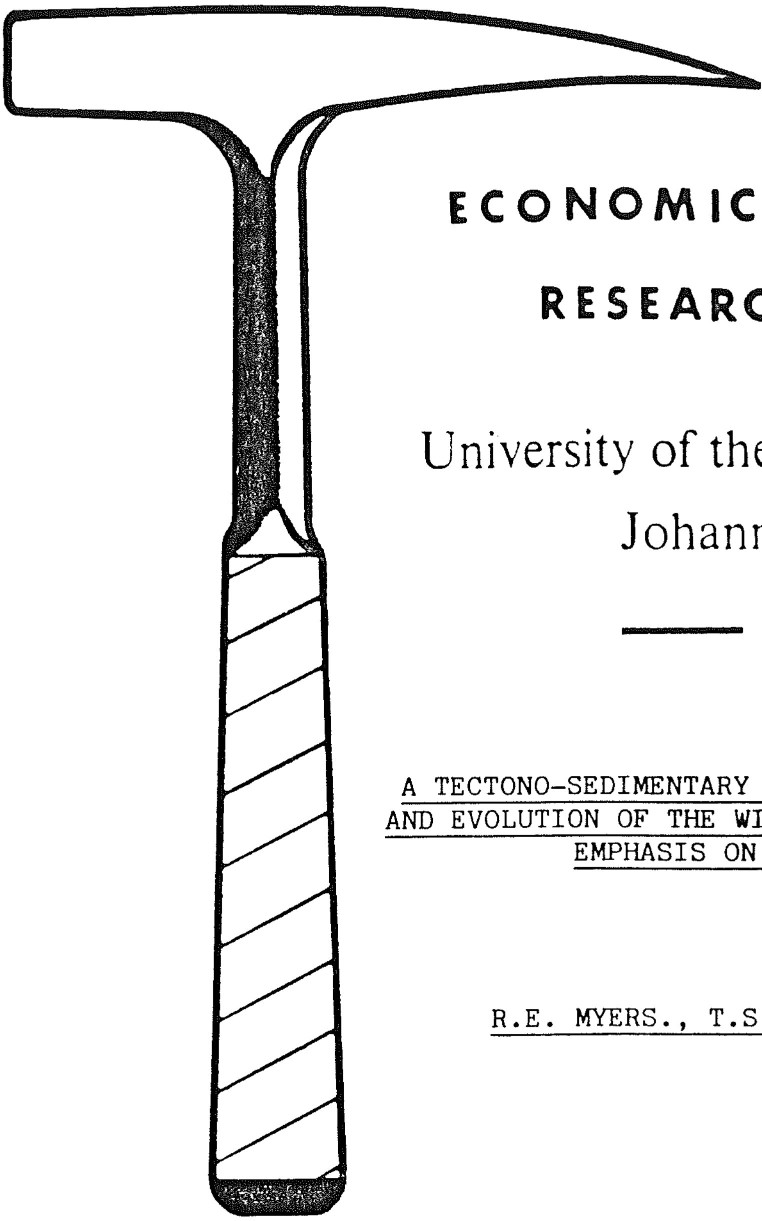

ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

A TECTONO-SEDIMENTARY RECONSTRUCTION OF THE DEVELOPMENT AND EVOLUTION OF THE WITWATERSRAND BASIN, WITH PARTICULAR EMPHASIS ON THE CENTRAL RAND GROUP

R.E. MYERS., T.S. McCARTHY and I.G. STANISTREET

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UNIVERSITY OF THE WITWATERSRAND
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by

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ABSTRACT

The Witwatersrand Basin has experienced several deformational episodes since its formation and it is therefore necessary to establish the sequential deformational history in order to obtain an understanding of the causes of basin development. The simultaneous use of structural and sedimentological information is essential in such an exercise. Back stripping of the deformations has allowed the writers to isolate those which occurred during Witwatersrand and Ventersdorp times. This analysis indicates that during Witwatersrand times the cratonic basement became fragmented into at least 18 large blocks which moved relative to one another by rotation and tilting, with the bounding structures behaving as reverse, oblique slip faults. Relative block motion gave rise to depressions in which sediments accumulated. Near to the edge of a depression adjacent to a rising block, sedimentary successions are characterized by rapid thinning and the development of vertically stacked sub-outcrops. Furthermore, in these areas the sedimentary rocks are often deformed into large monoclinal structures. In one case, syn-Witwatersrand uplift adjacent to such a monocline exceeded 7 km. In contrast, the interior of these blocks are characterized by very gradual changes in stratigraphic thickness. Although the individual blocks are discrete, all moved simultaneously in response to regional stresses, producing broadly similar stratigraphic sequences around the entire basin in spite of a diversity of entry points. Throughout most of the Central Rand Group times, the fluvial systems on the craton covered a far greater area than the present extent of the basin, but only sediments lying within the limits of subsiding blocks were preserved. Towards the close of basin history, the boundary structures became more active and may eventually have given rise to local source areas flanking the basin. Sedimentation was terminated by the eruption of the Klipriviersberg volcanics following which the regional stress field collapsed and the marginal faults were reactivated as oblique slip normal faults. Sediments and volcanics accumulated in the resulting grabens. The recognition of the role of basement fragmentation in controlling Witwatersrand Basin development and evolution has important implications for exploration for outliers of Witwatersrand stratigraphy.

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I. INTRODUCTION

The Witwatersrand Basin (Figure 1a,b) has attracted geological researchers for over a century because of its dominance in world gold production. In spite of this, concensus has not yet been achieved in regard to the true nature and evolution of this basin. Apart from the pioneering work of Brock and Pretorius (1964), researchers have tended to concentrate on stratigraphic and sedimentological aspects of the basin and the tectonic influences have only been considered in a broad, regional way. In recent years, the basin has been interpreted in the context of plate tectonics (Bickle and Eriksson, 1982; Burke *et al.*, 1986; Stanistreet *et al.*, 1986; Winter, 1987; Clendenin *et al.*, 1988) which is a major departure from previous studies.

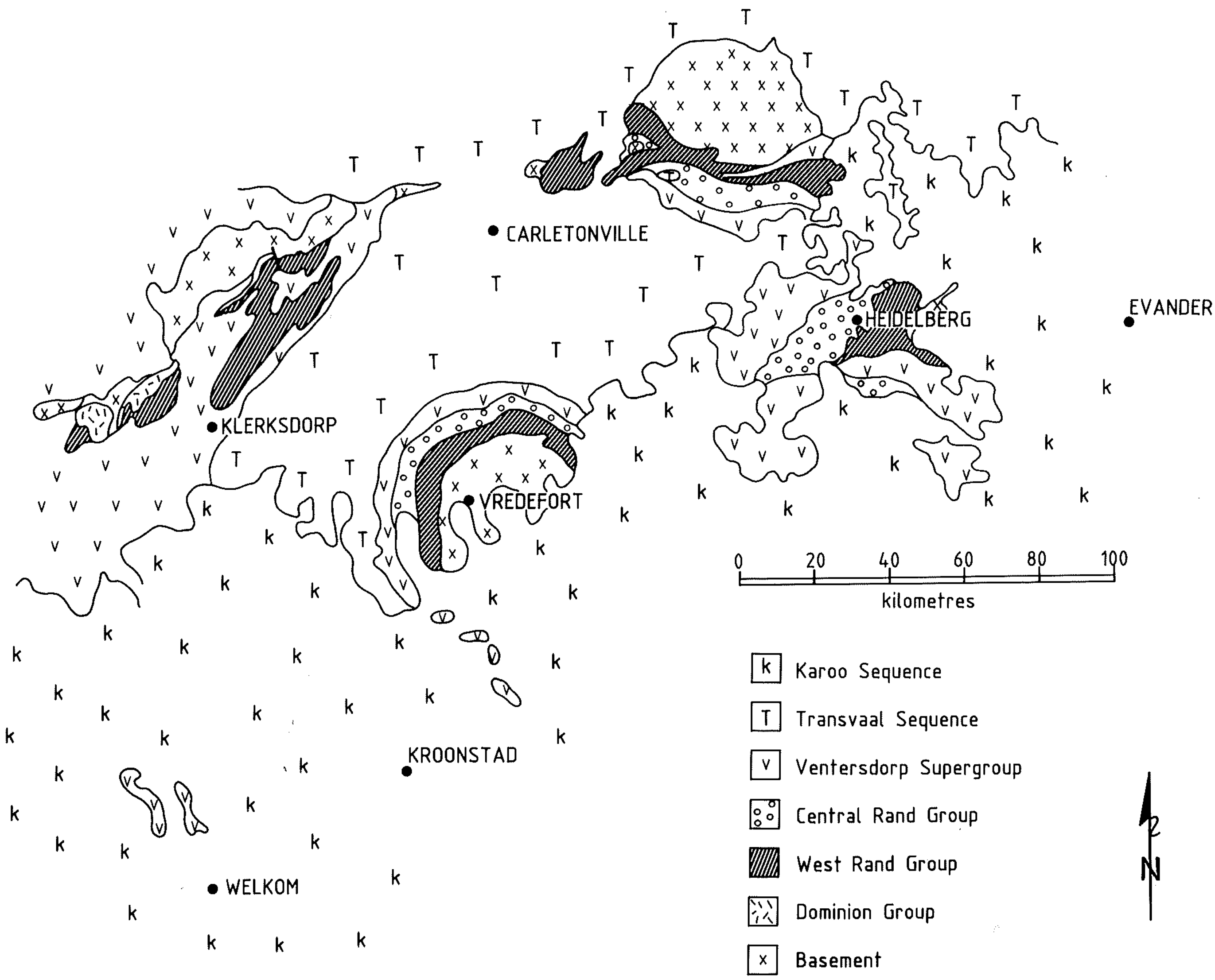


Figure 1(a): The surface exposures of the Witwatersrand Supergroup.

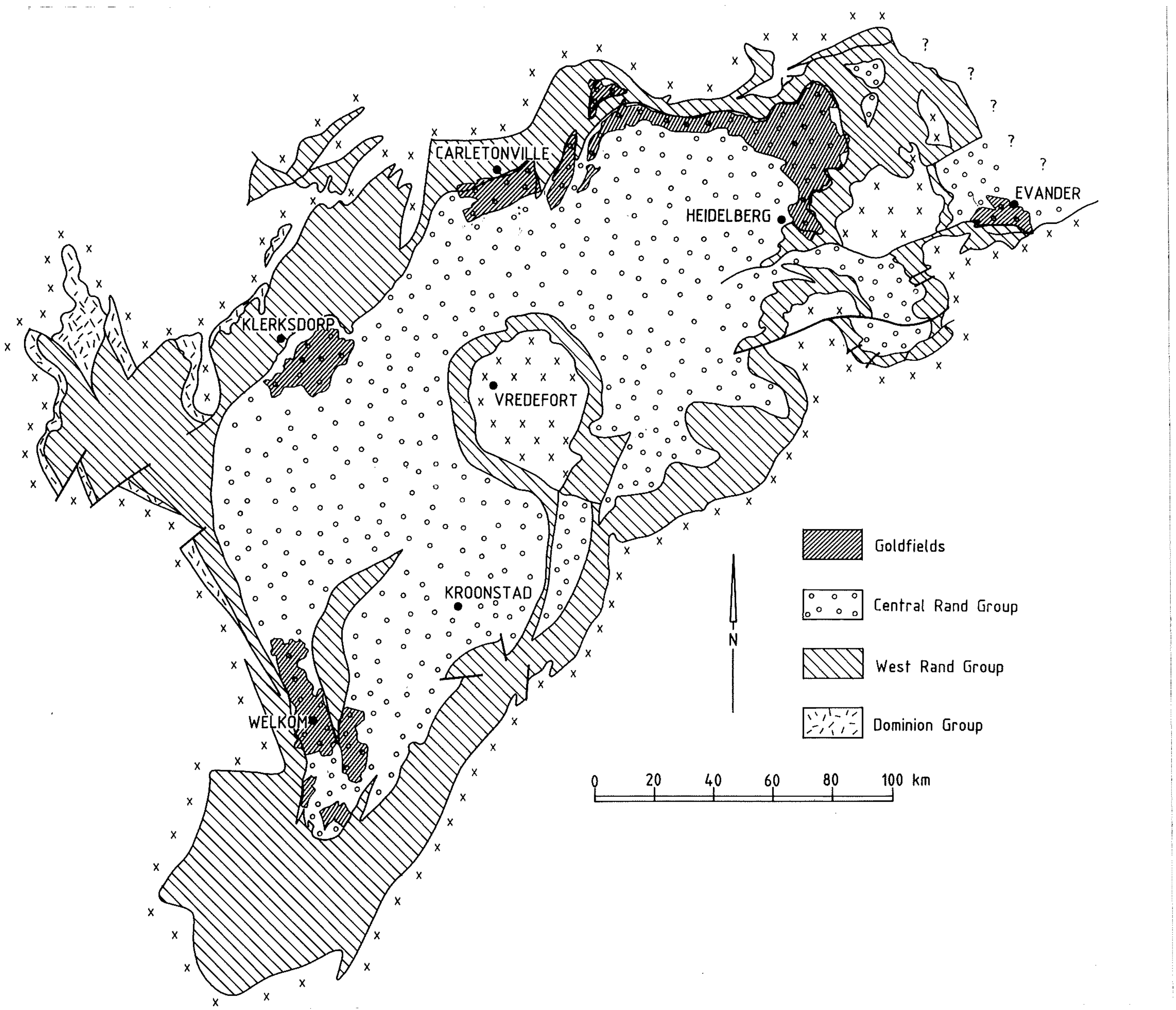


Figure 1b: The sub-Transvaal Supergroup geology in the area of the Witwatersrand Basin showing the distribution of Witwatersrand Supergroup.

The Witwatersrand Supergroup is composed of an epicontinental sequence which grades upwards into a more restricted basinal sequence and is underlain largely by 3000 - 3200 Ma granitoids and older greenstone remnants of the Kaapvaal Craton (Barton *et al.*, 1986). The western section of the basin is locally underlain by a sequence of coarse clastics and bimodal volcanics of the Dominion Group, which has been interpreted as a rift-like proto-basin by Bickle and Eriksson (1982) and Clendenin *et al.* (1988). The Witwatersrand Basin is overlain both conformably and unconformably by the Ventersdorp Supergroup, a complex sequence of volcanic and sedimentary rocks. The Witwatersrand and Ventersdorp successions were then buried beneath the Transvaal Sequence. Much of the Witwatersrand Basin was exhumed by the pre-Karoo (Permian) erosion but is currently buried directly beneath Karoo sediments (Figure 1a).

The age of the Witwatersrand Basin itself has not been determined, but is bracketed by the 3060 Ma Dominion Group and the 2700 Ma Klipriviersberg Group of the Ventersdorp Supergroup (Armstrong *et al.*, 1986). The basin has experienced low-grade regional metamorphism (Schreyer and Bischoff, 1982; Phillips, 1987; 1988) and temperatures of around 350°C and pressures of around 2-3kb are indicated. The age of this metamorphism is not known at present, but it is probably not associated with basin evolution. It has been suggested that this metamorphism is associated with resetting of the Rb/Sr and Pb/Pb systems at 2300Ma (Armstrong *et al.*, 1986).

The Witwatersrand Basin is divided, on lithostratigraphic grounds, into the West Rand Group and the Central Rand Group (SACS, 1980; Figure 2). The former is characterized by approximately equal proportions of mudstone and arenite, with minor conglomerate, while the latter contains only minor mudstone, protoquartzites which dominate, and conglomerates which are common. This arrangement is a reflection of an overall upward coarsening in grain size which becomes very pronounced in the Turffontein Subgroup, where the uppermost units in certain areas are characterized by extremely coarse boulder beds. This has been interpretted as reflecting an increase in tectonic activity associated with basin shrinkage (Mellor, 1917; Pretorius, 1976; Vos, 1975).

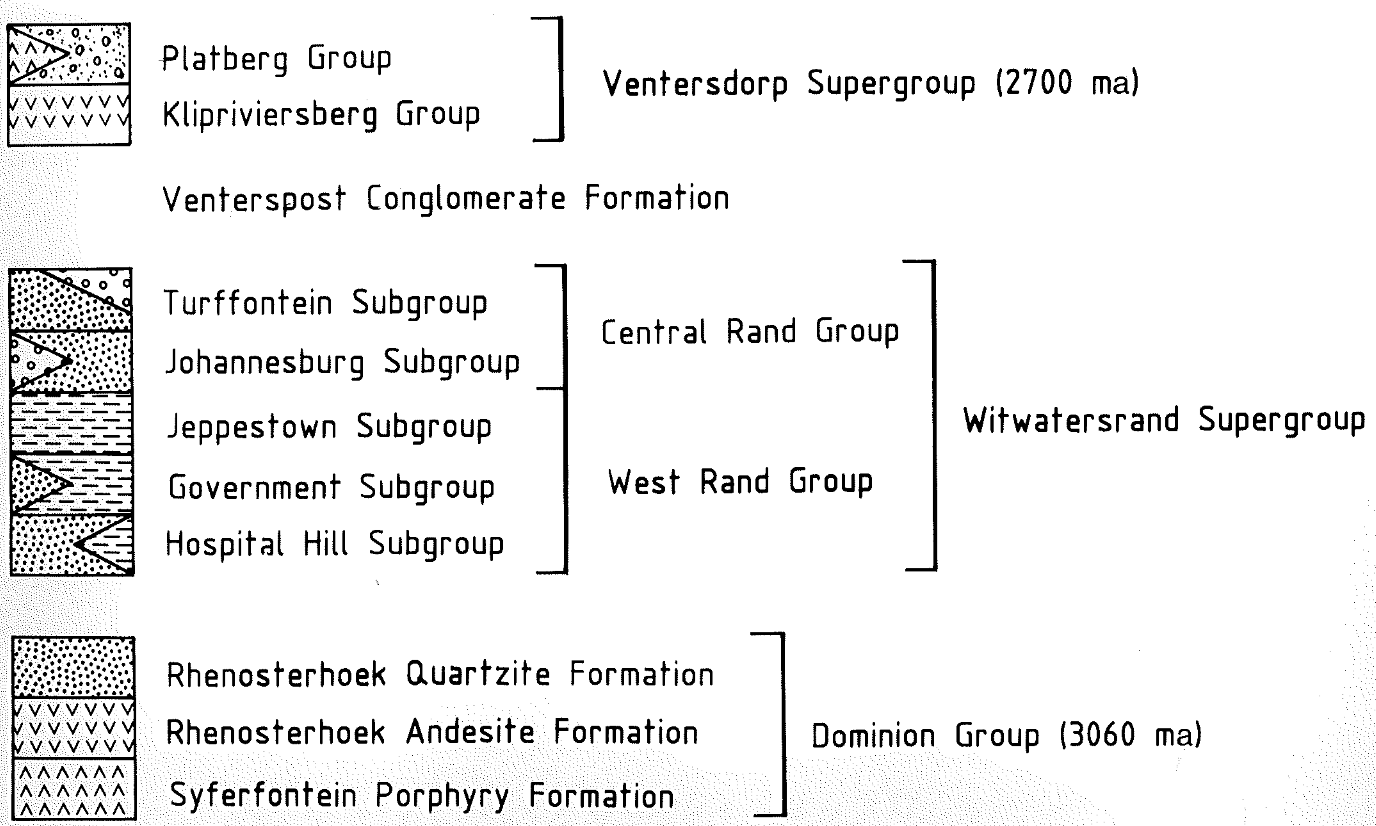


Figure 2: Generalized stratigraphic column from the Dominion Group to the Transvaal Supergroup.

A feature of both the Central Rand and West Rand Groups, as far as they are known, is the lateral correlatability of the stratigraphy (Tankard *et al.*, 1982). At the coarsest scale, major unconformity-bound sedimentary packages are correlatable around the entire basin and, on a fine scale, certain individual unconformity-based conglomerate layers less than 1m thick can be correlated for in excess of 100km along strike. For example, the Nigel-South-Middelvlei Reef conglomerates can be traced from the southern extremity of the East Rand Goldfield, across the entire Central Rand and the Carletonville Goldfields (Cousins, 1965), a distance of 150km, equivalent to one half of the strike length of the entire basin (Figure 1b). This basin-wide correlatibility is more remarkable in view of the fact that clast assemblages in the conglomerates and palaeocurrents indicate a wide diversity of sources and entry points.

Over a century of underground mining and exploration activity has shown that the Witwatersrand basin is extensively faulted and locally folded. As a result of cumulative research, it has become clear that several discrete phases of faulting have affected the basin (e.g. Ellis, 1943; Antrobus and Whiteside, 1964; Olivier, 1965; Fletcher and Gay, 1972; McCarthy *et al.*, 1986; Stanistreet *et al.*, 1986; Brink, 1986). However, the relationship between faulting and sedimentation has rarely been explored in detailed analysis of the entire Witwatersrand Basin, although some workers have discussed this relationship (Brock and Pretorius 1964; Olivier, 1965; Tucker and Viljoen, 1986). Stanistreet *et al.* (1986) have, however, recently documented an apparent causal relationship between certain faults and basin sedimentation across the northern portion of the Witwatersrand Basin, as have Winter (1987) and Burke *et al.* (1986).

In order to establish the tectonic controls on basin evolution, it is essential to consider the chronology of the many deformational phases which have affected the basin. This can only be achieved by establishing the movement history of specific structures or structural zones. To this end, several criteria need to be considered simultaneously: (i) analysis of the displacement of strata of different ages; (ii) sedimentary responses to specific structures or zones; (iii) displacement of structures; and (iv) nature of associated mesoscale structures. In this way, superimposed deformations can be removed and Witwatersrand-age structural controls can be revealed. The ultimate criterion in the recognition of Witwatersrand-age structures lies in the identification of associated changes in sediment thickness and/or facies.

It is the purpose of this paper to explore the relationship between tectonics and sedimentation in the Witwatersrand Basin and attempt to define the tectonic style associated with basin development and evolution. The writers propose to examine selected data from the northern margin of the known basin, where most information is available in the form of underground and extensive surface exposure, and establish the relationship between tectonic style and basin development. This relationship is then examined in other parts of the basin where the structures are less well known due to younger cover and, using this information, an overall model is developed.

II. GEOLOGY OF THE EAST RAND, WEST RAND, CENTRAL RAND AND CARLETONVILLE GOLDFIELDS

The Transvaal Sequence which unconformably overlies much of the area shown in Figure 1 is relatively undeformed. Structures which affect the Transvaal Sequence are: (i) broad, open to overturned folds; (ii) low angle, southerly dipping faults; and (iii) small, periclinal folds (Fletcher and Gay, 1972; Engelbrecht *et al.*, 1986; McCarthy *et al.*, 1986). Figure 3 shows the geology of the area with the Transvaal Sequence cover removed. Outstanding features include the middle Ventersdorp age grabens containing immature detritus (Platberg Group) such as diamictites and other mass flow deposits (Winter, 1976; McCarthy *et al.*, 1989a; Stanistreet and McCarthy, 1989). The best exposed of these is the Bezuidenhout Valley Graben which lies along the northerly dipping Rietfontein Fault zone (Engelbrecht, 1957).

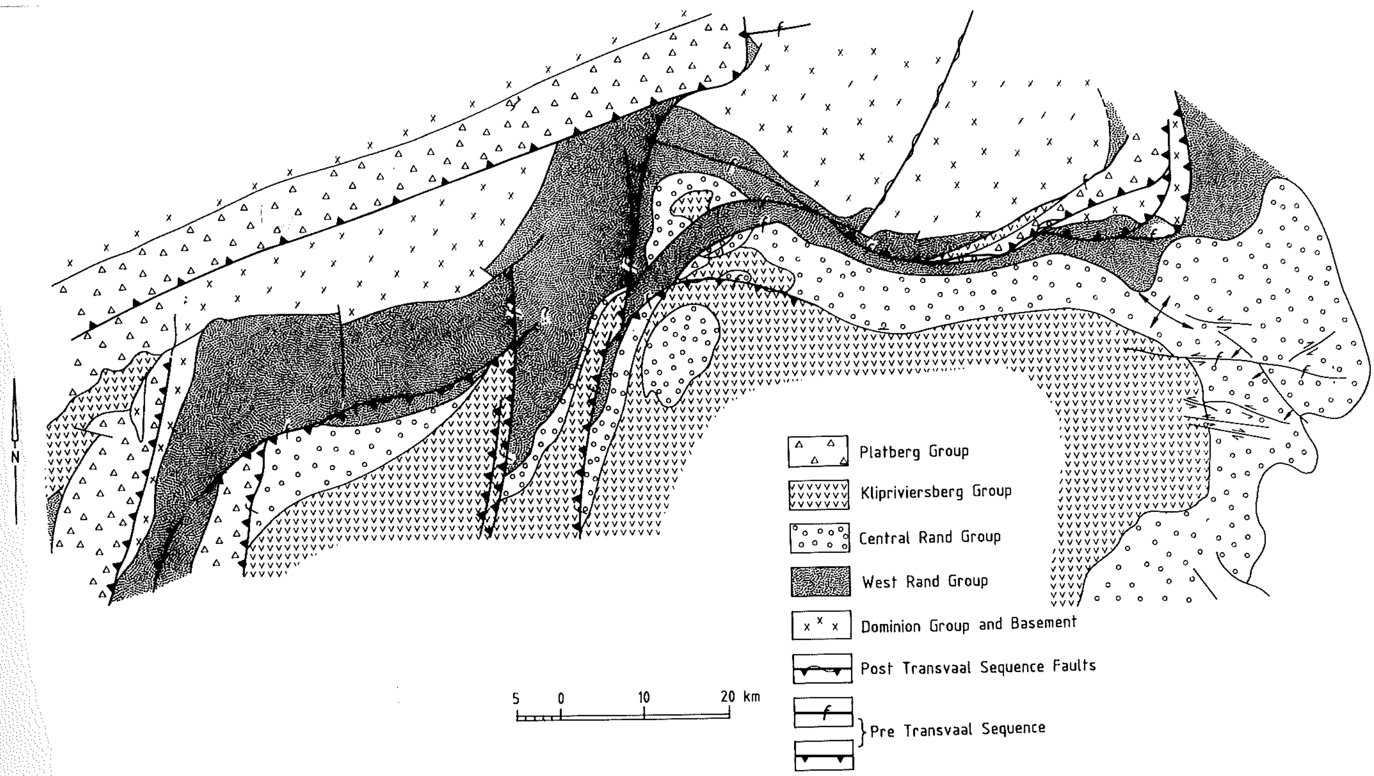


Figure 3: The sub-Transvaal geology of the northern portion of the Witwatersrand Basin.

The palaeoenvironmental reconstruction of these grabens indicates rapid deposition in narrow, deep, fault-bounded basins resulting from extensional faulting (McCarthy *et al.*, 1989a; Stanistreet and McCarthy, 1989). Along the north-south-striking structures (e.g. West Rand and Bank Faults) no Platberg Group sediments are preserved, but these structures show normal displacement of the Klipriviersberg Group lavas of the order of 1000 m and therefore also experienced middle Ventersdorp age extensional effects (Van Coller, 1986).

The major faults in Figure 3, which were important normal faults in middle Ventersdorp times (McCarthy *et al.*, 1989a; Stanistreet and McCarthy, 1989), were also active during Witwatersrand sedimentation. The most useful way to illustrate this activity is by means of carefully orientated structural and stratigraphic sections (Figure 4). A north-south

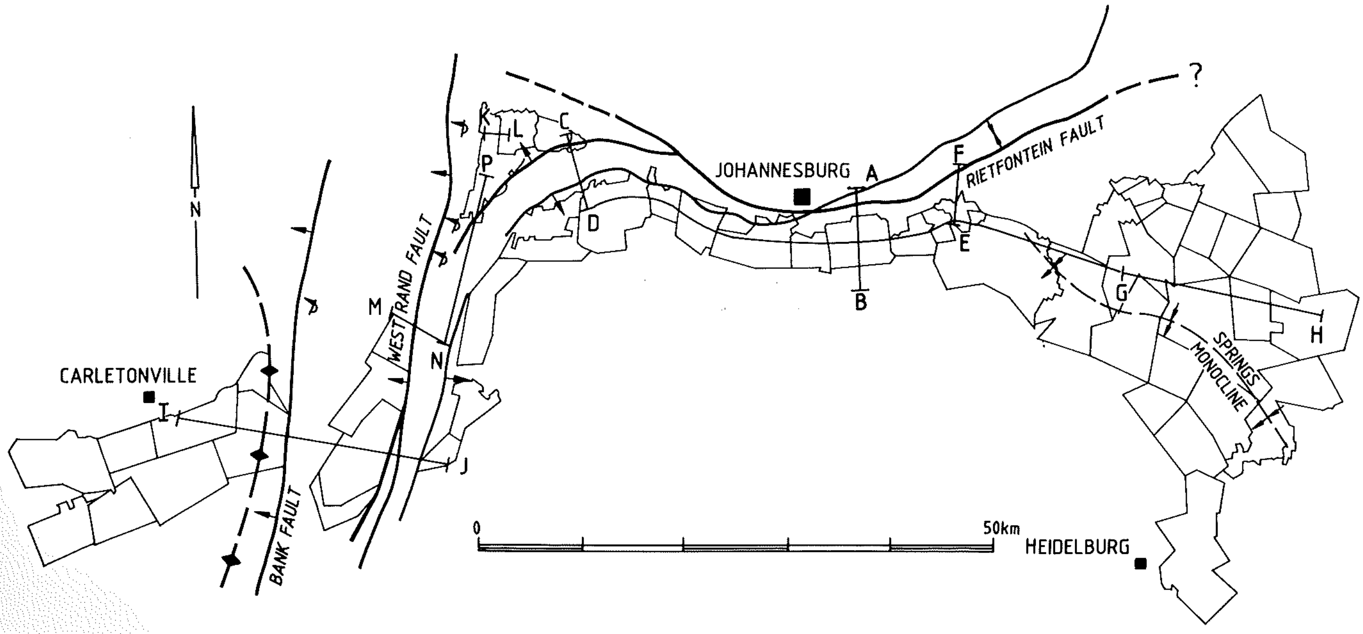


Figure 4: Major structural features of the northern portion of the Witwatersrand Basin.

structural section through Johannesburg is shown in Figure 5a and illustrates the presence of a monocline, several kilometres high, associated with the Rietfontein Fault. The fact that this structure had been initiated in Witwatersrand times can be illustrated by means of stratigraphic sections. Figure 5b shows three sections of the Johannesburg Subgroup (see Figure 4 for localities) illustrating changes in stratigraphic thickness both parallel to (D-E) and perpendicular to (C-D; E-F) strike. There is a marked thinning normal to strike, but in contrast, very little change along strike. Klipriviersberg Group lavas overstepped this monocline and lie unconformably on West Rand Group and even basement only 3-4 km north of the Rietfontein Fault (McCarthy *et al.*, 1989a). This indicates that the area north of the Rietfontein Fault has experienced considerable erosion during Witwatersrand times, which removed, in places, the entire West and Central Rand Groups. The resulting apparent vertical displacement across the Rietfontein structure, which occurred *during* Central Rand Group times and prior to the eruption of the Klipriviersberg Group lavas, is therefore 7 km (McCarthy *et al.*, 1989a). The fact that the conglomerate at the base of the Central Rand Group on Rietfontein Gold Mine shows a strong angular unconformity with the underlying West Rand Group (Engelbrecht, 1957) suggests that this deformation was initiated in pre-Central Rand Group times.

The stratigraphic relationships shown in Figure 5 indicate that the north side of the Rietfontein structure was rising relative to the south implying a reverse component of movement which controlled stratigraphic thinning and overstepping normal to the fault but did not affect stratigraphy parallel to strike. The fact that stratigraphic thinning normal to strike persists through most of the Central Rand Group

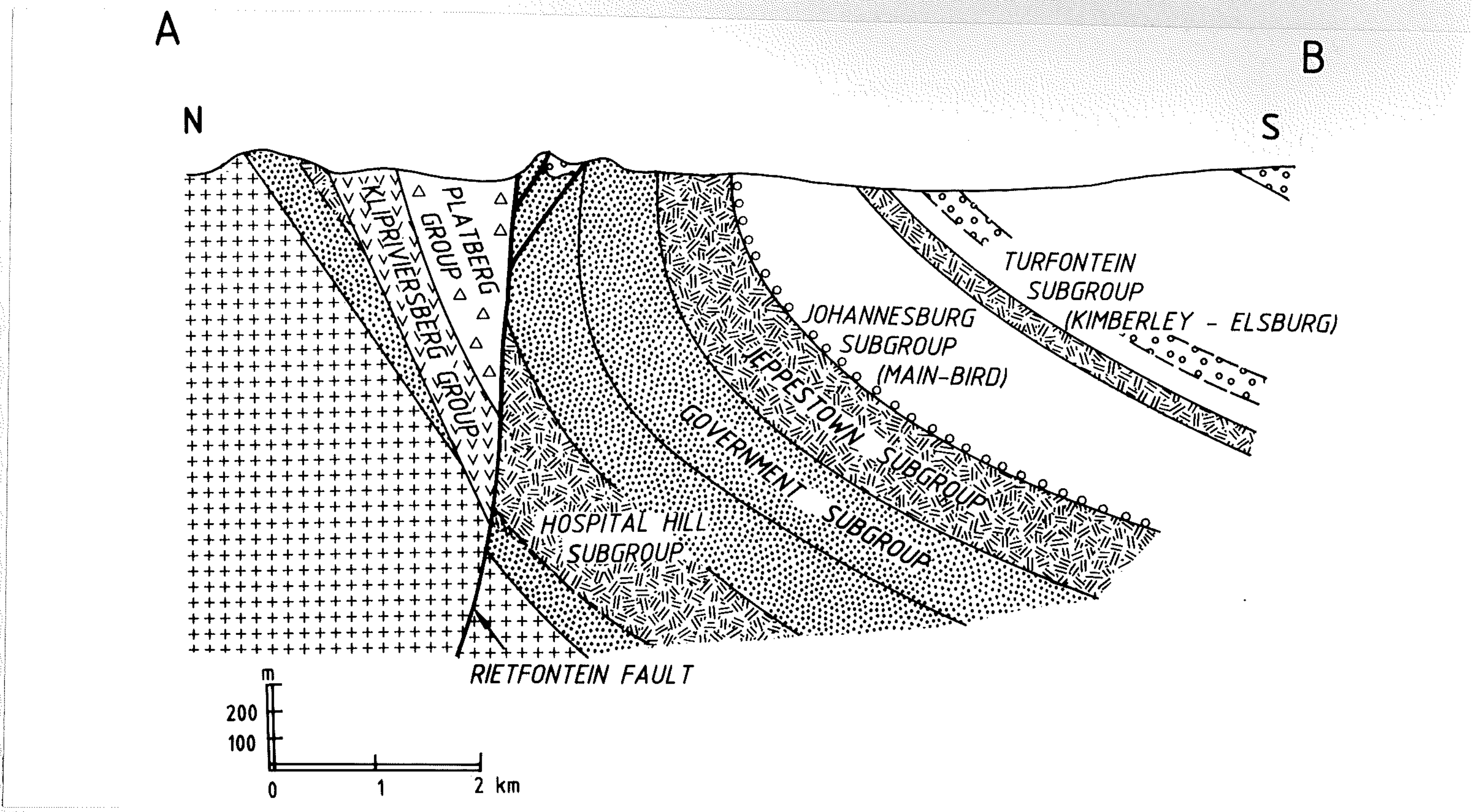


Figure 5 (a): A north-south section across Johannesburg. See Figure 4 for location (after Mellor, 1917).

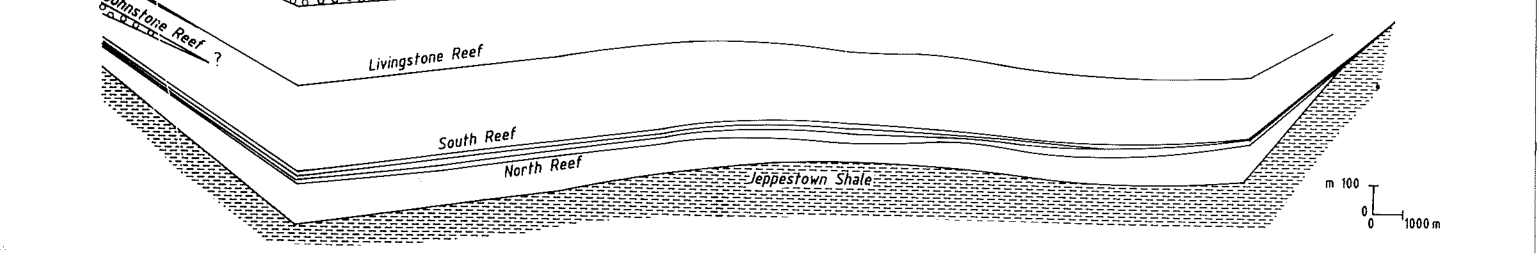


Figure 5 (b) : Sections perpendicular to (CD; EF) and parallel to (DE) on the northern edge of the Witwatersrand Basin (after Toens and Griffiths, 1964; Carleton Jones, 1936; Engelbrecht, 1957). See Figure 4 for location.

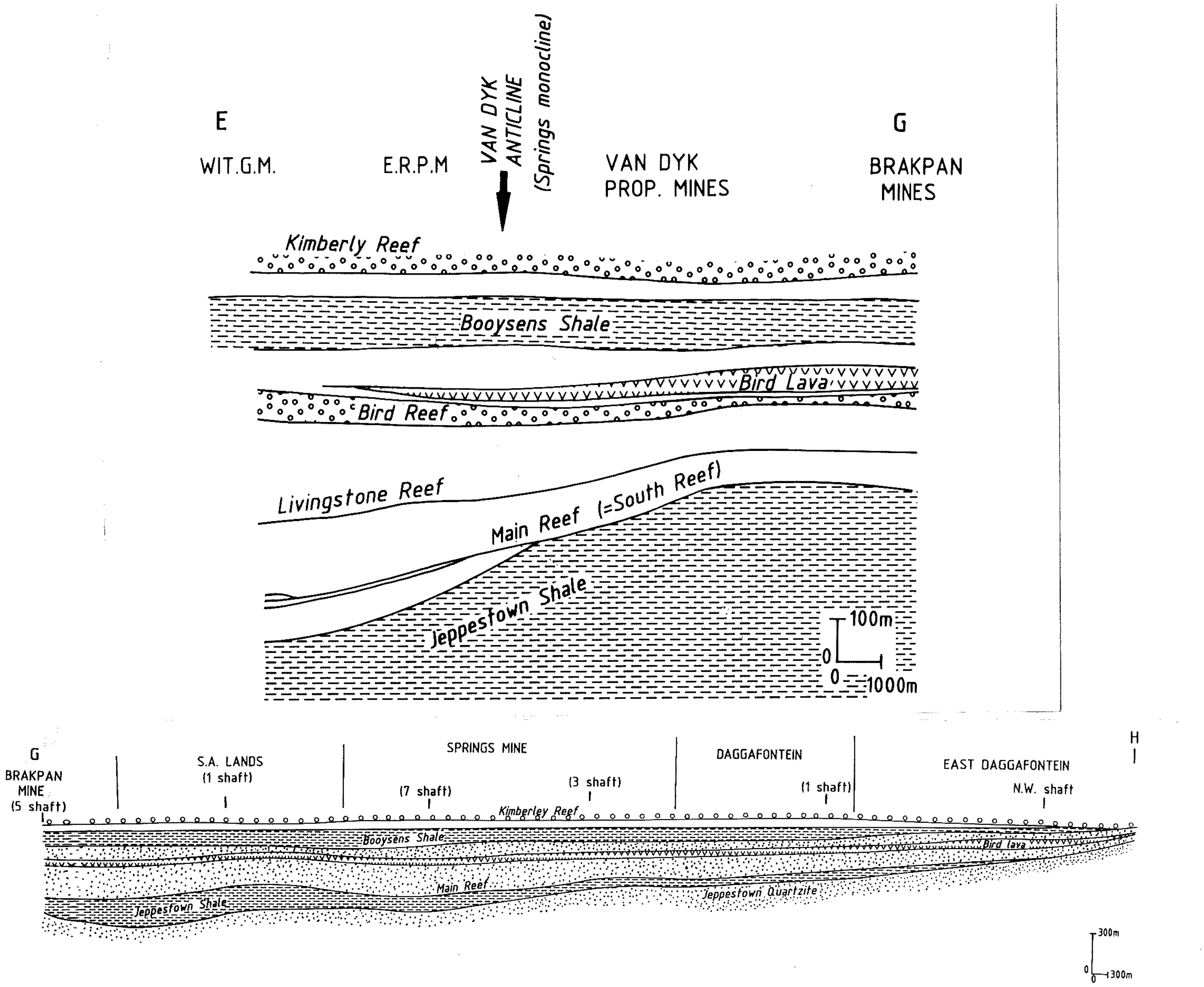


Figure 5 (c) : Sections across the western margin (E-G) and central portions (G-H) of the East Rand Basin (after Carleton Jones, 1936; Antrobus and Whiteside, 1964). See Figure 4 for location.

indicates that this reverse movement continued throughout this time. This implies that the monocline south of the Rietfontein Fault is at least, in part, a synsedimentary feature.

There is an apparent contradiction in the reconstructed movements on the Rietfontein Fault in that the sense of motion during Witwatersrand times had a downthrow to the south, with an apparent 7 km vertical displacement, whereas during middle Ventersdorp times, this same fault had a downthrow to the north in excess of 2,5 km. Detailed analysis of the structures in the area indicate that the Rietfontein Fault also had a significant component of left-lateral movement during both Witwatersrand and middle Ventersdorp times (Stanistreet *et al.*, 1986).

Carleton Jones (1936), Cousins (1965), and Camden-Smith and Stear (1986) have shown that the South Reef cuts down across lower stratigraphy over a syn-sedimentary warp orientated south-east across ERPM Gold Mine as shown in Figure 5c (E-G). The entire Johannesburg Subgroup thins across this structure and retains its reduced thickness across the East Rand Basin although it thins dramatically against the eastern margin of the latter (Figure 5c, G-H). The change in stratigraphic character between the Central Rand (section D-E, Figure 5b) and East Rand (section E-H, Figure 5c) is abrupt and coincides with a monoclinal structure which must have been active during Witwatersrand sedimentation. This structure forms the eastern boundary of the Central Rand Goldfield.

A series of northerly striking faults and associated folds separate the Carletonville from the West Rand Goldfields (Figure 4). Of these, the best known is the West Rand Fault which dips to the West at variable angles. The position and strike of the westerly dipping Bank Fault is poorly known, but its cumulative structural effects are well known (Engelbrecht *et al.*, 1986). These structures are largely pre-Transvaal Sequence in age and have a major (kilometre scale) component of post-Klipriviersberg normal movement (probably middle Ventersdorp in age).

The normal movement apparent in Figure 6a has been removed by rotating the fault blocks to horizontal Klipriviersberg in Figure 6b. From these two sections it appears that the Central Rand Group was deformed prior to the extrusion of the Klipriviersberg lavas, deformation taking the form of a gentle warp, causing dramatic changes in Central Rand Group thickness, including complete elimination in some areas. It is significant that the position of the Central Rand Group age anticlinal structure in Figure 6b coincides with the position of major post-Klipriviersberg faults. The implication of this coincidence is that the faults were incipiently active in a reverse sense during late Witwatersrand times, producing in this case warps rather than through-going fractures.

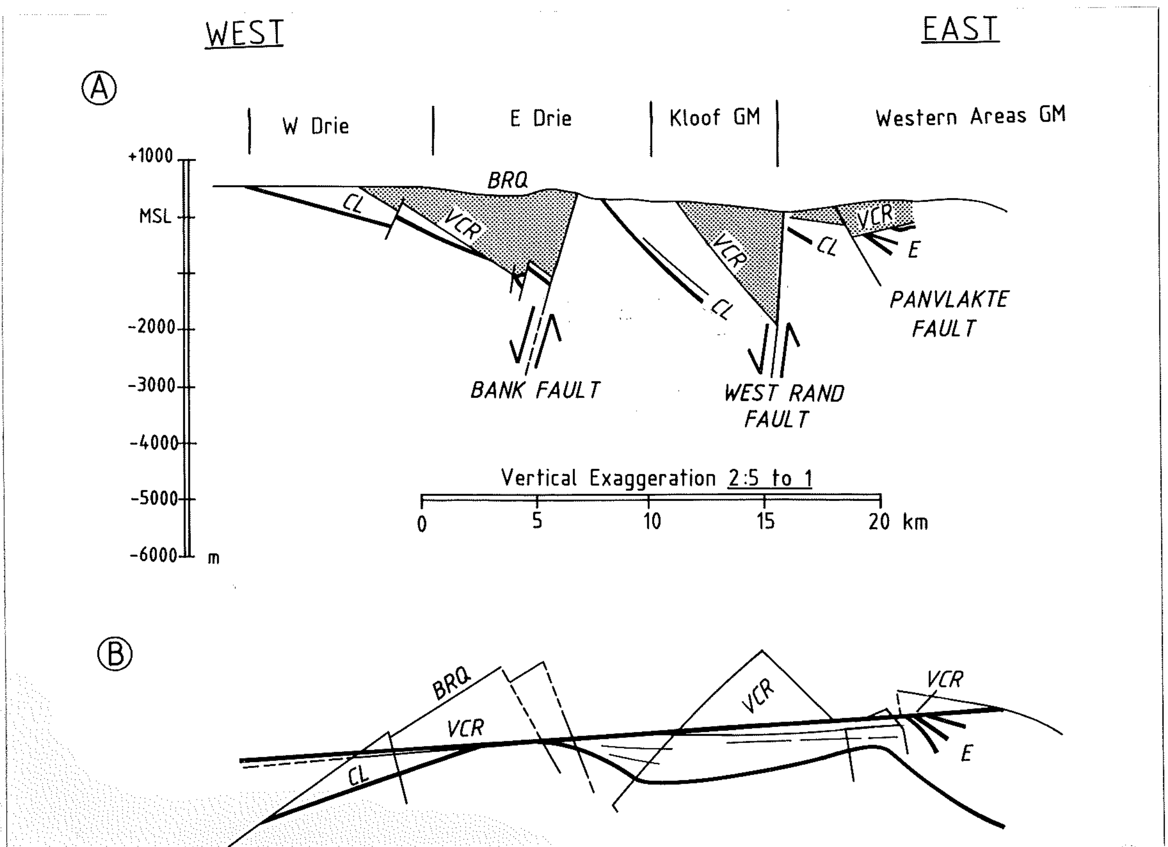


Figure 6 (a): Section from West Driefontein to Western Areas. See Figure 4 for location (based on Engelbrecht et al., 1986; Tucker and Viljoen, 1986; Lednor, 1986).
(b) Section in Figure 6a restored to horizontal Ventersdorp Contact Reef.

Additional evidence of reverse motion across the West Rand Fault is provided by the development of a locally overturned monoclinal fold, several kilometres high, with associated low angle reverse faults, to the east of the West Rand Fault in the West Rand Goldfield (Toens and Griffiths, 1964; and Figure 7a). That at least part of this reverse motion occurred during Central Rand Group times is shown by Figure 7b, in which rapid stratigraphic thinning across the West Rand Fault is indicated. In contrast to this dramatic thinning, a stratigraphic section parallel to the West Rand Fault shows relatively minor changes in thickness (Figure 7c).

The region of intersection of the east-west and north-south striking structures is a structurally complex, asymmetric syncline, known as the West Rand Syncline, in which Witwatersrand Supergroup stratigraphy reaches its maximum thickness (Tankard *et al.*, 1982). The axial plane of this syncline strikes north-northwest. Within this structure, marked changes in stratigraphic thickness occur as illustrated by Toens and Griffiths (1964) (Figure 7d). Thickening of stratigraphy occurs towards the axial plane and also in a south-easterly direction along the axial plane (Figure 5b, section C-D). This suggests that the structure reflects a superposition of the synsedimentary effects associated with both the Rietfontein and West Rand Faults. It therefore appears that the West Rand Fault was active during sedimentation in a reverse sense in the same way as has been shown for the Rietfontein Fault. The degree of displacement on the West Rand Fault appears to decrease southward, while that on the Rietfontein fault decreases westwards. The West Rand Syncline occupies the area of interference of these two fold structures. Stanistreet *et al.*, (1986) noted that the Rietfontein Fault has a left-lateral strike-slip component while the West Rand Fault and associated faults have right-lateral strike-slip motions. The West Rand Syncline may, therefore, also be, in part, an accommodation feature. It must be emphasized that, like the Rietfontein Fault, the West Rand Fault has also experienced middle Ventersdorp normal movement, which has been emphasized in a recent study (Van Coller, 1986).

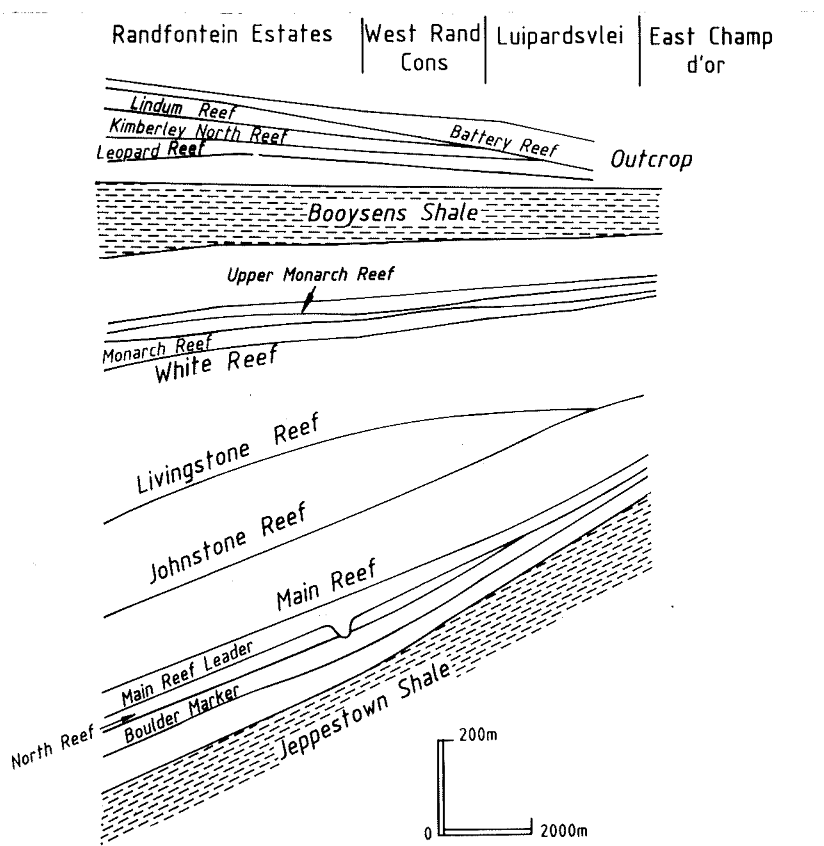


Figure 7 (a): Section perpendicular to the West Rand Fault in the West Rand Syncline (after Toens and Griffiths, 1964). See Figure 4 for location.

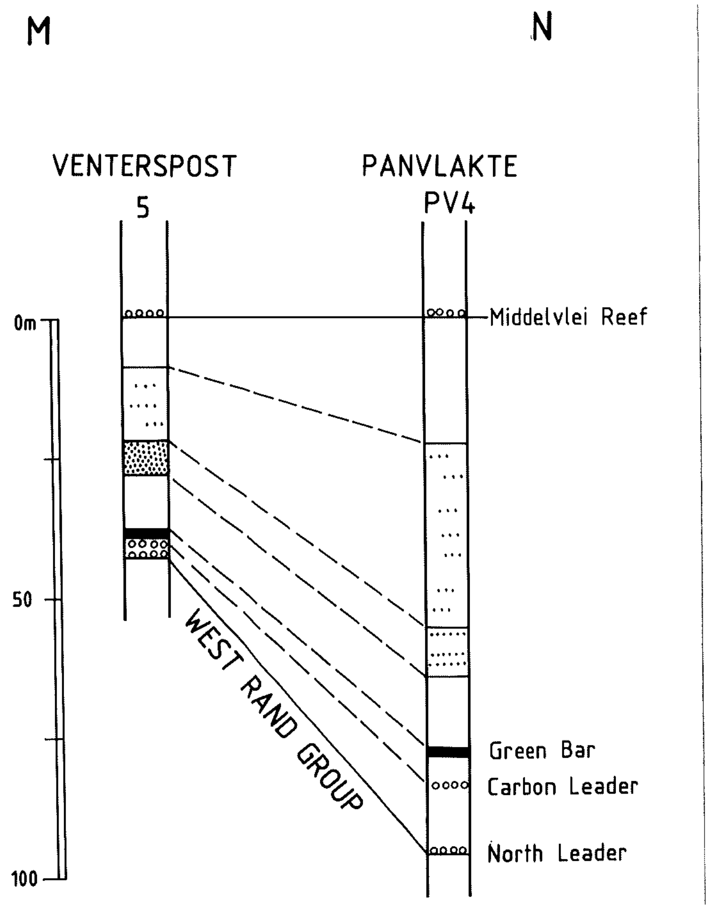


Figure 7 (b): Section normal to the West Rand Fault in the vicinity of Venterspost Gold Mine (based on data from Engelbrecht et al.,1986). See Figure 4 for location.

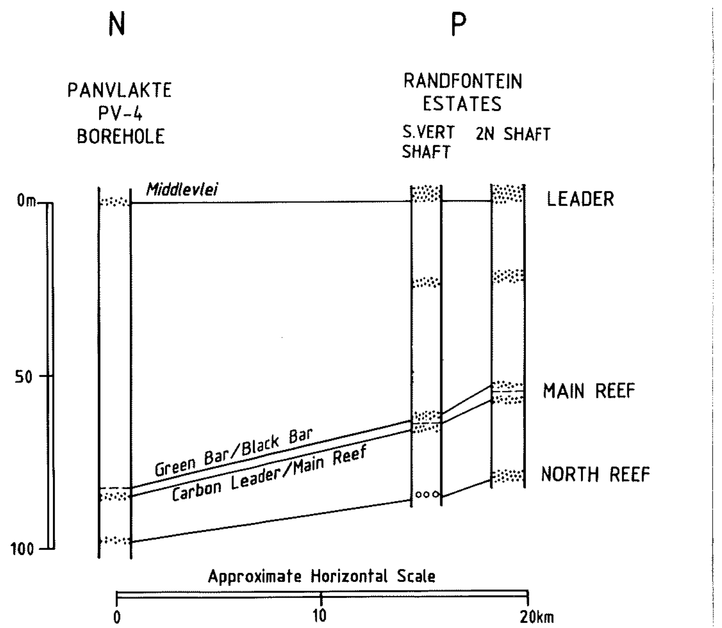


Figure 7 (c): Section parallel to the West Rand Fault (based on Tucker and Viljoen, 1986; Toens and Griffiths, 1964; Engelbrecht et al., 1986).

Within the West Rand Syncline is a major, arcuate horst, the Witpoortjie Horst, flanked in the north by the Witpoortjie Fault (3,8km displacement) and in the south by the Roodepoort Fault, which curves to the south where it is known as the Panvlakte Fault. These faults have a component of middle Ventersdorp movement as evidenced by the development of middle Ventersdorp (Platberg) sediments adjacent to the Roodepoort Fault (Toens and Griffiths, 1964). Tankard *et al.*, (1982) suggested that this horst was already developing in pre-Klipriviersberg times. However, information on movement during Witwatersrand times within the syncline is lacking. Tucker and Viljoen (1986) indicated that the Panvlakte Fault may have been active as a normal fault towards the close of Witwatersrand sedimentation. However, the proximity to the West Rand Fault and its associated monoclinal structure makes inference regarding the relationship of the Panvlakte fault to sedimentation ambiguous.

It is evident from the curvature of the Witpoortjie Fault that it is an integral feature of the West Rand Syncline. In the absence of contradictory stratigraphic evidence, the authors favour the view that this is a middle Ventersdorp age structure which developed in order to accommodate the conjugate wrench components on the bounding faults during the extensional movement.

III. AN INTEGRATED BLOCK FAULT MODEL FOR THE NORTHERN MARGIN OF THE BASIN

The writers have identified two major fault systems which controlled the distribution and accumulation of sediments in Central Rand Group times, viz, the Rietfontein and West Rand Fault systems. These are large-scale structures flanked by monoclines several kilometres high with associated changes in stratigraphic thickness and which displace the basement. They must therefore involve major crustal dislocation, with the faults defining major basement blocks. The block configuration which has been recognized is illustrated in Figure 8. On each of these blocks, the Central Rand Group shows a characteristic stratigraphy, with only gradual changes in thickness over lateral distances of tens of kilometres. The detailed stratigraphy of each block is unique to that block, but nevertheless broad inter-block stratigraphic correlation of major tectono-stratigraphic packages is possible. In contrast, block margins are characterized by very rapid changes in stratigraphic thickness beneath unconformity surfaces.

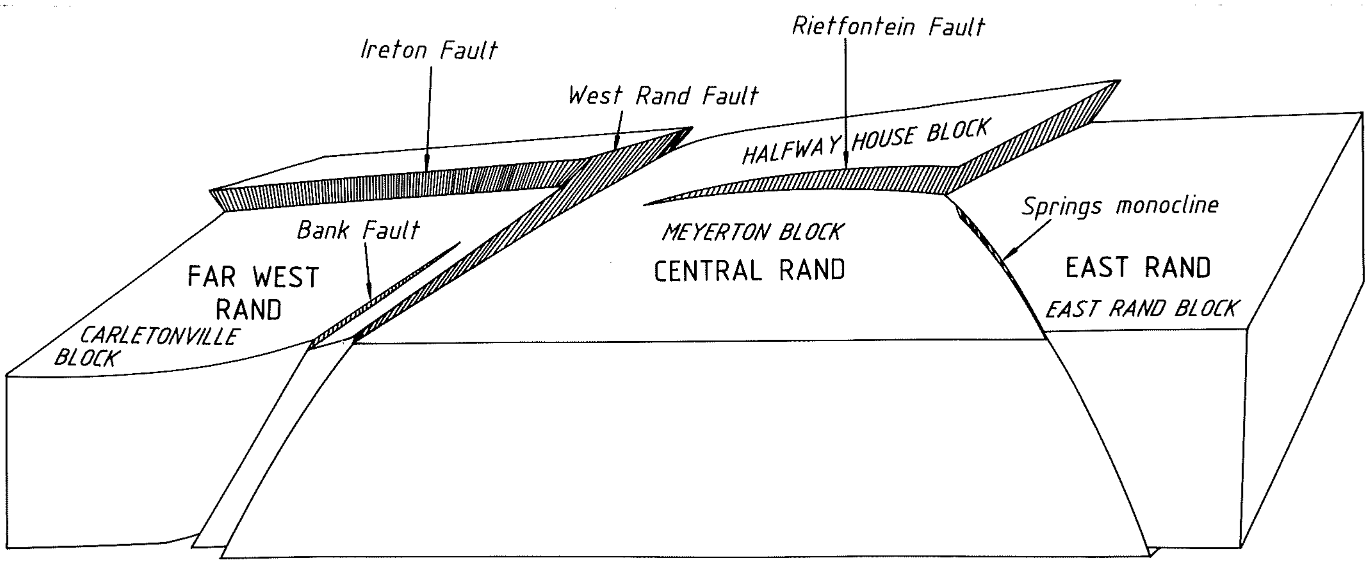


Figure 8 : Schematic diagram illustrating the nature of basement fragmentation across the northern margin of the Witwatersrand Basin. Each of the blocks moved independently, but responded simultaneously to the regional stress.

The blocks shown in Figure 8 are defined by faults or warps as follows. The Carletonville block is bounded in the east by the West Rand Fault and in the north by the Ireton (formerly Kromdraai) Fault (Stanistreet *et al.*, 1986). The Meyerton block is bounded by the West Rand Fault, the Rietfontein Fault and the Springs monocline in the east (a postulated synsedimentary warp separating the East Rand from the Central Rand Goldfield; Whiteside, 1964).

Using stratigraphic thickness it is possible to reconstruct relative motion across the block boundaries as well as the direction and degree of tilting during Central Rand times. The eastern margin of the Carletonville block rose relative to the Meyerton block. Isopachs, which thicken to the southwest (Engelbrecht *et al.*, 1986) indicate that the Carletonville block tilted downwards in the southwest. This block also rotated clockwise and overrode the Meyerton block in the area of the West Rand Syncline, simultaneously overriding the western edge of the Halfway House block, producing the highly folded West Rand Group Zwartkop outlier north of the syncline (Hendriks, 1961; Roering, 1984). The Halfway House block was at the same time rising and overriding the Meyerton block in the south. The Meyerton block tilted down in the northwest corner between the Halfway House and Carletonville blocks producing the great thicknesses of Central Rand Group in the West Rand Syncline. The East Rand block experienced only slight tilt, was rising relative to the Meyerton block, but sinking relative to blocks north and east. A significant point with regard to these inferred motions is that there is a reverse sense of motion across all of the block boundaries. This implies that the area was in an overall state of compression throughout Central Rand Group deposition.

The majority of the major block-bounding structures described above experienced relaxation during middle Ventersdorp times resulting in the development of local graben and especially half-graben structures in which rapid accumulation of sediment occurred. This later movement creates the misconception that these major structures are exclusively normal faults. The scales of normal displacement appear to have been of the same order of magnitude as the earlier reverse motions (kilometres). These normal movements had ceased by Transvaal Sequence times.

IV. THE APPLICABILITY OF THE FAULT BLOCK MODEL TO OTHER AREAS IN THE WITWATERSRAND BASIN

The geological features described above from the northern portion of the Witwatersrand Basin have also been recognized in other goldfields and the writers believe that the principles of the block fault model developed here can be fruitfully applied to these areas.

A. The Welkom Goldfield

This goldfield is developed at the southern limit of the presently known basin (Figure 1). The Witwatersrand and Ventersdorp rocks of this goldfield are completely buried beneath Phanerozoic cover (Figure 1b) and all information on this goldfield has been acquired during mining and exploration.

A structural map of the Orange Free State Goldfield is shown in Figure 9. The structure in this area is dominated by north-south striking faults. That these faults were active in middle Ventersdorp times is illustrated by the displacements of Klipriviersberg lava and their association with middle Ventersdorp basins (Minter *et al.*, 1986). A large horst, the Debron Horst, is a prominent feature which supplied sediment to the Middle Ventersdorp basins (Buck, 1980). Although these faults have a major normal component, several of them are known to have a component of right-lateral displacement (Olivier, 1965). The reconstruction by Kingsley (1984) suggests a 3 to 1 horizontal to vertical motion.

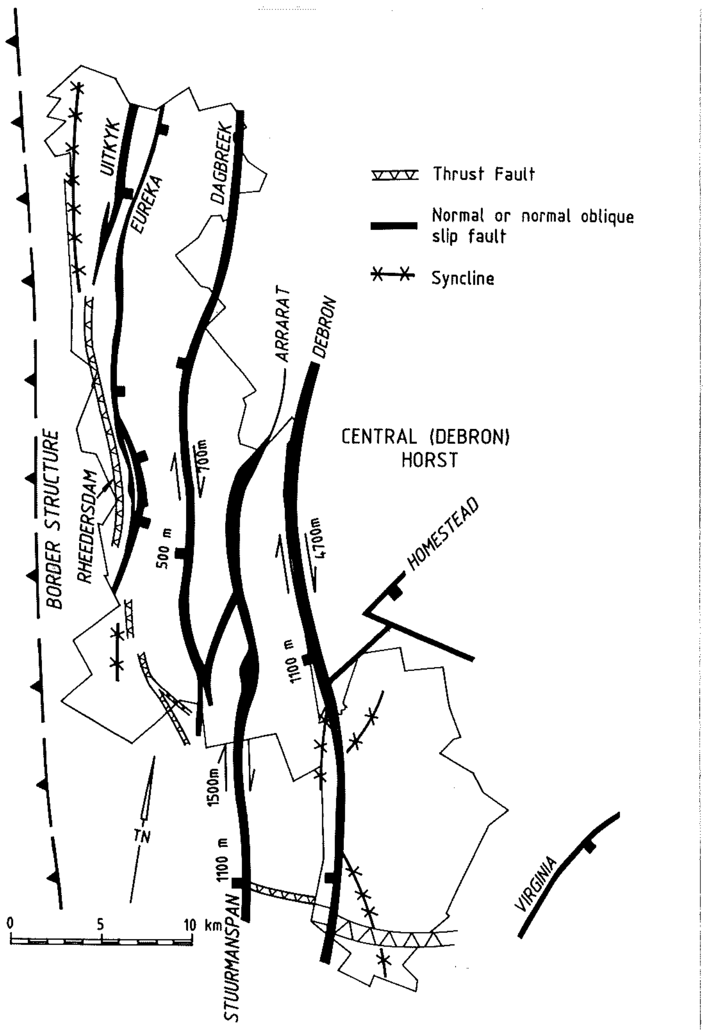


Figure 9: Simplified structural map of the Welkom Goldfield (after Minter et al., 1986).

A key feature of the goldfield is however, a large locally overturned monoclinal structure with associated reverse faulting, which is developed along the entire length of the western margin of the goldfield. This feature is known locally as the "Border structure" (Figure 9). Sections perpendicular to this structure are shown in Figure 10. From available information it is evident that the area to the west of the Border structure is underlain by West Rand Group sedimentary rocks and basement granites, with local development of middle and upper Ventersdorp sequences

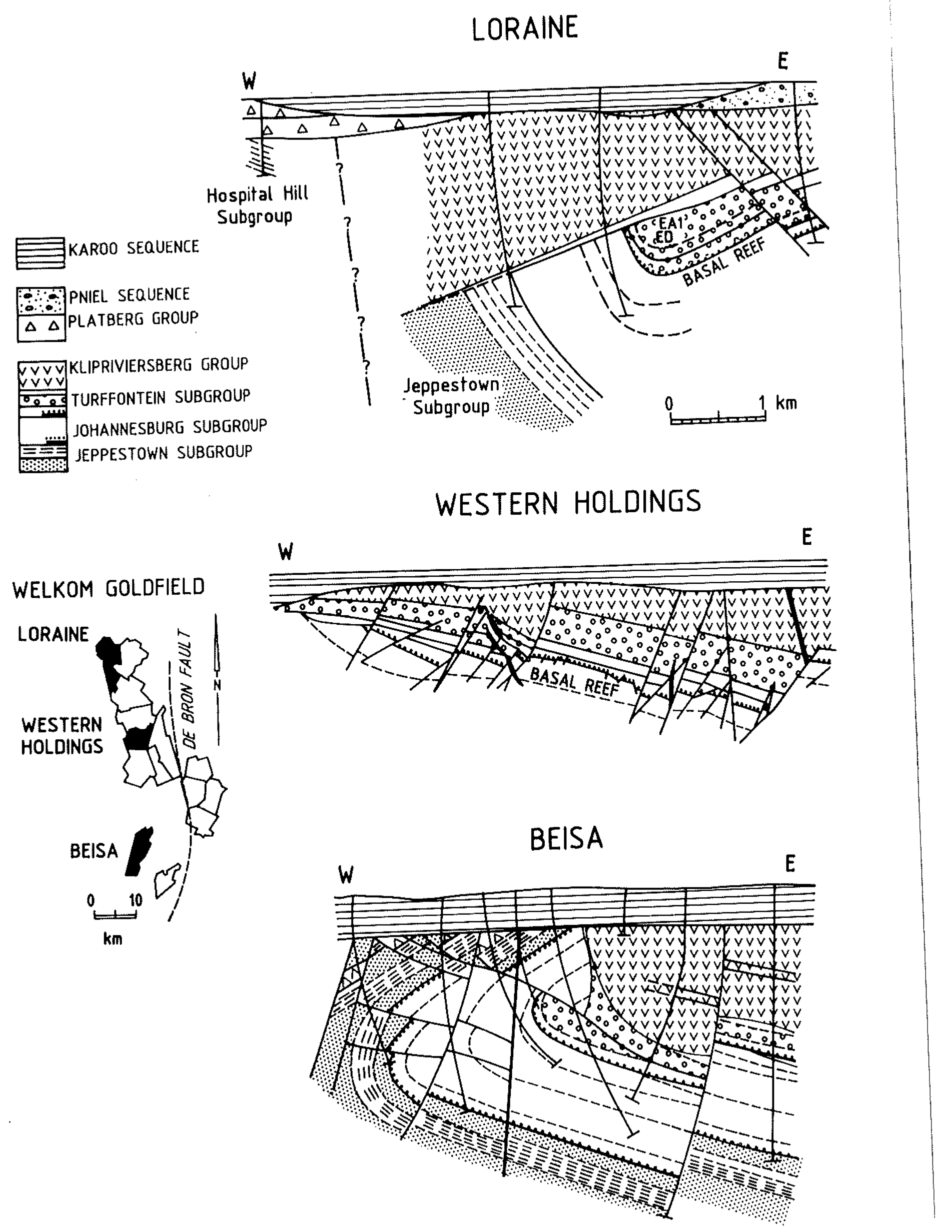


Figure 10: Geological sections across the western margin of the Welkom Goldfield.

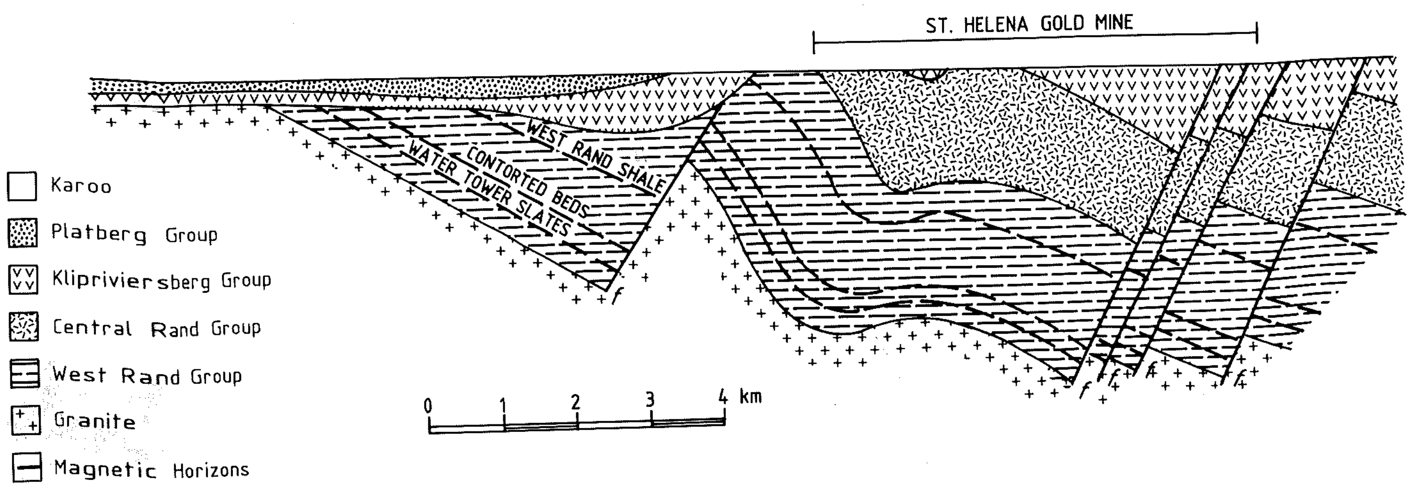


Figure 11: Geological sections across St. Helena Gold Mine and environs with Karoo cover removed (After Roux, 1970).

(Figure 11). The scale of the monoclinal fold, its association with reverse faults and its juxtaposition with older lithologies, including basement, indicate that, like the Central and West Rand areas, this structure is flanked by a major reverse fault which has involved basement.

Evidence for the timing of monoclinal folding is again provided by associated changes in stratigraphic thickness within the Central Rand Group adjacent to this structure. In this instance, however, the internal angular unconformities are very dramatic. This is illustrated by the section from the Oryx Gold Mine in Figure 12, which portrays the progressive thinning of the entire Central Rand Group into the monoclinal structure. This is a clear indication of progressive development of the monocline during sedimentation. The coarsening upward mode characteristic of the Central Rand Group is very pronounced in this area and the uppermost sediments consist of massive boulder conglomerates of the Eldorado Formation, an equivalent of the Mondeor Formation.

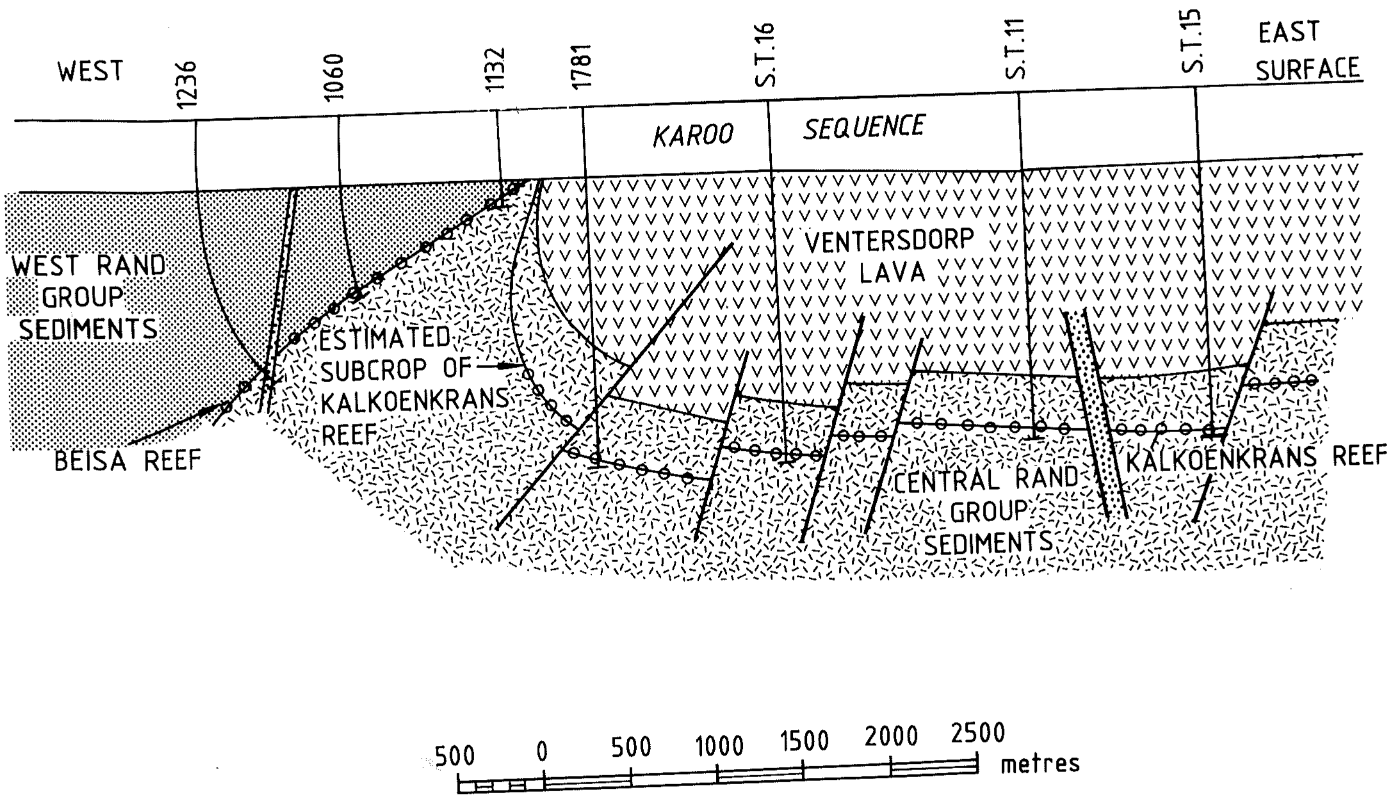
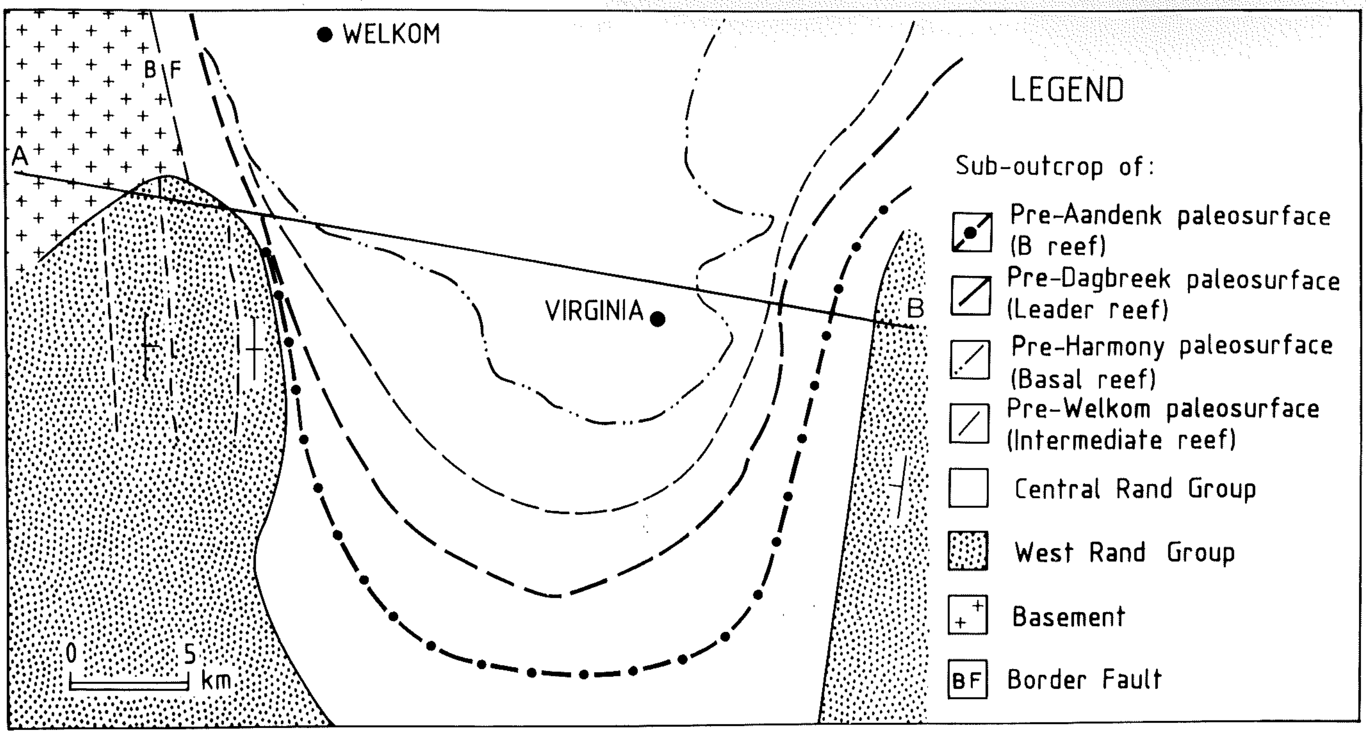


Figure 12: Summary geological sections across Oryx Gold Mine (Star, 1987).

The spatial relationship of the conglomerate suboutcrops beneath unconformities at the southern end of the Welkom Goldfield are illustrated in plan and schematic section in Figure 13. These indicate that there has been erosional truncation in Central Rand Group times not only along the monocline but also to the south and east. In the latter cases, however, the angles of unconformities are less, as indicated by the spacing of the suboutcrops. This implies that other structures were active during Central Rand Group times to the east and south. There is a remarkable similarity in the structural and particularly the sedimentary relationships between the southern Welkom Goldfield and the West Rand Syncline, both showing the same asymetric synclinal form with an inverted limb, and internal unconformities.



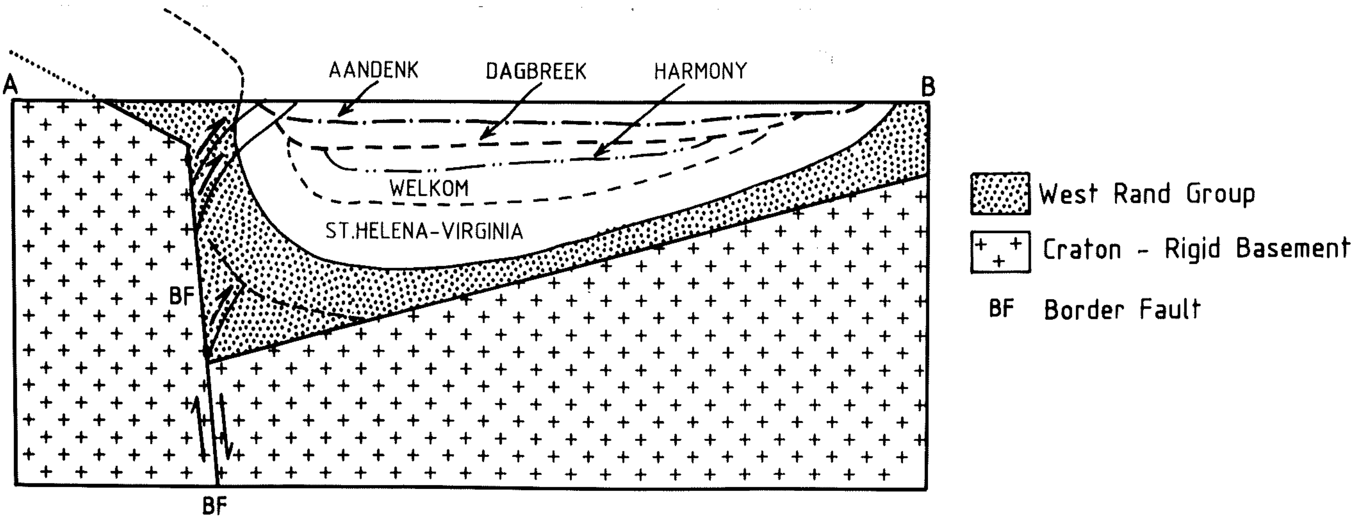


Figure 13: Suboutcrop relationships at the southern end of the Welkom Goldfield (after Callow and Myers, 1986).

The entire Orange Free State Goldfield experienced extensional faulting in middle Ventersdorp times (Olivier, 1965; Buck, 1980; Minter *et al.*, 1986). Many faults were initiated at this time but the fact that these parallel the older Border Structure suggests a single, underlying control related to the nature of the Border Structure.

There are remarkable parallels between the tectonic style of the Orange Free State Goldfield and that of the northern portion of the basin: (i) marginal monoclines and associated reverse faulting which developed in Central Rand Group times; (ii) middle Ventersdorp extensional collapse with the development of local, fault-bounded basins; and (iii) the oblique slip character of the faults. The block-fault model developed for the Central Rand can clearly be applied to the Welkom Goldfield. A major rising block developed to the west, while the blocks east of this tilted downwards towards the northwest (Callow and Myers, 1986).

B. The Klerksdorp Goldfield and Environs

The Klerksdorp Goldfield is located on the western margin of the basin (Figure 1) and is largely overlain by both Proterozoic and lesser Phanerozoic cover. As in the case of the Orange Free State Goldfield, much of the data available is derived from mine information.

A simplified structural map of the Klerksdorp Goldfield is shown in Figure 14. The structure is dominated by a set of north-easterly striking normal faults. Certain of these faults are post-Transvaal in age (Antrobus *et al.*, 1986; Brink, 1986), but two of the most important faults, the Kromdraai and Buffelsdoorn Faults, are pre-Transvaal in age, with only minor post-Transvaal re-activation. These faults define the boundaries of a middle Ventersdorp graben which is floored by Klipriviersberg lavas (Antrobus *et al.*, 1986).

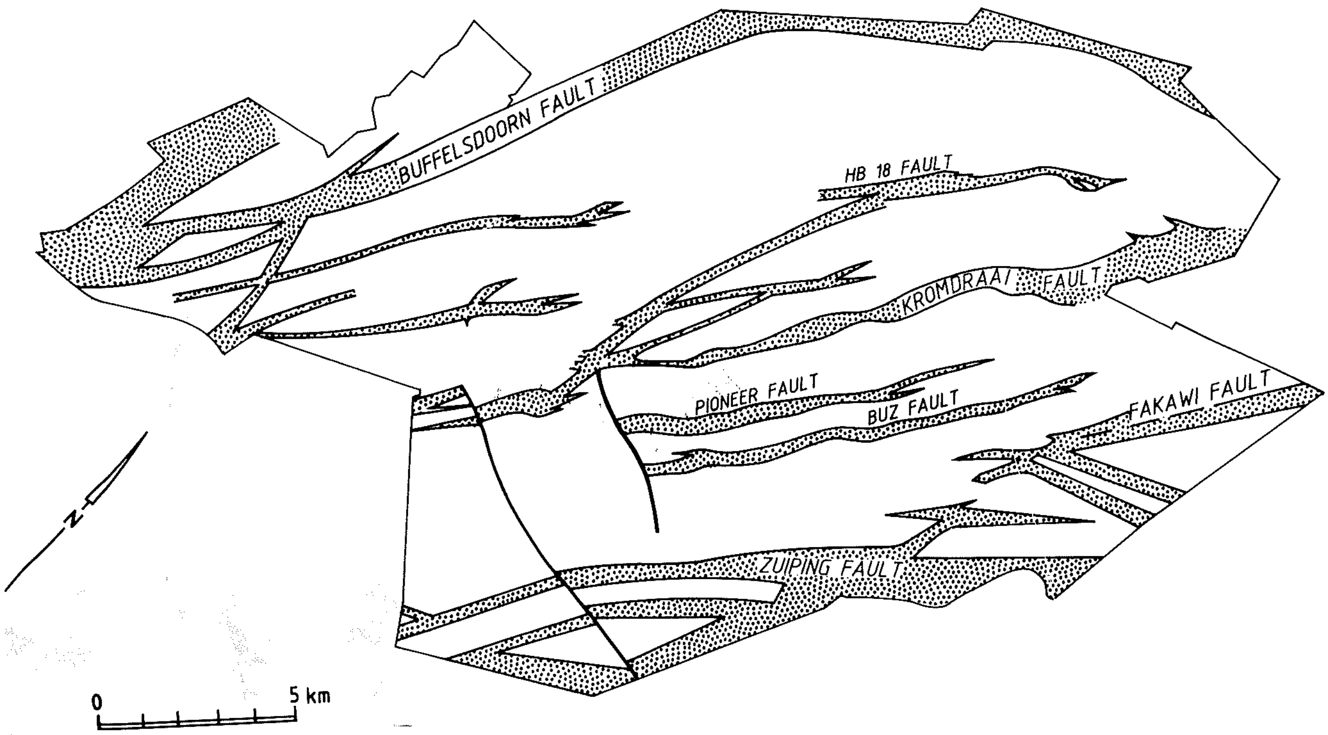


Figure 14: Simplified structural map of the Klerksdorp Goldfield (after Antrobus et al.,1986).

The dramatic monoclinal folds which are developed in the Central Rand and Orange Free State Goldfields are not clearly developed in the Klerksdorp Goldfield although they have been inferred by Brink (1986). There is, however, clear evidence of syn-sedimentarty uplift as indicated by the pattern of unconformities and the stacking of suboutcrops (Figure 15). These relationships indicate progressive, simultaneous uplift to the west and north.

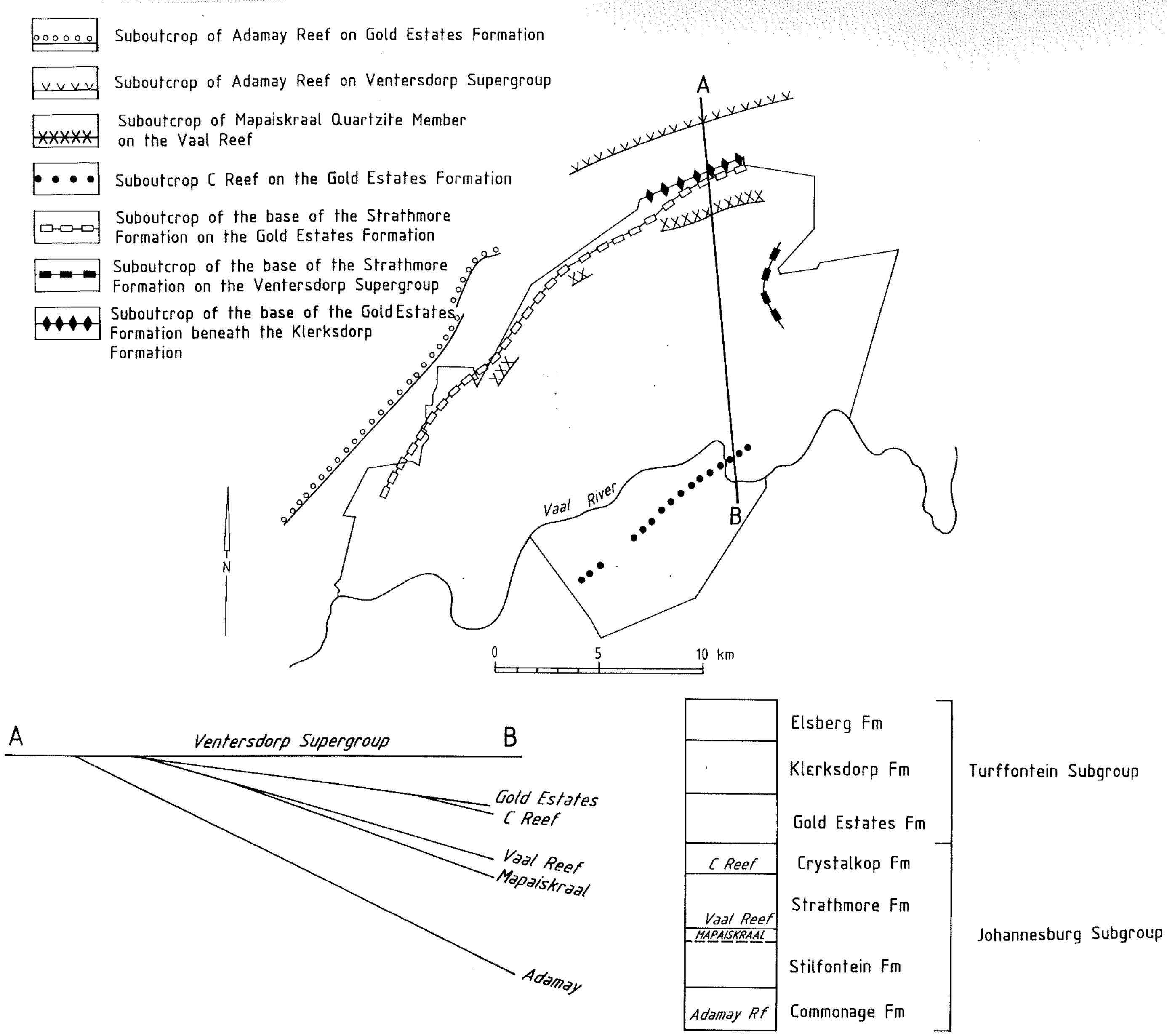


Figure 15: Suboutcrop relationships in the Klerksdorp Goldfield (after Antrobus et al., 1986).

Comparision of Figures 15 and 14 indicate that the orientation of the suboutcrop along the western margin is parallel to major middle Ventersdorp age structures. This is further emphasized in Figure 16, where the thickness of the Klerksdorp Formation shows a close association with the Kromdraai and Buffelsdoorn Faults. A similar association is also shown by the Gold Estates Formation. This indicates that the development of these faults was controlled directly or indirectly by the same features which influenced the accumulation of Central Rand Group sediments. Significantly, to the west of the Buffelsdoorn Fault the Ada May Reef

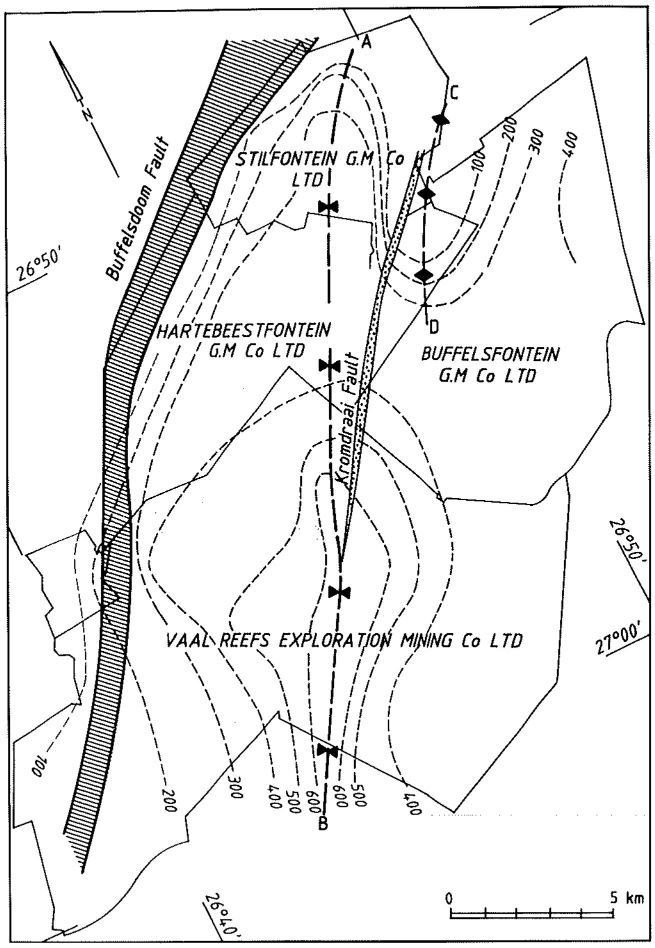


Figure 16: Isopachs of the Klerksdorp Formation (after Antrobus et al., 1986).

(equivalent to the Main Reef of the Central Rand) suboutcrops beneath the Gold Estates Formation, while east of this fault, it suboutcrops beneath Klipriviersberg lavas associated also with a change in strike to the east-northeast (Figure 15). This implies more pronounced uplift in the north prior to Klipriviersberg times. Although no easterly trending structures have been found north of the Klerksdorp Goldfield which could account for this closure of the basin to the north, there is a prominent east-northeast-striking magnetic anomaly in this area which has been interpretted as reflecting West Rand Group strata close to surface (Corner *et al.*, 1986a). This implies a major structure along the northern margin of this goldfield.

Although major marginal monoclinal structures are at present poorly documented in the immediate vicinity of the goldfield, to the northwest the West Rand Group rocks are involved in a broad zone of overturning and thrusting, with south-easterly vergence (Nel, 1935; Brink, 1986). This is flanked to the west by a large, middle Ventersdorp age graben. These structures subparallel those within the goldfield itself (ie. Kromdraai and Buffelsdoorn Faults). Brink (1986) has shown that the folding and thrusting in this area occurred in pre-Klipriviersberg but post West Rand Group times, probably synchronous with Central Rand Group sedimentation. In middle Ventersdorp times, the dislocation zone previously associated with thrusting to the southeast was reactivated as a normal fault, with in excess of 1km displacement (Myers *et al.*, 1989). Middle Ventersdorp sediments and felsic volcanics accumulated in the resulting half graben.

It is evident that the Klerksdorp Goldfield and environs has experienced a very similar structural history to that inferred for the Central Rand and the Welkom Goldfields, and the block fault model may also be applicable here.

C. <u>The Evander Goldfield</u>

This goldfield represents the eastern most extremity of the known Central Rand Group and is separated from the main basin by basement highs. Structurally and sedimentologically it appears to represent a separate Central Rand age sub-basin. The Central Rand Group is entirely under Phanerozoic cover and the full extent of this sub-basin is not yet known.

The dominant structural features are: (i) the major left-lateral Sugarbush Fault (Myers *et al.*, 1987) which defines the southern limit of the goldfield; (ii) a prominent set of northeasterly striking, post-Klipriviersberg, normal faults; and (iii) a northwesterly striking monoclinal structure which flanks the eastern margin of the Evander Goldfield (Tweedie, 1986).

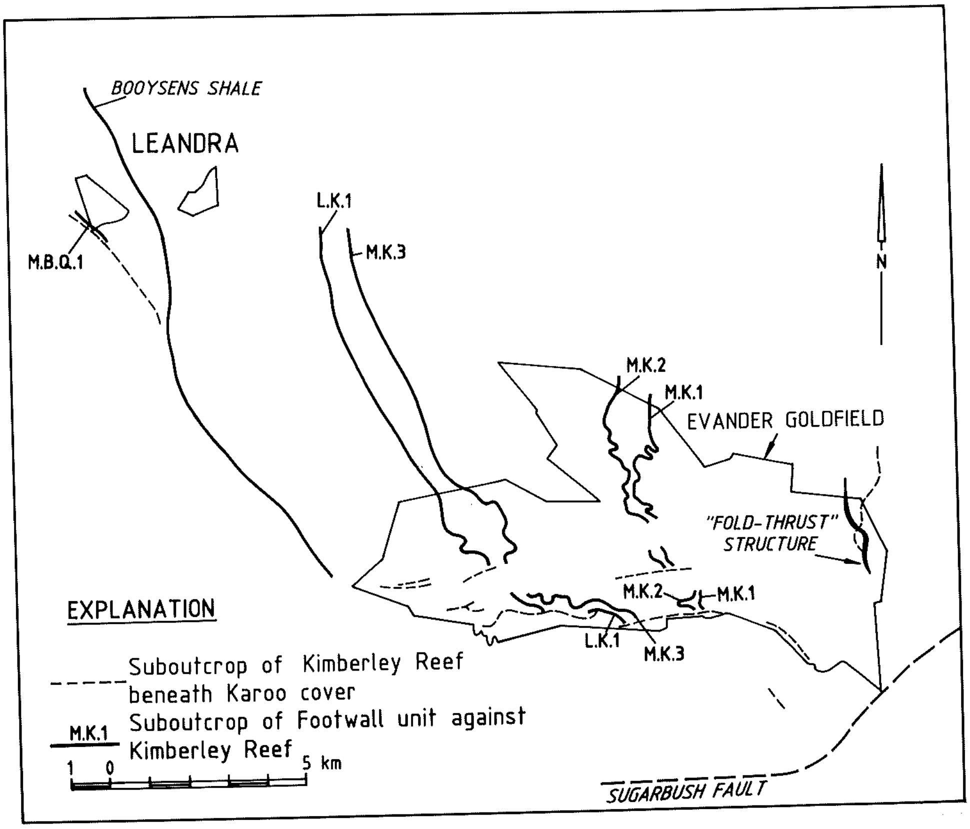


Figure 17 (a): Suboutcrop relationships beneath the Kimberley Reef in the Evander Goldfield (after Tweedie, 1981). M.B.Q. refers to the Main-Bird Quantities; M.K. to the Middle Kimberley markers and L.K. to the Lower Kimberley markers.

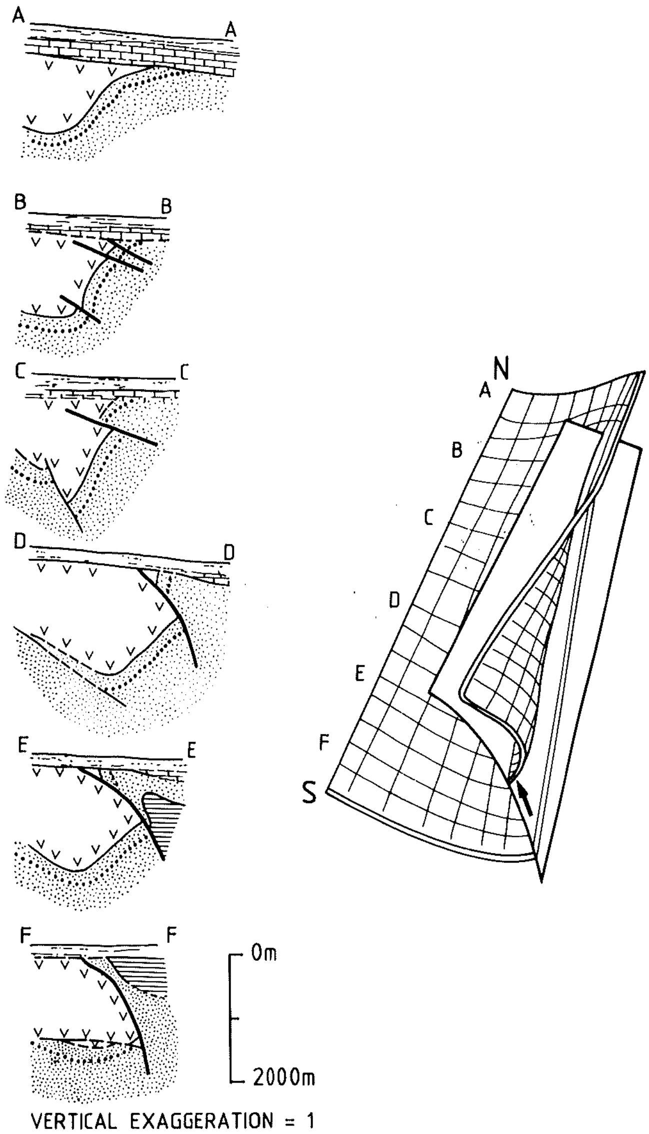


Figure 17 (b): Geological sections through the fold fault on Winkelhaak Gold Mine (Tweedie, 1981) and a reconstruction of the structure.

The Central Rand Group thins towards the south beneath the Klipriviersberg lavas. The Kimberley Reef, which is the main economic horizon, lies on a major unconformity and is associated with a change in palaeocurrent directions from the southeast prior to deposition of this reef to northwest during reef deposition. Suboutcrops of the footwall lithologies beneath this reef are shown in Figure 17a and illustrate a change in strike towards the southeast, where strikes tend towards parallelism with the Sugarbush Fault.

The eastern margin of this goldfield is defined by a monocline (Figure 17b) referred to as the "fold-thrust" by Tweedie (1981), which deforms both the Central Rand Group and the Klipriviersberg lavas and is flanked in the east by a middle Ventersdorp graben. Vergence on the fold-thrust is to the west.

Although detailed information pertaining to this goldfield is sparse, deposition of the Kimberley Reef was apparently preceded by major tectonic activity (Tweedie, 1981) which appears to be related to movement on the Sugarbush and possibly the fold-thrust faults. These relationships suggest that the southeastern region of the basin was rising in Turffontein Subgroup times. Detailed application of the block-fault model is, however, not possible in view of the lack of geological data.

V. CONFIGURATION OF THE STRUCTURAL BASIN

The writers believe that the widely scattered goldfields of the Witwatersrand Basin sample its overall tectonic style. In constructing a tectono-sedimentary map of the basin, the following features were included in the compilation: (i) known syn-Witwatersrand structures (folds and faults) as outlined above, (ii) Platberg-age structure as these often reflect relaxation of Witwatersrand-age features; and (iii) interpolated and extrapolated aspects of (i) and (ii) using aeromagnetic and gravity data (Corner *et al.*, 1986b; Durrheim *et al.*, 1986 and available geological data (Pretorius 1986). The resulting map is shown in Figure 18. This reconstruction is incomplete, especially along the southeastern margin of the basin where geological control is at a minimum, and in the centre due to loss of information because of the Vredefort Dome.

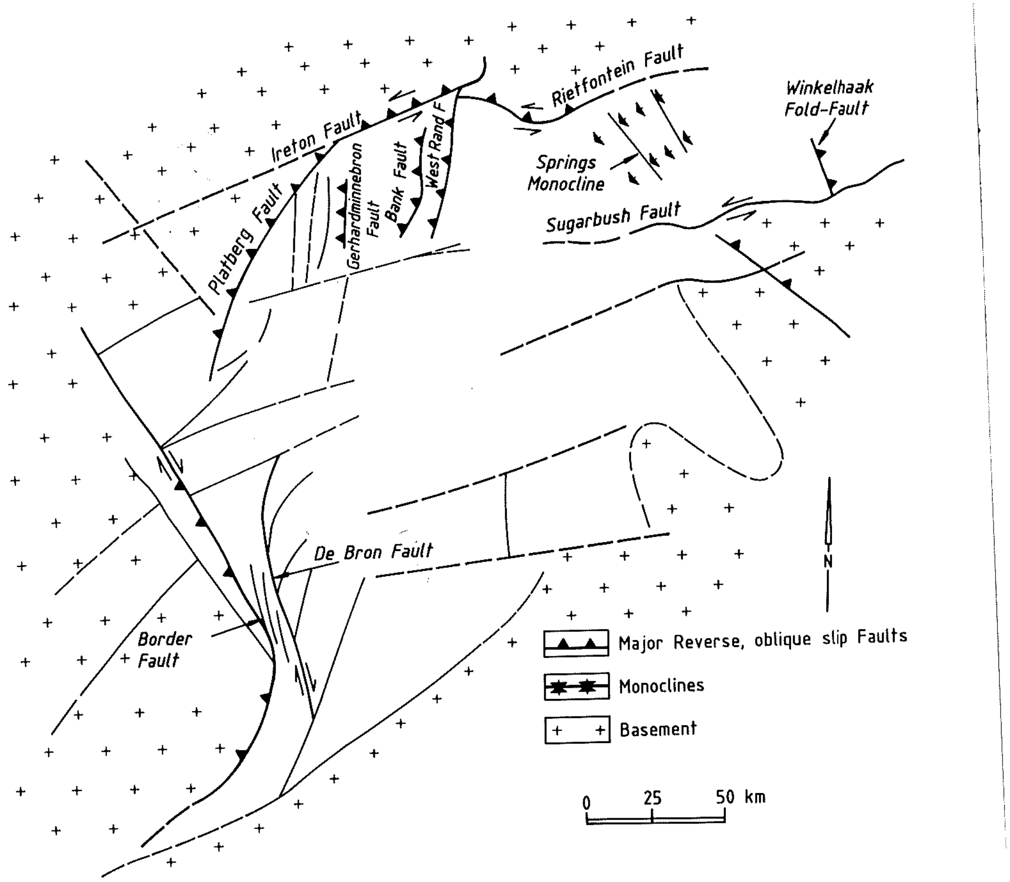


Figure 18: Structural map of the Witwatersrand Basin showing the major basement penetrating fractures which controlled the deposition and preservation of the Central Rand Group.

The Border Structure is a dominant feature of this reconstruction. A second major structure is the Ireton-Rietfontein Fault which, together with the Border Structure, defines a wedge. The Border and Ireton structures have right-lateral and left-lateral movement, respectively, defining a conjugate set southeast of which is the zone of major Central Rand Group preservation. This implies that the central basin experienced displacement in a southeasterly direction during Witwatersrand times, probably a consequence of northeast-southwest regional compression (Stanistreet *et al.*, 1986). South of the Ireton-Rietfontein Fault are several subparallel fault zones, of which the Sugarbush Fault is an example. In the Welkom Goldfield they are subordinate to the Border Fault, as they terminate against this structure.

North-south-trending structures such as the West Rand, Bank, and De Bron Faults act as connectors between the more east-west-trending structures, and typically have a sigmoidal "S" shape. In general these structures dip westward and experienced syn-Witwatersrand right lateral reverse, oblique-slip movement followed by middle Ventersdorp normal oblique slip relaxation. Also developed are fold structures, specifically those in the East Rand Goldfield, orientated in a northwesterly direction. The conjugate Border and Ireton structures are linked by the curved, westerly dipping Platberg Fault, which behaved as a reverse fault during Witwatersrand times.

This analysis reveals that the structures define at least 18 individual fault bounded blocks. The writers believe that additional blocks will be identified in the future. It must be noted that in this analysis consideration was given to block margins which were active at any time during Central Rand Group sedimentation. However, adjacent blocks may have behaved coherently during early Central Rand Group times, but separately during later Central Rand Group times. Each of the known goldfields is located on a separate block. Most of the block margins are complex and consist of suites of faults or warps, but some of the block margins are major, throughgoing structures, as described previously.

VI. THE TECTONO-SEDIMENTARY EVOLUTION OF THE WITWATERSRAND BASIN

The sequence of events began with the deposition of the Hospital Hill Subgroup over an extensive area of the Kaapvaal Craton. During early to middle Government Subgroup time a sequence of tectonic events caused the basement beneath the sedimentary cover to fragment into many large blocks in response to crustal stress. The positions and relative motions of these blocks during Central Rand Group times controlled the sedimentation and preservation of the Central Rand Group. These blocks were hundreds of square kilometres in area and moved independently of one another with a wide variety of movement styles which involved tilting, rotation, and differential uplift or subsidence. Bounding faults varied from inclined to vertical, and movement invariably had a major reverse oblique slip component. The block boundary fractures appear to have been relatively discrete planes within the basement but became more complex in the overlying sedimentary rocks. The sedimentary rocks overlying the basement responded to basement block movement by drape folding and the development of secondary thrust structures producing large-scale, syn-sedimentary monoclines such as those described above. Although the blocks moved independently these motions appear to have been orchestrated by the regional stress regime, and this has given rise to the long range correlatability of sedimentary sequences in the basin.

The surface manifestation of this fault block activity depended initially on the relative positions of the surface of the blocks and the depositional surface. In instances where the block surface rose consistently above the depositional surface, erosion was paramount and no sediment would have accumulated. Blocks whose surfaces were close to the depositional surface would have experienced periodic erosion or deposition reflecting small-scale adjustments relative to the depositional surface. Subsiding blocks were sites of maximum sediment accumulation. Within subsiding blocks, there is general uniformity in long range stratigraphy. Where blocks were tilting, one edge may have lain close to or continually above the depositional surface, while another portion may have been continually below. This would have produced an overall pattern of gradual stratigraphic thickening across the block (e.g. Carletonville).

The block boundaries may have been characterized by gentle warps which may or may not have accumulated sediment (e.g. Bank break; eastern edge of ERPM) or experienced marked steepening with pronounced unconformities and rapid thickening of sedimentary sequences (e.g. Loraine Gold Mine). Because of differential movement along an interface, the character of depositional sequences may have changed along strike (eg. West Rand Fault area from Randfontein Estates to Western Areas Figure 6, 7a).

The sedimentology of many of the conglomerate horizons as well as that of the associated sand bodies in the Central Rand Group indicates that the fluvially based aggradational systems covered a far greater area than is indicated by present day preservation. The fluvial systems particularly in the lower Central Rand Group extended far beyond the tectonic margins of the basin. Periodic adjustments across the tectonic margins in the form of block rise, resulted in erosion of sediment in the rising block. The tectonic margins therefore represent the limit of sediment preservation, rather than the depositional limit, and it is for this reason that the suboutcrops stack in the immediate vicinity of the tectonic margins in the basin. The overall coarsening-upward sequence in the Central Rand Group reflects the decreasing dimensions of the fluvial systems feeding the basin. It was only in the closing stages of Central Rand Group times (Upper Turffontein) that the tectonic margins and the depositional margins became coincident.

In effect, therefore, the writers make a distinction between the concepts of depositional basin and structural basin. The structural basin represents the preservational limit of the basin. The depositional basin was usually much larger than the structural basin, but there was no preservation beyond the limits of the structural basin. The implication of this concept is that since the depositional basin was much larger than the structural basin, there is the potential for preservation of Central Rand Group in as yet undefined structural basins which are outside the limits of the basin as presently known. An example of such an outlying, structurally preserved, remnant is the Evander Basin.

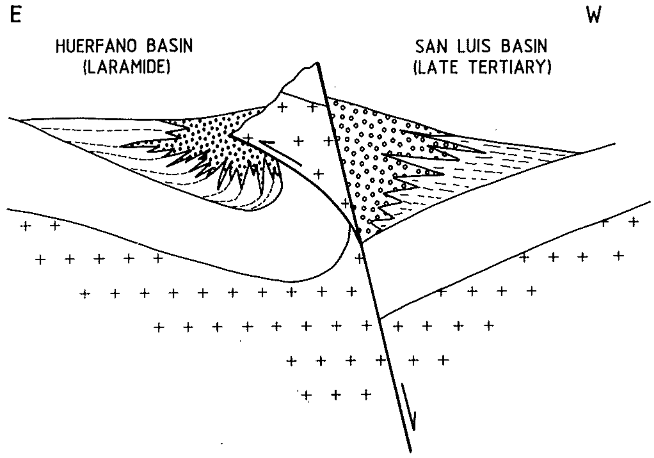
Sedimentation in the Witwatersrand Basin was terminated abruptly by the eruption of the Klipriviersberg flood basalts. The basalts were initially erupted through northeast-trending dykes reflecting the same northeast-southwest compression that controlled the Central Rand Group development (McCarthy *et al.*, 1989b). However, the later Klipriviersberg lavas were extruded from dykes in a variety of orientations suggesting the stress field had relaxed. At the same time, basement block boundaries which had previously been characterized by reverse motions were reactivated as normal faults forming half grabens which filled with Platberg Group sediments and volcanics.

In order to account for this change in the regional stress field the writers envisage the following scenario. The newly cratonized Kaapvaal Craton was put into compression, probably by a collision event, which resulted in the development of an overall northeast-southwest oriented compression (Burke *et al.*, 1985; Stanistreet *et al.*, 1986). As a consequence of this compression older structures on the craton were reactivated. These were most notably the old east-northeast orientations of the greenstone belts in the eastern and northern Transvaal and the north- northeast orientation of the Kraaipan greenstone remnants in the northern Cape and Western Transvaal. Movement on older established structures led to fragmentation of adjacent areas and in this way the collisional deformation propagated into the interior of the craton. It was during this time that the Central Rand basins developed. Eventually, previously discontinuous structures began to interconnect and stress was translated more quickly and effectively into the craton leading to an increased tempo and intensy of deformation. This style of deformation culminated abruptly when enough fractures were interlocked to form throughgoing craton-scale shear zones. These shears may be represented by the Colesburg magnetic trend (Corner *et al.*, 1986a, b) and an older period of movement on the Murchison Thabazimbi line. When these throughgoing shears developed the craton was effectively "broken" and the stress was rapidly dissipated along the shear zones. During Central Rand time it appears that σ_1, was horizontal and oriented northeast-southwest and σ_3 was vertical. However, following the development of the throughgoing shears the stress field was reorganized so that although σ_1 remained horizontal and northeast-southwest, σ_3 changed to horizontal. Towards the end of Klipriviersberg volcanism, the relative magnitudes of σ_1 and σ_3 declined and this culminated in a vertically oriented σ_1 (McCarthy *et al.*, 1989b).

This reorganization of the stress field under a single compressional event accounts for the continuous evolution of events from Central Rand time into Platberg time. The ultimate result of this reorganization was the development of the Platberg Rift to the west of Welkom and Klerksdorp.

VII. PHANEROZOIC ANALOGUES OF WITWATERSRAND-STYLE BLOCK FAULTING

In the model proposed here, the Witwatersrand Basin is considered to have formed in response to compression, which resulted in fragmentation of the crystalline basement, probably in many cases reactivating older lines of weakness. The resulting fault-bounded blocks responded by moving relative to one another both vertically and laterally (through rotation). This tectonic style has been described previously from western North America where it is referred to as the Laramide Orogeny (Matthews, 1978). Several features of the Laramides bear a striking resemblance to the Witwatersrand tectonics described above. The Laramide orogeny was characterized by rotational movements of fault bounded blocks (Couples and Stearns, 1978), which generated marginal structures (Davis, 1978) similar to those observed in the Witwatersrand Basin. Examples of such structure, from the Laramide Province of Wyoming are show in Figure 19. Here, reverse block movement has induced overfolded monoclinal structures involving low-angle thrusting of basement over Cretaceous shelf sediments. Sediments covering the rising block overstepped the monoclines on unconformities. These bear a striking resemblance to the Border Structure in the Beisa area (Figure 10). The Wyoming examples have a further parallel in that they also exhibit later relaxational fall back of the rising block, producing half graben depositories which were filled by Tertiary sediments. This style is analogous to the middle Ventersdorp grabens described above.



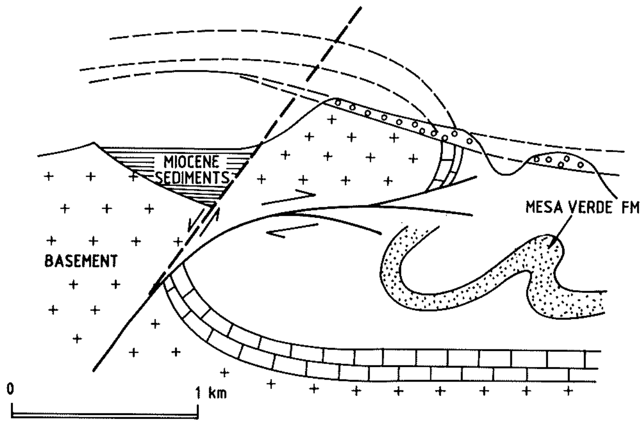


Figure 19: Structural sections across the Seminoe Mountains, Wyoming, an area deformed in the Laramide Orogeny (after Sales 1983).

The Laramide orogeny generated a number of basins on the Colorado Plateau (Stearns, 1978), separated by basement uplifts. The larger of these (e.g. Big Horn Basin) are similar in size to the Witwatersrand Basin. This orogeny developed as a result of continental collision and was superimposed on a large foreland basin. A foreland basin setting has been suggested for the Witwatersrand Basin (Burke *et al.*, 1986, Winter, 1987). However, these models fail to take the Laramide style of deformation into account. In such a comparison, the writers would equate the Hospital Hill subgroup with the tectonically stable pre-Cretaceous sequence of the Laramide province. The Government and Johannesburg Subgroups were deposited in an environment similar to early-to-middle Cretaceous sequences accumulated in the foreland basin under the influence of the Sevier Orogeny (Armstrong, 1958). The Johannesburg Subgroup is regarded here as a tectonic equivalent of the late Cretaceous sediments deposited after the initiation of the Laramide Orogeny and the fragmentation of the basement beneath the Sevier Orogeny foreland. The Turffontein Subgroup would then be equivalent to the early Tertiary sediments deposited exclusively under the control of the Laramide basement uplifts. The Tertiary collapse of the Laramide basement uplifts represents a re-organization of the regional stress field analogous to the Platberg-age relaxation in the Witwatersrand.

Another area in which syn-depositional uplifts similar to those of the Witwatersrand Basin have been documented is the Maracaibo Basin of Venezuela (Figure 20). Apart from the shape of the basin, an intriguing feature of the Maracaibo structure is the relationship between the major structures, e.g. Bocono and Marta Faults and the depositional margins of the basin. In some instances, the basin margins lie directly against these structures, but more frequently the basin margin lies 50 km or more from the major structure.

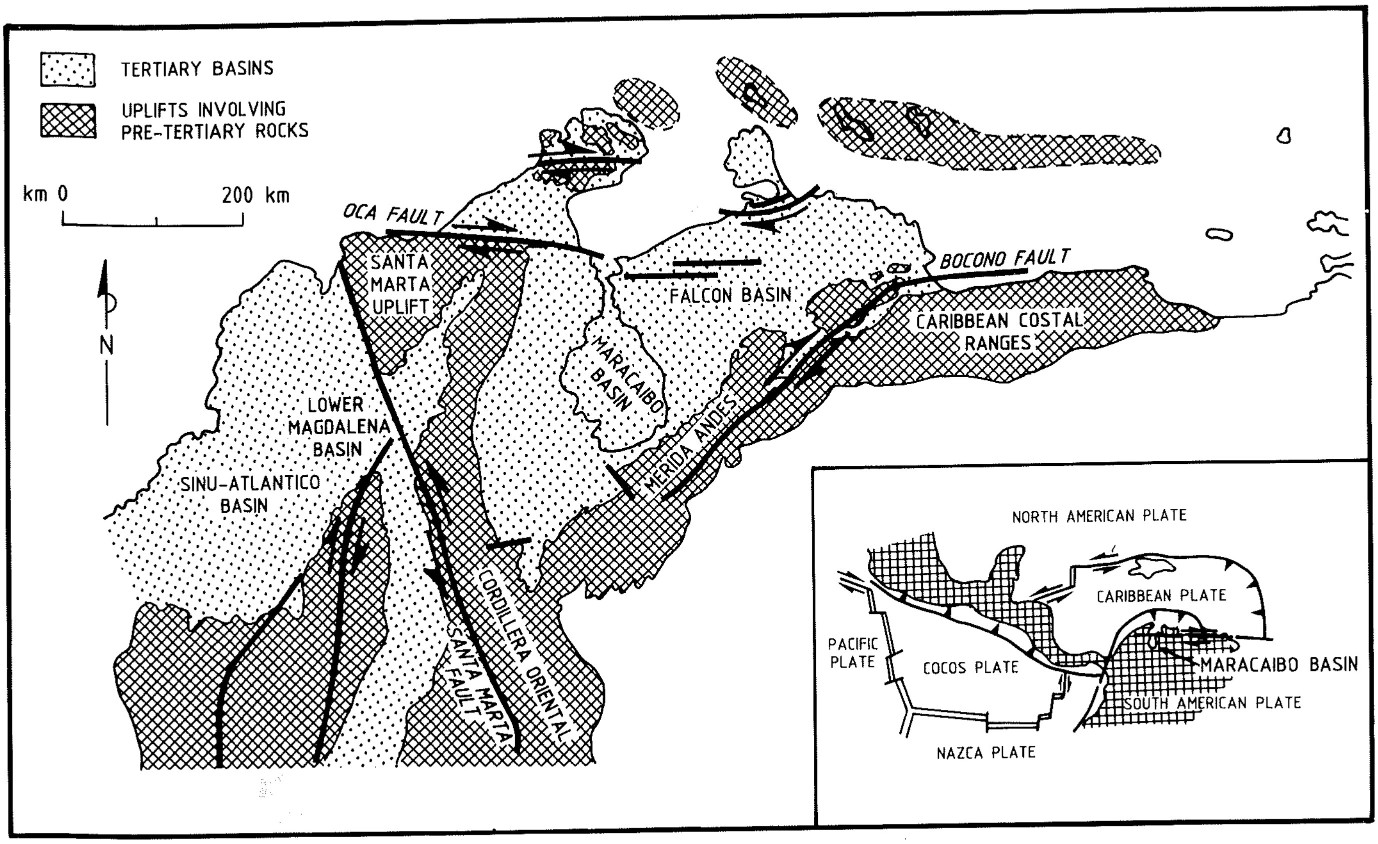


Figure 20: Simplified geological map of the Maracaibo Basin (modified after Reading, 1978).

In at least one case it has been shown that the basement uplifts have been thrust over the Tertiary basin sediments (Cordani *et al.*, 1985), suggesting that these uplifts may represent giant "palm tree" or "flower" structures similar to those associated with the San Andreas Fault. The block-like nature of the basin-margin uplifts is illustrated by abrupt dislocation on the basin margin (Figure 2). It is difficult to keep in perspective the fact that in the Maracaibo Basin, structures which have strike lengths of tens of kilometres and vertical displacements of thousands of metres are small-scale secondary structures related to a very large structures such as the Bocono Fault. Iit is suggested here that the major magnetic features paralleling the Witwatersrand Basin margin in the west and south and described by Corner *et al.*, 1986a) could represent structural zones similar to the Bocono and Marta Faults of the Maracaibo Basin.

VIII. CONCLUSIONS

This work has shown the importance of tectonic backstripping in the analysis of ancient basins. The removal of the effects of younger deformations, in this case middle Ventersdorp and post Transvaal events, is an essential prerequisite in modelling the important tectonic controls on Witwatersrand Basin formation and evolution. In order to distinguish the syn-sedimentary deformation, it is essential to interpret sedimentological data from a tectonic perspective and to try and establish a relationship, if any, between sedimentary patterns (e.g. isopachs) and observable tectonic features.

Using this approach, it has been possible to subdivide the known basin into many structural domains or blocks, each characterized by internal sedimentary and stratigraphic uniformity, but separated by discrete zones of syn-sedimentary disturbance. These boundaries take the form of monoclinal folds. This pattern arose as a result of block faulting in the basement beneath the Witwatersrand Basin and developed under regional compression, which caused mainly reverse, oblique-slip motion on the faults during Witwatersrand times.

This tectonic style continued into early Klipriviersberg Group times, but by late Klipriviersberg Group times, the regional stress system was reorganized in such a way that earlier faults were reactivated as normal faults, leading to the development of large, asymetric grabens in which sediment and volcanics accumulated. This extensional phase culminated the development of a major rift structure to the west of the Witwatersrand Basin.

The writers believe that useful tectonic analogues can be drawn between the Witwatersrand Basin, the Laramide Province of North America and the Maracaibo Basin in Venezuela. A hybrid model is preferred and it is also deemed unnecessary to place more constraints on the tectonic setting other than to say that the Kaapvaal Craton was in compression on a scale which suggests a collisional event.

This tectonic analysis of the Witwatersrand Basin has important broader implications in regard to the possible existence of remote outliers of Central Rand Group stratigraphy. The major structures which were important in localizing the Central Rand Group were driven by a craton-wide stress field. All similarly orientated Archaean lineaments may have been activated by this stress field and hence may also have resulted in the development of outliers of Central Rand Group strata. The most probable example is the Uitkyk Formation of Witwatersrand age (Robb and Meyer, 1985; Saager and Muff, 1986) which occurs in close proximity to the Murchison-Thabazimbi Fault zone. This Fault Zone parallels the Rietfontein and Sugarbush Fault Zones and has had a complex history throughout the Precambrian. Similarly, the thick Gondwan Formation, of possible Witwatersrand age lies juxtaposed against the easterly striking King Fault (Myers, 1986; Stanistreet *et al.*, 1986). Another possible candidate is the Colesburg line (Corner *et al.*, 1986a), which parallels the Border structure. In terms of the model proposed here, these structures and others may be prospective for Upper Witwatersrand outliers. However, the lesson of the Maracaibo Basin margins should be remembered. Nevertheless, both the Maracaibo and the Laramide provinces are characterized by multiple basin development. The presence of the separate Evander Basin suggests that the Kaapvaal Basin could also be characterized by multiple basins. The model proposed here gives some indication where they may be located.

ACKNOWLEDGEMENTS

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