fact that all the marker horizons of the Parktown Shale Formation are truncated by the Orange Grove Quartzites in the east.

Another odd feature of this area is the small hill of basal Orange Grove Quartzites which underlie the main fold in the northernmost exposure of Witwatersrand rocks (see Figures 2 and 4). This small ridge has no lateral extension and terminates against the larger structure. The base of the major fold is a fault-plane which has taken advantage of a shale unit occurring immediately above the underlying quartzite remnant.

Although the eastern limb of Orange Grove Quartzite appears to be continuous along its strike, it is transected by numerous cross-cutting mylonite zones. The zones have an east-west strike and dip southwards at



GEOLOGICAL AND STRUCTURAL MAP OF WITWATERSRAND SEDIMENTS AT SWARTKOPS

FIGURE 2

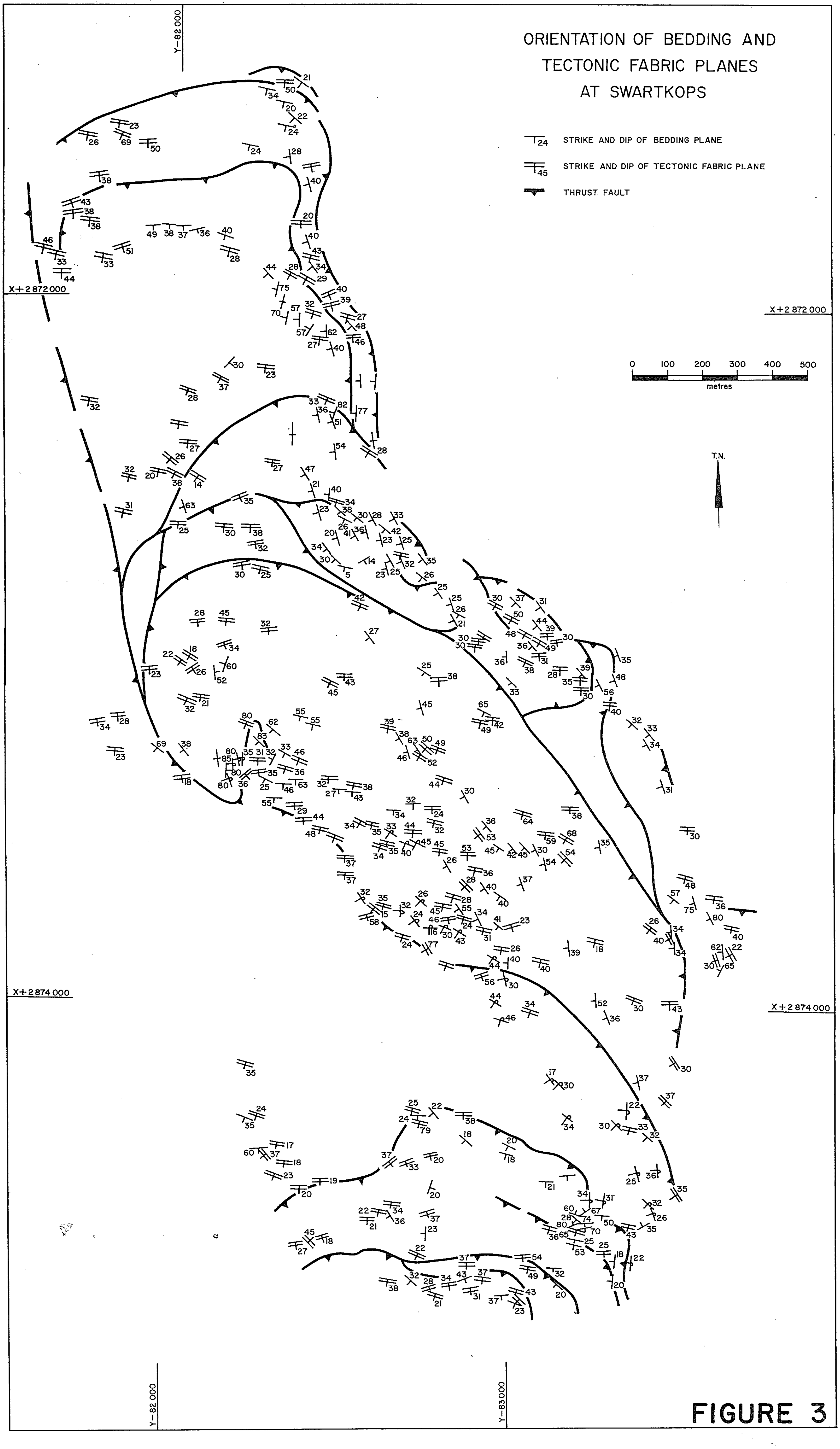

ORIENTATION OF BEDDING AND
TECTONIC FABRIC PLANES
AT SWARTKOPS
STRIKE AND DIP OF BEDDING PLANE
STRIKE AND DIP OF TECTONIC FABRIC PLANE
THRUST FAULT
0 100 200 300 400 500
metres
T.N.
Y-82 000
Y-83 000
X+2 872 000
X+2 874 000

FIGURE 3

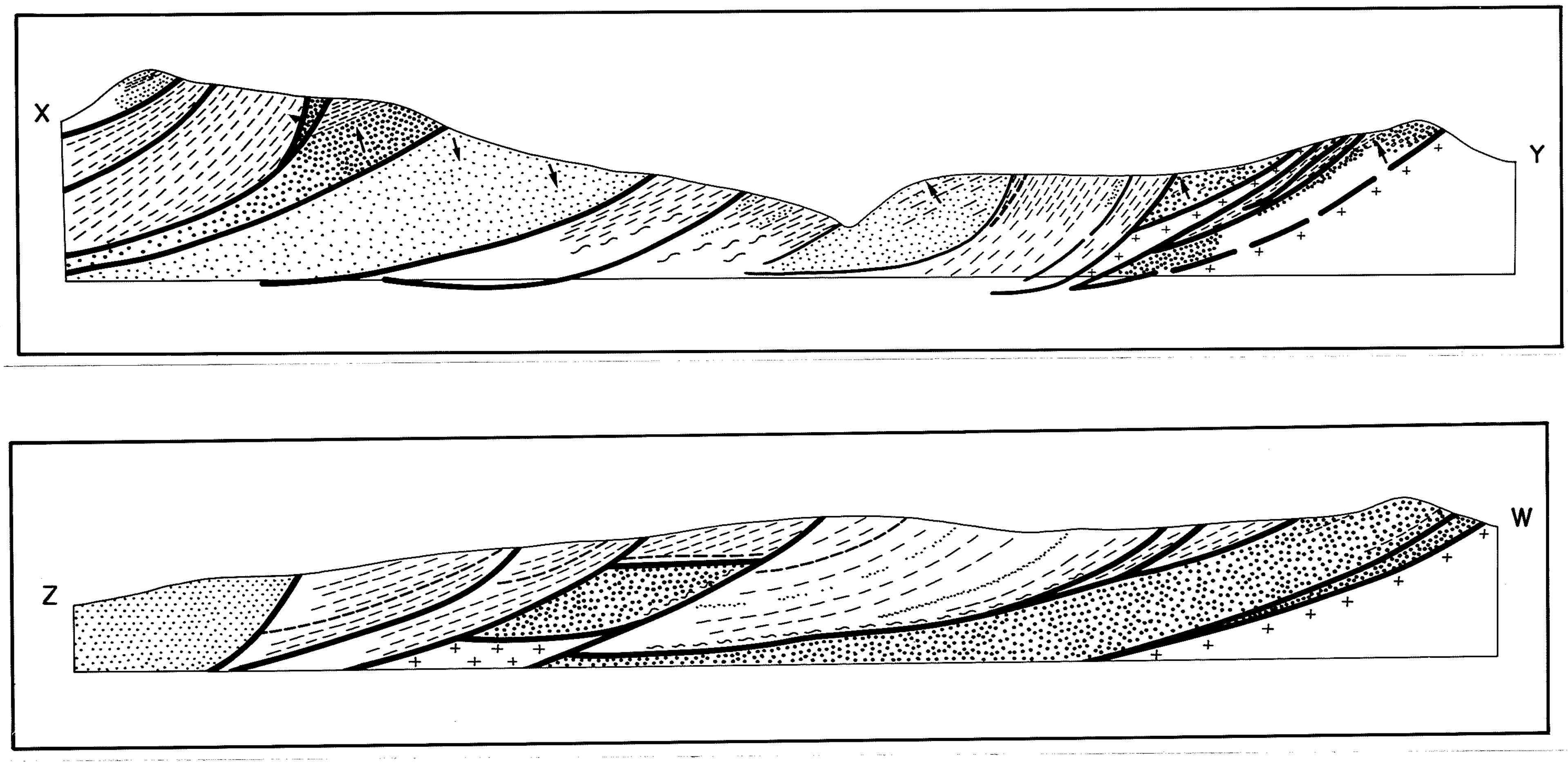


Figure 4 : *Westward-facing profiles through the section-lines shown on the geological map of Figure 2. The scale and symbols are the same as those used in Figure 2.*

angles of 25°-35°. The western fold limb, by comparison, is poorly and more intensely deformed. Mylonites and pseudo-tachylites are common, and the rocks are highly brecciated. Towards the west, the rocks could be referred to as a macro-breccia. The westward intensification of strain is an important factor in the interpretation of the significance of certain rock-types. For example, as the Ripple-marked Quartzite is followed towards the west, around the nose of the fold, it becomes progressively modified, until the ultimate product is a quartz-schist. Previously, these rocks had been considered to be altered felsitic lava, in which original phenocrysts could still be observed (Hendriks, 1961), or quartz schists of unspecified stratigraphic position. As a result of this study, these rocks are now considered to be derived from quartzites which were intensely deformed in a shear zone. The "phenocrysts" are regarded as recrystallized quartz grains of metamorphic origin. In support of this suggestion is the view that an original quartz phenocryst could not be expected to survive the intense deformation which led to the fine reduction in grain-size of all the other quartz grains (see Figure 5). On the western limb, where the Ripple-marked Quartzite is situated close to the Contorted Bed, the quartzites are also in the form of large lens-shaped bodies of quartz-schist, which plunge to the south in the main tectonic fabric-plane. The lenses are surrounded by phyllonites, and sometimes the cores of such bodies are comprised of normal quartzite. This again illustrates the transition from quartzite into quartz schist on the western margin.

The southern boundary of this domain is defined by a fault. When the eastern fold limb is followed southwards, it ends with a definite discordant relationship and has no southerly continuation along its strike. Basement rocks occur to the south of this Orange Grove Quartzite ridge. The exact nature of the discordant contact at this particular locality is important. The ridge of Orange Grove Quartzite occurring immediately to the south of the fold-structure significantly overlies the rocks belonging to the Parktown Shale Formation. The orientation of the fabrics and bedding-planes farther north clearly indicates that all the rocks dip towards the south and that the Orange Grove Quartzite lies on top of the Parktown Shales (see Figure 2, Location A; and Figure 6). A similar situation occurs on the western limb of the fold. Here quartzites are faulted against the Contorted Bed, and the fabrics in the fault-zone strike east-west and dip towards the south at 32°. Mylonites are also present at this locality.

The above examples illustrate the fact that older Orange Grove Quartzite overlies stratigraphically-younger rocks belonging to the Parktown Shale Formation. When older rocks are moved over younger rocks, the essence of faulting is contraction, i.e. shortening of an arbitrary datum-plane.

3. Central and Southeastern Domain

In broad terms, the structure of this domain can be described as a fold with an outer limb of Orange Grove Quartzite, an inner zone of Parktown Shales, and a core of quartzites belonging to the Brixton Formation. It was pointed out in the previous section that a fault separates the northern domain from the central and southeastern domains. From the outcrop pattern shown in Figure 2, it is also apparent that the structure in the southern area is more complex than the open fold developed towards the north.

The eastern margin of the Orange Grove Quartzite gives an indication of the actual complexity and illustrates the main mechanism of deformation which has affected the Swartkop area. The most striking example of this deformational style is where basement schists and granites, with associated pegmatitic veins, overlie Orange Grove Quartzite (see Figure 2, Location B). Shales and quartzites forming the immediate footwall of the basement rocks are intensely deformed (see revealing fold structures, breccias with lens-shaped fragments, and mylonites, Figure 7). This deformation rapidly decreases in intensity, with distance from the fault-plane. A large body of mobilized, hybridized rock, possibly a pseudo-tachylite product, is transgressive and intrusive into the underlying quartzites and is also associated with this fault-plane.

Individual shale horizons within the Orange Grove Quartzite Formation can operate as fault-planes. An excellent example of this phenomenon occurs immediately to the west and northwest of Locality B on Figure 2. When the prominent shale layer of this area is followed along its contact, it transgresses across the underlying basal conglomerate marker-zone, bringing the overlying rocks into contact with basement rocks. The upper quartzite, therefore, encroaches locally across the lower quartzite, onto basement rocks, with fault-movement represented by detachment on a shale layer. Similar, highly-complex assemblages, caused by bedding-plane movement on shale are also developed to the east and southeast of Locality B on Figure 2.

These two examples provide good evidence concerning the mode of deformation. Firstly, faulting develops on planes which tend to be parallel to the bedding and, in particular, take preferential advantage of shale layers. Secondly, certain faults give rise to an upward repetition of the stratigraphy, whereby older rocks come to overlie younger rocks. The manner by which the strata are deformed, therefore, is contractional faulting.

It must be pointed out, however, that this is not the only manner of faulting. The northernmost occurrence of Orange Grove Quartzite belonging to this particular domain, at Locality A on Figure 2, is bounded by a north-south-trending fault along its western contact. A vertical fault-plane, with conspicuous slickensides plunging gently towards the north, brings the Contorted Bed virtually into contact with Orange Grove Quartzite (Figure 8). Intimately associated with this fault is the development of pseudo-tachylite which injects into, and brecciates, the surrounding quartzite (Figure 9). Some of these pseudo-tachylite veinlets reveal a cleavage which is parallel to that developed regionally over the whole of the Swartkops area. This fault is clearly older than the bedding-plane fault which occurs immediately towards the north, and, because the formation of cleavage is intimately related to the younger period of faulting, it is superimposed on the pseudo-tachylite. The gently-plunging slickensides on the fault-plane indicate that the movement was close to horizontal. Since the fault-plane is vertical, it can be deduced that the direction of the maximum principal stress component was also near horizontal. Investigations in the field of thrust-fault tectonics confirm the close association of wrench and thrust faults (Bally, 1981). A simple example of this association would be a lateral ramp in the footwall-block of a single thrust sheet (Butler, 1982).

Figure 7 : *Mylonite breccia, in which a quartzite has been mylonitized and forms the matrix of the quartz fragments.*

Figure 8 : *Shallow-plunging slickensides on a vertically-oriented fault-plane which separates Parktown Shale and Orange Grove Quartzite formations. The vertical joints are frequently filled with pseudo-tachylite material.*

Figure 9 : *Veinlets of pseudo-tachylite intruding and brecciating Orange Grove quartzite adjacent to the fault-plane shown in Figure 8. The large vein is 4 cm in width.*

FIGURE 7

FIGURE 8

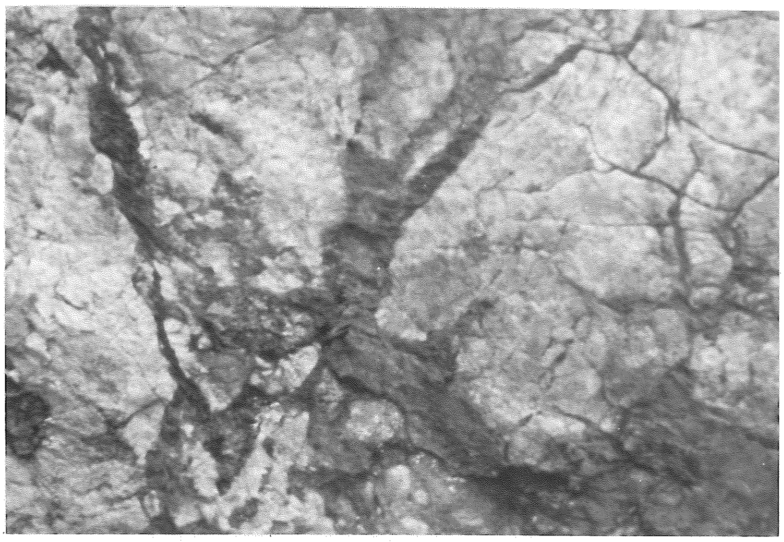


FIGURE 9

The quartzites belonging to the Orange Grove Quartzite Formation, occurring on the west side of this structural geological domain, are highly deformed, and the bedding-plane structures have been obliterated. The rocks have been transformed into typical, whitish quartz-schists in, and adjacent to, the major shear-zone on the west. They are also traversed by injections of pseudo-tachylite material.

The Parktown Shale Formation provides clear evidence of the style of faulting. If the distribution of all the marker-horizons is considered, it is significant that noticeable thicknesses of the stratigraphy are missing adjacent to the quartzites of the Orange Grove Quartzite and Brixton formations. The actual contacts with these quartzites are sites of stratigraphic elimination and, consequently, must be fault-planes. This fact can be substantiated by the presence of deformational structures and mylonites at certain localities along the contact.

The manner in which the Contorted Bed is disrupted in the northern part of the central domain indicates the presence of at least three sheets of faulted Parktown Shale Formation (see Figures 2 and 14). Such a stacking of layers, or fault-bounded sheets, can best be accounted for by a mechanism of reverse, or thrust, faulting whereby a hangingwall block in the south has been pushed up, and over, a footwall block in the north. The specific distribution of individual marker-horizons within each of the three sheets suggests that the structures are even more complex than was assumed above (see Figure 2).

Quartzites and shales belonging to the Brixton Formation and rocks which collectively have been termed 'fault-tectonites' form the core of the central domain. In spite of the lensoidal shape of the quartzitic elements of the Brixton Formation, which are surrounded by 'fault-tectonites', the structural information, when pieced together, gives evidence of a more coherent fold-pattern. Overall, the quartzites have the same basic orientation, viz. a strike of 315° and a dip of 34° towards the south. This does not, however, apply to the northern extremity of these rocks, where they occur within a fold-hinge. All the quartzites which are in line with the eastern margin of the Brixton Formation are the right way up, but are immediately overlain by overturned quartzites (see Figure 2). In the hinge-zone, the quartzites become younger towards the east. Sedimentary structures tend to be eliminated in the hinge-zone because of the intense deformation.

The uniform orientation of bedding-planes, except for the hinge-zone, and the younging direction of the Brixton Formation quartzites demonstrate that the structure is essentially an isoclinal fold. This fold subsequently was disrupted into a series of similarly-oriented lens-shaped bodies to form a macro-breccia. Some of the quartzitic lenses attain the following dimensions : 870 m x 300 m; 600 m x 265 m; 450 m x 265 m; and 225 m x 75 m. A significant proportion of the quartzitic material at Swartkops is sheared into lens-shaped bodies, and the process occurs on all scales, varying in size from the large bodies described above to microscopic fragments.

Starting in the southeastern corner of the mapped area (see Figure 2), the zone of intensive deformation is more-or-less confined to the axial plane and the lower limb of the isoclinal fold of the Brixton Formation. When followed northwards, it cuts across the axial-plane trace of the fold, placing the fold-hinge on its northern side. It continues, to form the western boundary of the northern half of the area. This structure is considered to represent a major shear-zone which contributes to the intense deformation present on the western fold-limb of the northern Orange Grove Quartzite Formation. The rock-types forming the matrix to the quartzitic lenses within the major shear-zone vary from recognizable shale, through schist, to pseudo-tachylite. A detailed petrographic study of these fault-zone rocks is presently being undertaken, and, until the results become available, they will be referred to, collectively, as fault-tectonites.

A concordant, iron-rich 'shale' horizon occurs close to the base of the southernmost overturned quartzite body, at Locality C on Figure 2. This layer becomes clearly discordant to quartzites, when followed northwards. Ultimately, the 'shale' cuts across the bedding and disrupts the surrounding quartzite. The 'shale' is not simply a conventional sedimentary unit. Where the layer is concordant, small folds are developed within the adjacent quartzite and this indicates movement. In the distinctly cross-cutting localities, a persistent zone of narrow, highly-elongated, lens-shaped bodies occurs adjacent to the quartzites. The lenses have their long axes parallel to the contact, consist of quartzite, and are generally not more than 40 cm in width (see Figure 10). Such an horizon, which is made up of 'shale' and a marginal zone of quartzite lenses, could be confused with a normal sedimentary sequence, were it not for the cross-cutting relationship with, and ultimate disruption of, the surrounding quartzite. This false 'bedding' is, therefore, of tectonic origin and the 'shale' layer is a shear-zone 20 m thick. It displays all the characteristics to be found in larger stratigraphic entities, such as the Parktown Shale Formation.

4. Southern Domain

This domain is of major significance, because it demonstrates, in a simplified manner, the principal type of deformation that affects the Swartkops area. Strata in the southern domain are relatively well exposed, and the topography permits a study of the vertical sequence of the stratigraphic units. In essence, the overall structure can be considered to be a series of nappes, or thrust-slices, that have been piled up on top of one another. Generally, the sheets strike east-west and dip towards the south at 30°.

The first group of quartzites which overlie the overturned beds of the Brixton Formation is the right way up. These rocks are the massive, glassy variety of quartzites which are typical of the Orange Grove Quartzite Formation and which occur immediately below the Parktown Shale Formation. The lower fault contact with the Brixton Formation is a well-developed mylonitic zone (see Figure 2). The next nappe upwards also transgresses the overturned Brixton Formation and consists of rocks belonging to the lower portion of the Orange Grove Quartzite Formation. The numerous old prospect shafts and trenches are located in the basal conglomerate zone. Mylonites and folds within the underlying quartzites of the Brixton Formation are developed in, and adjacent to, the thrust-fault at the base of this nappe. Occurring on top of these two nappes is a structural unit

Figure 10 : *Quartzite layers in a 'shale' band that transgresses the surrounding quartzite. These quartzite lenses are formed next to the massive quartzites which are cut by the 'shale' layers. The layer between the shale and quartzite is of tectonic, and not sedimentary, origin.*

Figure 13 : *Foliation in a quartzite mylonite. The lighter-coloured material is made up of quartzite in the form of tectonic-breccia fragments.*

Figure 14 : *The product of significant simple-shear on a Parktown Shale layer. The lighter fragments are remnants of thinner arenaceous layers in a dominantly argillaceous sequence, which are completely disjointed by fault movement.*

FIGURE 10

FIGURE 13

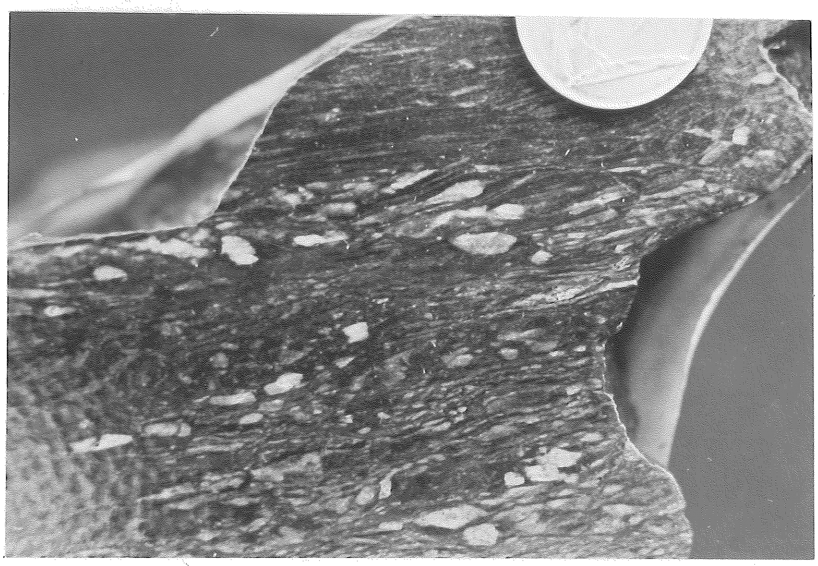


FIGURE 14

which is made up of rocks belonging to the Orange Grove Quartzite and Parktown Shale formations. The strata have been strongly deformed, but the characteristic marker-horizons of the Ripple-marked Quartzite, the Contorted Bed, and the Water Tower Shale Member can be recognized. At Locality D on Figure 2, the Water Tower Shale Member forms a tight fold, with a core of Orange Grove Quartzite which, together with the nearby Parktown Shale marker-horizons, belongs to a separate folded nappe (see Figure 2). The remaining unit of Parktown Shale has been subjected to intense deformation, revealed by the repetition of the Ripple-marked Quartzite and the numerous exposures of mylonites. The Parktown Shale Formation has been reduced markedly in thickness, from 420 m, elsewhere in the Swartkop area, to 190 m in the southern domain. If repetition of strata is taken into account, then the true thickness may only be about one quarter of this, i.e. about 50 m. The conspicuous decrease in stratigraphic thickness is taken as evidence of severe tectonism within this Formation. The highest exposures consist of rocks considered to belong to the Brixton Formation, in which extensive bedding-plane faulting can be deduced from the disposition of the quartzites and shales.

Previous investigators interpreted the structure of the rocks occurring in the southern domain as being represented by a synclinal fold. For this to be the case, overturning of the Orange Grove Quartzite and Parktown Shale formations would have to be present, so that the strata could be conformable with the overturned limb of the Brixton Formation isoclinal fold. Available field data contradict the likelihood of such a fold structure because : (i) the younging direction of the quartzites occurring in the different nappes above the Brixton Formation fold are the right way up and not overturned; the only exception to this is a small part of the folded nappe of Parktown Shale and Orange Grove Quartzite formations at Locality D on Figure 2; and (ii) the overall stratigraphy of the pile of nappe-structures is also the right way up, progressing from the Orange Grove Quartzite, through the Parktown Shale, to the Brixton Formation. It is believed that the evidence obtained from the present mapping indicates that thrust-faulting is the mechanism of deformation (see Figure 4).

(b) *Minor Structures*

1. Bedding-Plane Data

The study of the orientation of bedding-planes followed two directions : firstly, a geographical distribution, determined during the course of mapping; and, secondly, a stereographic projection of this information. A map of the generalized distribution of the attitude of bedding-planes reveals that the strike of the strata varies between north-south and east-west (see Figure 3). Although individual horizons can be followed around the fold-hinge, the western limb is generally so highly deformed that the original bedding structures cannot be observed, as is apparent in the western portion of Figure 3. The quartzites, in particular, frequently exhibit a strong tectonic fabric which is responsible for the elimination of the primary bedding.

The geographical distribution of bedding-plane orientations at Swartkops, when considered in conjunction with the distribution of rock-types and tectonic fabrics, indicates that the western margin is more intensely deformed than the rest of the area. Some of this deformation may be attributed to the presence of the thrust-fault, identified by Hendriks (1961), that occurs at the base of the Ventersdorp Supergroup, immediately to the west of the mapped area. A certain proportion of the deformation may also be ascribed to the shear-zone that transects and brecciates the fold in the Brixton Formation. Unfortunately, there is not sufficient outcrop to determine the exact relationship between these two major shear-zones.

If the actual dip-directions of the bedding-planes are considered, then the general form of the fold appears to be a relatively-open synclinal structure which plunges towards the south. Little more can be said of the structure in the north, because the attitude of the western limb is unknown. Except for the thrust-slices occurring in the southern domain, it seems feasible to link the other fold-structures in the area to the tight isoclinal fold defined by the Brixton Formation. This would mean that the altered Orange Grove and Ripple-marked quartzites, occurring on the western side of the northern fold-area, would have to be overturned, so that the 'open' syncline, in fact, would be part of an isoclinal fold. This structure would then be compatible with the Brixton-Formation fold.

When the attitudes of bedding from the entire area are plotted on a stereographic projection, the poles tend to concentrate, indicating that the strata have a relatively uniform orientation. The average orientation of these planes defines a surface which has a strike of 315° clockwise from north and a dip to the southwest of 34° (see Figure 11). If the actual scatter of points in Figure 11 is considered, a wide range of differently-oriented great-circles can be drawn to fit the distribution. This emphasizes the cluster nature of the pattern. The great-circle which has been selected to fit the data has been derived from information obtained in the northern domain, which is the only area showing a relatively wide range of bedding-plane orientations (see Figures 2 and 3). Although there are not many points, the spread of poles is sufficient to define accurately a great-circle (see Figure 12). Using this information, a fold axis can be determined which plunges to the south-southwest at 30°.

Bedding-attitudes from the Brixton Formation occurring in the central domain indicate basically the same distribution as for the whole area. If the average bedding-plane orientation, with a strike of 315° and a dip of 34° to the southwest, is used in conjunction with the almost vertically-oriented, north-south-trending beds which are located in the hinge of the fold structure, it defines a fold-axis which plunges southwards at 25°. This orientation broadly confirms that obtained from the northern domain.

2. Tectonic Planar Fabrics

Several markedly-different types of planar fabric are developed within the various lithologies at Swartkops, but they all have virtually the same orientation. Because of this geometrical characteristic, they are considered together, as a group which is related to a single period of deformation. The planar fabrics that have been considered include : (i) cleavage in shales; (ii) schistosity in shales and quartzites; (iii) planes of flattening and schistosity in fault-breccias;

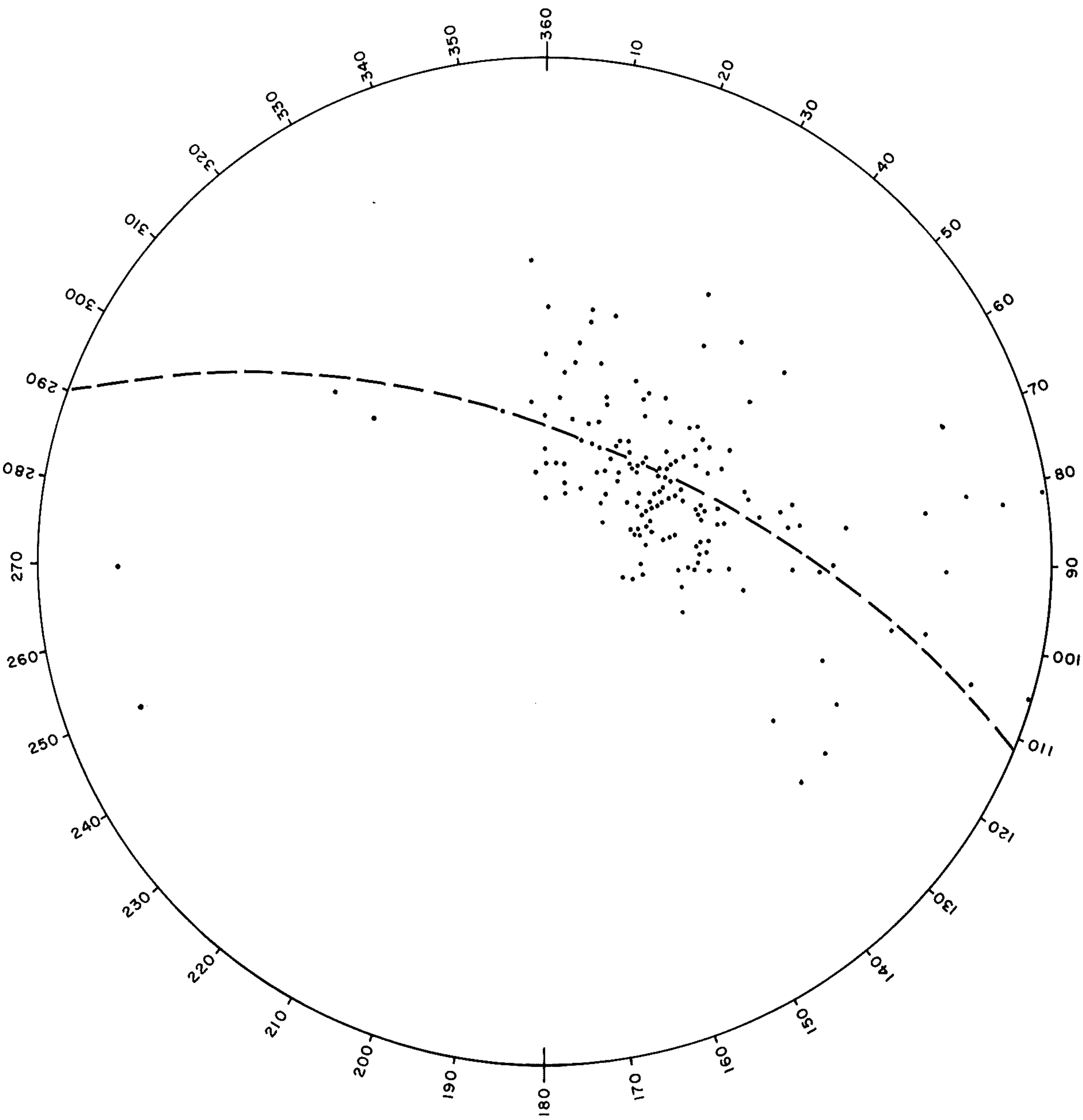


Figure 11 : *Stereographic projection of poles to bedding-planes in the Swartkops area. The great-circle has been derived from Figure 12. Data are plotted onto the lower hemisphere.*

(iv) foliation in mylonites and ultramylonites; (v) and cleavage in pseudotachylites. Where flattening and rotation of more rigid layers are extreme, the layering resembles bedding, but the discontinuous nature of cleavage planes indicates the tectonic origin of such fabrics. Examples of different types of fabrics are shown in Figures 5, 13, 14, 15, 16 and 17.

The surprising property of all these structures is their uniform orientation. This fact can be established, both from the geographical distribution and from the stereographic projection of this parameter (see Figures 3 and 18). Local deviations in the orientation of these planes occur

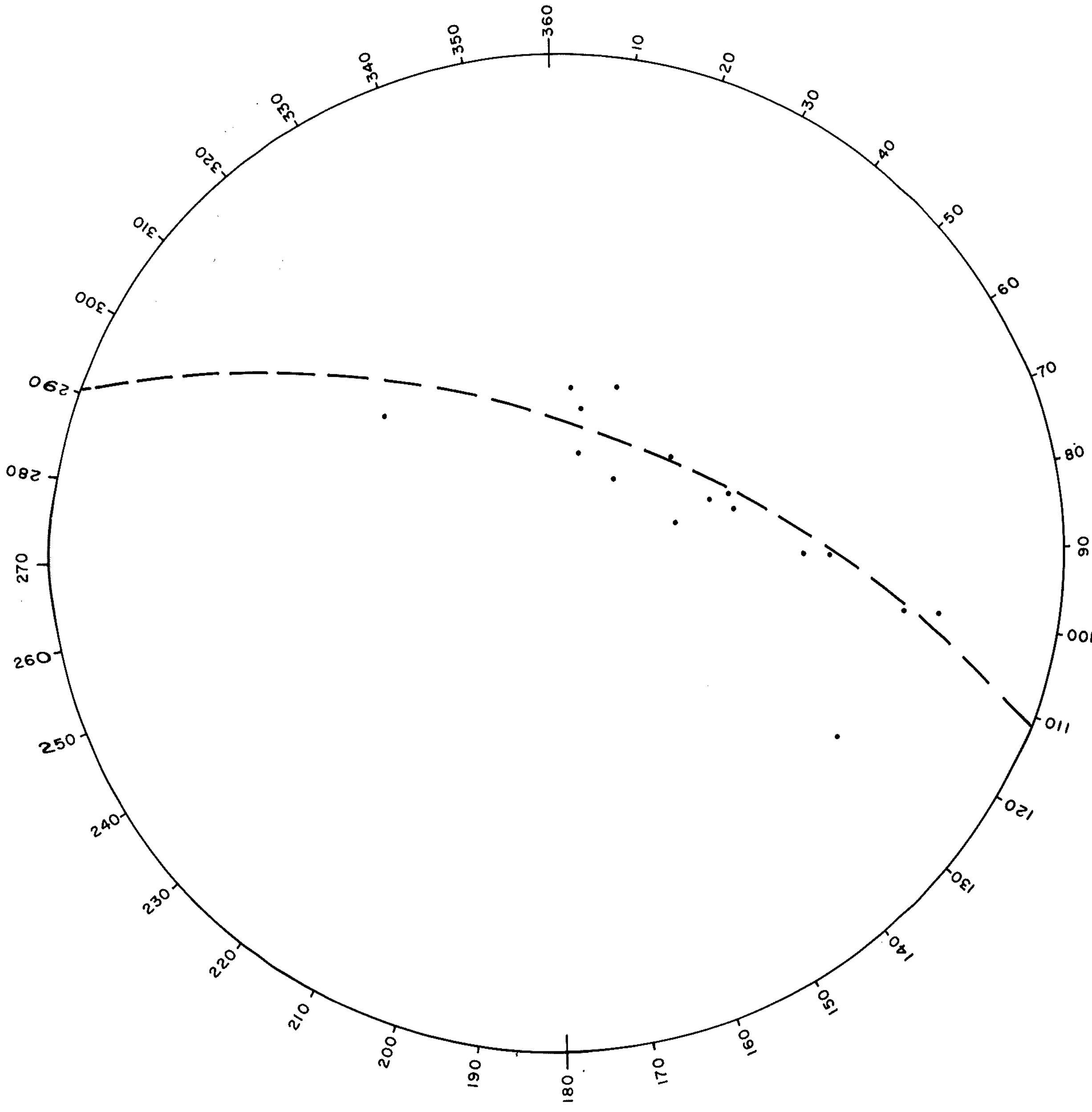


Figure 12 : *Stereographic projection of poles to bedding-planes in the northern domain of Figure 2.*

adjacent to the large lenses of quartzites, where the enveloping tectonites wrap themselves around such inclusions (see Figure 19). The average strike of this plane, as determined from Figure 18, is 276°, and the dip is 30° towards the south.

Small shear-zones, giving rise to fabrics of similar orientation, are developed in the granites immediately to the east of the Orange Grove Quartzite at Locality D on Figure 2. The basement granites, therefore, have been subjected to the same tectonic processes as the overlying Witwatersrand rocks. If the great-circle of the poles to the bedding-planes, as determined from Figure 12, is transferred to Figure 18, it falls

Figure 15 : *Quartzite in the process of deformation in a ductile shear-zone. The quartzite becomes disrupted into a mass of lens-shaped remnants lying in a matrix of fine-grained mylonitic material.*

Figure 16 : *The same process as is depicted in Figure 15, but on a significantly-larger scale. Figures 13-16 all illustrate the product of a simple-shear deformation on stiffer material in ductile shear-zones, i.e. the development of lens-shaped remnants of quartzite in a matrix of softer material which is commonly shale, but which, in certain instances, can be mylonitised quartzite.*

Figure 17 : *Parktown shale within a thrust-fault. All the layering is virtually parallel, due to excessive simple-shear strain.*

FIGURE 15

FIGURE 16

FIGURE 17

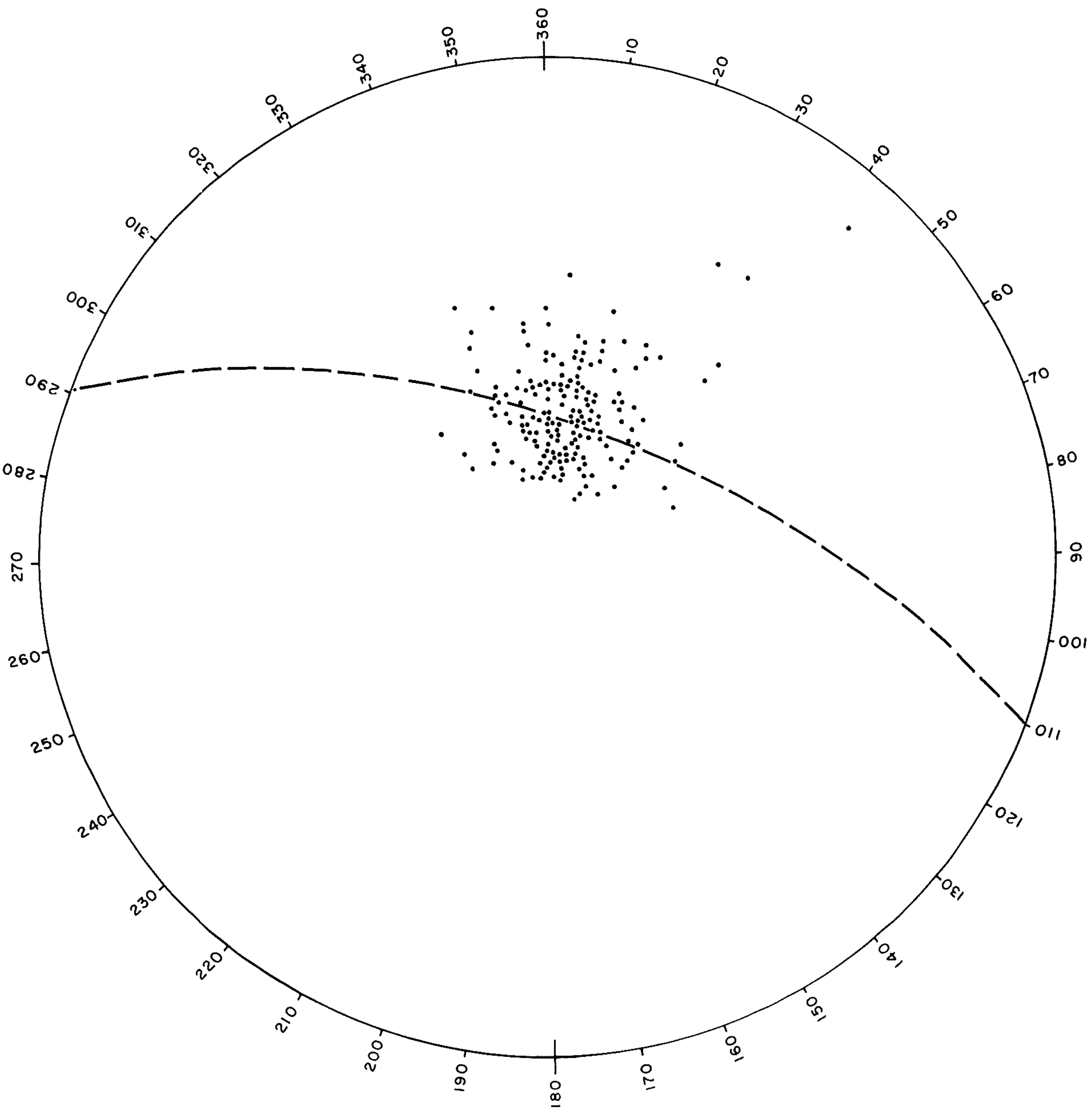


Figure 18 : *Stereographic projection of poles to tectonic fabric-planes. These include : cleavage in shale; schistosity; mylonitic banding; planes of flattening in ductile shear-zones; and superimposed cleavage of pseudo-tachylite intrusions.*

on the maximum of the fabric-plane poles. This indicates that the folding is also associated with the formation of the tectonic foliation. However, the fabrics in mylonites and fault-breccias from the shear-zone located within the Brixton-Formation fold also have this orientation. The cleavage which is prominent in the Parktown Shales, similarly, belongs to this population. All these different associations demonstrate that the

Figure 19 : *Foliation in a mylonite breccia which clearly steepens over a relatively small distance. This is due to the fault-tectonite wrapping itself around a larger quartzite inclusion which occurs towards the top left-hand corner.*

Figure 21 : *Lineations in the Parktown Shale Formation, formed from the intersection of cleavage and primary layering.*

Figure 23 : *Lensoid remnants of quartzite (light-coloured) occurring in a fault-zone.*

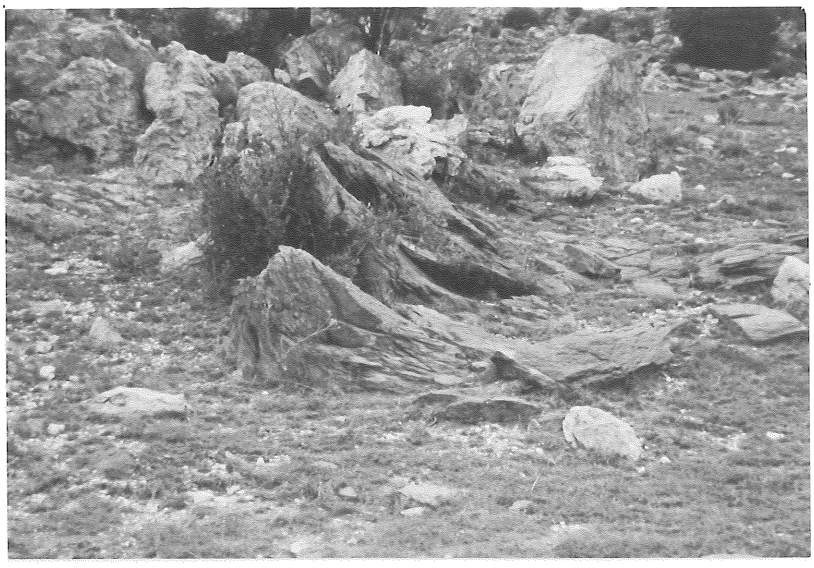


FIGURE 19

FIGURE 21

FIGURE 23

deformation at Swartkops centres around this uniformly-oriented planar fabric. Furthermore, both fold- and fault-structures can be related to this foliation.

Since the angular difference between the average orientation of the bedding-planes and the tectonic fabric-planes is only 22°, the populations of these two structural elements, shown in Figures 11 and 18, will overlap each other. In physical terms, this would mean that the fabric-plane often can be parallel to a bedding-plane. This parallelism is to be expected in a process of thrust-faulting, particularly where it takes place on a relatively-thin shale layer, since, for parallel displacement of a set layer, the component of shear-strain will increase with decreasing layer-thickness, bringing the flattening-fabric closer to the plane along which the displacement took place.

An important aspect of the deformation is that the fabric is oriented east-west, which is at right-angles to the trend of the fold outcrop-pattern. This point is significant, because earlier workers considered that the tectonic forces giving rise to the fold-structure were directed from the west towards the east. The implication of this interpretation is that the axial-plane cleavage, which would develop from such forces, would have a strike conformable with the fold-trend, i.e. north-south. If thrust-faulting from west to east was the dominant mechanism, and not folding, the fabrics in shear-zones would also have a north-south strike. Clearly, this is not the case at Swartkops (see Figures 2 and 3).

Within the Parktown Shales occurring to the east of the Brixton-Formation fold, there is a suggestion that the fabric tends to become deflected into a west-northwest trend, close to the quartzites. Two points emerge from such behaviour : firstly, higher strain is adjacent to the quartzites, and contact-zones are thus fault-planes; and, secondly, higher strata have moved in a generally-northwards direction (see Figure 20 for a diagrammatic explanation of these points).

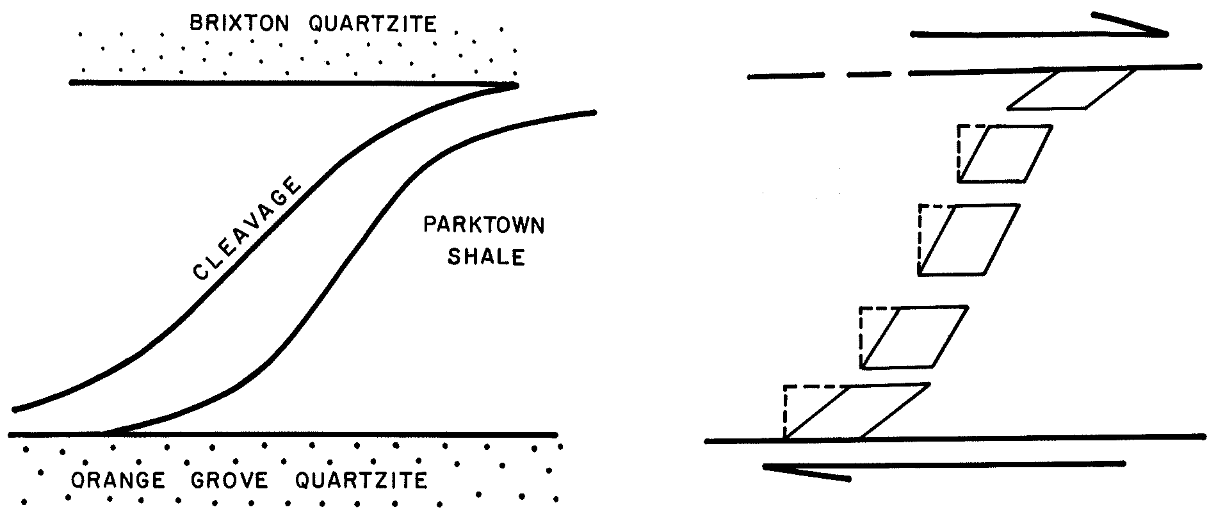


Figure 20 : *Deflection of planes of flattening in Parktown Shales, adjacent to the competent quartzites of the Brixton and Orange Grove formations. This is attributed to a larger component of simple-shear, i.e. increased faulting, along these contacts.*

3. Lineations

Within the Parktown Shale Formation, there is an abundance of lineations, developed mainly from the intersection of tectonic fabric-planes and bedding-planes (see Figure 21). The scatter of lineations in the fabric-plane confirms that the Parktown Shales are folded. In general, the lineations plunge in a southwards direction, more-or-less conforming to the fold-orientations determined from the bedding-planes (see Figure 22).

There are, however, other types of lineation which also relate to the deformation. They are not readily recordable, because measurements have to be made in the fabric-plane, which is only rarely exposed, on weathered surfaces. An example of such a different type of lineation is the long axis, or cylinder-like axis, of the lensoid inclusions developed in fault-breccias (see Figure 23). This lineation can be determined ideally as an axis along which there is no change of shape in an elliptical cylinder. In the Blaubankspruit area, smaller quartzitic lenses of this type are found, and the orientation of the axes referred to above can be measured with reasonable accuracy. The average orientation is 250°, with a plunge of 20° towards the west. It should be noted that this lineation occurs at an angle of 53° to the fold-axis, when measured in the plane of the fabric.

Within certain mylonites, the quartzitic remnants become rounded, possibly due to intensive shearing. They are also less frequent in number and relatively small in size, i.e. less than 5 cm in diameter. These smaller fragments become smeared out in the fabric-plane, giving the rock a streaky character, with a lineation which is parallel to the main transport direction. The following orientations have been obtained for this lineation, the values given being averages :

Direction of Plunge	Amount of Plunge
200°	25°
190°	24°
172°	32°
162°	21°
165°	19°

A well-developed lineation in the granitic shear-zone occurring on the east of the map-area also plunges at 13° in a southerly direction (190°). When this lineation is considered, together with those described above, a general northerly tectonic transport direction is indicated.

Evidence that confirms the northerly transport direction was obtained from the thrust-fault (Hendriks, 1961) which occurs at the base of the Ventersdorp Supergroup. The outcrops investigated occur just to the west of the mapped area. Here, a debris-flow conglomerate has suffered intense deformation close to the thrust-fault. Where the rock is highly weathered, and where flattening of the pebbles is severe, its conglomeratic nature might not be recognizable, and the rocks might be confused with schists or shales (see Figure 24).

Measurement of pebble-shapes, when plotted on a Flinn diagram (see Figure 25), indicates that the majority of pebbles plot around and underneath

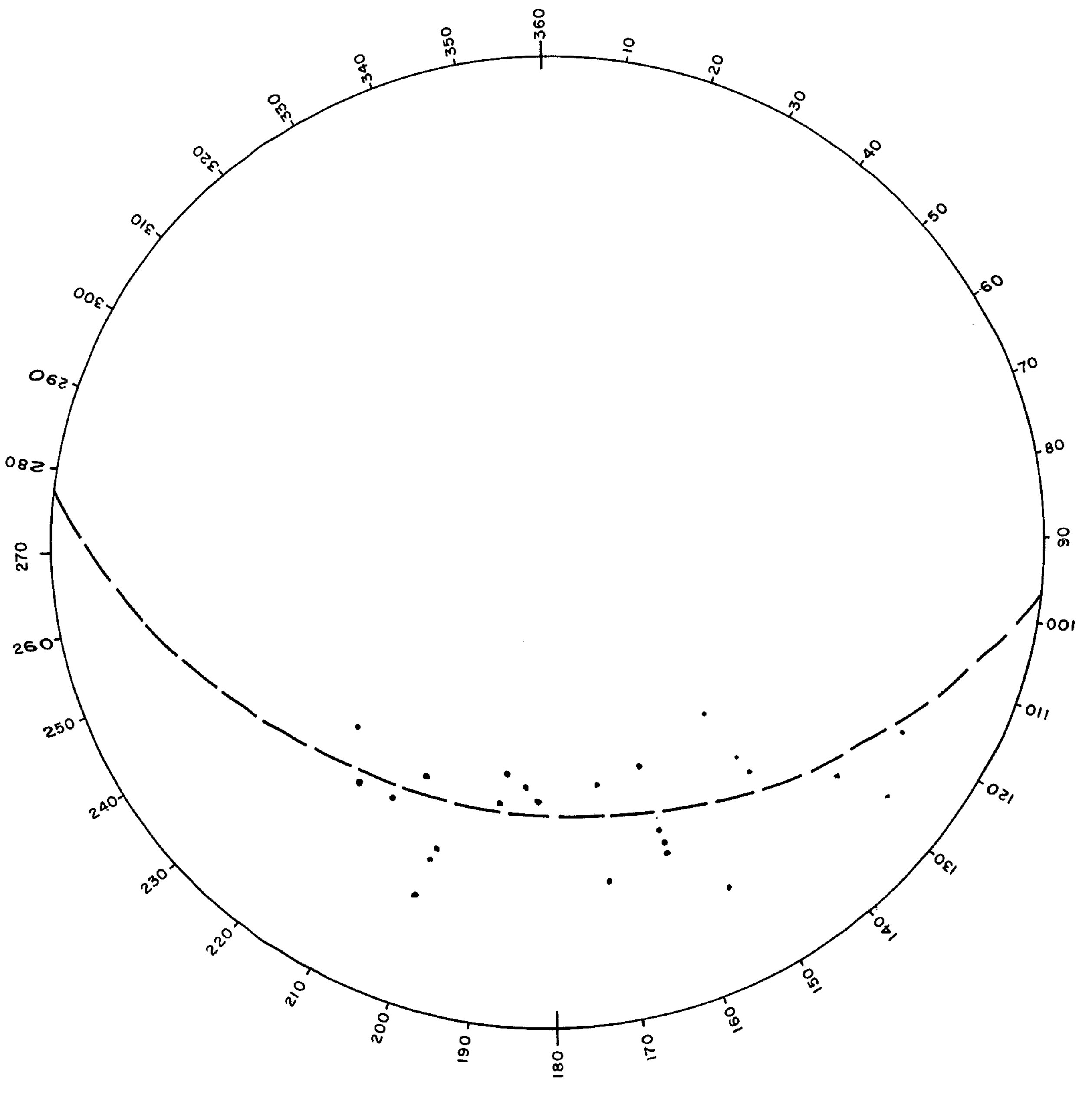


Figure 22 : *The orientation of lineations measured in the Parktown Shale Formation. The great-circle is the average orientation of the tectonic fabric, as deduced from Figure 18.*

the simple-shear model of strain (Ramsay, 1980). This fact, when considered with the observation that high strain is confined to a relatively narrow zone in the Ventersdorp succession, indicates the existence of a zone of heterogeneous strain at the base of these rocks, i.e. a zone of shearing and ductile deformation. These data support indications of the presence of a thrust-fault (Hendriks, 1961).

Figure 24 : *Extreme flattening of a conglomerate, close to the thrust-fault occurring at the base of the Ventersdorp Supergroup.*

Figure 26 : *Foliation boudin, with quartz infilling (white) in Orange Grove quartzite.*

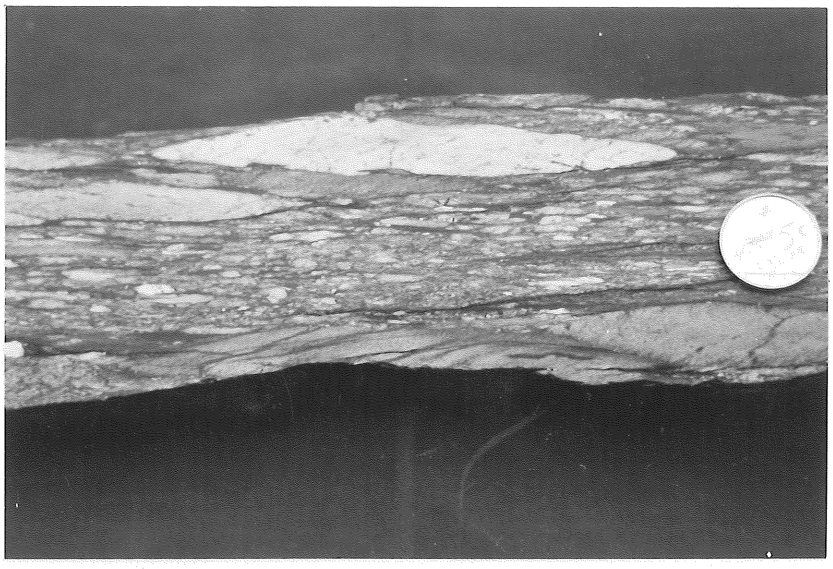


FIGURE 24

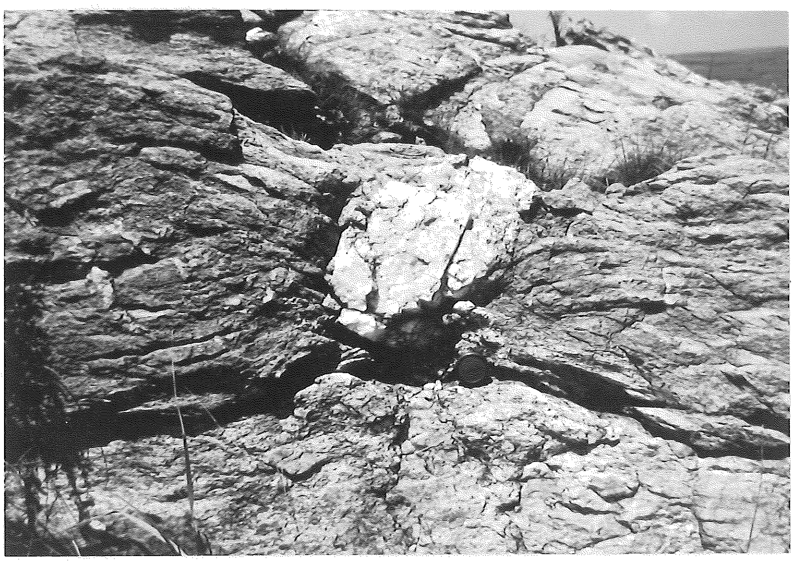
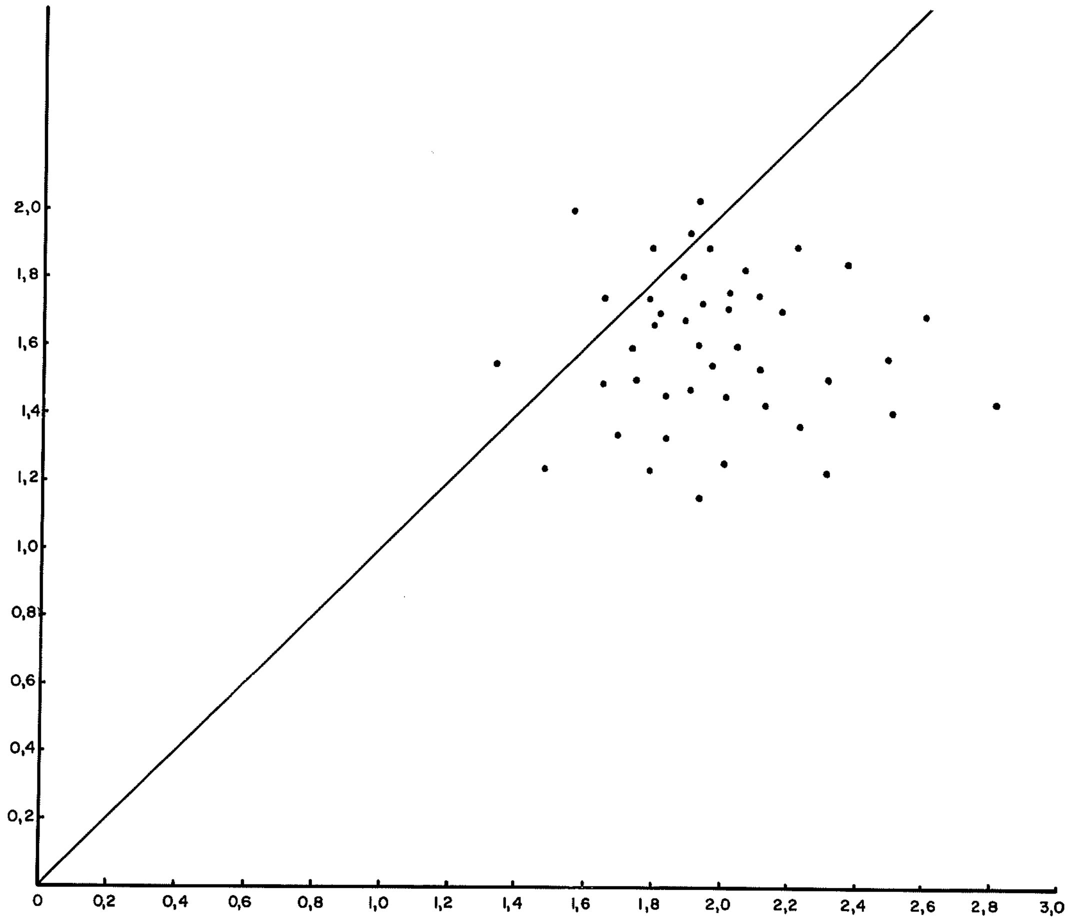


FIGURE 26



<u>*Figure 25*</u> : *Flinn-diagram of flattened pebbles occurring within a deformed, debris-flow conglomerate, close to a major thrust-fault (see Hendriks, 1961). Y-ordinate: ratio of long pebble-axis to intermediate axis. X-ordinate: ratio of intermediate pebble-axis to short axis.*

Of particular importance to the present discussion of lineations and transport directions is the orientation of the long axes of flattened pebbles. The pebbles, although intensely deformed, are more competent than the surrounding matrix, and all have their long axes oriented in a northerly direction. Ramsay (1980) has pointed out how lineations tend to become oriented parallel to the movement direction, particularly in cases that have been subjected to a large component of shear-strain.

It must be reiterated that major fold-axes are also oriented in a north-south direction. It was this orientation that led earlier workers to suggest an easterly thrust-movement, with fold axes at right-angles to this. However, it has been established subsequently that, in ductile shear-zones, lineations, and even fold-axes, can be rotated into the fabric-plane and can tend towards parallelism with the main tectonic transport-direction

(Cobbold and Quinquis, 1980; Ramsay, 1980; and Skjerna, 1980). The implication for the Swartkops area is that very large strains were required from a simple-shear deformation for both pre- and syn-deformational linear elements to become parallel to the transport direction.

4. Extensional Structures

Competent members of the Witwatersrand Supergroup could be expected to form boudins, with the axes of 'pinching' perpendicular to the long axis of the strain-ellipse and, in the case of a simple-shear mechanism, at right-angles to the direction of transport. Numerous examples of this phenomenon can be observed throughout the area. On a very large scale, the lenses of Brixton Formation quartzites, which are shown in Figure 16, can be considered to be macro-boudins. The same geometry can be observed on smaller scales (Figures 15 and 23). The direction of pinching tends to be east-west. Excellent examples of 'foliation boudins' (Platt and Vissers, 1980) have also been observed in the massive quartzite sequences (see Figure 26). The necking directions, again, are perpendicular to the postulated northwards tectonic-transport vector.

Quartz veins are frequently developed within the more massive quartzites. A frequency diagram of these veins reveals a maximum in the 280°-290°-azimuth range (see Figure 27). This coincides with the strike-direction of the tectonic fabric. The dips of the quartz veins are generally steep, with the greater percentage tending to dip northwards. The majority of quartz veins are oriented at right-angles to the transport-direction.

These examples emphasize the importance of the relative ductilities of different rock-types during deformation. Although the basic mechanism of deformation proposed for the Swartkops area is one of contractional faulting and simple shear, competent horizons, surrounded by more ductile material, become stretched, fracturing in a systematic manner. Tensile phenomena are, therefore, reconcilable with dominantly compressional tectonics and can be used as indications of the main transport-direction.

(c) *Estimates of Strain*

Although the rocks at Swartkops reveal clear indications of strong deformation, the data are of little value, unless some quantitative estimate of the strain can be made. Fortunately, there are several different methods that can be employed to determine the amount of displacement involved in shear-zones (Ramsay, 1980) and in thrust-faulted areas (Boyer and Elliot, 1982; Sanderson, 1982). An initial estimate of the strain can be made by simply neglecting the younging directions and describing the structure as a duplex model of thrusting (Boyer and Elliot, 1982). By making these assumptions, the strain will be underestimated, because the fold structure has been disregarded.

A lower bounding fault could separate the duplex of Witwatersrand rocks from the underlying granites and an upper thrust-fault could separate them from the Ventersdorp nappe proposed by Hendriks (1961). Such suggestions lead to the problem of selecting the depth to the granite floor and the height to the Ventersdorp thrust-fault, which elevations determine the structural thickness of the duplex (Boyer and Elliot, 1982) influencing

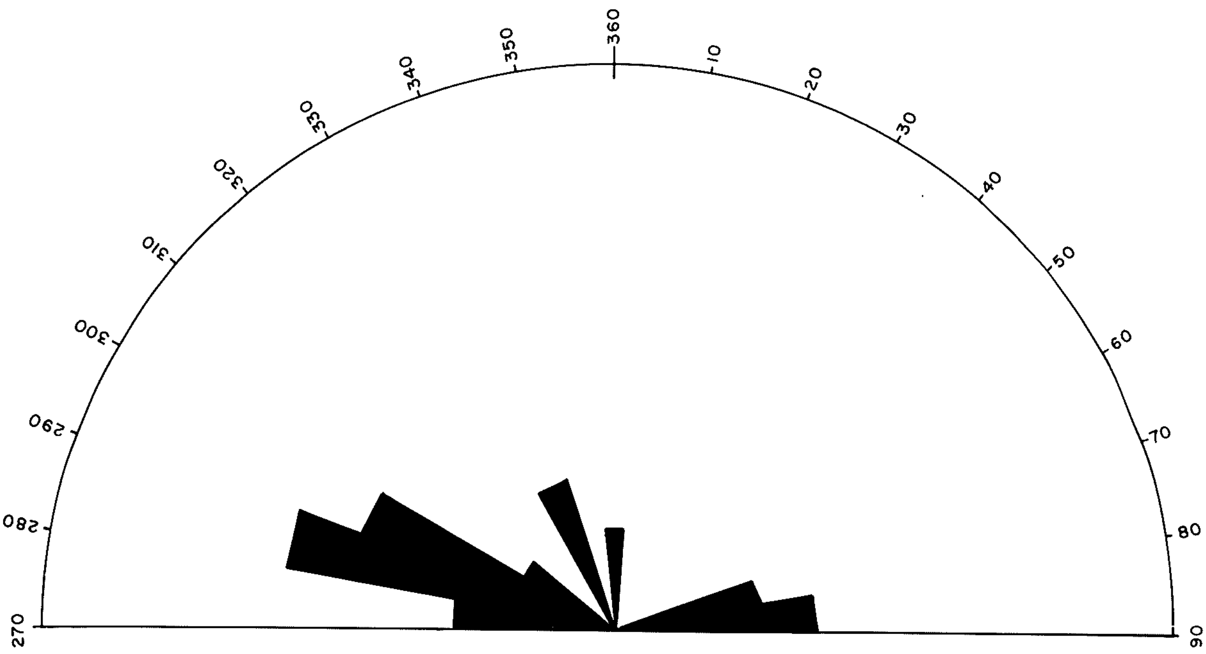


Figure 27 : *Frequency diagram of the azimuths of the strike of 73 steeply-dipping quartz-veins. The most common alignment is at right-angles to the direction of tectonic transport.*

the final estimates of strain. A structural height of 490 m has been obtained from sections through the area. This gives rise to an average bedding-length (l_n) of 710 m for the horses of the duplex. The average spacing between subsidiary faults, measured parallel to the floor thrust (p'), has been taken as 215 m. Using relationship (8) of Boyer and Elliot (1982), the strain can be estimated as :

$$\frac{L'}{L_o} = \frac{p'}{l_n} = \frac{215}{710} = 0{,}303$$

L_o is the original length of the duplex, and L' is the present contracted length. L' measured in a north-south direction, i.e. at right-angles to the tectonic transport, is 3,18 km. From this, an original length of 10,5 km can be established, which implies a contraction of about 7,3 km. It must be pointed out that the weakness of this particular estimate lies in the selection of the structural height, which determines the value of l_n. Keeping the other parameters constant, an increase in the structural height would result in an increase in the amount of strain. If this aspect has been overestimated, then it must be remembered that shortening associated with folding has not even been considered in the calculated strain.

Another estimate of the strain has been based on palinspastic reconstruction of the existing profiles. Two separate profiles have been used for determining shortening and apply to the non-folded sequences at Swartkops (see Figures 28 and 29). The estimates derived from these two profiles are conservative, because they are largely based on the reconstruction of the Orange Grove Quartzite Formation. The Parktown Shales have not been fully reconstructed, since the absolute thicknesses of the various members are not known. However, the reconstructed profiles do emphasize the faulted relationship between the Parktown Shale and the Orange Grove Quartzite.

The shortening estimates are :

Figure 28 : $\frac{L'}{L_o} = 0{,}62$ (average dip of Orange Grove Quartzite is 29,5°)

Figure 29 : $\frac{L'}{L_o} = 0{,}64$ (average dip of Orange Grove Quartzite is 13,0°)

If the data are corrected for the relevant dips of the sections shown, the following values can be obtained.

Figure 28 : $\frac{L'}{L_o} = 0{,}54$

Figure 29 : $\frac{L'}{L_o} = 0{,}62$

The average shortening for these two sections is 0,58, and this value has been applied to the unfolded rocks north of the Brixton Formation fold and to those rocks lying on top of this structure. The fold-structure has been considered as one entity and the remainder of the rocks as belonging to another entity. This stratigraphic division separates strain from the Orange Grove Quartzite and the Parktown Shale formations from strain for the Brixton Formation. The unfolded rocks define a total distance of 2,245 km, when measured in a profile drawn at right-angles to the direction of tectonic transport. A shortening of 1,63 km is obtained from the relationship :

$$\frac{2{,}245 \text{ km}}{L_o} = 0{,}58$$

A value of shortening associated with the Brixton Formation fold has to be added to this in order to obtain a better estimate of the strain. In considering the fold, two points are important. Firstly, the structure is clearly synclinal and is immediately overlain by members belonging to the Orange Grove Quartzite Formation, which are the right way up. This indicates that an anticline has been removed from, and faulted out of, the structure at Swartkops. Secondly, the structure is isoclinal and the axial-plane dips towards the south at 30°. An idealized portrayal of the syncline is shown in Figure 30. Here again, it must be pointed out that, in reality, a major fault disrupts the structure, and this effect has not been taken into consideration. The shortening in the idealized fold-structure of Figure 30 is :

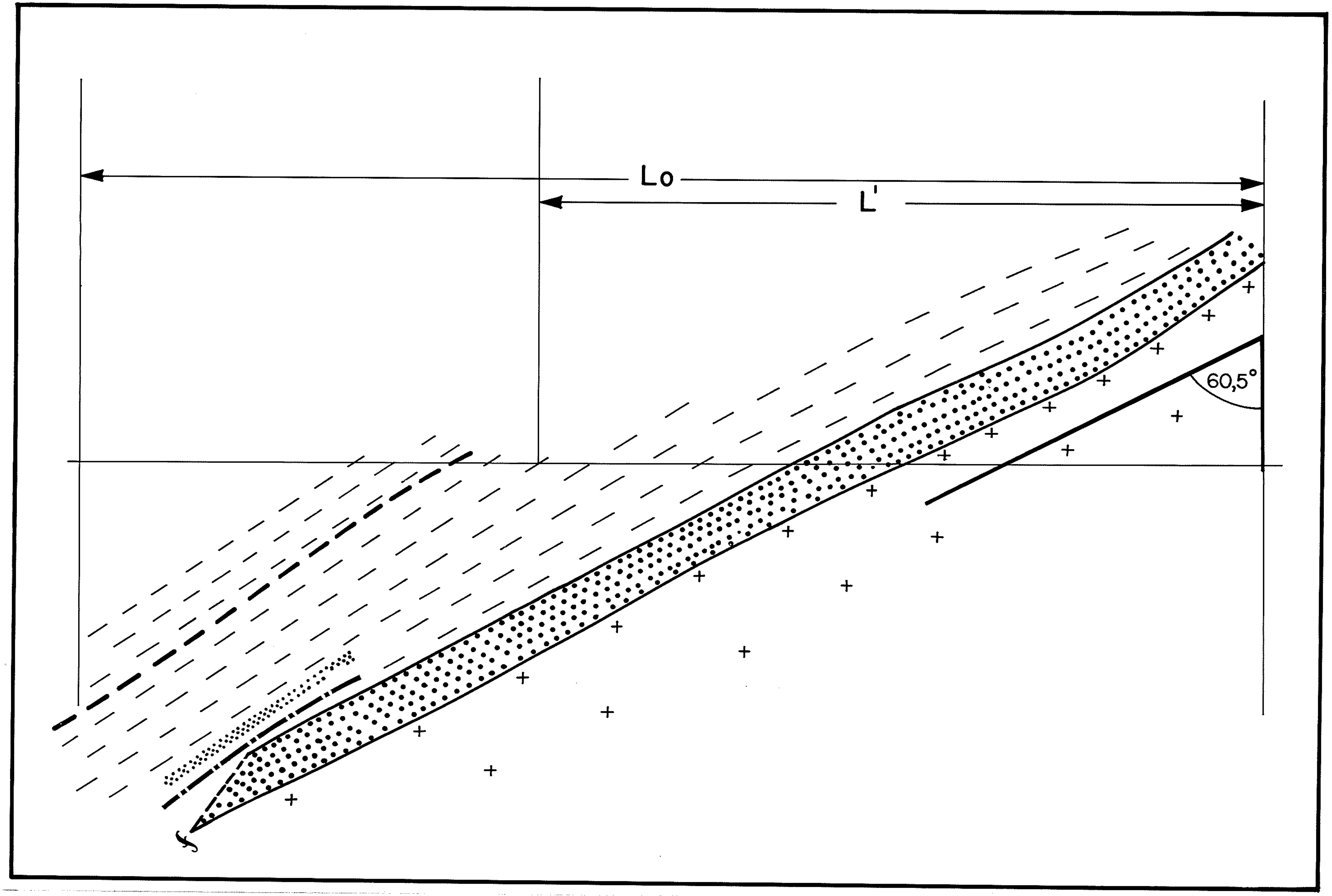
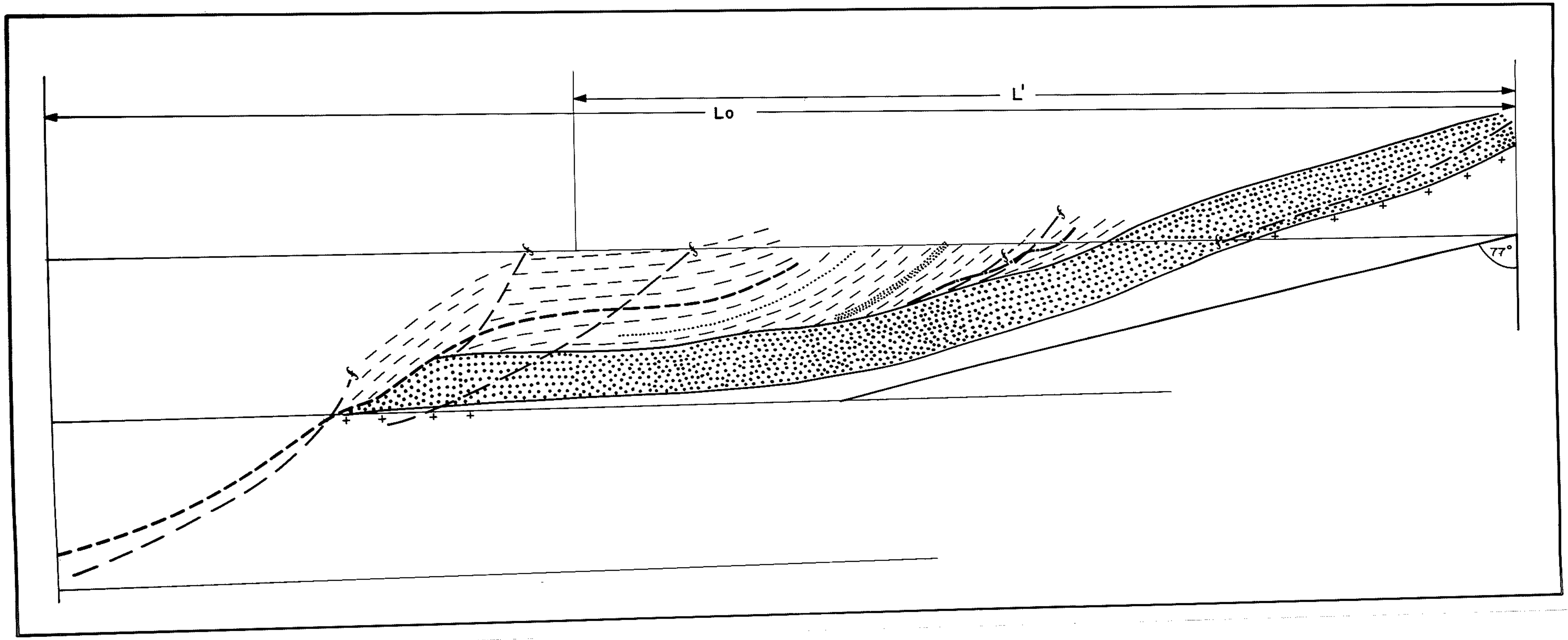


Figure 28 : *Palinspastic reconstruction of Section x–y in Figures 2 and 4. The reconstruction has been taken up to the Brixton Formation Quartzite only, i.e. it incorporates the Basement, Orange Grove Quartzite and Parktown Shale formations. The effect of bedding-plane-faulting on the lowermost contact of the Parktown Shale Formation has not been accounted for. Estimates of strain are thus clearly conservative.*



<u>Figure 29</u> : Palinspastic reconstruction of Section w-z in Figures 2 and 4. The reconstruction has been taken as far as the Brixton Formation Quartzite only. The reconstruction was not completed, because of the faulted relationship between the Parktown Shale and Orange Grove Quartzite formations. Since the absolute stratigraphic thicknesses of the lowermost members of the Parktown Shale Formation are unknown for this area, more precise reconstruction is not possible. The calculation of strain, based on this section, therefore is underestimated.

$$\frac{L'}{L_o} = \frac{2r}{2\left(2r + \Pi r + \frac{2r}{\tan 30^\circ}\right)} = 0{,}116$$

The factor 2 in the denominator is for the anticlinal structure that has been removed by thrust-faulting. The value of 2r measured from geological sections is 566 m. L_o is, therefore, 4,87 km, and the amount of shortening for the fold-structure is about 4,30 km. When this value is added to that obtained from the palinspastic reconstruction of the unfolded members, i.e. 1,63 km, a total of 5,9 km is obtained.

Both calculations serve to illustrate that estimates involving at least 6-7 km of shortening are indicated for this area. These values are considered to be a minimum, for reasons indicated above and also because the flattening component of strain has not been taken into account. The large lens-shaped bodies of Brixton Formation quartzite, for example, indicate that flattening has taken place.

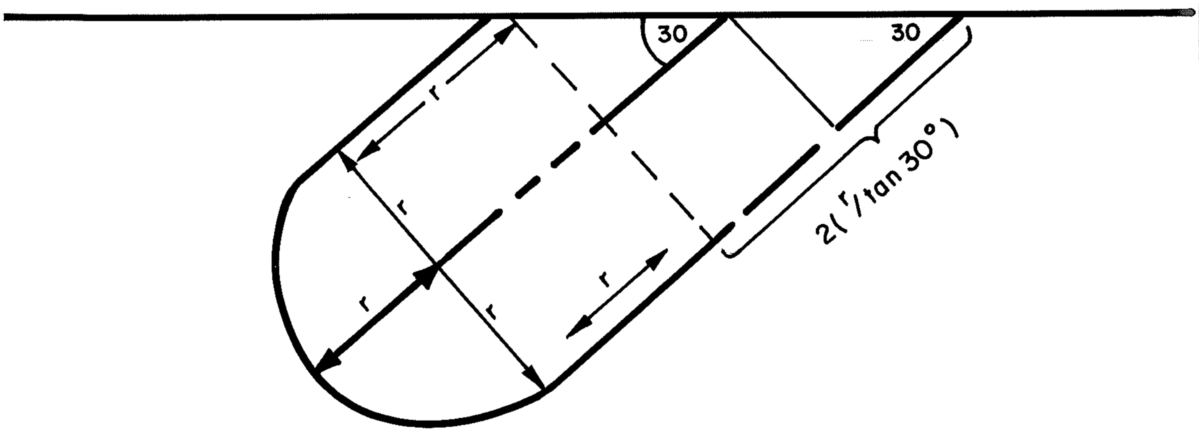


Figure 30 : *An idealized fold-profile of the Brixton Formation quartzite, prior to disruption by faulting.*

Another factor for the estimation of strain can be derived from the tectonic fabric of the Parktown Shale. The component of shear-strain in a ductile shear-zone can be calculated from the angle between the plane of flattening and the plane of shearing (Ramsay, 1980; Sanderson, 1982). In its simplest, two-dimensional form, the pertinent relation is :

$$\delta = \frac{2}{\tan 2\Theta'}$$

where δ is the component of shear-strain and Θ' is the angle between the maximum principal-strain axis and the shear-plane (Ramsay, 1980). At Swartkops, the assumption has been made that shear-planes are parallel to bedding. The tectonic fabric-plane is oriented at 22° to the bedding-planes. Using this angle, the component of shear-strain can be calculated as :

$$\delta \;=\; 2,07$$

Integrating over a total thickness of 530 m for the observed width of Parktown Shale results in a finite shear displacement of 1,1 km. This value can be compared with that of 1,63 km, derived from the palinspastic reconstruction for essentially the same group of rocks. The value is smaller because : (i) it does not take into consideration any of the Orange Grove quartzites; (ii) it has been shown earlier that Θ' becomes smaller where Parktown Shale lies in contact with the Brixton and Orange Grove quartzites; (iii) it does not account for any bedding-plane slip between the quartzites and shales; and (iv) δ is a component of shear-strain and not total shortening.

The comparison of values does indicate that shortening in excess of 1 km is feasible for the unfolded and thrusted Orange Grove and Parktown formations at Swartkops.

CONCLUSIONS

The present investigation has revealed that the rocks at Swartkops have been subjected to deformation of a magnitude which, previously, has not been anticipated within the confines of the Witwatersrand Basin. The fact that the area consists of an imbricated zone of thrust-slices involving both Witwatersrand strata and rocks which are generally correlated with the Ventersdorp Supergroup necessitates a re-examination of current concepts of pre-Transvaal tectonics.

Although previous workers have made suggestions about the existence of thrust-faults within the area, their interpretations have met with resistance and have not been accepted unequivocally. Hendriks (1961), correctly, proposed the existence of several thrust-faults, but his observations made no mention of the abundance of fault-tectonites, such as mylonites, pseudo-tachylites, and breccias, within the Witwatersrand rocks. Mention was made of the intense shearing and brecciation which is associated with the thrust-fault at the base of the Ventersdorp Supergroup. Earlier workers did not investigate the significance of the tectonic fabric, and, because of this, thrusting was suggested to be from west to east. Where the fabric was examined, it was considered to have formed from a pure-shear, and not from a simple-shear, deformation.

In general, most Witwatersrand geologists have considered the deformation within the Basin to be largely due to faulting, and, where folds are developed, they have been considered to be open (Brock and Pretorius, 1964; Toens and Griffiths, 1964; Roering, 1968). It is clear that the quartzites have not been subjected to any significant regional metamorphism, i.e. the intensity of folding and metamorphism has not been strong enough to produce a regional, pure-shear, axial-planar fabric. Folds associated with reverse-faults have also been described, but are uncommon (Winter, 1964; Olivier, 1965). The deformation, as revealed by the folds at Swartkops is, therefore, quite different to any described so far in the Witwatersrand Basin. The Brixton Formation quartzites, lying in the core of the structure, are isoclinally folded and the overlying limb is overturned, which indicates severe deformation. However, even in this instance, no axial-planar fabric has been developed in these quartzites, and the structure has been sheared subsequently, to produce a macro-breccia.

Although reverse- and thrust-faults have been referred to by other investigators (Winter, 1964; Olivier, 1965; McCarthy et al., 1982) these have been seen as isolated faults. The thrusting at Swartkops is not confined to an isolated fault, but comprises a system of thrust-faults, which is more characteristic of major folded-mountain regions, such as the Alps. Fletcher and Gay (1971) have been the only researchers on Witwatersrand structure, to date, who have suggested that bedding-plane faults, with displacements of several kilometres, are present within the Witwatersrand Basin. They quote an example, in the Carletonville Goldfields, of a gravity-slide into the basin, which type of deformation differs from that recognized in the Swartkops area.

When all the data from the investigated area are integrated, the structure is best interpreted by means of a thrust-fault system. A uniformly-oriented tectonic fabric is associated with the faulting and is, therefore, a result of a simple-shear strain. This fabric has an east-west orientation and dips towards the south at 30°. The orientation of the fabric implies that the overlying layers, or thrust-slices, moved in a northerly direction, to produce this shear strain in which the fabric was formed. The large fold-axes and certain of the lineations are oriented in a north-south direction and lie in the fabric-plane, indicating that pre- and syn-deformational linear structures tend to orient themselves in the direction of tectonic transport. Tensile phenomena, revealed by boudins, foliation boudins, and quartz veins are oriented in a dominantly east-west direction. These combined data support a tectonic movement directed from the south towards the north. All the major and minor structures can be integrated into this single deformational period.

Observations made in rocks surrounding Swartkops indicate that this deformational period also involved successions which are currently correlated with the Ventersdorp Supergroup, but not those of the Transvaal Supergroup. This confirms the previous observations of Hendriks (1961). The small shear-zone in the underlying granite indicates that the relatively-homogeneous granites also have been subjected to shearing in an east-west direction.

Estimates of strain suggest a shortening of at least 6-7 km. If this same degree of shortening is applied to the entire area from Swartkops, through the Witwatersrand outcrops at Honingklip, to the West Rand Syncline, a contraction of 40 km would be involved. Such estimates indicate that the deformation of Witwatersrand rocks is much greater than has been thought previously to be the case.

Several large shear-zones, which have an east-west strike and a steep dip to the south have been found in the granites of the Johannesburg Dome. These are significantly large structures and are clearly pre-Transvaal Supergroup in age. When considered together with the highly-sheared and mylonitized rocks at Honingklip, these shear-zones reveal that the deformation at Swartkops was not an isolated event, but is related to a major period of crustal contraction.

REFERENCES

Bally, A.W. (1981) - Thoughts on the Tectonics of Folded Belts - *in* K.R. McClay and N.J. Price (eds.), Thrust and Nappe Tectonics, Geological Society, London, p. 13-32.

Boyer, S.E., and Elliot, D. (1982) - Thrust Systems - Bulletin, American Association of Petroleum Geologists, v. 66, p. 1196-1230.

Brock, B.B., and Pretorius, D.A. (1964) - An Introduction to the Stratigraphy and Structure of the Rand Goldfield - *in* S.H. Haughton (ed.), The Geology of Some Ore Deposits in Southern Africa, Volume I, Geological Society of South Africa, Johannesburg, p. 25-62.

Butler, W.H. (1982) - The Terminology of Structures in Thrust Belts - Journal of Structural Geology, v. 4, p. 239-245.

Cobbold, P.R., and Quinquis, H. (1980) - Development of Sheath Folds in Shear Regimes - Journal of Structural Geology, v. 2, p. 119-126.

Corstorphine, G.S., and Jorissen, E. (1908) - The Stratigraphy of Swartkop 82 - Transactions, Geological Society of South Africa, v. 11, p. 55-68.

Fletcher, P., and Gay, N. (1971) - Analysis of Gravity Sliding and Orogenic Translation : Discussion - Bulletin, Geological Society of America, v. 82, p. 2677-2682.

Frankel, J.J. (1939) - The Green Colour of the Hospital Hill Quartzites - Transactions, Geological Society of South Africa, v. 42, p. 15-17.

Hall, A.L. (1905) - Annual Report for 1905 - Transvaal Geological Survey, Pretoria, p. 63-77.

Hall, A.L., and Humphrey, W.A. (1906) - The Black Reef Series and the Underlying Formations in the Neighbourhood of Kromdraai and Swartkop, North of Krugersdorp - Transactions, Geological Society of South Africa, v. 9, p. 10-18.

Hatch, F.H. (1905) - Geological Map of the Transvaal (Second Edition) - Stanford's Geological Establishment, London.

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

Kynaston, H. (1906) - Annual Report for 1906 - Transvaal Geological Survey, Pretoria, p. 12.

McCarthy, T.S., Cadle, A.B., and Horrocks, P. (1982) - Thrust Faulting in Witwatersrand Rocks at Langerman's Kop, Johannesburg - Transactions, Geological Society of South Africa, v. 85, p. 189-201.

Mellor, E.T. (1917) - The Geology of the Witwatersrand : Explanation of the Geological Map of the Witwatersrand Gold Field - Geological Survey of South Africa, Pretoria, 46 pp.

Molengraaff, C.A. (1902) - Geological Sketch Map of the Transvaal - E. de Geest, ?

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 - Transactions, Geological Society of South Africa, v. 68, p. 143-175.

Platt, J.P., and Vissers, R.L. (1980) - Extensional Structures in Anisotropic Rocks - Journal of Structural Geology, v. 2, p. 397-410.

Ramsay, J.G. (1980) - Shear Zone Geometry : a Review - Journal of Structural Geology, v. 2, p. 83-99.

Roering, C. (1968) - The Tectonics of the West Rand Syncline : a Field Study of Brittle Failure in the Witwatersrand Basin - Information Circular 48, Economic Geology Research Unit, University of the Witwatersrand, Johannesburg, 28 pp.

Sanderson, D.J. (1982) - Models of Strain Variation in Nappes and Thrust Sheets : a Review - Tectonophysics, v. 88, p. 201-223.

Skjerna, L. (1980) - Rotation and Deformation of Randomly Oriented Planar and Linear Structures in Progressive Simple Shear - Journal of Structural Geology, v. 2, p. 101-109.

Toens, P.D., and Griffiths, G.H. (1964) - The Geology of the West Rand - *in* S.H. Haughton (ed.), The Geology of Some Ore Deposits in Southern Africa, Volume I, Geological Society of South Africa, Johannesburg, p. 283-322.

Watchorn, M.B. (1981) - The Stratigraphy and Sedimentology of the West Rand Basin in the Western Transvaal - Unpublished Ph.D. Thesis, University of the Witwatersrand, Johannesburg, 154 pp.

Winter, H.D. (1964) - The Geology of the Virginia Section of the Orange Free State Goldfields - *in* S.H. Haughton (ed.), The Geology of Some Ore Deposits in Southern Africa, Volume I, Geological Society of South Africa, p. 507-548.

oOo