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Inhoud

Thrusting, folding and stratigraphy of the Ghaap Group along the southwestern margin of the Kaapvaal Craton

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The lower sedimentary sequence of the Transvaal Supergroup, i.e. the Schmidtsdrif Subgroup, the Campbellrand Subgroup, the Naute Shale Formation, and the Asbesheuwels Subgroup (BIF), underwent multiple folding and thrusting along the southwestern margin of the Kaapvaal Craton, between Prieska and Boegoeberg Dam. This tectogenesis is expressed in three folding phases with successively diminishing intensities. Thrusting occurred during the first and second phase. The first tectonic episode predates the Makganyene mixtite and thus the Ongeluk lava (>2240 Ma). The second deformation postdates the deposition of the Matsap strata (>1780 Ma). Various types of thrust phenomena peculiar to the BIF are described. Crustal stress was directed into the northeastern quadrant, very low angle thrusts being exposed as far as 80 km away from the southwestern craton rim (northeast of Niekerkshoop). The effects of the thrusting in BIF of the Asbesheuwels Subgroup may reach as far north as Kuruman. The stratigraphy of these rocks needs to be reviewed, taking into account the complex structure.

Die laer sedimentêre eenhede van die Supergroep Transvaal, nl. die Subgroep Schmidtsdrif, die Subgroep Campbellrand, die Formasie Nauteskalie en die Subgroep Asbesheuwels (GYF), het almal veelvuldige plooiing en oorskuiwing meegemaak langs die rand van die Kaapvaalkraton tussen Prieska en Boegoebergdam. Hierdie vervorming word weerspieël in drie plooifases met progressief afnemende intensiteit. Oorskuiwings het gedurende die eerste en tweede fases plaasgevind. Die eerste episode is ouer as die Makganyene mikstiet en dus die Ongeluk lava (>2240 Ma). Die tweede vervorming is jonger as die Matsap strata met 'n ouderdom van >1780 Ma. Verskillende oorskuiwingsverskynsels wat kenmerkend van GYF is, word beskryf. Oorskuiwing was altyd ooswaarts en lae hoek oorskuiwings kan so vêr as 80 km noordoos van die suidwestelike kratonrand (noordoos van Niekerkshoop) opgespoor word. Tekens van oorskuiwing in GYF van die Asbesbeuwel Subgroep word sovêr as Kuruman (260 km noord van Prieska) gevind. Die stratigrafie van hierdie gesteentes moet hersien word in die lig van die jongste struktureel-tektoniese bevindings.

Introduction

The stratigraphy and sedimentary facies development of the Griqualand West Sequence of the Transvaal Supergroup were investigated by Beukes (1980, 1983), who introduced a new stratigraphic subdivision, based mainly on borehole core data. The lower part of the supergroup was named Ghaap Group and subdivided into the Schmidtsdrif-, Campbellrand-, Asbesheuwels-, and Koegas Subgroups (Beukes, 1983). The Schmidtsdrif Subgroup starts with a basal conglomerate upon the Upper Archaean Seekoebaard Formation. The Koegas Subgroup is overlain with an angular unconformity by the Makganyene mixtite, which is

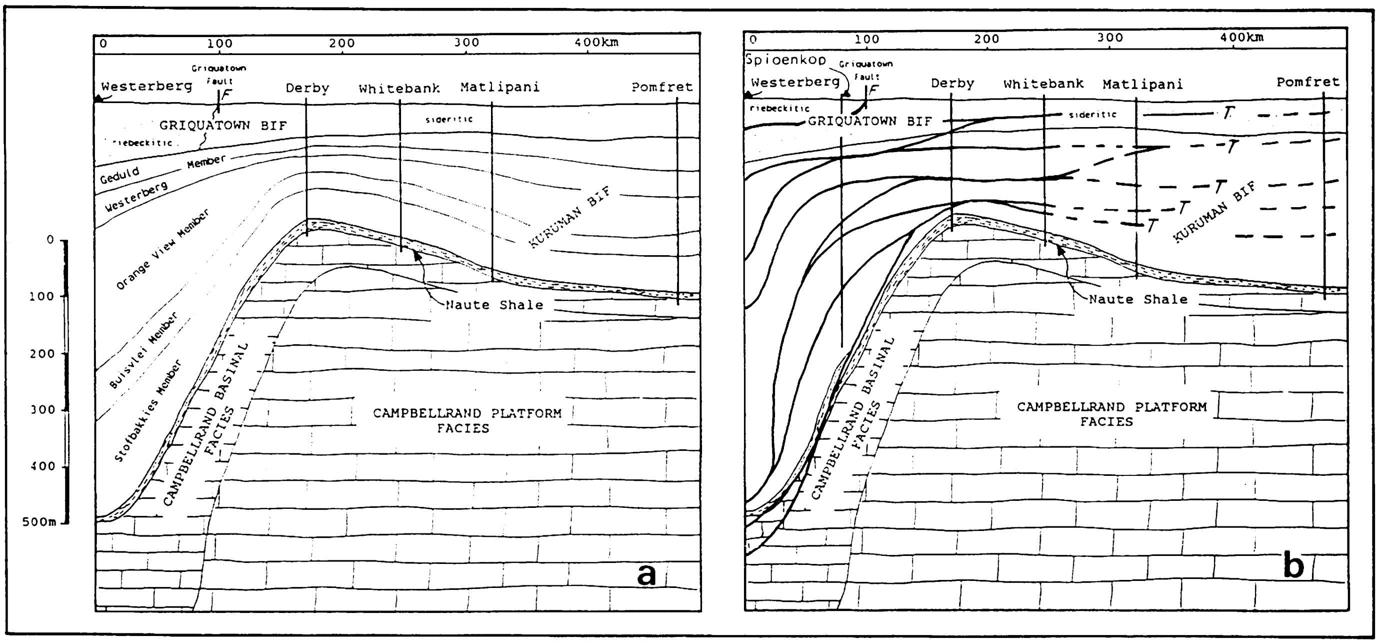

Figure 1 Simplified schematic sketch of the Transvaal sediments in Griqualand West, in a N–S profile. (a) as interpreted by Beukes (1980), (b) as interpreted in present paper. Note the distances between the borehole localities. Thrusting was observed in the Whitebank (WB98) and Spioenkop (SPI) boreholes (compare Figure 22 and text).

unconformably followed by the Ongeluk Andesite Formation (Altermann & Hälbich, submitted). The subgroups were divided into formations of which mainly the lower, microbanded Kuruman Formation and upper, clastic-textured Griquatown Formation (Beukes, 1983) of the Asbesheuwels Subgroup are dealt with in the present paper. In the area discussed, the Campbellrand Subgroup is separated from the Kuruman Formation of the Asbesbeuwels Subgroup by the Naute Shale - a pile, several tens of meters thick, of pelites and intercalated cherts. The thicknesses as reported by Beukes (1983) are from bottom to top: 10 – 250 m for the Schmidtsdrif, 650 – 1 900 m for the Campbellrand, 150 – 750 m for the Kuruman, 200 – 300 m for the Griquatown and 240 – 600 m for the Koegas. According to Beukes (1983) the stratigraphic thickness of the Kuruman and the Griquatown Formations increases southwards from the NNW-SSE-trending Griquatown synsedimentary fault zone to almost double their thickness north of the fault (Figure la).

However, recent fieldwork in the area between Prieska, Koupoort and Boegoeberg Dam (Figure 2) has revealed structural features mainly in the Campbellrand and Asbesheuwels Subgroups that call for a reinterpretation of the tectonic and stratigraphic history of this area. The aim of the present contribution is to alert the reader to the fact that the stratigraphy of the formations in the area between Koupoort, Prieska, and Boegoeberg Dam (Figure 2) is influenced by tectonics to such an extent, that lateral correlations of members in the Kuruman and Griquatown BIF from the Kuruman - Danielskuil area in the north to the present southwestern craton margin should only be accepted after the stratigraphy has been mapped out in detail. We suggest that the rapid changes in thickness of the formations and subgroups towards the southwestern margin of the Kaapvaal Craton are not of sedimentary origin, but rather caused by folding and thrusting of the strata as proposed in Figure lb.

Previous work

The age of the Griqualand West Sequence can only be fixed by the ages of the associated volcanic rocks.

According to SACS (1980) and Schlegel (1988), the Matsap Formation which overlies the Ongeluk lava tectonically as well as with an unconformity in the present study area (Vajner, 1974a,b; Altermann & Hälbich, submitted) is a part of the Volop Group. The Volop Group

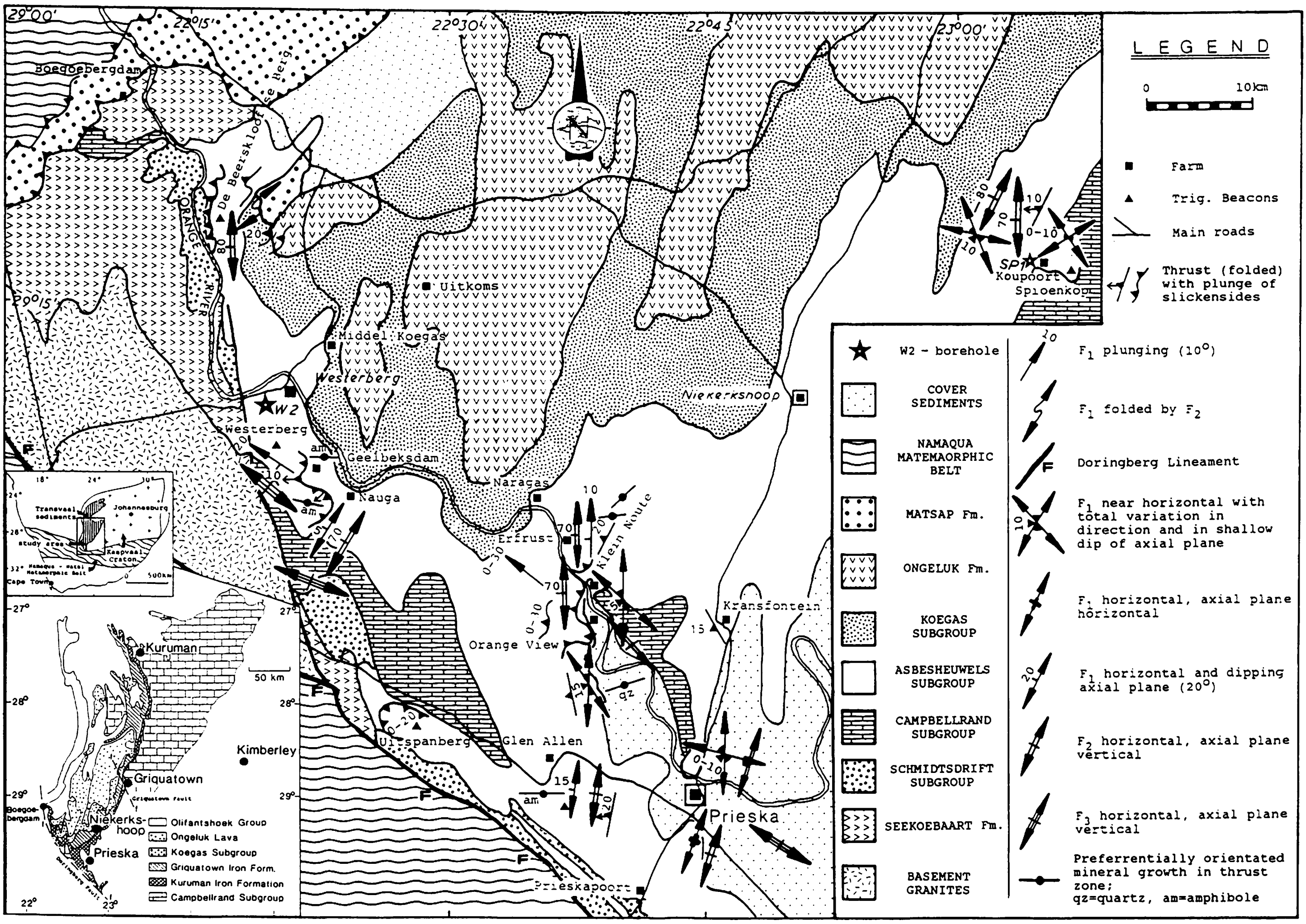

Figure 2 Koupoort - Prieska - Boegoeberg Dam area showing thrust and fold fabric as measured and mapped. SP1 = Spioenkop borehole. Stratigraphy is simplified after Vajner, (1974a). The Ongeluk lava forms the cores of upright, open F_2 mega-synclines, gently refolded during F_3 to produce F_2-axial depressions.

again, is a part of the Olifantshoek Sequence. The latter is apparently now considered (Schlegel, 1988) as a time equivalent of the Kaaien Group of the Kheis Tectonic Province. The Matsap Formation must have an age between that of the underlying Hartley Andesite Formation at a minimum of 2 070 ± 90 Ma and the overlying Groblershoop acid lavas at a minimum of 1 780 Ma (SACS, 1980).

The Ongeluk lavas in Griqualand West have been dated at 2 240 ± 57 Ma (Walraven *et al.*, 1982). The equivalent Hekpoort lavas from the Transvaal Sequence have an age of 2 224 ± 21 Ma (SACS, 1980).

The Seekoebaard Formation of Vajner (1974a) has been subdivided especially along its northern outcrops in the type area (SACS, 1980). Some parts are thought to belong to the Vryburg Formation of the Schmidtsdrif Subgroup (Fölscher, 1978) and others are correlated with even younger rocks of the Hartley Formation (Smit, 1977). The absolute age of the remaining parts of the Seekoebaard Formation was dated at the order of 2 200 Ma (Walraven *et al.*, 1982) which, compared to the much better determined age of the Ongeluk lava (2 240 ± 57 Ma, Walraven *et al.*, 1982), is too young. Lavas from the Ventersdorp Supergroup of the Transvaal date between 2 300 Ma and 2 600 Ma and it is likely that the Seekoebaard lavas are of similar age. This was recently confirmed by Armstrong (1987) who found an age of 2 745 ± 628 Ma for the Seekoebaard Formation, and an age of 2 363 +114/−120 Ma for the unconformably overlying Vryburg Formation (Schmidtsdrif Subgroup).

From the above considerations it is clear that the deformation episodes recorded in the Ghaap Group rocks of the study area can not be accurately defined at present.

Although thrusting and complex folding was discussed already by Visser (1944) in the area under investigation, the possible effect on stratigraphy was never considered by previous workers.

The tectonic imprint on the Boegoeberg - Westerberg area (Figure 2) was discussed by Vajner (1974a), who recognized three deformation episodes. The first one of pre-Skalkseput basement granite age (2 542 ± 50Ma, Walraven *et al.*, 1982) produced two sets of structures, F_1 and F_2, that are manifested mainly in the Kheis Tectonic Province and will not be further discussed here. The second episode 'indicates that deformation of the deposits in the Kaapvaal intrageosyncline and the subsidence of the basin were closely related'. (Vajner, 1974a, p.171). This author also recognized different styles of structures, that could have resulted from gravity gliding mainly in the banded ironstones. However, he states (Vajner, 1974a, p.172): 'Important is the fact, that large scale thrusts and nappes are absent in the area under consideration and that cascade folds have also not been found.' Vajner also misinterpreted the mechanism. According to him these structures formed by flexural slip (Vajner, 1974a, p.111 and 172). The third episode is marked by post-Matsap deformations that affected all rocks on the craton and the foreland and produced F_3 and F_4 folds. F_3 is characterized by N to NE plunging structures with E to SE vergence, whereas F_4 folds are mainly upright with a northwesterly trend.

The same author investigated the influence of the Doringberg Fault in the area under discussion. This feature runs from Prieskapoort, northwestwards (Figure 2) and is a major tectonic lineament zone, that affects both the Kheis Tectonic Province and the exposed craton basement (Draghoender, 2 900 Ma and Skalkseput, 2 542 ± 50 Ma basement granites) alike. Fault splays trending northerly (Figure 2), also penetrate the cover rocks slicing through the Seekoebaard Formation and the Ghaap Group along the Orange River. According to Vajner (1974a,b) the Doringberg Fault system is genetically related to the F_4 phase of deformation manifesting N–S directed right-lateral, oblique slip, produced by anticlockwise rotation of the craton relative to the Namaqua Metamorphic Complex.

Vajner (1974a) also described limited thrusting in the Ghaap Group (p.114 and p.110) and relates it to both post-Matsap fold phases. However, he does not comment on the consequences of this faulting and its possible relationship to the gravity tectonic phase.

According to Vajner (1974a) metamorphic grades in the Ghaap Group do not exceed the lawsonite – albite facies (Winkler, 1979) at 250°C.

Visser (1944) made a significant - and in the past often underrated - contribution to the tectogenesis of the rocks in northern Griqualand West. He recognized up to six thrust planes pushing slabs of the Transvaal Supergroup eastwards onto the craton. Some of his profiles are very reminiscent of what we see at Debeerskloof (Figures 6+7).

Potgieter & Nel (1979), mapped a locally restricted, double thrust plane in the Kuruman Formation, near Uitspanberg beacon, west of Prieska (Figure 2). The planes dip westwards at low angles. From Potgieter's (1981) figure 3.18, it is not clear whether these thrusts are folded. Drag effects point to north-eastward movements in the hanging wall.

More recently Beukes & Smit (1987) presented stratigraphic and structural evidence of thrusting that postdates the deposition of the Olifantshoek Group along the north-western margin of the Kaapvaal Craton. The system of low angle westerly dipping faults and mylonite zones is described as the Blackridge thrust system and has been traced from Black Rock in the north to Rooinekke in the south over a distance of about 180 km. The authors suggest that this happened 2 000 to 2 200 Ma ago, during the Koranna - Kheis orogeny.

Altermann & Hälbich (submitted) describe three phases of deformation along the southwestern craton rim and demonstrated that the first phase of deformation predates the deposition of the Makganyene mixtite and therefore predates the 2 240 Ma for the Ongeluk lavas as the mixtite cuts with an angular unconformity across cataclasites in the Koegas Subgroup. A D_4 (here called F_2) is of post-Matsap (>1780 Ma) age since it affects Matsap sediments. Furthermore they suggested that a D_6 (here called F_3) is most probably of Namaquan age (1 100 Ma).

Structural features

Folding

In the area under consideration the intensity of deformation generally decreases in a north–easterly direction. Open, upright north plunging mega-folds are a prominent regional feature along the Asbestos Mountains in southern

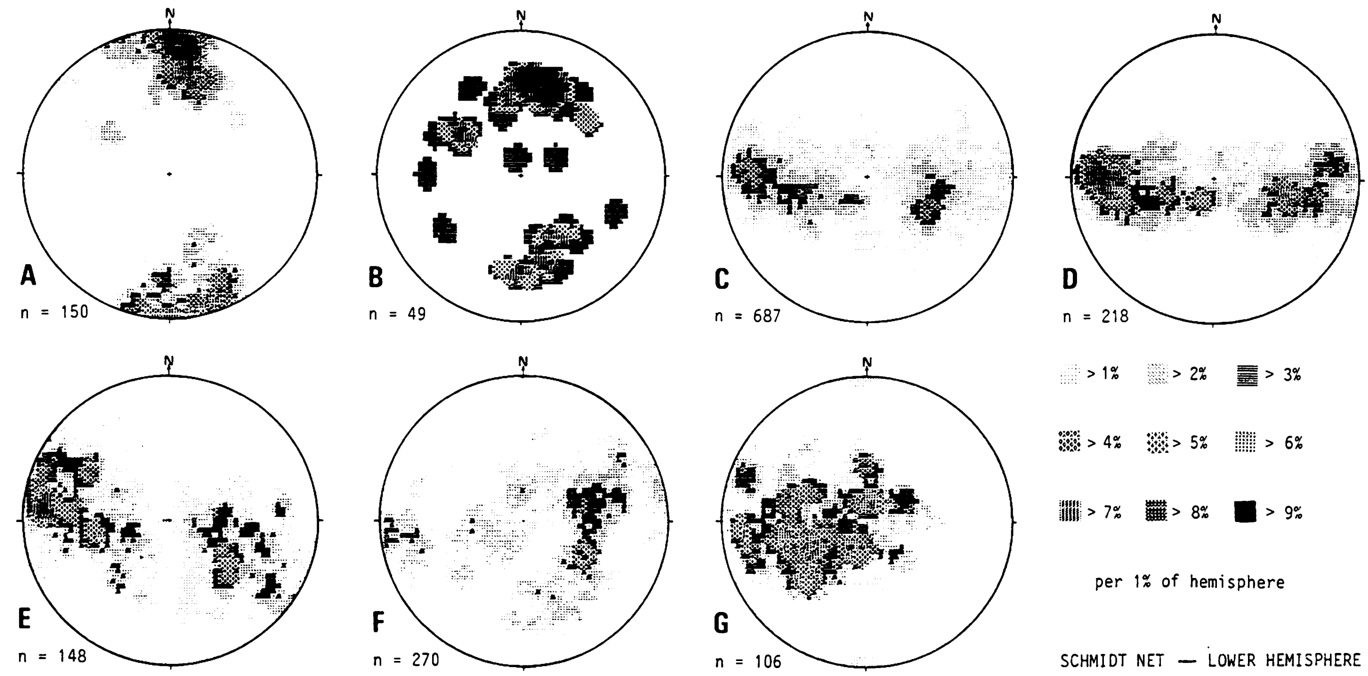

Figure 3 Fold-fabric from Westerberg Mountain. A: All directly measured fold axes. B: Directly measured fold axes plunging >30° (included in A). C: π_{ss}-poles from all bedding planes. D: π_{ss}-poles to bedding planes from all N–S trending folds. E: π_{ss}-poles to bedding of all NE–SW trending folds. F: π_{ss}-poles to bedding of all NW–SE trending folds. G: π_{ss}-poles to all conical and non-cylindrical folds.

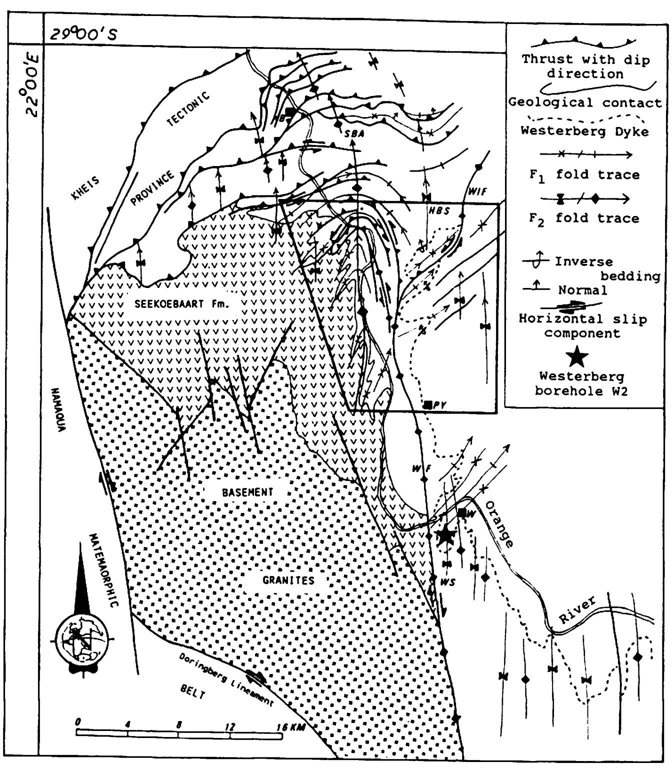

Figure 4 The Namaqua Foreland at the western edge of the Kaapvaal Craton between Westerberg (W) and Boegoeberg Dam (B). WF = Westerberg Fault, WIF = Witberg Fault, PY = Pypwater, WS = Westerberg Syncline, HBS = Hardeberg Synform, SBA = Seekoebaard Antiform. Inset shows area covered by Figure 6.

Griqualand West. However, tight meso-folds and single monoclinal macro-structures verging E to SE also occur. In the area around Westerberg beacon (Figure 2) bedding attitudes and fold axes plots indicate that near horizontal as well as plunging structures occur on mesoscopic to macroscopic scale (Figure 3). Folds plunging at more than 30° constitute about one third of the total set of B-axes (Figure 3b) in BIF. This shows that more than one folding phase occurred. A well defined B-maximum plunging north at a very low angle (Figure 3a) reflects the general attitude of most folds. This is well supported by rather wide but distinct great circle girdles of bedding poles (Figures 3c,d) defining a β-maximum (or π_{ss}-pole) coinciding with this B-maximum. The subset of B-axes (Figure 3b) defines a small circle girdle of steeply plunging B-axes about a vertical cone axis. This is also born out by the small circle of π-poles of conical, plunging folds in Figure 3g. π_{ss} from NE and NW plunging folds in Figures 3e and 3f affirm that different sets of folds exist. Linear and bedding data from the area around Debeerskloof give similar results.

In the field two generations of minor folds commonly interfere in the same outcrop to produce a type 3 pattern (Ramsay, 1967), and less frequently also type 2. Vajner's map clearly shows that these interference patterns of type 3 on a mega-scale dominate the entire Ghaap Group outcrops between Boegoeberg Dam and Debeerskloof (Figure 4). On the farm Bo Seekoebaard, south verging F_1-anticlines of Campbellrand carbonate that plunge NE to the west of the Orange River, are wrapped around the N-plunging Seekoebaard antiform (SBA) to become NW-plunging synforms east of the river (Figure 6). This pattern is repeated several times from north to south. It is obvious that

Figure 5 Oblique view of interference folding in BIF south of and along the axial trace of the Westerberg Syncline (Figure 4). High amplitude (several 100 m), low wavelength south-trending F_1-folds dominate the picture. Vergence of F_1 is to the left, i.e. to the east. Refolding by subparallel F_2 and cross-trending F_3 can be made out from the variation in axial plane and axial plunge attitude respectively of deformed F_1 folds. Bedding discontinuity, occurs below arrow. The photograph displays a major double dêcollement in Kuruman BIF with upper and lower less intensely folded zones separated by a highly folded sequence with recumbent F_1 folds.

the SBA is an F_2 structure superimposed on SW–NE trending, and southeast-verging, or recumbent asymmetric earlier folds. Its effect rapidly diminishes south of Lelikstad and into the Seekoebaard lavas. The F_2 Hardeberg synform (HBS) of much lesser intensity is best developed in the Matsap Formation and rapidly wanes southwards against the Witberg Fault (WIF) (Figure 4). F_2 mega-structures developed west of the Orange River in Matsap beds are rather open folds and Vajner (1974a) reports similar styles from the Seekoebaard Formation. It seems that the more or less rectangular block of basement granite partly covered by a thin veneer of Seekoebaard lavas as shown in Figure 4, served along its eastern edge as a step over which the cover rocks were folded obliquely down to the south during F_2 east–west compression, causing intense shortening and left lateral shear. The strike direction of the SBA is paralleled southwards by the much younger dextral Westerberg Fault (WF), that merges with earlier, folded thrusts of the F_1 phase having a left lateral component (Figure 4).

The style of macro- to mega-folding near Westerberg is between type 2 and type 3 (Ramsay, 1967) interference, except that F_2 fold wavelengths are much shorter than north of Debeerskloof. F_1 recumbent folds trending N–S as refolded by subparallel upright F_2 structures and by cross-trending F_3 folds are displayed in Figure 5, taken only 3 km south of the Westerberg syncline, near Westerberg beacon (Figure 2). The stratigraphic borehole W2 was drilled in this syncline to a depth of 960 m below surface. The stratigraphic profile as recorded by Beukes (1980) from this borehole does not show any tectonic complications in the penetrated strata. In our opinion Figure 5 proves that correlations of strata intersected in this borehole with those from any other boreholes or profiles (Beukes, 1980) can no longer be done without palinspastic reconstructions.

The F_3 fold phase was of minor importance throughout the area under investigation. It is defined by upright, WNW–ESE trending very open structures, tens of metres to kilometres in wavelength. Because of their low amplitude the effect on F_1 and F_2 structures is difficult to assess quantitatively, but some of the N- and S-plunging fold axes maxima in Figure 3 and the variable plunge effect seen in Figure 5, may be due to this factor. F_3 folds are best detected only east of the Westerberg - Prieska line

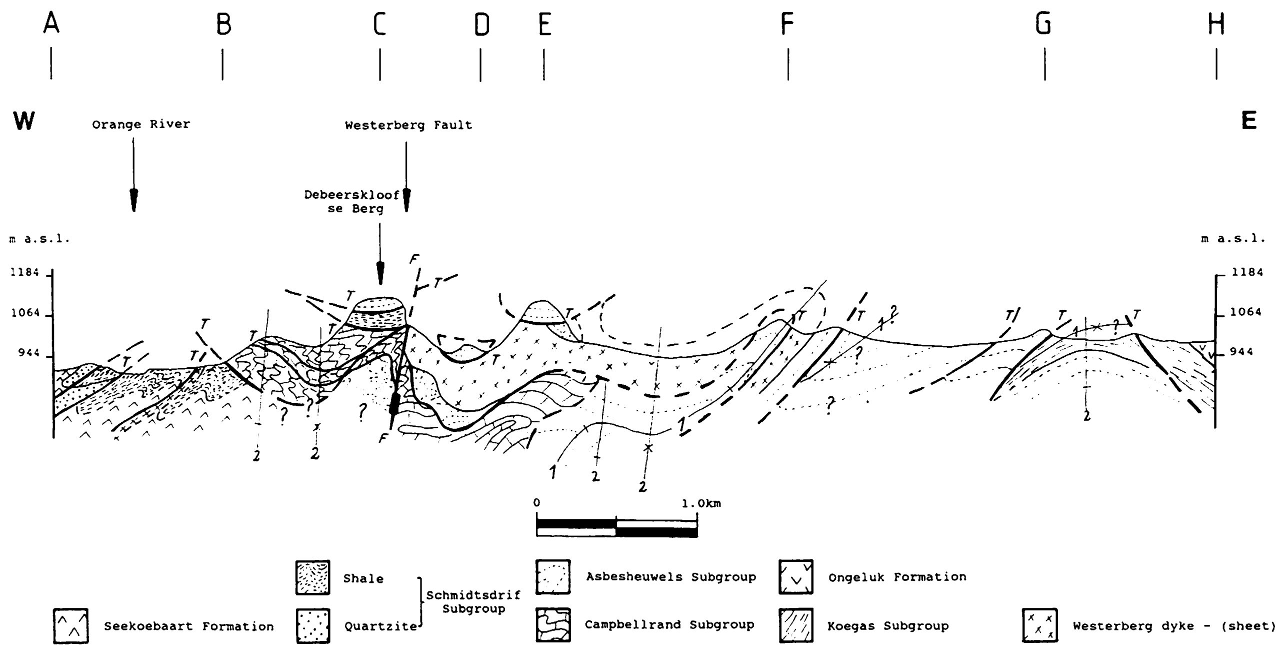

Figure 7 Tectonic and stratigraphic section through Debeerskloof with interpretation. For positioning see Figure 6.

Figure 8 Silicified and ferruginized thrust breccia at the Debeerskloof. The zone dips easterly at about 50°, subparallel to the bedding in carbonates and can be followed for several kilometres, to the north and south of Debeerskloof, east of the Orange River.

Figure 9 Ferruginous and siliceous solution breccia along a thrust plane in carbonate at Debeerskloof.

(Figure 2) and away from the area of intense F_2 folding. No cleavage related to F_3 folding has been found. Where the pelitic rocks exhibit two cleavages in riebeckite-lutites, the younger is always an axial plane feature of F_2 folds.

In places thin lutite bands in BIF carry two cleavages oriented at large angles to each other and to slip lineations on bedding planes. Two generations of asbestos fibre have grown in the BIF of the Koupoort area (Figure 2) and elsewhere. The first generation developed at right angles to bedding and was later rotated by simple shear parallel to bedding. In some cases this fibre assumes a fan-shaped orientation around F_1 folds and a new generation of crocidolite has grown parallel to the axial plane within the core of these structures.

Faulting phenomena

Vajner (1974a) mapped many N–S trending faults along the Orange River. The most prominent one, here named Westerberg Fault (WF in Figures 4 and 6), is probably part of the Doringberg Lineament, for it is parallel to the strike direction of this lineament and rapidly develops right lateral displacement towards the south. We found that some of the N-S faults in BIF and Koegas strata north of Pypwater (Figures 4 and 6) are actually steeply dipping, deformed thrust faults that fit the refolding pattern with its very intense first phase of deformation. On the farm Pypwater, and southwest of the farm house, the Westerberg Fault joins a thrust plane in carbonates (Figure 6), where the thrust has been rotated subvertically by F_2 folding. From here on towards the north, the Westerberg Fault clearly develops a new breccia within the older thrust zone. Dextral dislocation seems to have been superimposed on a first order F_1 thrust plane. The Doringberg Lineament and its splay faults, such as the Westerberg Fault are late Namaquan structures (Vajner, 1974b) and will not be further discussed here.

A detailed E–W profile through Debeerskloof reveals the following structural and stratigraphic features (Figures 6 and 7). From west to east many dislocations are found over a 6 km section. Several of these are folded by F_2. They follow sedimentary contacts or cut across them on all scales. They merge and bifurcate, and also duplicate the stratigraphy by thrust stacking (Figure 7). On a more regional scale thrust breccias can be followed (Figure 4) from Pypwater to Boven Seekoebaard, where they wrap around the Seekoebaard F_2 megafold (SBA) together with the F_1 folds. The authors mapped one breccia around a synformal closure just west of the mega-F_2 (SBA) trace (Figure 6) and reinterpreted the geology on Vajner's map (1974a) taking the new findings into account. There can be little doubt that these thrust faults originated during the F_1 phase. In some of the structures a left lateral component is recognized, eg. the Witberg Fault (Figure 4). Before refolding by F_2, these initially NE-trending structures probably originated by oblique slip in a direction which agrees fairly well with movements deduced from preferred mineral growth directions across F_2 folds within thrust zones further south in the study area (Figure 2). However, it is also possible that the observed left lateral slip component on maps is produced by flexural slip on the F_2 Seekoebaard antiform, reactivating existing thrusts of the F_1 phase.

Various thrust phenomena have so far been identified in BIF and other lithologies on Debeerskloof, Westerberg, Geelbeksdam, Nouga, Klein Naute, Orange View, Glen Allen, Prieska, Kransfontein and Koupoort-Spioenkop (Figure 2). The thrust planes exhibit various features, partly dependent on the lithology. In carbonate formations at Debeerskloof (Figure 7) the western most thrust breccia is from 1–2 m thick and consists of ferruginous carbonate-quartz breccia. Aggressive iron- and silica-rich fluids obviously migrated along the movement zone producing a gossan-like appearance (Figures 8 and 9). Where thrusts affect shales, the latter are comminuted and sheared with concomitant silicification. The rock has lost its primary, well bedded, or continuously laminated character to develop a flaser texture over zones from decimetres to many metres thick.

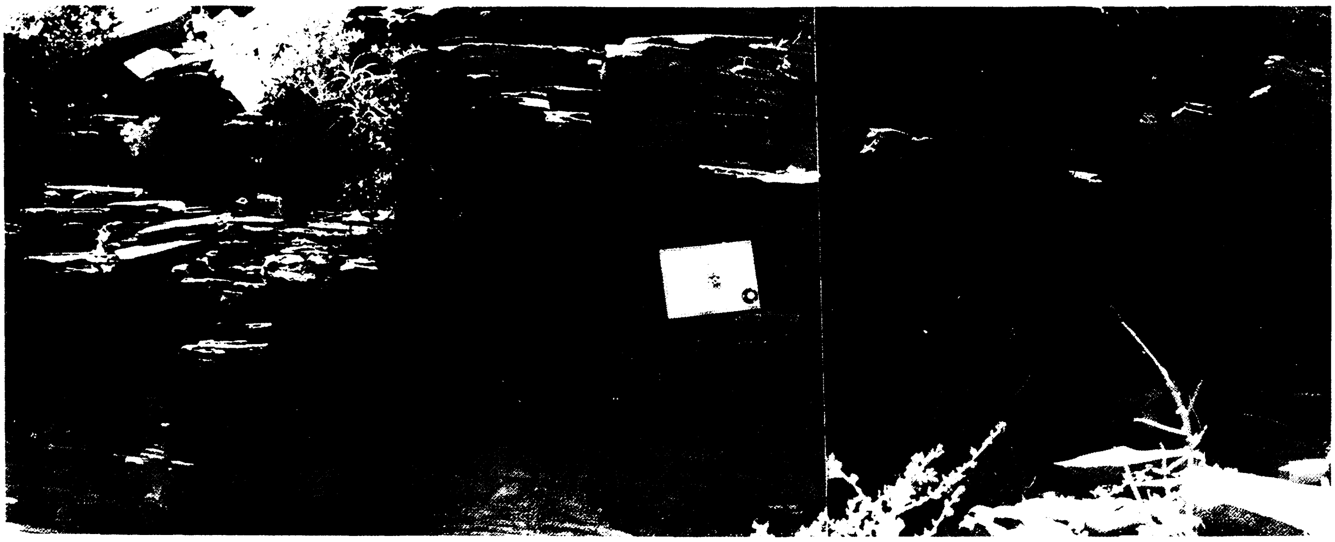

Figure 10 Discrete thrust plane at Koupoort, intersecting bedding planes in BIF, at an angle of about 10°. The long edge of the sun-compass (15cm long) rests on the dislocation plane which exhibits slickensides trending E–W. Note the brecciation to the right (northeast) of the compass and above the dislocation plane.

Some examples of the thrust phenomena from banded iron formations are discussed below:

(1) smaller thrusts that often go unnoticed, appear as discrete bedding-parallel slip planes, that become visible only once they cut across the primary bedding at very low angles (Figure 10). They can be followed for at least several metres. Displacements are of the order of decimetres along a single plane and always from the SW into the NE quadrant for the hanging wall, as determined by duplication and verified by slickensides. Usually thrust zones in stratigraphic sequences contain several of these thrusts per vertical metre of section, as for example at Koupoort;

(2) another example occurs at Koupoort, where a mylonitic ferruginous carbonate breccia, 10–50 cm thick and subparallel to bedding, has developed with sharp contacts to the overlying and underlying strata (Figure 11). It exhibits drag and shear effects, dips about 10°–15° to the NW across the bedding and is accompanied by higher angle synthetic splay faults. Slickensides are oriented ±W–E while rod structures lie across this trend. This carbonate breccia must be the concentrated residuum of the sideritic part of the BIF, since no pure sedimentary carbonate bands crop out here within the entire sequence. These zones have been followed for at least several hundreds of metres along and across strike. At Koupoort for instance the structure is clearly displayed on both walls of the canyon that is some 400 m wide;

(3) in other places, as at Kransfontein and Prieska, there are sheet-like zones, up to 1 m thick of high amplitude,

Figure 11 The Koupoort thrust looking southeast. Note the very acute angle with which the thrust plane cuts down through the stratigraphy near the right hand edge of the picture. Strata dip at 5°–10° to the west along the eastern limb of the Ongeluk-Witwater synclinorium. Cliff is about 70 m high.

Figure 12 Type 3 thrust zone writh sharp upper contact to undisturbed BIF of the Kuruman Iron Formation and 'grading' lower contact. A dislocation obliquely transects the zone from the lower left to the upper right. Movement of the hanging wall is from left to right (W to E). Locality: Prieska National Road-cut. Scale bar = 10 cm.

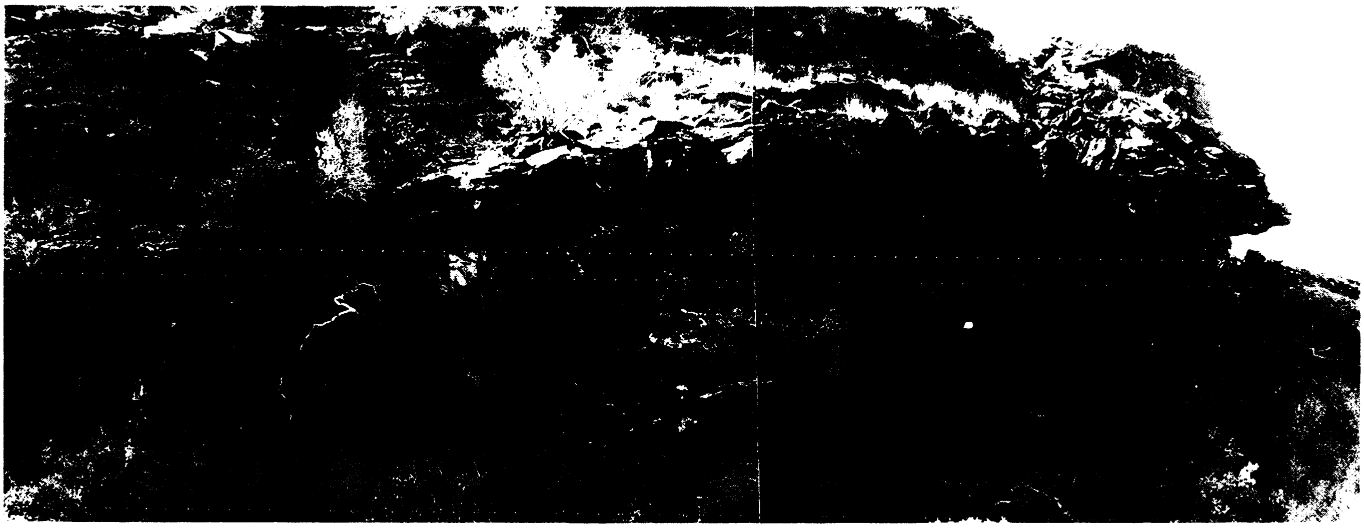

Figure 13 Thrust zone of type 4 on Glen Allen (Figure 2). East is on the right. Movement was from W to E in the hanging wall as proven by drag and slickensides. The central portion, weathering positively is a phyllonite, about 1 m thick. Long edge = 30 m.

recumbent intrafolial folds. Within these, discrete shear planes may develop parallel to the axial planes of these folds, cutting through the hinges and limbs. The direction of movement of hanging walls as indicated by the fold geometry and rather variable axial orientations, is to the NE, E, and SE. Contacts to unaffected bedding above and below are usually sharp decollement planes (Figure 12). Folds are stacked on top of each other (cascade folds), as at Spioenkop (Figure 2), where a disturbed sequence, over 10 m thick, can be traced for at least 1 km across and along strike. The recumbent nature of many of the folds in type 3 dislocation zones, as well as the considerable variation in the direction of fold hinges indicate substantial translation along early-formed gravitational slumps of major proportions following a regional gradient (Farrell & Eaton, 1987). North-trending, upright-to-NE-vergent, open F_2 folds such as the SBA or the Westerberg Syncline may refold cascading recumbents that must have originated during the F_1 phase of deformation (c.f. Figure 5);

(4) a fourth variety is represented by zones of phyllonitized BIF (Figures 13, 14 and 15), metres to tens of metres thick, with internal areas and marginal subzones of chaotic folds (Figure 16) grading into breccia (Figure 17). Sliced mesofolds stacked on top of each other reveal the intensity of deformation (Figure 18). These faults have been followed for several kilometres in places, without a termination (Figure 2). All transitions from type 4 to type 3 above are encountered.

The thrust on Glen Allen (Figures 2 and 13) grades upwards and downwards into zones of asymmetric shear folds (Figure 14) that reveal the easterly movement of the hanging wall. The thrust plane dips across the bedding at very low angles to the west. At Klein Naute and Erfrust (Figure 2) two thrust zones separated by some 30 m of undisturbed BIF strata can be mapped in the lowermost Kuruman Iron Formation. The lower one, some 50 m above the Naute Shale is of the Koupoort breccia variety (type 2), but with siliceous gouge. The upper thrust is of the Spioenkop variety (type 3) with transport directions of the hanging wall towards E and NE as is evidenced by slickensides and rod structures.

On Orange View (Figure 2) three thrust zones occur

Figure 14 Detail of drag folds above and below the phyllonite in Figure 13. Looking south.

Figure 15 The lowermost thrust zone of type 4 on Orange View. Just below the middle of the picture a 1,5 m thick phyllonite zone cuts via a sharp tectonic contact across a prominent chert lens (light grey) in dragfolded, brecciated BIF. Looking southwest.

Figure 16 Chaotic folding found in marginal subzones and irregular masses inside wide thrust zones of type 4. Scale bar = 10 cm, location Klein Naute.

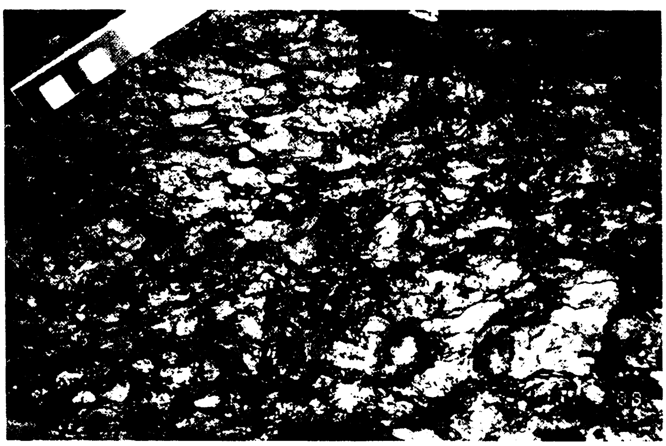

Figure 17 Brecciated BIF in a thrust zone of type 4. Scale bar subdivided in cm, location Klein Naute.

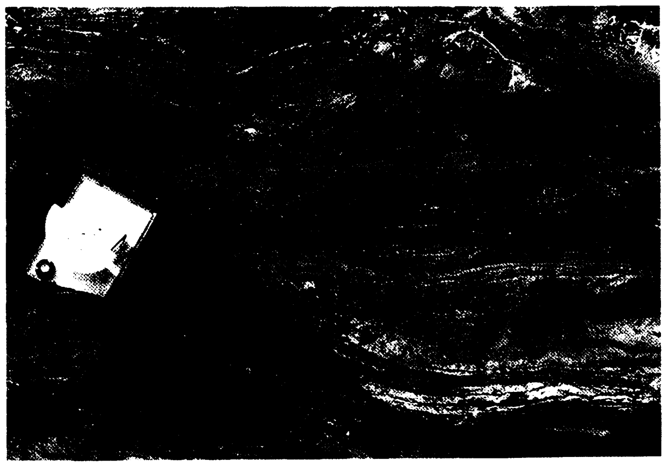

Figure 18 Disrupted and sliced recumbent folds stacked on top of each other reveal the internal structure of the 1,5 m thick disturbed zone above the knife sharp thrust plane in Figure 15. Looking north. Long edge of sun-compass = 15 cm, location Orange View.

higher up in the Kuruman Iron Formation. The lowest one is an up to 3 m thick type 4 feature, whereas the two upper ones are the Spioenkop type, with intrafolial folds on a centimetre to decimetre scale. The structures on Orange View were later folded by NNE-trending, E-facing, F_2 macro-folds (Figure 19).

On Geelbeksdam and Nouga (Figure 2) type 4 thrusts are accompanied by metamorphic growth of large pyroxene and amphibole crystals (Figure 20) with strongly preferred orientation (Altermann, Cornell and Hälbich in preparation). They lie parallel to the movement direction and to the dip of the type 4 thrust, but across associated small shear fold axes. Silicified asbestos fibre (tiger's eye) recrystallized in short limbs of these shear folds (Figure 21).

In the Geelbeksdam area (Figure 2) slickensides and dragfolds at the direct contact between the Kuruman Banded Iron Formation and the Campbellrand carbonate show that the former is thrust onto the carbonates. This was already mapped as a normal contact by Vajner (1974a).

Between Middle Koegas and Westerberg (Figure 2) a slab of iron-rich dolomite with magnetite bands, several tens of metres thick and a few hundred metres long, is infolded into the Kuruman Iron Formation with no intervening Naute Shales. However, the contacts with the banded iron strata are obliterated by an intrusion of the diabase dyke (Westerberg sill of Vajner, 1974a). Contact metamorphism produced centimetre size magnetite crystals in the dolomite and the iron formation.

The Westerberg 'sill', usually several tens of metres thick, definitely is more of a dyke-like intrusion, which in some places exhibits intense cleavage or even schistosity. In most places the dyke, however, appears unfoliated. It

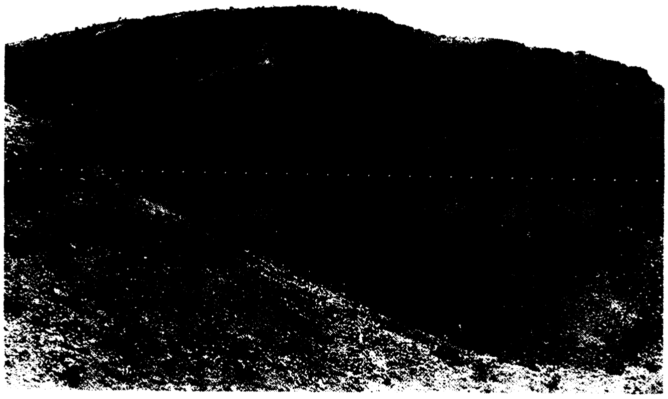

Figure 19 F_2 folds at Orange View, facing east. Thrusts almost parallel to the bedding are folded by these north-trending structures and therefore belong to the F_1 phase of recumbent flow folding and thrusting.

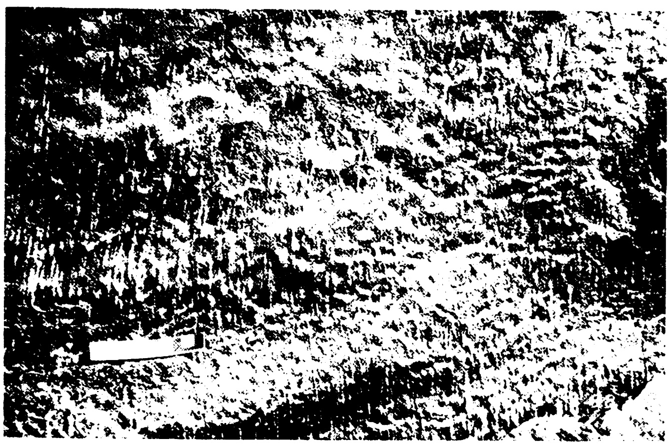

Figure 20 Preferred orientation (top to bottom) of metamorphic amphibole and pyroxene in a thrust zone of type 4 on Geelbeksdam (Figure 2). Note the orientation across tectonic ripples. Scale bar = 10 cm.

Figure 21 Silicified asbestos fibre ('tiger's eye') recrystallizing in cores of small shear folds developing inside type 3 and type 4 thrust zones on Klein Naute (Figure 2). East is to the right. Note the much lower pseudoviscosity of two (light grey) riebeckite-lutite layers in the lower half of the picture. These are loci of decoupling with concentration of slip movement to the extent that kink bands above and below these layers no longer match. Scale: long edge of photo = ±20 cm.

commonly follows the F_1 and F_2 structures along the F_1-related thrust planes. Therefore the intrusion is post F_1 and pre-F_2 in age.

At Debeerskloof (Figures 6 and 7) most thrust zones in BIF are of type 3 or 4 and may be several tens of metres wide in outcrop. Where these are refolded by the Seekoebaard F_2 antiform farther north, some of them have very steep dips with moderately to steeply plunging refolded meso-cascade folds.

The core of the 500 m deep borehole SP1 (Figure 2) from the farm Spioenkop (lat. 29°12′09″, long. 23°02′57″) was studied for correlation with the surface features. In the vicinity of the collar the strongly riebeckitic, nearly horizontally disposed units of the riebeckite jaspilite zone in the Danielskuil Member of the Asbesheuwels Formation (Du Plooy, 1986, Griquatown Formation of the Asbesheuwels Subgroup of Beukes, 1980; 1983), become intensely folded and sheared along intrafolial zones. These represent type 3 and type 4 thrust fold phenomena none of which can be recognized in the 4 cm diameter core. This could be expected because the fold structures are recumbent with large amplitudes and small wavelengths. However, some features reminiscent of 1–2 cm thick bands of pseudo-conglomerate are seen, which would normally be obscured in surface outcrops. These features were sampled at depths of 100,48; 102,70; 121,23; 150,00; 200,30; 318,00; 323,80; and 318,00 m, and also occur at other levels in the core.

Microscopically only the slides from 150,00 and 200,30 m depth show sedimentary clasts, together with flow banding and eye structures (possibly tectonic). The other samples are tectonic microbreccias with cataclastic textures, showing microshear planes (Figure 22a). All transitions from parallel to anastomosing and mylonitic foliation with microblastesis of minerals (mainly recrystallized carbonate) are present (Figure 22b). A well-developed second generation of transverse cleavage is seen in riebeckite and greenalite bands. The mineralogy of these sections is still under investigation (Altermann, Cornell and Hälbich in preparation).

On Koupoort, in the riebeckitic jaspilite, close to the intrafolial zone mentioned above, a sheared and brecciated jaspilite band is overlain by a strongly cleaved riebeckite-lutite band. The latter has sheath folds with long axes parallel to cleavage. There can be no doubt that intense shearing has disrupted these structures (Figure 23).

The relationship between F_1 folds and thrusts

The style of F_1 megafolds that developed north of Westerberg is very similar to that of the regular folds in thrust zones found everywhere in the study area. Also, north of Westerberg F_1 megafolds and thrust zones are both deformed by F_2 structures. We have to conclude that many

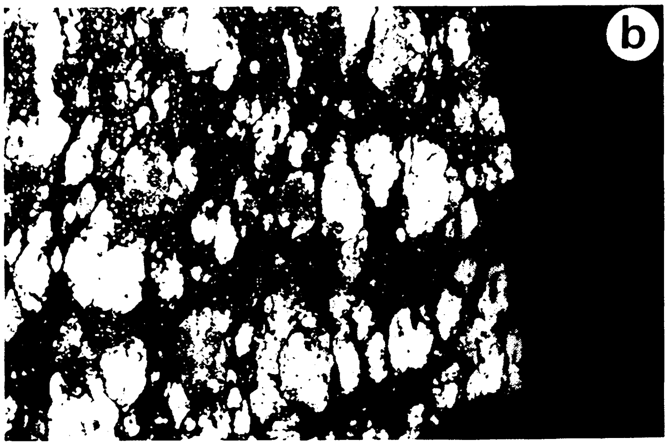

Figure 22 Photomicrographs of a shear zone. **a**: at 318 m in borehole SP1. Note the cataclastic to mylonitic texture along and above the upper dislocation. Less distinct, but just as real are similar textures along the lower discontinuity which follows bedding for some distance from the lower middle. Long edge of the photomicrograph = 7 mm. **b**: borehole SP1 at 102,7 m. Riebeckitic mylonite to cataclasite with microblastesis of carbonate and quartz. Long edge of photomicrograph = 14 mm.

of the thrusts found in the study area have originated during the F_1 phase of folding, probably towards the end of that phase. South of Westerberg the only F_1 folds found have developed in thrust zones. A rejuvenation of some F_1 thrusts may have occurred during the F_2 phase as discussed above and faults such as the Witberg Fault may represent post F_2 thrusts.

Crocidolite mineralization

Mobilization of riebeckite lutites along shear planes and fold-thrust zones is very conspicuous in the field as far north as Koupoort - Spioenkop. Riebeckite crystallizes along shear bands in thrust zones. Large volumes of BIF south of the Griquatown Fault display very conspicuous zonally developed riebeckitization. This change in the geochemistry of the BIF is being investigated in conjunction with crocidolite mineralization, regional metamorphism, thrusting and tectonic pumping of fluids along bedding planes of the BIF- sediments.

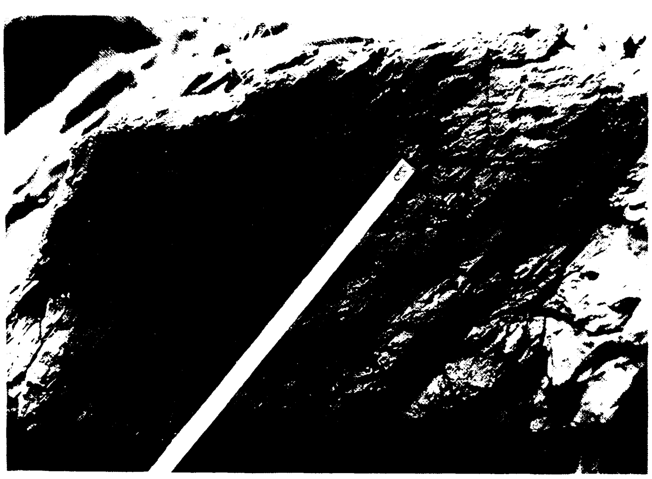

Figure 23 Intensely folded and cleaved riebeckite-lutite band within a cataclastic jaspilite band (not seen). Cleavage set parallel to long axis of sheath fold seen in vertical E–W section, looking north.

Discussion

Thrusts and their stratigraphic significance

The geology described above asks for a new interpretation including the stratigraphy and facies distribution of the Transvaal basin in Griqualand West.

Beukes (1980) interpreted the rapidly increasing thickness of the sequence above the Campbellrand Subgroup from the Griquatown Fault southwards as a thickening sedimentary fill of a basin at the edge of the Kaapvaal Craton. Considering the tectonic complications reported above, this explanation becomes somewhat problematic. Even more difficulties arise when trying to correlate the facies distribution and stratigraphy of the Westerberg - Koegas area with the banded ironstones farther north i.e. from Derby, Whitebank, and Matlipani, as proposed by Beukes (1980). These boreholes are located tens to hundreds of kilometers apart from each other (Figure la). Beukes (1980) relied strongly on evidence from borehole cores and applied cyclic sedimentation principles. The general usefulness of the latter cannot be doubted, but its reliability is in question when correlating over vast distances in rocks now found to have been repeatedly disturbed by low angle thrusts. In none of the borehole profiles published by Beukes tectonic features are described or taken into account. However, it suffices to compare our Figure 5 with Figure la or with the Figure 10 of Beukes (1980, pp.80) to realize that the stratigraphic correlations can not be that simple.

Furthermore, in the borehole WB98 from Whitebank, north of Kuruman (comp. Figure 1b), a pseudo-conglomeratic lenticular, bedding parallel layer was found at a depth of 228,3 m, within laminated to finely bedded autochthonous iron formation of the lower Tsineng Member of the Kuruman Iron Formation (Beukes, 1980). Meso- and microscopically this conglomerate is a bedding-parallel breccia consisting of fragments of finely bedded, ferruginous shale with stilpnomelane laminae set in a chlorite - epidote matrix. Epidote is of late growth, filling straight fissures and arcuate cracks in the matrix and penetrating the fragments along an incipient cleavage that is parallel to axial planes of micro-folds of pre-fragmentation age. The chlorite in the matrix grows along shear zones that detach the fragments and flow around them. Where matrix chlorite becomes shear-folded and comminuted a new generation of chlorite grows parallel to new shear planes. The pre-fragmentation folds in the shale might still be of synsedimentary derivation, but the recrystallization in a bedding parallel shear zone at greenschist grades must be of tectonic origin. The Kuruman Formation north of Kuruman therefore bears evidence of layer-parallel dislocations with accompanying metamorphism. Layer-parallel breccias can be followed out in several places in the transition zone from the Campbellrand Subgroup to the Asbesheuwels Subgroup, along the Asbestos Mountains from Kuruman to just north of the Griquatown Fault. A nearly horizontally disposed fold at a depth of 173 m in the borehole WB 89 seems to be of tectonic origin. The drill twice penetrated the core of the fold and clearly exhibits duplication of strata on a metre scale. At 244,8 m a stratigraphic discontinuity is repeated three times over a core length of several decimetres. It is possible that more duplications of this kind remain unrecognized in borehole cores used directly for thickness estimates and stratigraphic correlation. D.D. Klemm (pers. comm.) reports quartz mylonitic textures from thinsections of banded iron formation in the Finsch Mine area.

The investigation of Beukes & Smit (1987) following earlier ideas of Nel (1929) and especially Visser (1944), demonstrates thrusting and stratigraphic duplication of post-Olifantshoek age (post-Matsap), in the area between Black Rock in the far north and Rooinekke (the latter 90 km directly north of Westerberg). Surprisingly, they seem to assume that this did not affect the stratigraphy of BIF in the Kuruman Mountains to the east, probably because of the intervening Maremane Dome structure. However, this is the ideal tectonic setting for generating very low angle thrusts under supplementary tectonic stresses decreasing exponentially from the point of applied stress, in this case the original western rim of the craton and the pre-deformational Maremane promontory (Jaroszewski, 1984). In the present study the strongest tectonic impact occurs along the south-western margin of the Kaapvaal Craton. In Figure 7 for example, a vertical section across Debeerskloof se Berg shows Kuruman BIF overlain by Campbellrand carbonate, followed by shale overlain by Kuruman BIF again. Lithological units are separated by folded thrust planes and tectonic breccias (Figures 6 and 7). Further to the east and south, on the farm Pypwater thrusting of BIF strata onto Koegas strata has been mapped (Figure 6). A similar situation has been found on the farms Grasgat, and Koegas (Altermann & Hälbich, submitted.)

The subdivision of the BIF into autochthonous and detrital or endoclastic iron formation by Beukes (1980) is not doubted by the present authors, but considering the tectonic complications described above, the stratigraphical significance of the lithology is questioned. The two facies may represent lateral equivalents and some of the so-called marker beds should therefore be re-examined in the light of possible tectonic origin and stratigraphic duplication on a large scale.

It is suggested here, that within what is commonly regarded as the Griquatown Formation (Beukes 1980, 1983), there are tectonised horizons that went unnoticed. In the Koupoort/Spioenkop area, Du Plooy (1986) mapped the upper part of the banded ironstones, including the thrust zones as the Danielskuil Member (Griquatown Iron Formation of Beukes), obviously also interpreting tectonic features as synsedimentary slumping and clastic sediments. Structures regarded as drag-induced folds along vertical faults and monoclines by Du Plooy (1986), have now been recognized as thick piles of thrust folds (cascalde folds), because of their lateral extent and recumbent attitude similar to those shown in Figure 5. The various members of the Kuruman Iron Formation as distinguished by Beukes (1980) in Griqualand West are not traceable along the southwestern present rim of the Kaapvaal Craton and in the Westerberg borehole (see discussion above and Figure 5) . Therefore, we suggest that the lithostratigraphic subdivision of the Kuruman and Griquatown Iron Formations should be reestablished by taking into account the tectonic development described here. This of course can only be done after more detailed studies, which would allow palinspastic reconstruction of the entire Ghaap Group in Griqualand West. Because of a lack of valid mappable subdivision of the BIF, it is impossible at the present stage of investigation to demonstrate stratigraphic duplications by thrusting within the BIF. However, stratigraphic duplication of BIF upon Koegas Subgroup has been demonstrated together with the occurrence of intense and repeated folding and thrusting on all scales. Duplication of strata by isoclinal recumbents, and by vergent folds on a scale up to hundreds of meters is clearly evident from our Figures 5, 18, and 19.

Age of the sedimentation and tectogenesis

Mineral phases that developed a preferred orientation during blastesis in thrust zones are at present being extracted for radiometric dating of this episode. This hopefully will tell us when the cover rocks of the Kaapvaal Craton were deformed for the first time along its present north-western and western rim. Zircons from tuff in BIF and newly grown micas from cleaved shales are under investigation to determine the age of sedimentation and the tectogenesis respectively.

The basic intrusion in Figures 4, 6, and 7 (Westerberg sill of Vajner 1974a) postdates F_1 as well as some of the thrusts, considering that it follows type 3 and type 4 thrust zones for many kilometres and cuts across them in places. Other faults interpreted as renewed or extended thrusts (eg. Witberg Fault, Figure 4) cut across the intrusion. Multiple movements seem to have occurred on some thrust planes that were reactivated during F_2.

Altermann & Hälbich (submitted) have argued that the first deformation episode is older than the 2 240 ± 57 Ma (Walraven *et al.*, 1982) or 2 239 + 90/− 92 Ma (Armstrong, 1987) age for the Ongeluk lava, but postdates the deposition of the Koegas Subgroup because it affects these rocks but not the lava. The second episode must postdate the deposition of the Matsap sediments, which are affected by F_2- megafolds trending N–S. This episode would best correlate in time with the Blackridge thrust system of Beukes & Smit (1987).

The syn- to post-depositional, NE-trending, gravitational tectonics and the F_3-stage of Vajner (1974a) in the Transvaal sediments most probably correspond to our F_1 stage. Our F_2 stage is considered identical with Vajner's F_4 event, as their morphologies and their strike directions are very similar. The F_3 stage of the present paper was apparently overlooked by Vajner, possibly because he concentrated on the heavily tectonised areas along the border of the craton to the Namaqua Mobile Belt.

The sequence of deformation

Recumbent, refolded F_1 flow folds (Figures 4 and 5) are initially produced varying in orientation from N–S to E–W (Figure 2). Vergencies are always to the NE, E, or SE. East of a line through Glen Allen and Naragas (Figure 2) the total variation is developed in meso-structures that occur only within thrust zones of the style shown in Figure 12, but often much wider than that and stacked on top of each other in cascades. West of this line the orientation of F_1-folds tends to become more stable with northeasterly trends dominating. In this area macro- and mega-F_1-folds are also found.

The entire F_1 episode testifies to unstable tectonic conditions near the present southwestern rim of the craton. In this area the outer boundary of basement blocks changes systematically from a NW–SE orientation in the south to a NE–SW orientation in the north, southwest of Boegoebergdam (Figure 2). It seems that the movement was constantly directed towards the boundaries of the basement blocks. This systematic change in movement direction produced varying fold trends on the craton. At present it is unknown whether this is progressive and whether a time sequence is also involved. The F_1 megafolds developed coevally with thrusts in the area north of Westerberg (Figure 2). These thrust zones bear internal F_1 mesofolds and seem to be of pre-Ongeluk age (>2 240 Ma), as can be seen on the farm Uitkoms (Figure 2), where the Makganyene mixtite cuts F_1 shear zone with an angular unconformity (Altermann & Hälbich, submitted).

The second stage (F_2), was associated with an E–W compression that produced rather open, upright megafolds in all rocks including the Seekoebaard lava. Along the eastern edge of a basement block shown in Figure 4, a prominent megafold pair, the Seekoebaard antiform and the Hardeberg synform, developed to higher intensities with left-lateral drag along existing thrusts along the closure of the antiform. The deformation of the eastern limb of this structure is very intense with dips and plunges being reversed in places. The authors assume a draping effect of older F_1-structures over an activated N–S trending step or edge in the basement. This may be a weak zone that also controlled the sedimentation of cover rocks. It was rejuvenated during the Namaquan tectogenesis when the Westerberg Fault, with a right lateral component developed along it.

The origin of the very gentle F_3-folds is rather obscure. They postdate F_1 and F_2 because they have an effect on F_1–F_2 axes distributions. Because their axes are more or less parallel to the general strike of the structures in the Namaqua Metamorphic Belt, it is suggested that they are of Namaquan age (1 100 Ma).

The distribution of rocks according to Vajner's (1974a) map is the result of F_2 interference with F_1. The Matsap and Ongeluk rocks, i.e. the youngest ones in the sequence, crop out where F_2 and F_3 synclinal structures intersect, while the oldest strata in the sequence are generally found along intersections of anticlines (Figure 2).

The influence of oblique wrench faults of Namaquan age on the rocks under investigation is not addressed in this contribution because they are of much younger age (Stowe, 1983; Vajner, 1974b) than the events discussed, and appear to be unrelated to movement directions described here. Their main area of influence is outside our study area. The Westerberg Fault, which is a splay fault of this age only transects or partly remobilises some of the thrusts.

Conclusions

1. The Kuruman and Griquatown Iron Formations (Beukes, 1980) south of the Griquatown Fault have been extensively affected by thrust faults during the F_1 and F_2 phase of deformation. Movements were directed east, north-east and south-east (Figure 2).
2. These deformations become more intense towards the present rim of the craton and affected mainly the Banded Iron Formations because of the incompetency of some of its beds, and their laminated character.
3. The F_1 phase pre-dates the Ongeluk lava (>2 240 Ma) but post-dates the deposition of the Koegas Subgroup. The F_2 phase is of post-Matsap (post-Olifantshoek, <1 780 Ma) age.
4. A third fold phase complicated matters especially near the craton margin, but its effect diminishes northwards and eastwards into the craton. The F_3 phase is probably related to the Namaquan event (1 100 Ma).
5. Thrusts severely affect the stratigraphy at the present (tectonic) craton margin and can be traced at decreasing intensities up to 80 km into the craton. Their full impact has not yet been evaluated towards the centre and north of the Transvaal Basin in Griqualand West.
6. There is evidence pointing to bedding-parallel thrusts and stratigraphic duplication in BIF even as far north as Kuruman.
7. The entire F_1 phase seems to be strongly influenced in direction and intensity by the configuration of rigid blocks in the basement along the present tectonically controlled south-western craton margin.

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