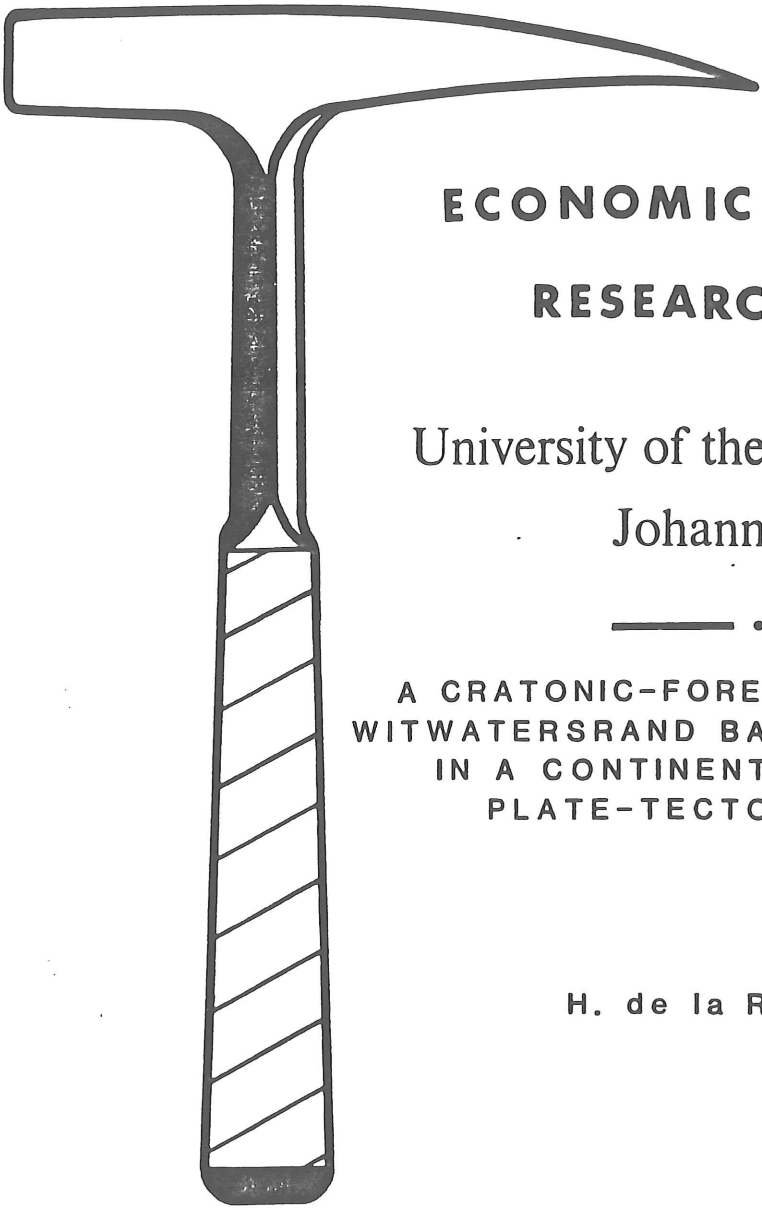


ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

A CRATONIC-FORELAND MODEL FOR WITWATERSRAND BASIN-DEVELOPMENT IN A CONTINENTAL, BACK-ARC, PLATE-TECTONIC SETTING

H. de la R. WINTER

INFORMATION CIRCULAR No.193

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

A CRATONIC-FORELAND MODEL FOR WITWATERSRAND BASIN-DEVELOPMENT IN A CONTINENTAL, BACK-ARC, PLATE-TECTONIC SETTING

by

H. de la R. WINTER

ECONOMIC GEOLOGY RESEARCH UNIT

INFORMATION CIRCULAR No. 193

December, 1986

A CRATONIC-FORELAND MODEL FOR WITWATERSRAND BASIN-DEVELOPMENT IN A CONTINENTAL, BACK-ARC, PLATE-TECTONIC SETTING

ABSTRACT

Definitive features of Witwatersrand Basin development are: its asymmetric shape; early compression along a foredeep, from the positive side of which most of the sedimentation was derived; marginal unconformities; progressive basinward advance of depo-axes, with consequent coarsening-up facies; regular isopachs uninterrupted by rifting; and tholeiitic volcanism terminated by rifting. A typical cratonic, foreland basin is described.

The taphrogenic model, with concurrently rising granite domes and interfering folding directions persisting through time, is discarded. Other proposed models also do not fit the favoured, continental, back-arc-basin model of plate-tectonic theory.

Phanerozoic, back-arc basins are remarkably similar to the Witwatersrand in their style of evolution, deformation, and regional, geological setting. Analogous, back-arc, regional characteristics of alternating, compressional and extensional periods, with volcanism increasing towards the magmatic arc, rising-arc isotherms, plutonism, and uplift also typify the Witwatersrand, the succeeding Ventersdorp rocks, and their hinterland to the north and west. The Transvaal Basin is seen as a younger, composite, fore-arc basin, lapping over older, back-arc and inter-arc, fault-bound basins and intruded by basic, Bushveld Complex, magmatic-arc plutonism.

Inevitable collision with a continent riding on the subducting oceanic slab resulted in post-Transvaal folding and thrusting, followed by felsic and granitic igneous activity, plateau uplift, and red-bed deposition. Large-scale wrench-faulting and impactogenal rifting on the Kaapvaal Craton accommodated the uneven margins of the colliding continents.

An originally stable, late-Archean Kaapvaal Craton became metastable by Andean subduction, spawning the Witwatersrand Basin, and eventually cratonized as a large, Middle-Proterozoic shield, after continent-continent collision.

oOo

A CRATONIC-FORELAND MODEL FOR WITWATERSRAND BASIN-DEVELOPMENT IN A CONTINENTAL, BACK-ARC, PLATE-TECTONIC SETTING

CONTENTS

_____ oOo _____

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

ISBN 0 85494 960 7

A CRATONIC-FORELAND MODEL FOR WITWATERSRAND BASIN-DEVELOPMENT IN A CONTINENTAL, BACK-ARC, PLATE-TECTONIC SETTING

INTRODUCTION

Studies on the role of compressional tectonics in the history of the Witwatersrand Basin (McCarthy et al., 1982; Roering, 1983; Stanistreet and McCarthy, 1984) rekindled interest in the compression that affected late-Witwatersrand sedimentation along the western border of the Welkom Goldfield (Winter, 1964a; Olivier, 1965). A recent revisit to Loraine Gold Mine by the author led to the conclusion that the folding and thrusting of the western limb of the syncline are not products of an isolated, compressional event, caused by lateral spreading of a hypothetical horst bounded by the Western Border Fault lineament, as was previously thought (Winter 1964a), but represent a significant, tectonic event which effectively controlled Witwatersrand basining, as well as dictated the subsequent depositional, volcanic, and tectonic events that followed during Ventersdorp and Transvaal times.

This report is designed as a preliminary documentation of the main factors known, thus far, in support of a new depositional model for the Witwatersrand Basin and to offer a tentative, plate-tectonic setting that would be consistent with the latest observations. The consequences of the plate-tectonic setting are briefly outlined, and some Phanerozoic analogues are compared. New problems arising from this model are mentioned, indicating the wide scope for additional research.

MODELS OF THE WITWATERSRAND BASIN

Taphrogenic-Basin Model

The generally-accepted theory of depositional-basin control of the Witwatersrand is one developed by Pretorius (1981). The basic elements of the model were originally stated in the landmark paper "Rand Basin Sedimentation and Tectonics" by Brock and Pretorius (1964) and subsequently refined by the latter. These refinements do not fundamentally affect the model developed in 1964. Important elements of the Middle-Proterozoic, taphrogenic-basin theory of Pretorius (1981) are presented below. In 1984, Pretorius revised his earlier thinking and seriously considered the Eastern Great Basin of the Rocky Mountains, a foreland basin, as an analogue of the Witwatersrand Basin. As a consequence, he actively encouraged the preparation of this paper.

The Proterozoic, tectonic framework of the Kaapvaal Craton is based on pre-plate-tectonic concepts reminiscent of Beloussow et al. (1974), where vertical tectonics give rise to syneclises and anteclises in a pattern of superimposed interference-folds. Intermittent subsidence of the resultant basins and uplift of domes are envisaged. These controlled the Witwatersrand basining (Fig. 1). The pattern and growth of domes controlled the paleocurrent directions in the Witwatersrand Basin. The environments of deposition relate to fan-delta distribution of braided,fluvial systems. Winnowing of distal deposits could have been affected by wave action. The economically-viable, placer deposits are intimately associated with unconformities within the basin (Fig. 2).

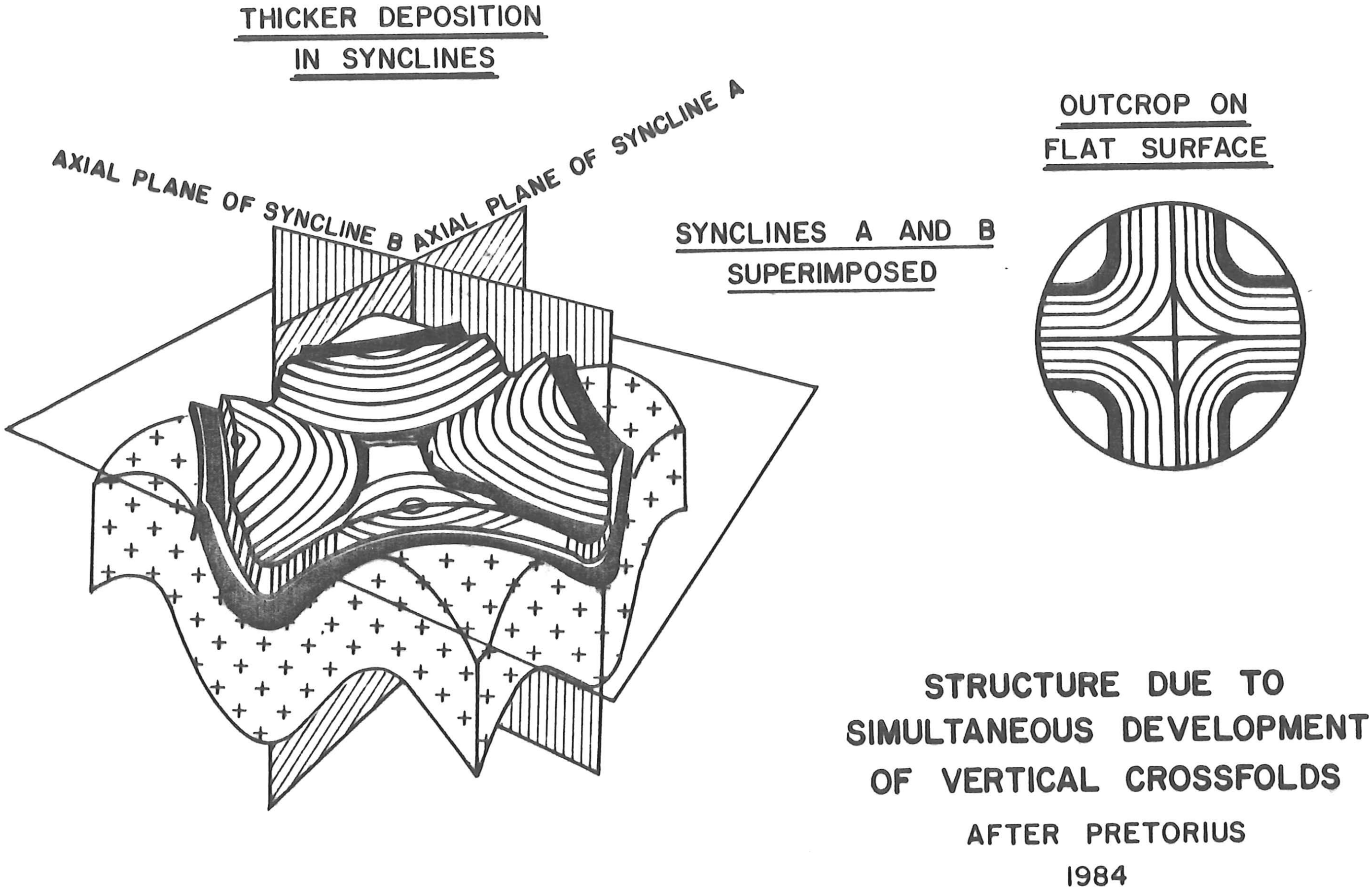


Figure 1 : *Basin-and-dome structures resulting from superimposition of two sets of orthogonal folds (after Pretorius, 1984).*

The basin is asymmetric. The short side displays high-energy sediments, linked genetically to extensive, normal, strike faults. The long side is characterized by low-energy sediments and is downwarped, rather than down-faulted. The stratigraphic succession of the complete geological cycle comprising the Witwatersrand Basin commences with high-energy volcanics of the Dominion Group, has a pivotal, fine-clastic unit, represented by the Jeppestown Subgroup, and terminates with the volcanism of the Klipriviersberg Group (Pretorius, 1981). The high-energy, proximal side of the basin shrank with time. The various goldfields define fan-delta entry-points of major river-systems draining the hinterland, and these were confined, through time, by the interference pattern of vertical displacements. Re-working of sediments off domes (Pretorius, 1981), was a major, concentrating factor for placer-mineralization.

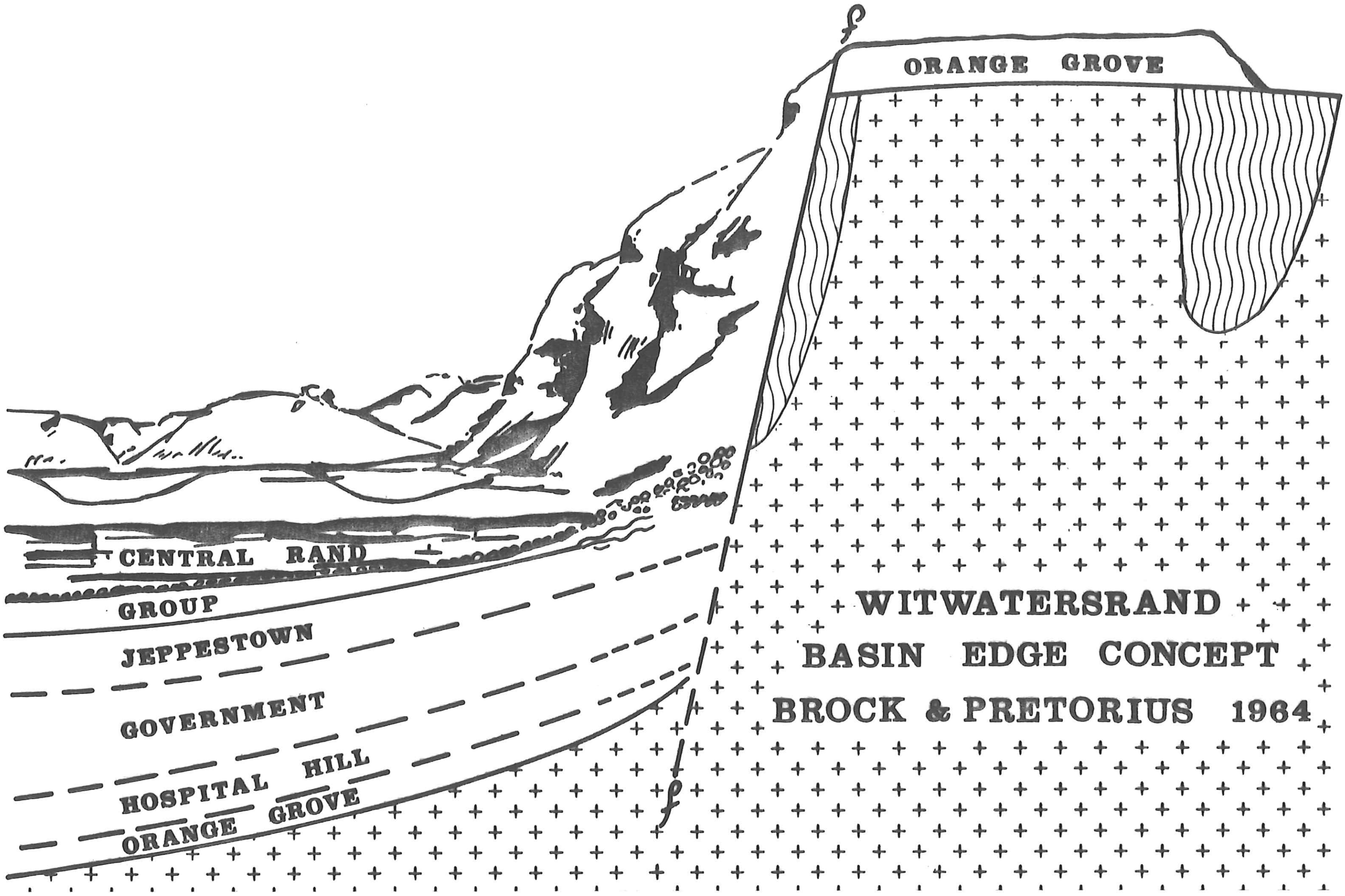


Figure 2 : The classical depositional response to taphrogenic basin development (after Pretorius, 1981).

The paleo-topography of the basement was structurally controlled and this tectonic pattern exercised epidosic control during the whole history of infilling of the Witwatersrand Basin and, even, of the later Proterozoic succession on the Kaapvaal Craton.

Intracratonic, Alluvial-Plain, Lacustrine Model

Vos (1975) introduced some refinements into the taphrogenic-basin model (Fig. 3). He did not include the Dominion or Klipriviersberg groups. He accepted, without questioning, an intracratonic setting, which limited the range of possible sedimentary environments postulated. Though more sedimentary facies were visualized than in the taphrogenic model, the range was still too limited to account for the filling-up of a basin covering about 40 000 square kilometres. A tectono-stratigraphic concept of reworking of sedimentary cycles was introduced, as he postulated a lower, sedimentary sequence truncated by an upper. Transgressions and regressions were considered to have been important factors governing sedimentation and placer mineralization.

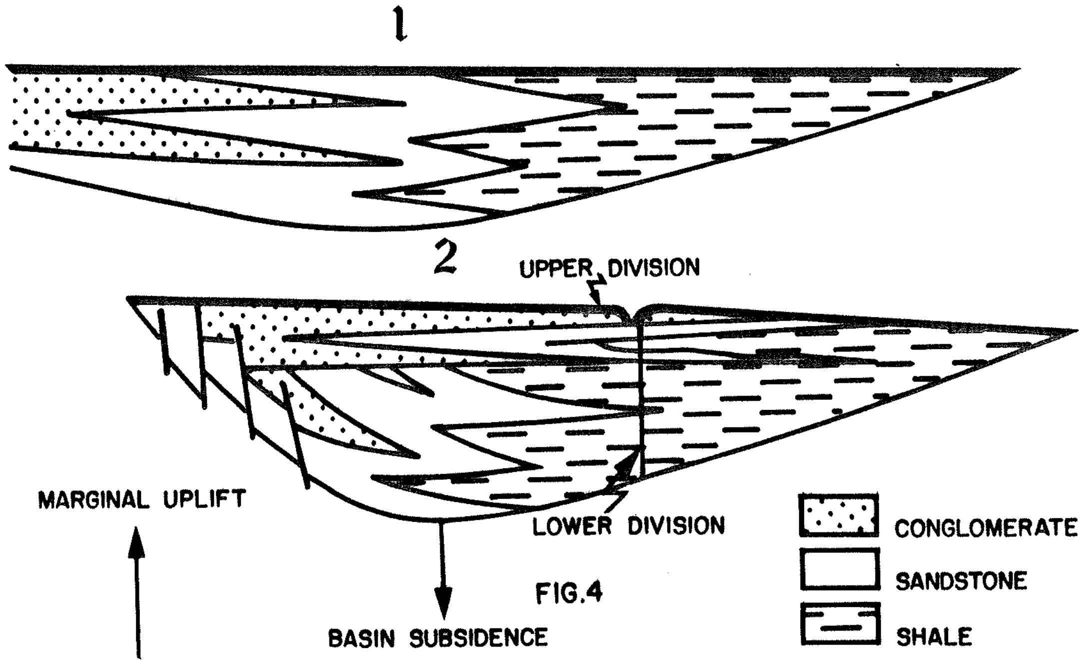


Figure 3 : *Schematic illustration of proposed manner of evolution of the Witwatersrand Basin; inward migration of the basin-margins occurred contemporaneously with marginal uplift and basin-subsidence, after Vos (1975).*

Hutchison (1975) favoured the Witwatersrand to be a model of sedimentation in an intracratonic basin. He emphasized the general coarsening-up in grain-size, coupled with increased immaturity of sediment-composition. It was noted that, with the advance basinwards of depo-centres in time, earlier cycles were eroded to form detritus for later accumulations. No faulting contemporaneous with sedimentation was indicated, and basin-edge folding and associated thrusting was regarded as pre-dating normal faulting and as being attributable to active uplift of the hinge area. The Vredefort Dome was considered to be a protrusion of the northwestern basin edge. Significant sediment influx from the southeastern flank, in the Edenville area, was not supported by his work.

Plate-Tectonic Models

Bickle and Eriksson (1982) proposed a plate-tectonic, extensional model in which a downwarped, cratonic Witwatersrand Basin, without rifting, was followed by a rifted, Ventersdorp succession. An important conclusion, based on mathematical modelling, was that lithospheric thicknesses during the Early Proterozoic could not have been much less than today, validating the consideration of similar, Phanerozoic basins as analogues. They postulated a cratonic-shelf setting for the Witwatersrand Basin and a cratonic, rift-controlled succession for Ventersdorp deposition.

Van Biljon (1980) analyzed the Witwatersrand rocks and the tectonic events that affected them, in the light of a continent-continent-collision model (Fig. 4). He concluded that the Witwatersrand Basin could represent an embayment along a suture-zone between two Archean continents. Subsequently, the two, facing continents collided, with the Witwatersrand Basin preserved at the margin of one of them.

Burke et al., (1985) considered that Ventersdorp rifting is transverse to a collision-zone between the Kaapvaal and Rhodesian cratons and came to the conclusion that the Witwatersrand is a foreland basin (Figs. 5a and b).

Cratonic, Foreland-Basin Model

Recent observations concerning aspects of Witwatersrand deformation and the relations between sedimentation and tectonics, the perusal of recent literature, and attendance at an advanced course on structural geology organized in 1984 by the American Association of Petroleum Geologists, led the author to consider a new model for the development and subsequent deformation of the Witwatersrand Basin, as a hypothetical framework for guiding exploration and research.

A study of sediments that were emplaced concurrently with rift-faulting (Winter, 1983) showed that the time-stratigraphic succession on a horst is abbreviated and intermittently truncated by unconformities, compared with the sequence in an adjacent graben (Fig. 6). From such relations, the growth-histories of major rift-faults can be derived. This type of analysis is impossible to conduct in the Witwatersrand Basin, because the distribution of isopachs and the truncation of stratigraphy below marginal uncomformities are not affected by extensional faulting; sedimentation is pre-rifting. Across such horsts as the Witpoortjie, Kromdraai, and De Bron, deposition concurrently with fault-movement can be demonstrated only for the Kameeldoorns Formation, though it is possible for faulting to have commenced during Klipriviersberg time. The taphrogenic-basin model is thus incompatible with detailed, analytical studies that have been conducted in specific parts of the Witwatersrand Basin.

Late-Witwatersrand, contemporaneous, compressional structures occur on Loraine Gold Mine, on the western limb of a syncline truncated before the last sediments prior to the outpouring of the Klipriviersberg volcanics were laid down (Winter, 1964a; Olivier, 1965). Originally, these structures were interpreted as a result of the local, horizontal spreading of a horst bounded by a large, normal fault, the conjectural Border Fault of the Welkom Goldfield. Loraine Mine was re-visited by the author in 1984 after a considerable amount of mining had been done on the Basal Reef on the western flank of the syncline (Fig. 7). At least two thrust-faults of major proportions displace the Basal Reef. One of these has been demonstrated (Winter 1964a) to have terminated prior to deposition of the last sediments. Therefore, an imbricated sequence of thrust-faults is present in the hinterland of the late-Witwatersrand, contemporaneous, synclinal fold. Such a situation is common to most interfaces between a fold-thrust orogenic belt and its foredeep, and the presence of a back-thrust lends additional credence to the belief that the basin-margin at Loraine is an example of the foredeep of a foreland basin (Bally et al., 1966). This common type of structure is called a triangle zone (Butler, 1982).

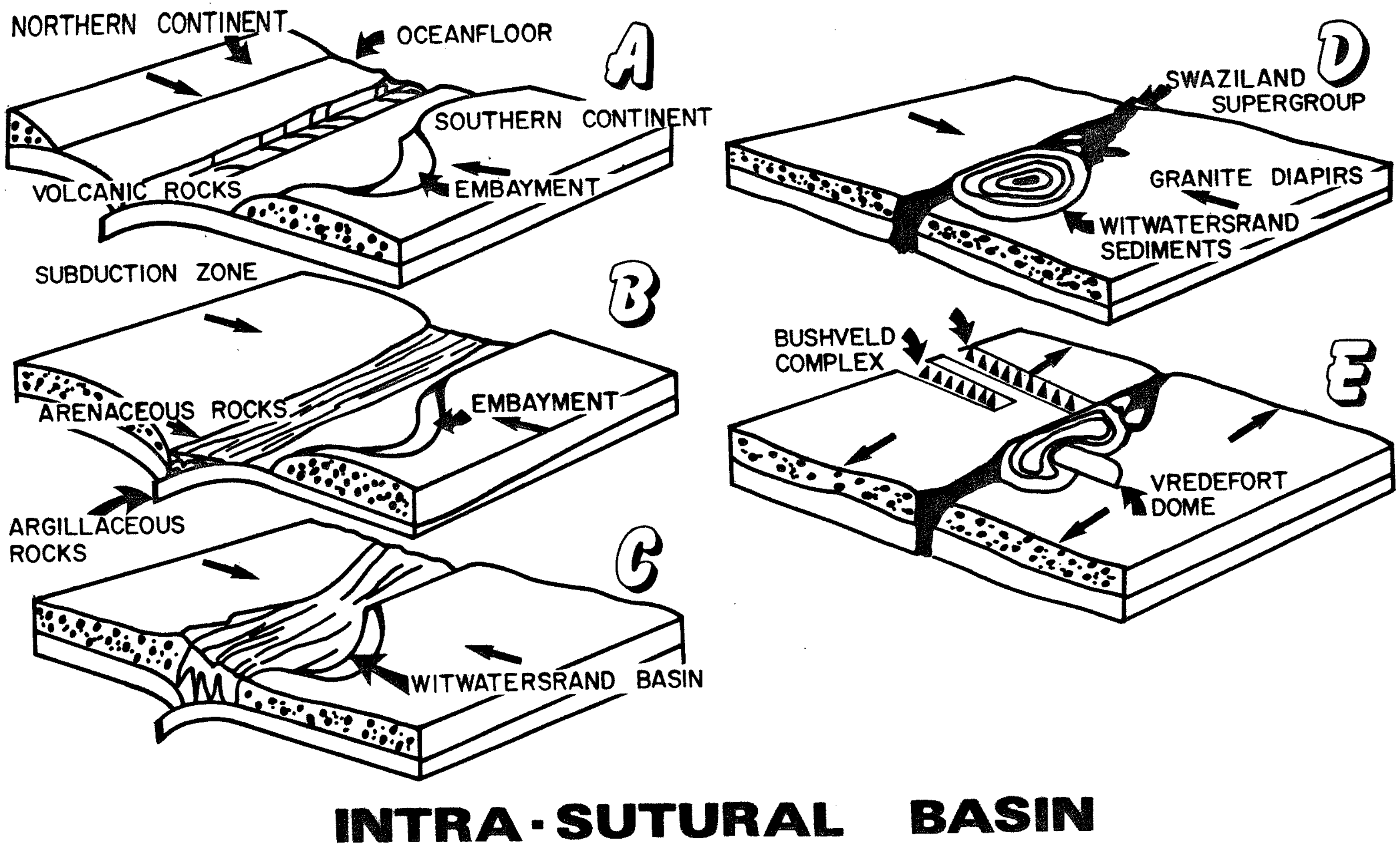


Figure 4 : *Schematic representation of the formation of the Witwatersrand Basin, according to the continent-continent, collisional theory of van Biljon (1980).*

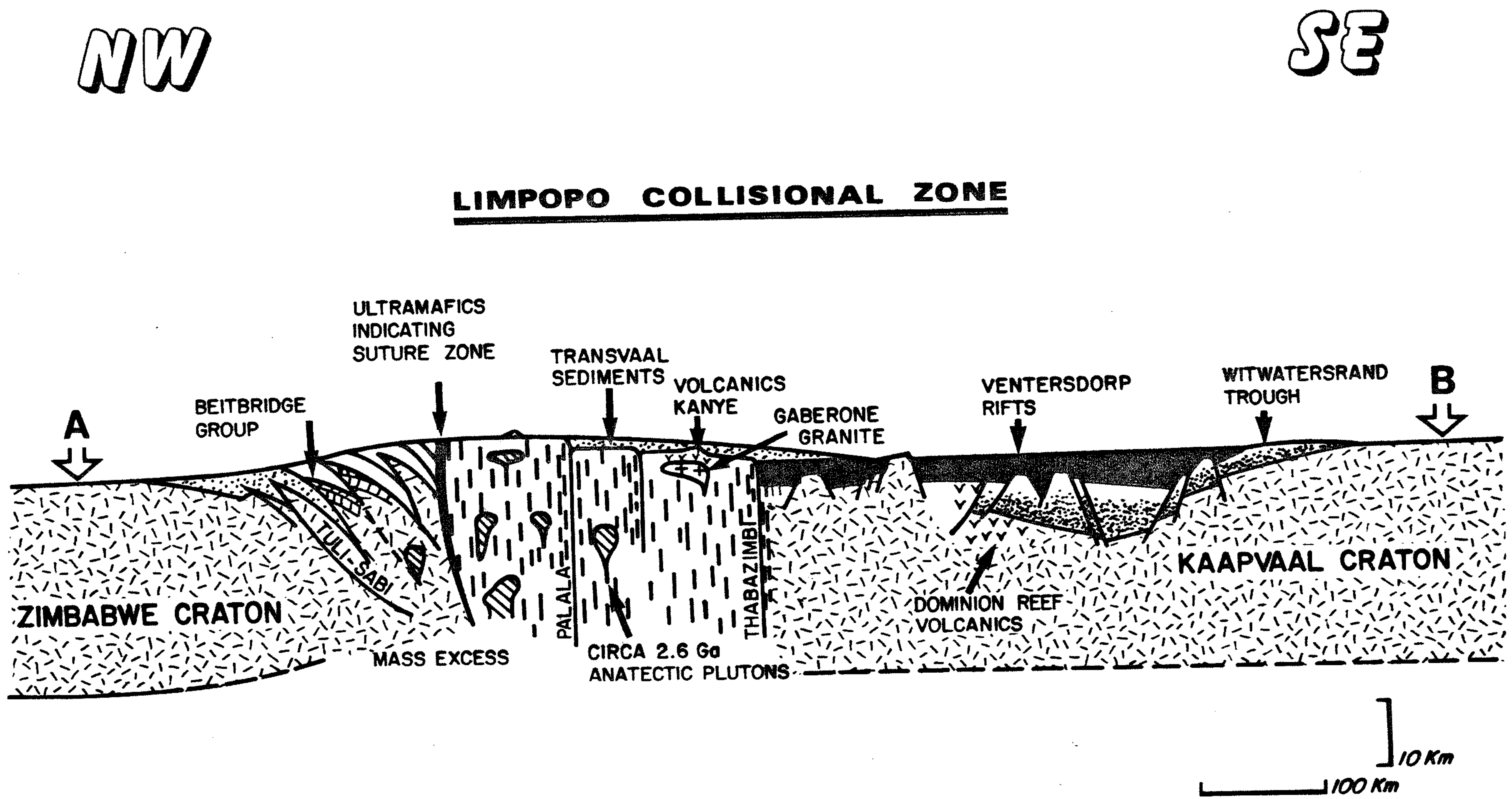


Figure 5a : Cross-section through the Rhodesian and Kaapvaal Cratons across the Limpopo Province, which is interpreted as the product of 2640Ma continental collision. The Witwatersrand Supergroup was deposited in a foreland-trough behind an Andean-type arc. The Ventersdorp rifts striking at high angles into the Limpopo collisional zone and are interpreted as impactogens, accommodating extension in a zone of imperfect, left-lateral, strike-slip faulting induced by collision (after Burke, Kidd, and Kusky, in press).

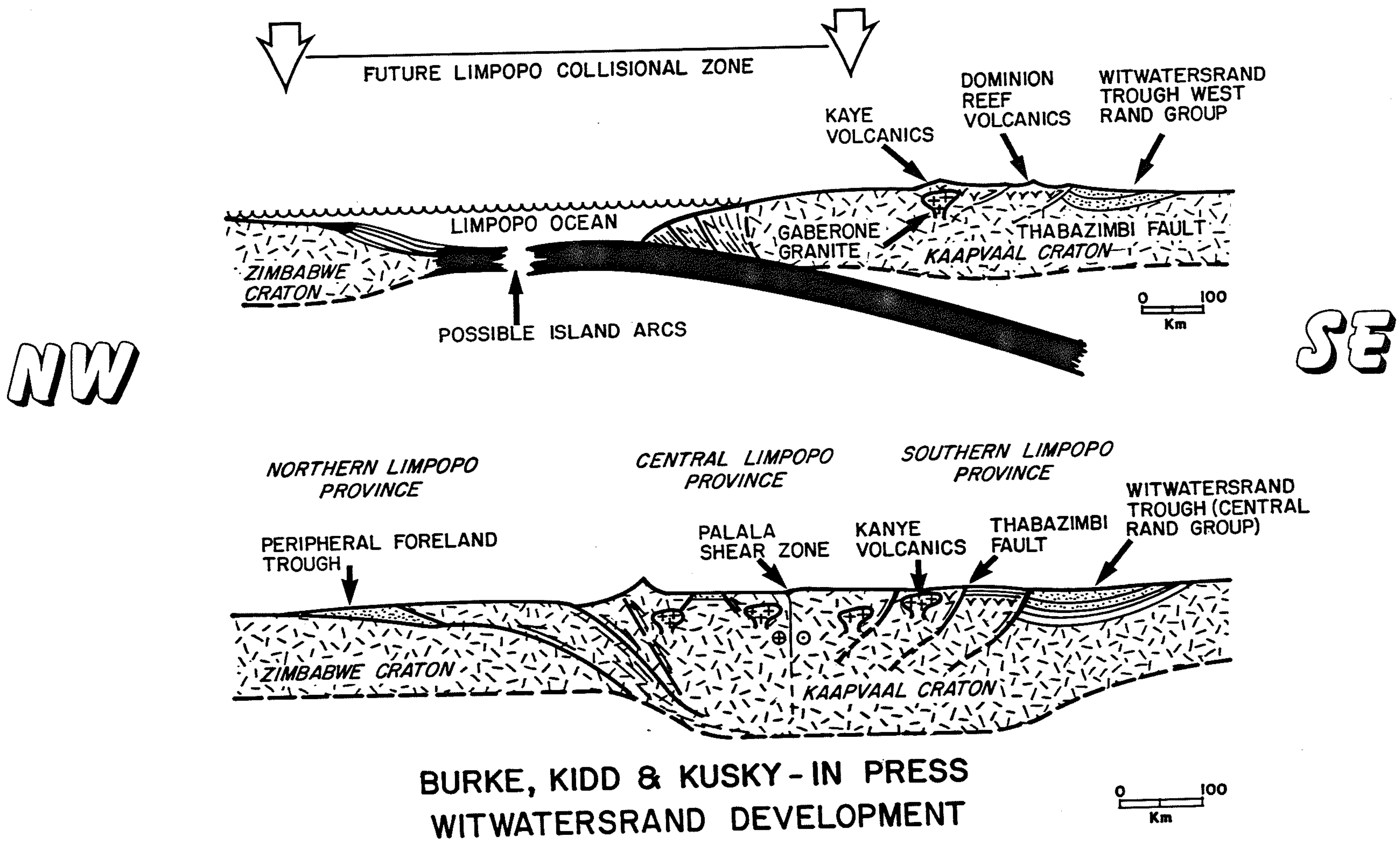


Figure 5b: *Interpretation by Burke, Kidd and Kusky (in press) of possible plate-tectonic events: (above) the West Rand Group as a retro-arc basin; (below) the Central Rand Group as the product of continent-continent collision.*

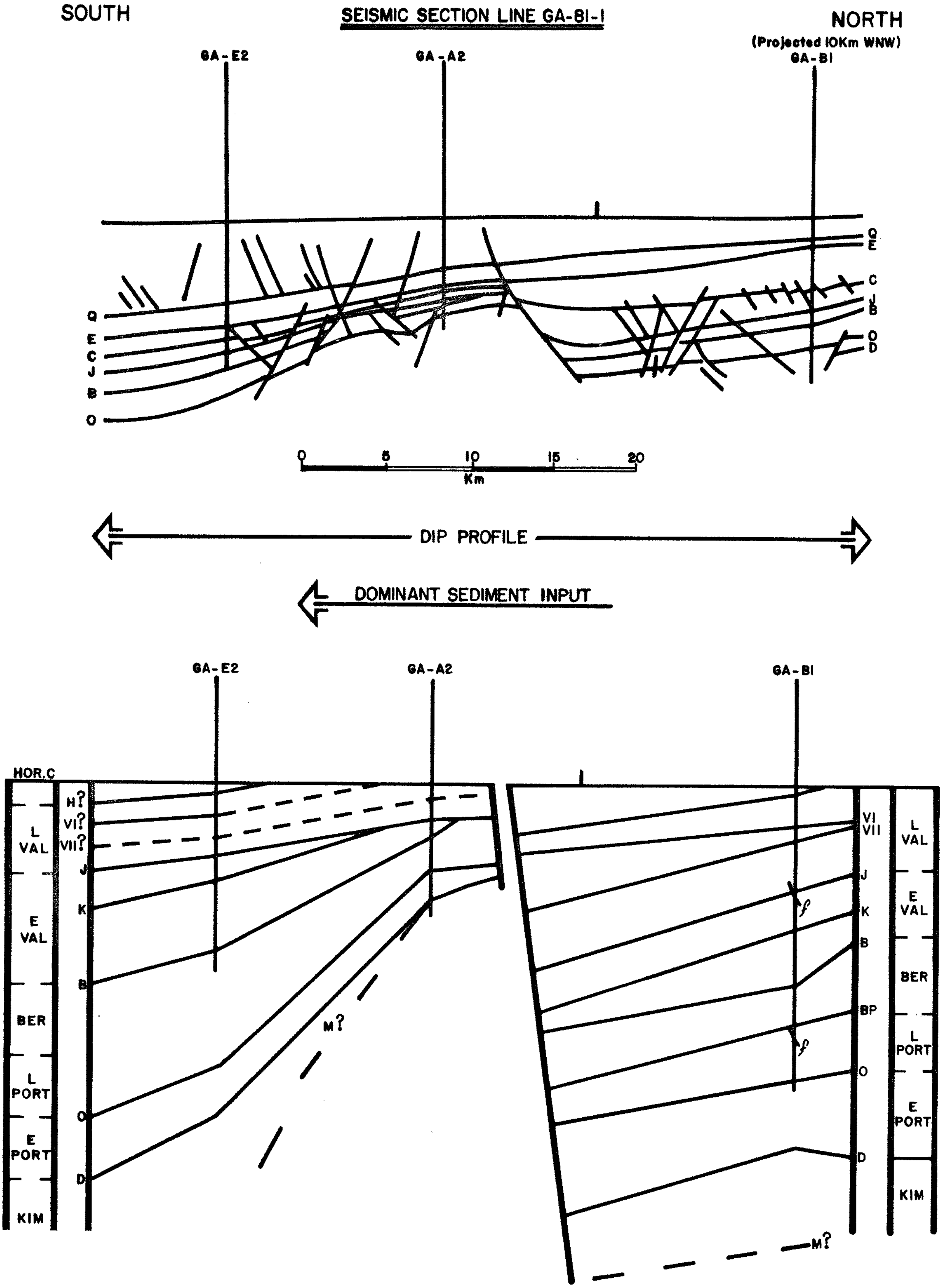


Figure 6: *Tectono-stratigraphic analysis of taphrogenic sedimentation, as influenced by graben-and-horst structures in the southern offshore Pletmos Basin (after Winter, 1983).*

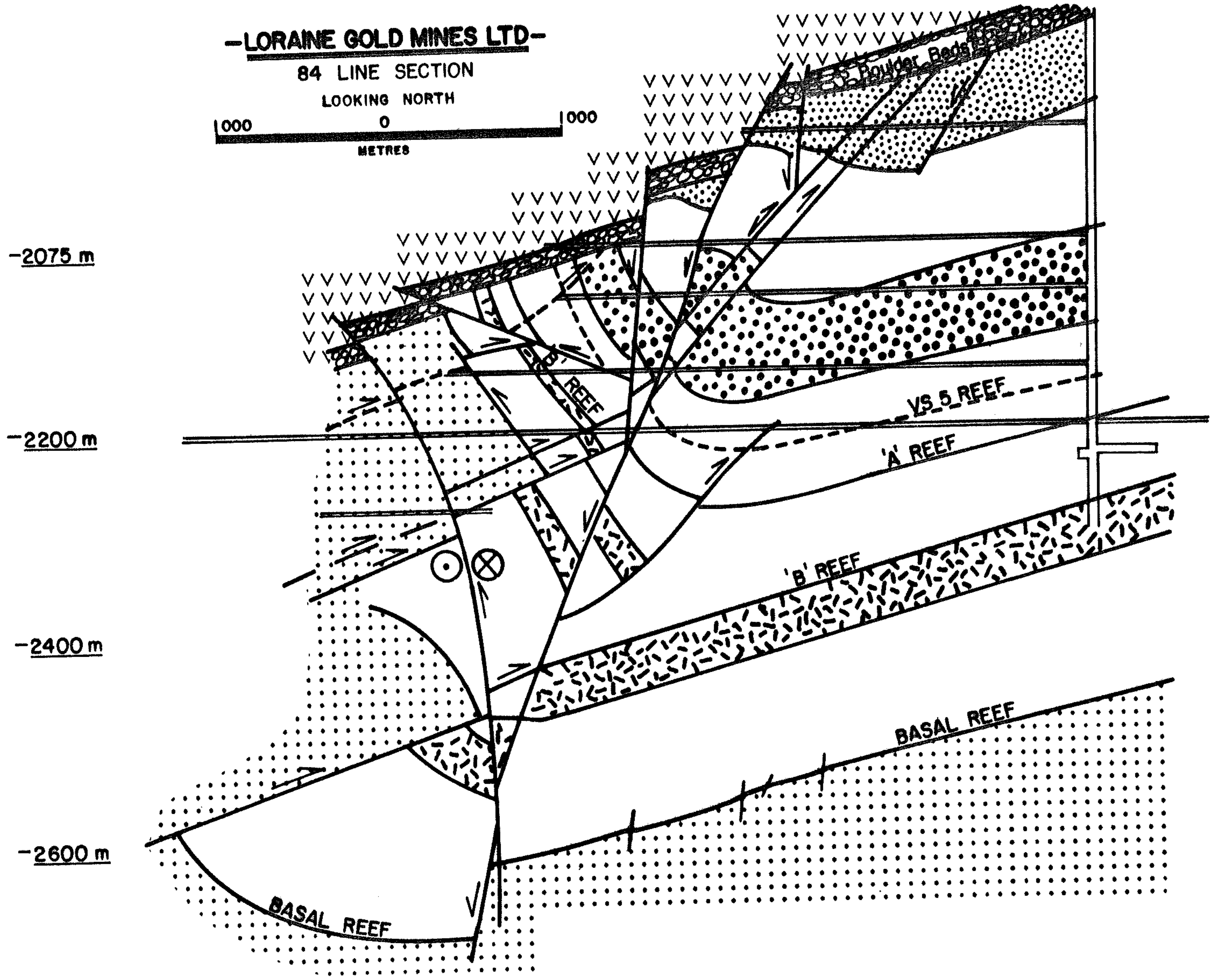


Figure 7 : Geological cross-section through mine-workings on Loraine Gold Mine, showing intimate relations between sedimentation and tectonics from before Basal-Reef (Bird) time to the base of the last phase of deposition prior to the outpouring of the Klipriviersberg volcanics.

Similar thrusts have been recorded along the western margin of the Welkom Goldfield, as far south as Western Holdings Gold Mine. At St. Helena Gold Mine, the Basal Reef is preserved in a syncline isolated by pre-Karoo erosion from the remainder of the field to the east. Farther south, in the Beisa Mine, the Main Reef Conglomerate Formation is overturned, proving a stretch of at least 60km where the basin-margin is limited by compression. A study of the Alberta Trough of the Canadian Rockies indicates that such a marginal syncline is orthogonal to the regional compressional force, and, therefore, is a good indicator of the regional tectonic transportation direction. Steep dips are generally localized in the vicinity of the marginal trough or foredeep. Farther back, most of the thrust-sheets are soled onto incompetent beds, or ramp over the more-competent layers. Thus, moderate dips are the rule in the fold-thrust belt of the hinterland.

A feature that is commonly noticed in fold-thrust belts is an inversion from listric thrust-faulting to younger, listric, normal faulting (Shelton, 1984; Bally et al., 1966); often, the reversal of movement makes use of favourably orientated thrust-planes. Figure 7 illustrates this to be a feature of Witwatersrand deformation. Thrust faults are thus displaced, a complicating factor in their recognition as continuous structures, both in the mines and on seismic sections.

Evidence is mounting for the recognition of an extensive, compressional, tectonic period to have existed in late-Platberg times (McCarthy et al., 1982; Roering, 1983; Stanistreet and McCarthy, 1984), associated with thrusting, in the northern Central Rand and West Rand areas. Cleaved, Platberg, volcanic conglomerates have been observed immediately west of Ventersdorp, and, in cores of boreholes in the vicinity of the northern continuation of the Loraine marginal trough, minor and meso-structures of undoubted compressional origin occur, which suggests that the type-Platberg formations (Winter, 1976) should be re-examined for possible tectonic duplications. The facts so far gathered lead to a tentative hypothesis that a younger, compressional phase, followed by relaxational extension tectonics, structurally modified the Platberg Group. Brink (1982) has recorded such pre-Pniel (Winter, 1976) rifting.

Extensive strike-slip faults have been recorded in mines and in the field, between Heidelberg and Balfour (Nel and Jansen, 1957). Association of porphyritic dykes with these and their younger age, relative to the early, post-Witwatersrand normal faults, suggest that wrench-faulting may be a common deformation of the Platberg period. Lateral shifts on major, earlier, normal faults could also have occurred during this period. In the Heidelberg-Balfour area and in the southern portion of Harmony Mine in the Orange Free State, distal thrust faults appear in the Witwatersrand Basin, and might be foreland thrusts, similar to those in the Rocky Mountains foreland areas (Brown, 1984), transmitted across the basin along weak formations and then localized as ramps by thinning out of the Witwatersrand Basin (Winter, 1964b).

Coetzee (1960) has demonstrated, from both faulting and the stratigraphic succession, that, whilst the De Bron Horst was uplifted during early-Platberg times, it was depressed, relative to its surroundings, as a result of displacements on reverse faults. This was probably a late- or post-Transvaal tectonic event, which can be related to the Vredefort doming. Brink (1982) has demonstrated that the late-Transvaal deformation included large-scale normal faults. Even later structural features may have contributed towards complicating the deformational history of the Witwatersrand Basin.

THE CRATONIC-FORELAND MODEL

The benchmark paper by Dewey and Bird (1970) on the relation between plate tectonics and geosynclines gave impetus to the evaluation of depositional basins as controlled by plate-tectonic processes. That plate-tectonic cycles, prior to the present one, as indicated by sutures, also controlled depositional basins, have been amply demonstrated (Burke et al., 1977). Plate-tectonic models have been fitted to Proterozoic basins, and the debate as to when Wilson cycles originated has moved towards the Archean. Foreland basins are yoked to orogenic, fold-thrust, tectonic belts. Such basins have been related to specific plate-tectonic environments (Dickinson, 1974). Characteristic features of different types of foreland basins allow them to be further subdivided into a plate-tectonic classification scheme. Bally's (1984) proposals (Table I and Fig. 8) cannot be applied to Proterozoic basins, though his theoretical considerations are eminently suitable as a base. Perhaps the most important reason is that the classification was designed to fit the present plate-tectonic cycle, with the result that it suffers in the case of previous cycles, where continent-continent collisions have taken place. A number of such collisions probably affected most Early-Proterozoic plates. An aspect of the problem with this classification is whether certain back-arc, foreland, cratonic basins are the direct result of collision between continental slabs upon plates (peri-cratonic basins) or whether they began to form earlier. This point, of great importance to the understanding of the tectonic controls on Witwatersrand Basin, will be discussed later.

Convergent Boundaries

It is clear that orogenies and fold-thrust belts, as well as the linked foreland basins, are associated with convergent plate margins, where subduction of oceanic floor is the active process. Wrench-fault tectonics accompanies compressional tectonics in the general case where the direction of movement of the downgoing slab is not orthogonal to the trench.

Four types of convergent boundaries are known (Bally, 1974) (Fig. 9):

Subduction Boundaries : Mariana type, where an oceanic plate is driven beneath another oceanic plate, upon which an island arc is formed.

Andean type, where an oceanic plate subducts beneath a leading, continental-plate margin, upon which a magmatic arc is formed.

Collisional Boundaries : Alpine-Himalayan type, where two continental-plate segments collide and the one tied to the original, downgoing, oceanic plate attempts to force its way below the other.

Taiwan type, where a continental-plate segment on the downgoing plate collides with the island arc of the opposing plate and is forced below it.

The common collision events, where island arcs, micro-continents, oceanic islands, and plateaux are accreted onto the leading edge of an overriding continental plate, do not seem to fit into this classification. Bally (1974) possibly considers this case as a variety of an Andean-type subduction-boundary, with such collisions not having a marked effect on major, plate-boundary conditions.

Foreland basins situated on the subducting side of a volcanic arc are called fore-arc basins, and those on the opposite side are back-arc basins (retro-arc basins). Cratonic-foreland basins, by definition, are founded upon tectonically stabilized, granitic terrane. Depositories found as a result of collisions are known as pericratonic or peripheral basins.

TABLE I

BASIN CLASSIFICATION

1. BASINS LOCATED ON THE RIGID LITHOSPHERE, NOT ASSOCIATED WITH FORMATION OF MEGASUTURES

    11. Related to formation of oceanic crust

        111. Rifts

        112. Oceanic transform fault associated basins

        113. Oceanic abyssal plains

        114. Atlantic-type passive margins (shelf, slope & rise) which straddle continental and oceanic crust

            1141. Overlying earlier rift systems
            1142. Overlying earlier transform systems
            1143. Overlying earlier Backarc basins of (321) and (322) type

    12. Located on pre-Mesozoic continental lithosphere

        121. Cratonic basins

            1211. Located on earlier rifted grabens
            1212. Located on former backarc basins of (321) type

2. PERISUTURAL BASINS ON RIGID LITHOSPHERE ASSOCIATED WITH FORMATION OF COMPRESSIONAL MEGASUTURE

    21. Deep sea trench or moat on oceanic crust adjacent to B-subduction margin

    22. Foredeep and underlying platform sediments, or moat on continental crust adjacent to A-subduction margin

        221. Ramp with buried grabens, but with little or no blockfaulting
        222. Dominated by block faulting

    23. Chinese-type basins associated with distal blockfaulting related to compressional or megasuture and without associated A-subduction margin

3. EPISUTURAL BASINS LOCATED AND MOSTLY CONTAINED IN COMPRESSIONAL MEGASUTURE

    31. Associated with B-subduction zone

        311. Forearc basins
        312. Circum Pacific backarc basins

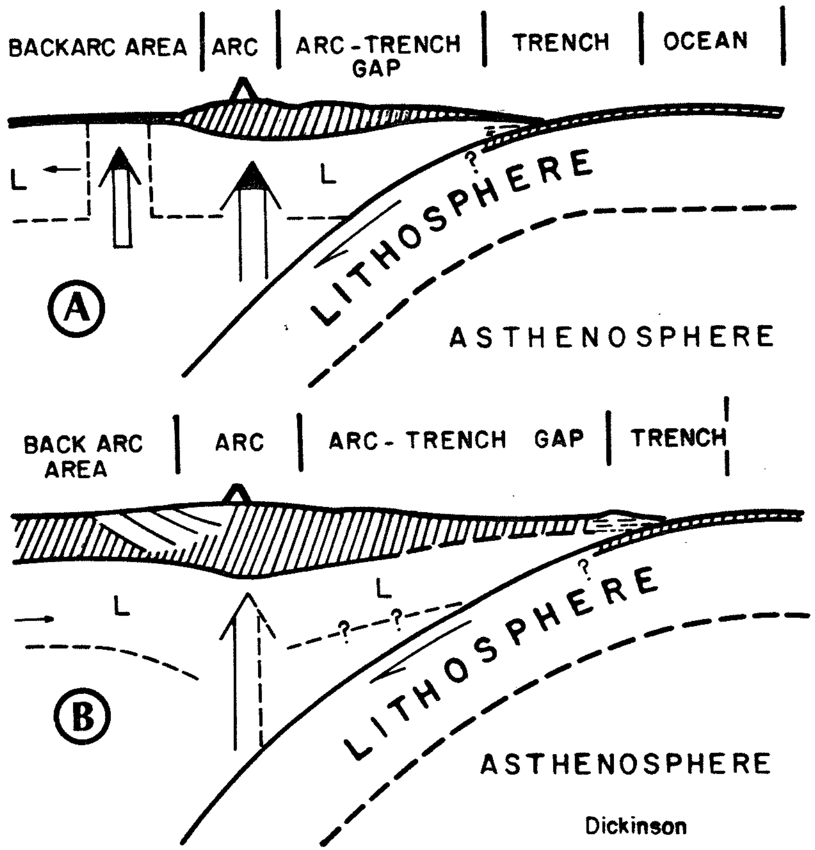
            3121. Backarc basins floored by oceanic crust and associated with B-subduction (marginal sea sensu stricto).
            3122. Backarc basins floored by continental or intermediate crust, associated with B-subduction

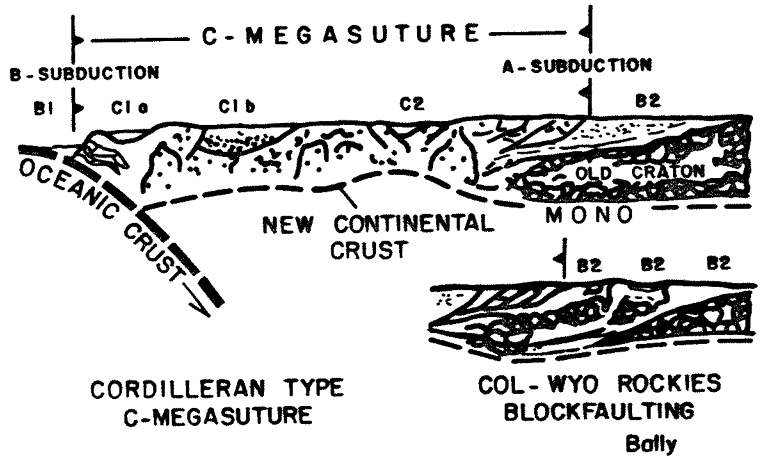
    32. Backarc basins, associated with continental collision and on concave side of A-subduction arc

        321. On continental crust or Pannonian-type basins
        322. On transitional and oceanic crust or W. Mediterranean-type basins

    33. Basins related to episutural megashear sytems

        331. Great basin-type basin
        332. California-type basins





<u>Figure 8</u> : Plate-tectonic models and nomenclature involving subduction of oceanic lithosphere, at a convergent continental margin. That according to Dickinson (1974) shows (A) extension and (B) compression in the back-arc area. That of Bally (1984) shows thin-skinned thrusting, as in Alberta, and thick-skinned, or foreland, thrusting involving granitic craton, as in the Colorado-Wyoming Rockies.

CONVERGENT BOUNDARIES

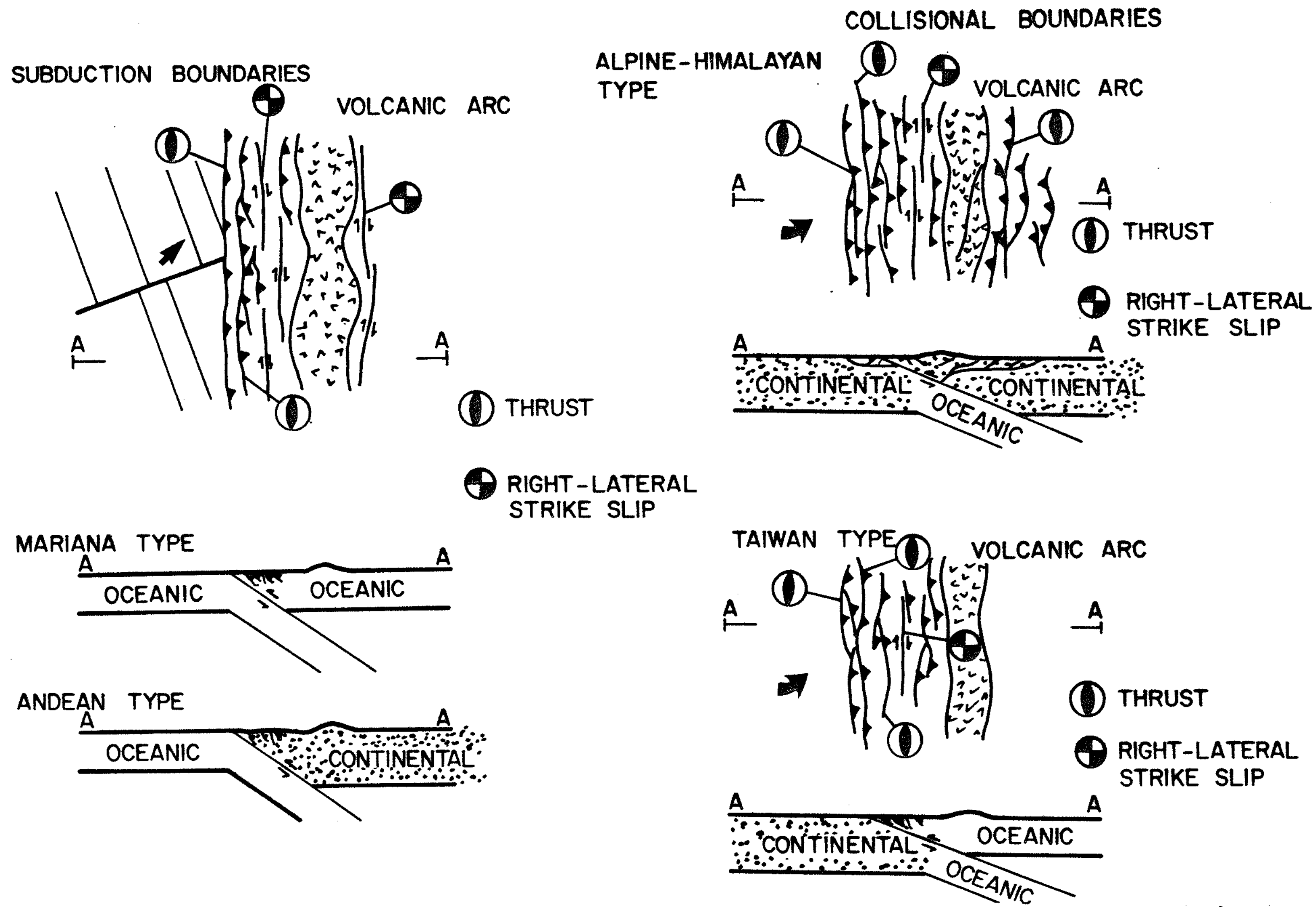


Figure 9 :*Schematic diagrams illustrating the four types of convergent boundaries. Typical first-motions of faults are illustrated in each case (after Bally, 1984).*

Fore-Arc, Back-Arc, and Collisional Basins

Dickinson and Seely (1979) have analyzed the features of five types of fore-arc basins (Fig. 10), and, from these it is clear that the Witwatersrand Basin cannot be considered such a depository. This is understandable, since most ancient fore-arc basins were distally deformed by the process of subduction and by collisions leading to continental-crustal accretion (Burke et al., 1977).

It is necessary to differentiate back-arc basins on continental crust (Fig. 11) from basins associated with collisions, keeping in mind that Andean-type subduction must precede continent-continent or Alpine-Himalayan-type collision. According to Molnar and Atwater (1978) and Dickinson and Seely (1979), flat-plate subduction of Andean type would lead to back-arc compression, and steeper angles of the Benioff zone to extension (Fig. 8). Dewey (1980) analyzed these variations and their causes and effects, in a study of the kinematics of convergence. Some of his conclusions might fit the Witwatersrand and subsequent Proterozoic, geological history of the Kaapvaal Craton. The subduction angle relates to the absolute and relative rates of convergence and to protuberances on the oceanic plate (Cross and Pilger, 1982). Bally (1984) has demonstrated that back-arc foreland-basins, founded on continental crust, can form prior to continental collision. The back-arc area characteristically has a history of compression, followed, or alternated by extension, often associated with strike-slip systems (Dewey, 1980). Along lines initiated by Gilluly (1971), it remains to be demonstrated that magmatic-arc volcanism may not be incompatible with Ventersdorp volcanism.

The best model of a foreland basin, that is demonstrably the product of collision between continental portions of plates, has been documented by Dickinson (1974). Dickinson's (1974) pericratonic foreland basin occurs on the underthrusted plate and, typically, has some or all of the characteristics described below (Fig. 12).

The leading, passive, continental margin, approaching the trench, is draped with a sedimentary prism, commonly described as a miogeosynclinal deposit. This prism is deformed by collision, resulting in an uplifted, thrust-fold belt, directed towards a linked, asymmetrical basin. Characteristically, there is a major reversal of sedimentary-source direction in this foreland basin, compared to the deformed miogeosyncline, and the foredeep is affected by the collisional orogeny. An ophiolitic suture zone may often be detected at the collision contact, followed by a subduction complex, as normally found in fore-arc regions, but these may be difficult to locate (Light, 1982). Volcanism is rare to absent in the pericratonic,foreland-basin setting. The overriding, continental plate inherits all the geological features of its Andean-type precursor, including the back-arc, cratonic, foreland basin. Large-scale plateau-uplift, major wrench faulting and acid, igneous activity affect the overriding plate.

Foreland basins, such as the Molasse Basin, have been directly attributed to collision. It would be more logical to consider the back-arc foreland-basin to have been further deformed by collisional compression, and the resulting uplift, due to duplication of granitic crust, to have terminated basining in the hinterland. Back-arc foreland-basins of Andean type may continue to develop, in spite of exotic terranes accreting to the leading edge.

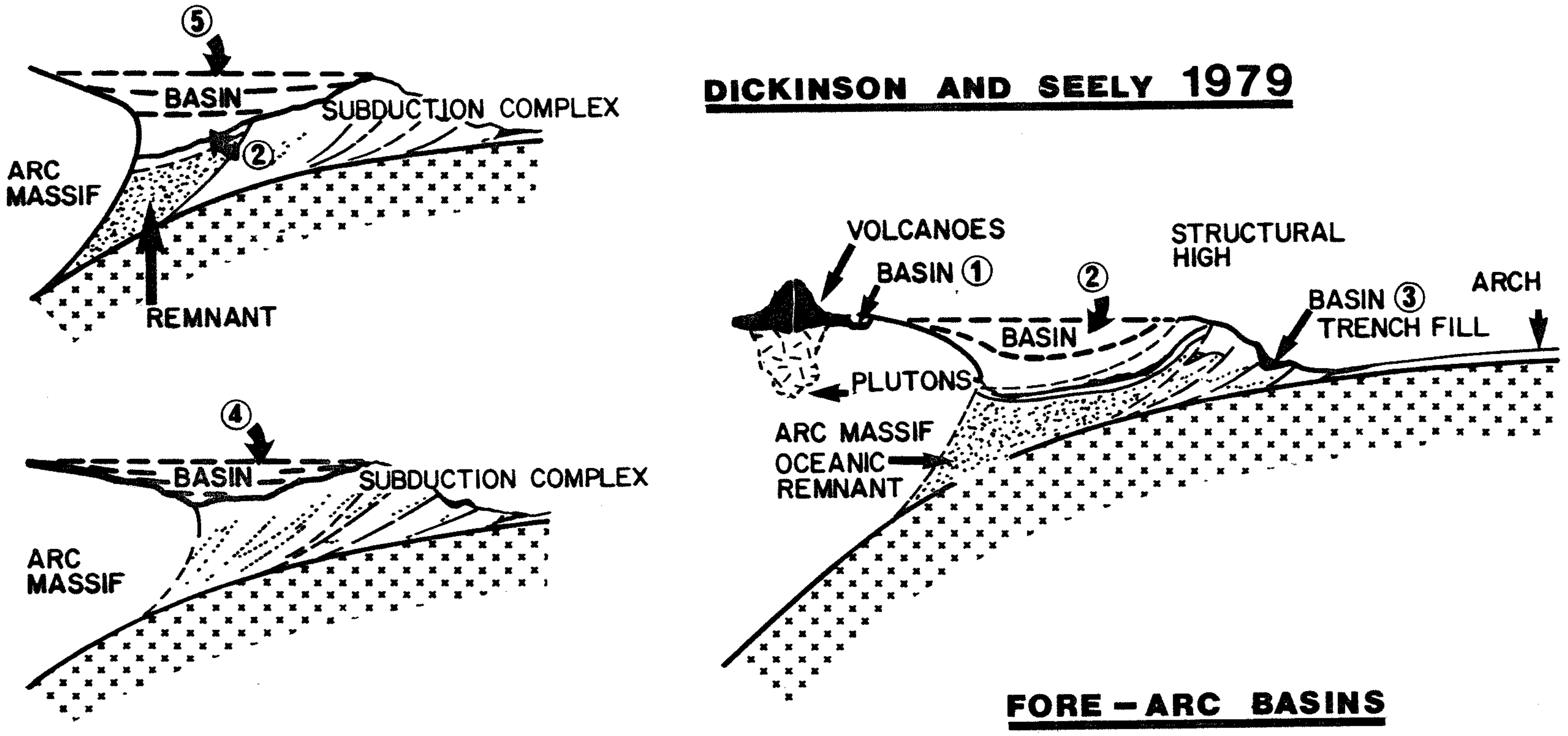


Figure 10 : *Variations of generalized fore-arc models (Dickinson and Seely, 1979). The fold-thrust belt is distal to the basin; oceanic remnants are involved in a subduction complex; and vergence is in the opposite sense, relative to the basin compared with the back arc (see also Figure 11).*

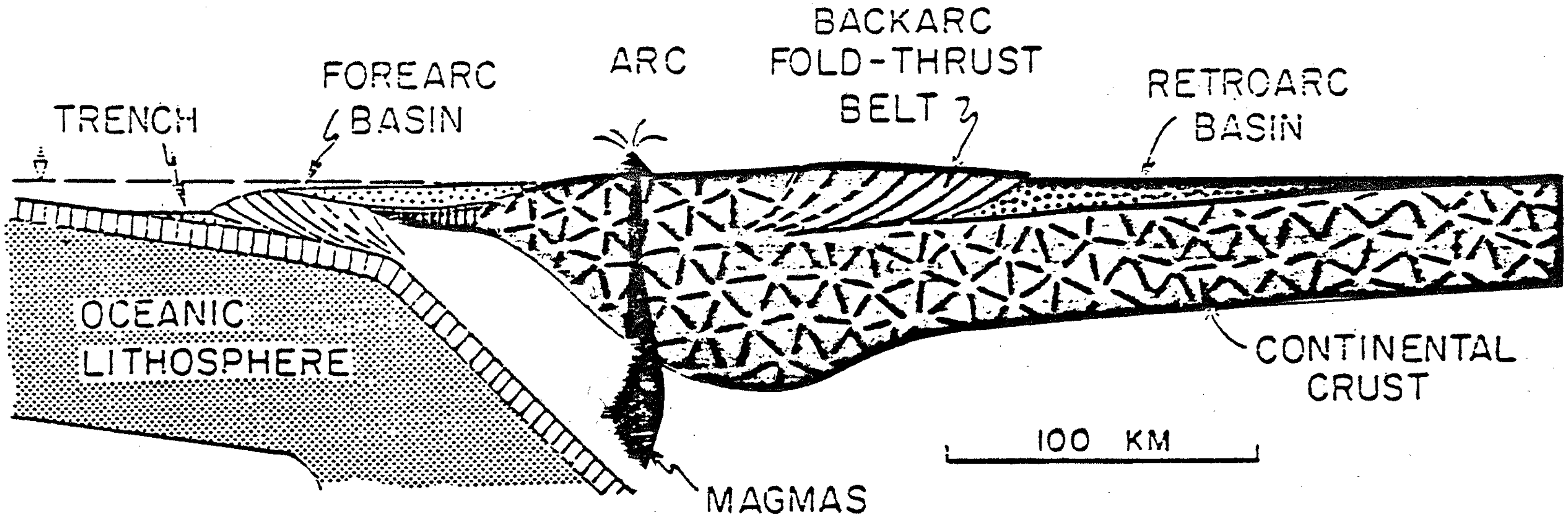
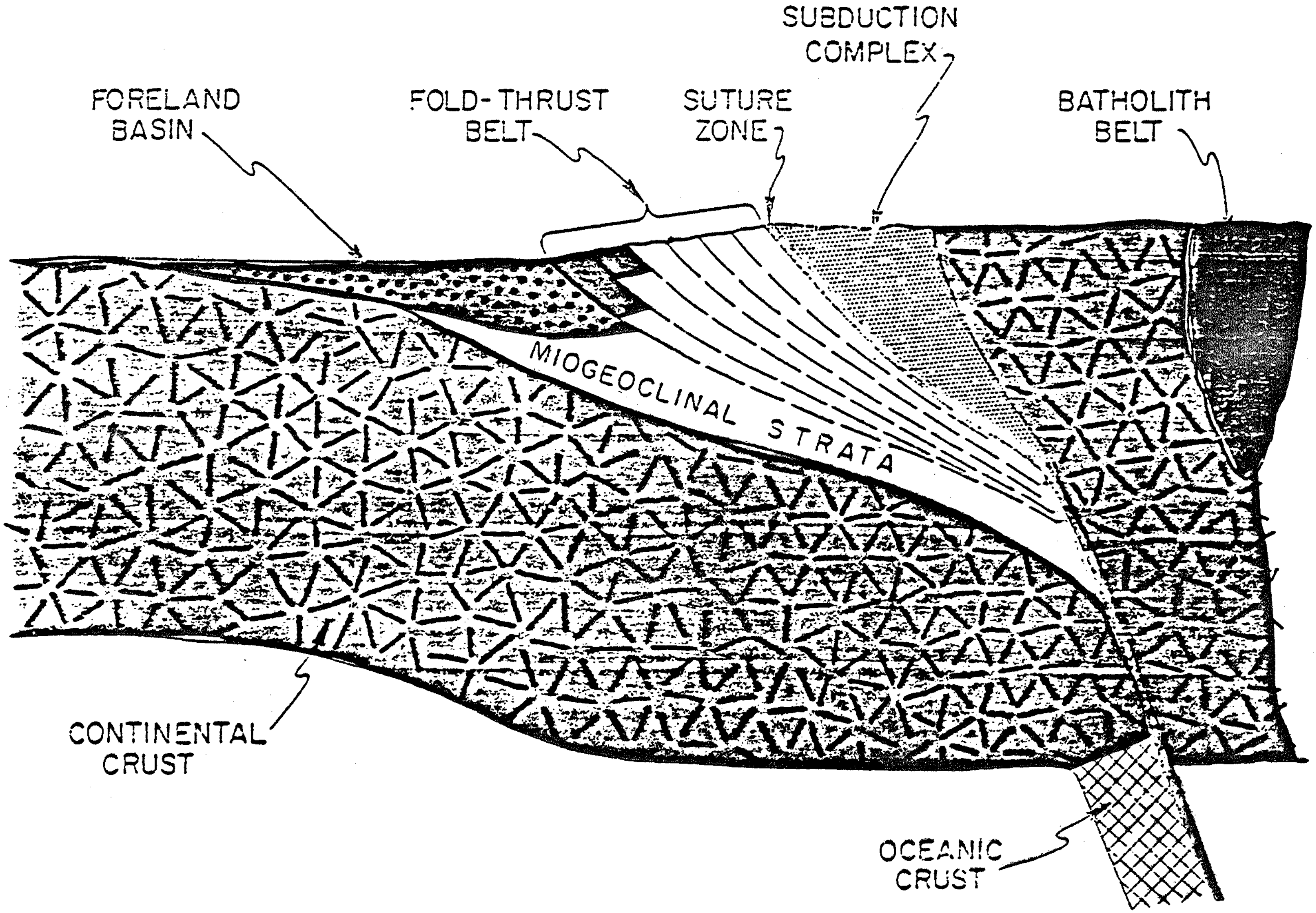


Figure 11 : *Simplified model (after Dickinson, 1974) of the plate-tectonic setting of a cratonic back arc, here named a retro-arc basin.*



<u>*Figure 12*</u> : *Basin development with active-margin, continent-continent collision (after Dickinson, 1974). Alternative plate-tectonic setting for a fold.thrust-belt yoked basin, called a pericratonic or peripheral foreland basin.*

The known Witwatersrand-Ventersdorp geology favours a back-arc (retro-arc), cratonic, foreland-basin model for the Witwatersrand sedimentary basin and an alternating inter-arc-to-back-arc, extensional and compressional model for the subsequent Klipriviersberg and Platberg Groups of the Ventersdorp Supergroup.

Comparison with Taphrogenic-Basin Model

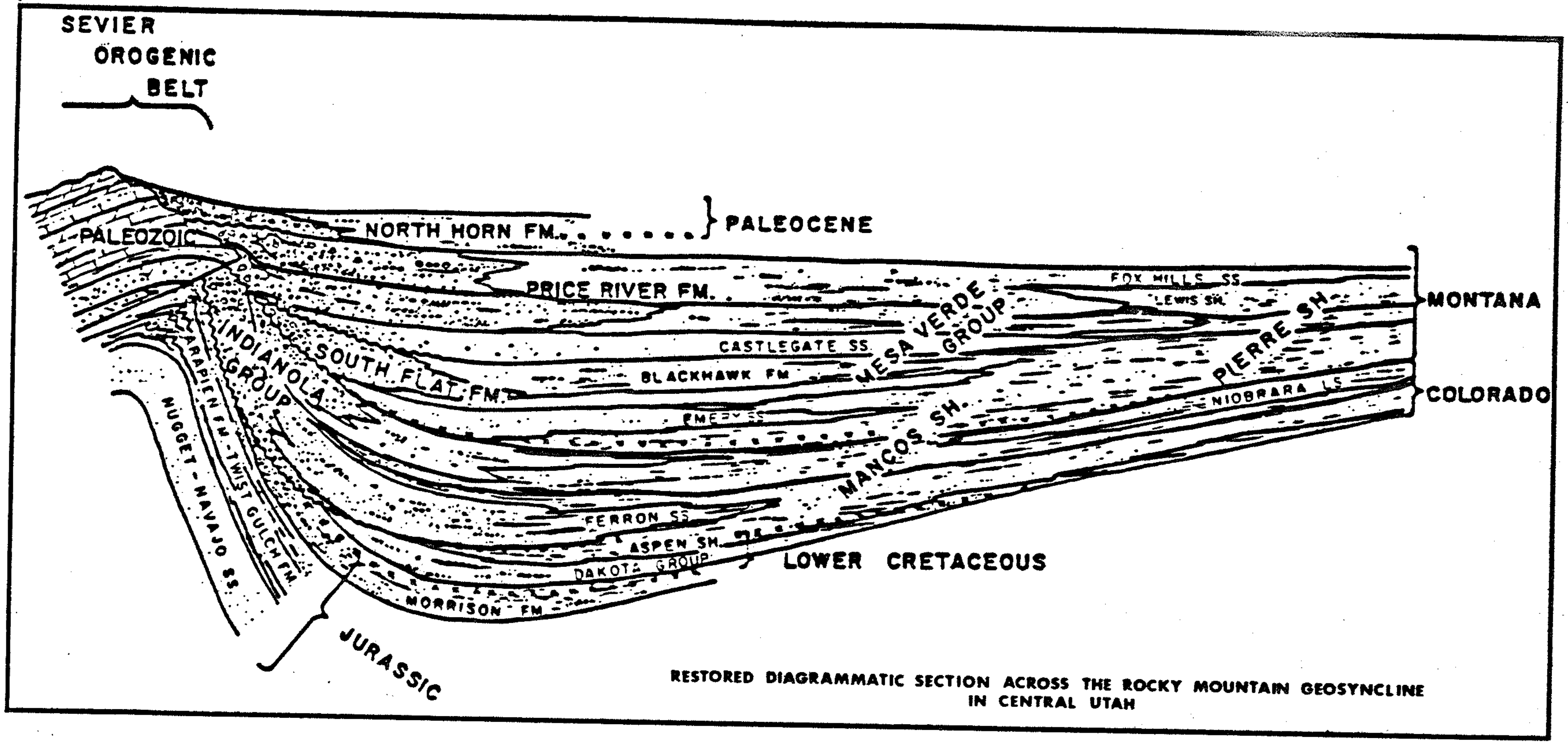
The model selected for Witwatersrand-basin development has well documented, Phanerozoic counterparts, such as the Eastern Great Basin of the Rocky Mountains (Fig. 13), from which many analogues can be chosen, to study both the sedimentological and the tectonic aspects and the expected variations in these.

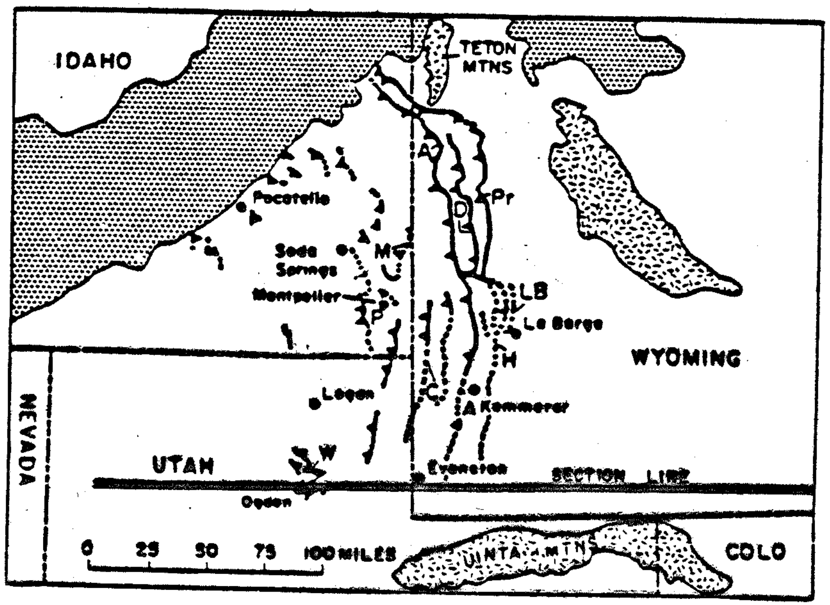
The basin shape is determined by back-arc basining and concurrent, compressional, horizontal forces directed away from the magmatic arc (Fig. 11). The floor is a passive, cratonized, Archean, granitic crust, originally dipping at a low angle into the hinterland. The basining is accentuated by isostatic adjustment to thrust-sheet pile-up and coarse molasse-deposition associated with it (Jordan, 1981) to form a foredeep thinning distally to a tapering foreland (Figs. 11 and 13). Various theories have been advanced to account for the initiation of basining (Dickinson, 1974; Molnar and Atwater 1978, Dewey, 1980). Mathematical modelling of this type of loading predicts the development of a foreland uplift within the asymmetric basin (Royden and Kamer, 1984). The distal foreland gradually wedges out. Lateral variations are determined by lateral ramps, wrench faults, interfering foreland uplifts, and irregularities in the subducting, oceanic, flat plate. The overall shape of the proximal basin edge is also determined by later, collisional tectonics, where the outlines of the colliding continents control the deformation. Van Biljon's (1980) model is of relevance in this respect, but falls down where it predicts a collisional type of provenance reversal not experienced in the Witwatersrand Basin. The subsequent Ventersdorp volcanism also fits poorly into a late-stage, collisional scenario. Inversion tectonics is common in the analogues and is well known in the Witwatersrand foredeep-equivalent (Fig. 7). Those normal faults, genetically related to Kameeldoorns clastic wedges, are of this type.

Analogues suggest that continental deposition and intermittent, marginal unconformities should dominate the foredeep, with marine deposition farther into the foreland. As a rule, depo-centres advance into the basin, with time. Paleocurrents often turn parallel to the depositional axis. This pattern is typical of the Witwatersrand depository.

In contrast, unconformities do not occur marginally within taphrogenic basins, but on intra-basinal, contemporaneous horsts (Fig. 6), and depo-centres remain close to the master faults. If such a fault should form the basin margin (Fig. 2), the depo-centres would migrate towards the basin edge with time, a characteristic of growth faults.

Though thick deltaic lobes are known to exist within a foreland basin (Weimer, 1970), correlation of tectono-stratigraphic intervals can be made readily across later, structural compartments. This is in accordance with regional correlations of the Witwatersrand strata between goldfields, which indicate that the various fan deltas are not as discrete as suggested by





<u>*Figure 13*</u> : *The Mesozoic Rocky Mountain, Eastern Great Basin (after Armstrong, 1968), as an analogue of the Witwatersrand Basin.*

the taphrogenic model and its interference pattern of domes and basins within the depositional domain.

Marginal unconformities increase steadily in magnitude of hiatus towards the margin of the Witwatersrand Basin, as predicted by the foreland-basin model, in contrast with the taphrogenic model (Winter, 1983). These should not be confused with the marginal unconformities in a coastal, miogeoclinal deposit, overlying a taphrogenic succession.

Both the taphrogenic and the foreland models predict asymmetry, with the high-energy sediments along the short side. With the former, it would be expected that a larger proportion of bedding dips would be towards peripheral faults than is observed. The presence of a marginal trough, such as that occurring along the western margin of the Welkom Goldfield, is best explained as a foredeep. The taphrogenic model predicts thickness and paleocurrent changes across intra-basinal horsts, which are not present in the Witwatersrand Basin (Fig. 6).

This empirical observation for Early-Proterozoic basins is not applicable to cratonic, back-arc basins, where the rule is for sedimentation to coarsen upwards cyclically (Sharpe, 1949, Vos, 1975), with the bulk of volcanism occurring after relaxation of the compressional regime that controlled the position and structure of the proximal margin. The latter pattern fits the Witwatersrand-Klipriviersberg deposition much closer, if the Dominion Reef Group is taken out of consideration.

It is easier to reconcile the regional isopach pattern and prograding depo-centres (Pretorius, 1981) with the smooth isopachs of a foreland-basin model. Taphrogenic, step-fault-induced shrinkage is an incompatible concept (Winter, 1983). Rift belts tend to widen with time. The isopach and depo-centre pattern convinced Burke et al. (1985) that the Witwatersrand is a foreland basin.

Basement control would be much less important in the foreland basin, because the floor is passive, but, as a counterpart, the underthrust plate is considered to have played an important role in deep-crustal deformation that affects foreland areas of the Great Basin of the Rocky Mountains (Brown, 1984). These areas are characterized by large, upthrust blocks, exposing basement and outlined by both forward and back thrusts. The Wind River Mountains and the Vredefort Dome could have similar origins as late-upthrust structures.

Resolution by Study of Analogues

A number of puzzling geological problems can be resolved by studying analogues and applying methodologies developed in well-explored, cratonic, back-arc, foreland-basins. Such problems relate, not only to sedimentology, but also to the controlling, tectonic and post-depositional, geological history of such areas.

Basin development requires extension - the production of volcanic products even more extension - but the proximal basin margin is apparently defined by compressive tectonics. The Andean, back-arc-basin model provides an all-embracing theory that can explain when and why certain lithological and structural changes occur on specific parts of the Kaapvaal

Craton. Within the framework, cause and effect can be related. Questions can be answered, such as why quartz porphyries abound in some areas and not in others and where large-scale, inverse, tectonic effects can be expected to bring Witwatersrand sediments within the reach of mining, instead of being covered by thick accumulations of Ventersdorp and Transvaal rocks.

The geometries of thrust systems are now well understood (Butler, 1982; Boyer and Elliot, 1982). In order to ensure correct structural interpretation, profiles, preferably seismically controlled, should be drawn in the direction of tectonic transport and then balanced for palinspastic restoration. It is possible that Central Rand Group strata occur locked within thrust sheets in certain hinterland areas.

Most investigators, according to Bally (1984), believe that there is a definite and extended period of time required for the development of a thrust sequence, and that only the piggy-back sequence, where the youngest thrust fault carries the overlying sheets forward into the foredeep, can stand the test of balancing the section.

Figure 7 indicates a thrust fault terminating against, and being unconformably overlapped by, the Boulder Beds of the Uitkyk conglomerates, suggesting a late-Witwatersrand age for the fault. The lower thrusts, therefore, should be younger than the Boulder Beds. The thrust displacements, thus, have been dissipated basinwards by back thrusting and flexural folding, such as the folds of the Loraine, St. Helena, and Beisa mines and by slip along incompetent beds within the basin. Similar leading edges to disturbed belts have been identified in the Cordillera, the Appalachians, and the Molasse and Pannonian Basins as fundamental features of a foreland basin. An obvious, post-Transvaal, contractional episode can serve only to obscure the evidence of pre-Ventersdorp compression in the hinterland of the Witwatersrand Basin.

Folding associated with these thrust systems is generally of the concentric type, and detailed structural analyses can also be subjected to a balancing process. The intimate relations between thrusting and folding have been thoroughly investigated (Brown, 1984). Cleavage is not considered to be significant or to lend itself readily to analysis in the foreland area, because of widespread, flexural-slip phenomena, but it is more pervasive in the hinterland. Large stretches of thrust sheets exhibit so little deformation that it is difficult to believe that these sheets have been displaced by many kilometres. In the western Transvaal, where relief is low and outcrop is poor, some of the major thrust planes, which tend to run selectively along the incompetent, soil-covered shales, may have escaped detection.

Unconformities of remarkable angularity occur at different stratigraphic levels along the western Welkom Goldfield. No satisfactory explanation for this feature has been found yet, but, if the various thrust sheets are of different ages, it would be expected that the unconformity between the syntectonically folded beds and the post-tectonic molasse would vary in age, depending upon which thrust sheet caused the folding. Various diamictites occur within the Witwatersrand Supergroup at different stratigraphic levels. Should all of these be related to thrusting, then the orogenic period could have lasted as long as the Sevier orogeny of the Rocky Mountains (Armstrong, 1968), with important implications concerning the shape of the basin, the interpretation of palinspastically uncorrected isopachs, and the discovery of new gold mines along the foredeep margin of the depository.

IMPLICATIONS FOR KAAPVAAL CRATONIC HISTORY

The Early- and Middle-Proterozoic history of the Kaapvaal Craton can be unravelled, using analogues of the plate-tectonic environment, in conjunction with field and geophysical observations.

The back-arc, foreland-basin theory calls for the floor of the Witwatersrand Basin to have been cratonized at the beginning of its deposition. The floor acted as a passive element, though it is possible that the lowest thrust planes form a sole within the granite. Certainly, the Archean tectonic style of active mantled domes had become stabilized.

The back-arc environment also fits the lithology and petrography of the volcanic rocks, as well as the tectonic regime of the Klipriviersberg and Platberg Groups (Winter, 1976). The rapid and explosive outpouring of tholeiitic-basaltic lavas, ash flows, tuffs, and agglomerates is typical of back-arc extensional conditions (Garcia, 1978), which continued into Kameeldoorns time. The porphyritic, acid volcanics of the Makwassie Formation suggest rising isotherms or depression of continental crust into the zone of remelting. The resumption of the more-basic volcanism of the Rietgat Formation is unexpected. A compressional regime in late-Platberg time is suggested by tectonics which have definitely deformed the Makwassie and, apparently, also the Rietgat Formation. The regional Pniel hiatus is demonstrably of post-Platberg-compression age, and the unconformity surface is gently warped, conformably with overlying Bothaville sediments, Allanridge plateau basalts, and rocks of the Transvaal Sequence. The Black Reef unconformity, where it is underlain by the Pniel sequence, does not terminate any markedly variant, tectonic event, so that it can be postulated that Pniel and Transvaal geological history are closely related. The geological map of the Wolmamransstad area of the western Transvaal confirms this by demonstrating a Platberg folding terminated by the Pniel unconformity.

Perhaps it would be appropriate to quote the prophetic words by Windley (1977) on the question of the position of the Ventersdorp volcanics in the Kaapvaal Craton: "If a comparison were made with late Phanerozoic volcanics on the basis of general chemistry and relative abundance and association of lava types, this sequence is most akin to the calc-alkaline lavas of the continental margins, such as the Andes, Cascades and New Zealand, which are also underlain by sialic crust. The question arises, what are these type of lavas doing in so-called stable ensialic cratonic basins? Alternatively, could they not be the result of some plate movement and subduction activity not yet recognized?"

Part of the cratonized, granitic crust probably became remobilized as the downthrust oceanic floor reached depths where it remelted. According to the model, a ring of plutons of the calc-alkaline suite should occur on the magmatic arc, volcanism should be rife, and that part of the hinterland should have been subjected to high-temperature metamorphism. Related tectonism should be intra-arc, extensional subsidence. Various authors (Light, 1982; Burke et al., 1985) have commented upon magmatism dated at around 2,5Ma, an age lately favoured for the Witwatersrand Basin, but pending clarification of the zircon-based, Makwassie dating of 2,65Ma.

The Griqualand West-Transvaal depositional basin, where slope- and deep-sea-facies face westwards, can be compared with a carbonate-platform model. Interpreted to be a composite, fore-arc basin (Fig. 10), with easterly subduction and final, magmatic-arc intrusion during Bushveld times, it was modified by continent-continent collision, with the granitic Namaqualand terrane (Kheis Province) riding on the subducting, oceanic plate. The late felsites and granites of the Bushveld Complex and covering red beds resemble the Tibetan pattern, as the Namaqua terrane tried to force its way down. A similar sequence of events can be argued for collision from a northerly direction.

It is unlikely that the geometries of the colliding, granitic, continental-crust plates would match: large-scale wrenching, rifting, thrusting, and block rotation could be required to achieve a fit It is more than likely that, at least, some of the irregularities in the outline of the positive margin of the Witwatersrand Basin can be attributed to such major adjustments.

The cratonic history of the Kaapvaal Craton, from the terminal stages of Witwatersrand deposition up to the end of the Ventersdorp-Pniel hiatus is illustrated in Figures 14, 15, 16, and 17.

Figure 15 is a schematic cross section of the Witwatersrand Basin at the close of the proximal, marginal orogeny, illustrating the concept and possible mechanism of evolution of the foreland basin in a cratonic, back-arc, plate-tectonic setting. It is here postulated that the rapid transition to Klipriviersberg volcanism could have been due to subduction of a mid-ocean ridge. The terms "sima" and "sial", respectively, denote the subducting oceanic plate and the continental leading edge of the overriding plate.

Figure 16 is a schematic cross section, at the same position as Figure 15, showing the deformation of the Witwatersrand Basin during the ensuing extensional period. The Early Ventersdorp, Klipriviersberg volcanics and clastic wedges of Kameeldoorns sediments are illustrated. Older formations are not shown for clarity of demonstration. Hypothetical oceanic obstruction is invoked to account for later Platberg events shown on Figure 17. The rapid relaxation accounts for the preservation of the margin of the economically important Witwatersrand Basin.

Figure 17 shows the same cross section viewed at the time of the regional Pniel unconformity. The observed structural-stratigraphic relationships are illustrated as the result of a minor, collisional effect of a hotspot, micro-continent, triple-junction, or other obstruction, on the subducting plate. Only Middle-to-Late-Platberg events are illustrated, to show clearly a complex history of Makwassie acid volcanism, followed by folding and thrusting, a relaxation accompanied by overlapping Rietgat tholeiitic volcanism and late sedimentation. Late-extensional faulting is truncated by peneplanation, ending a completely different Middle-Ventersdorp tectono-stratigraphic scenario.

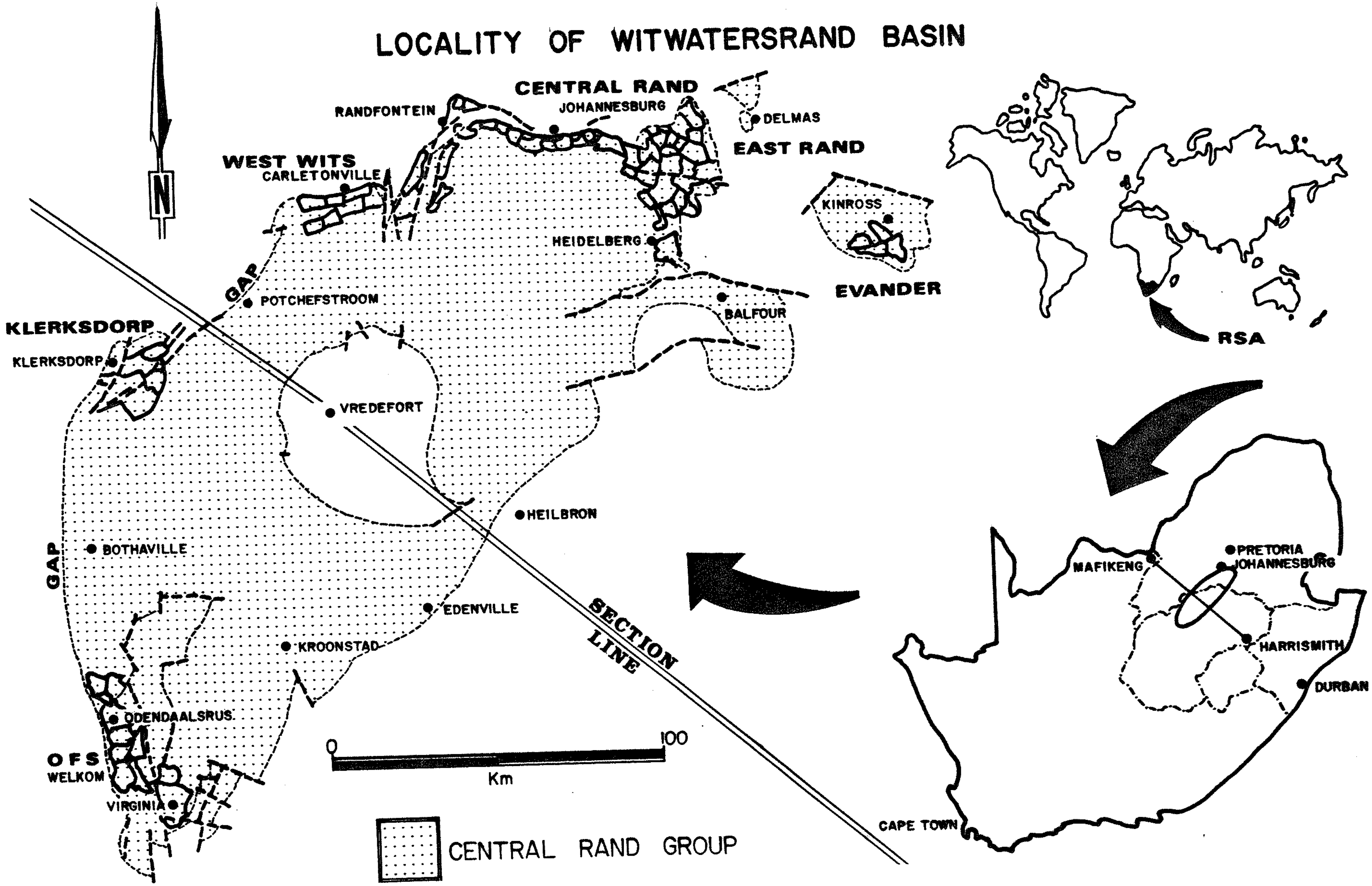


Figure 14 : *Surface geological map of the Witwatersrand Basin.*

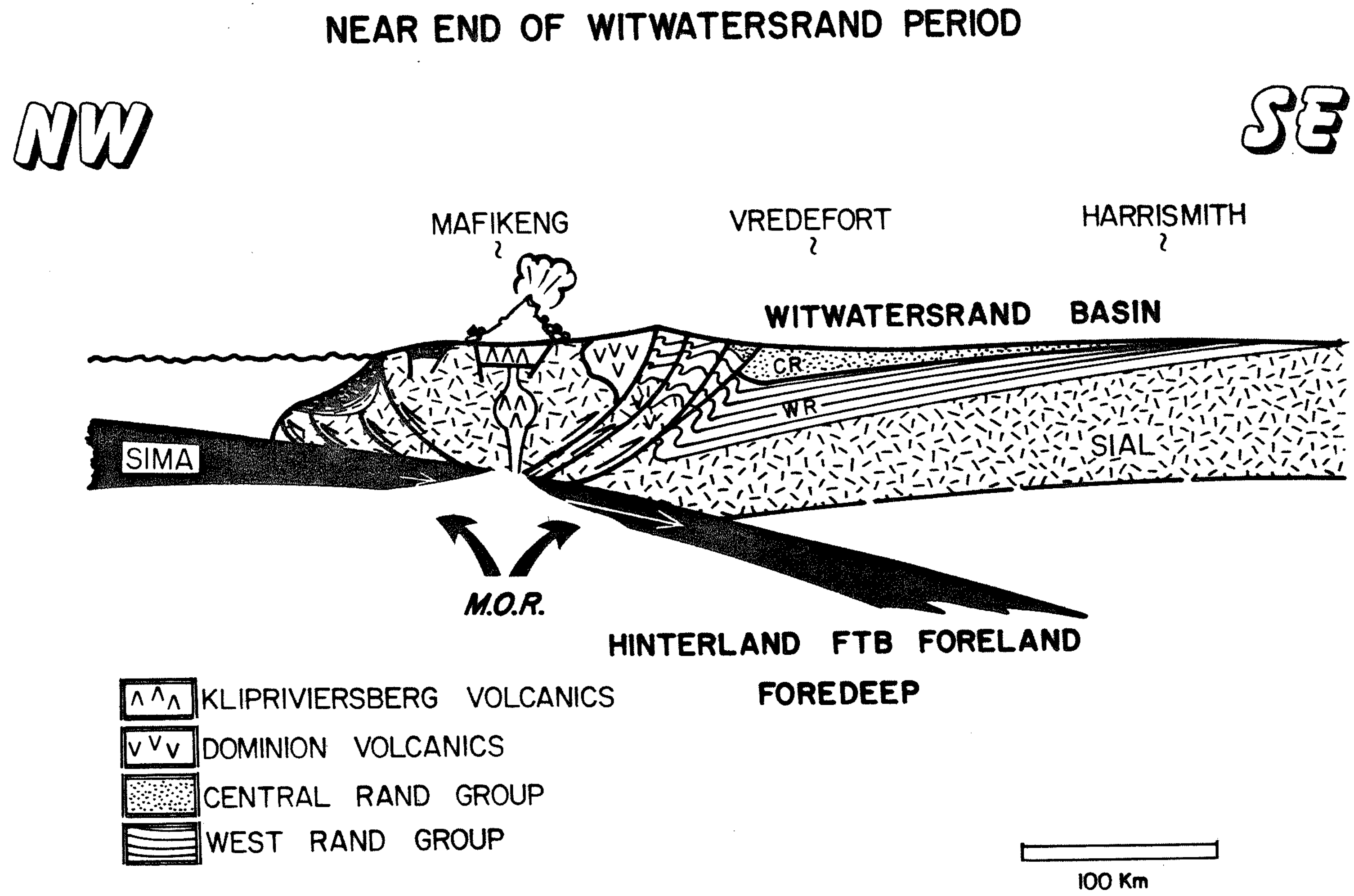


Figure 15 : *Schematic cross section of the Witwatersrand Basin at the close of the proximal, marginal orogeny.*

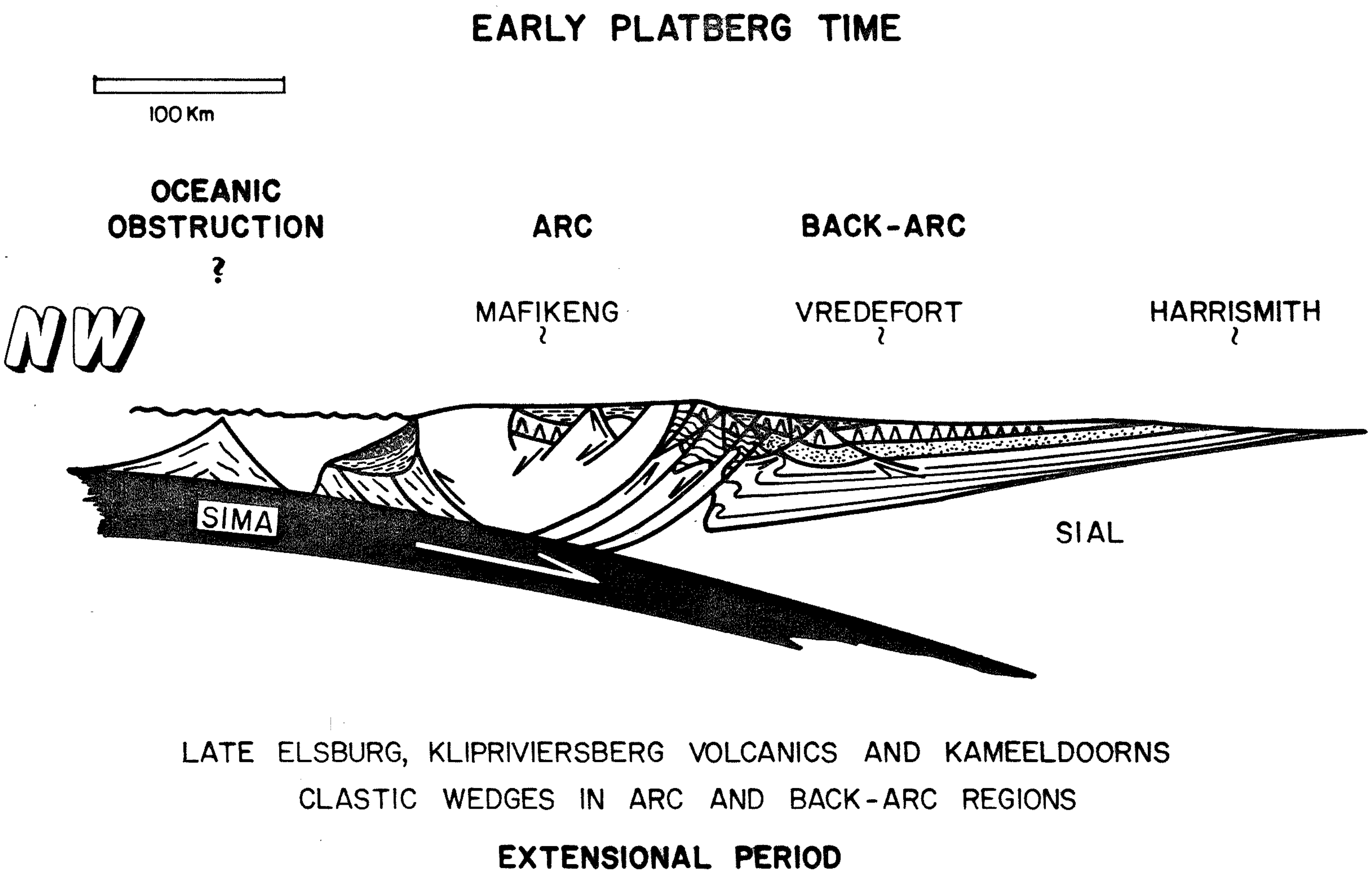


Figure 16 : *Schematic cross-section of the Witwatersrand Basin, showing the deformation of the basin during the ensuing extensional period.*

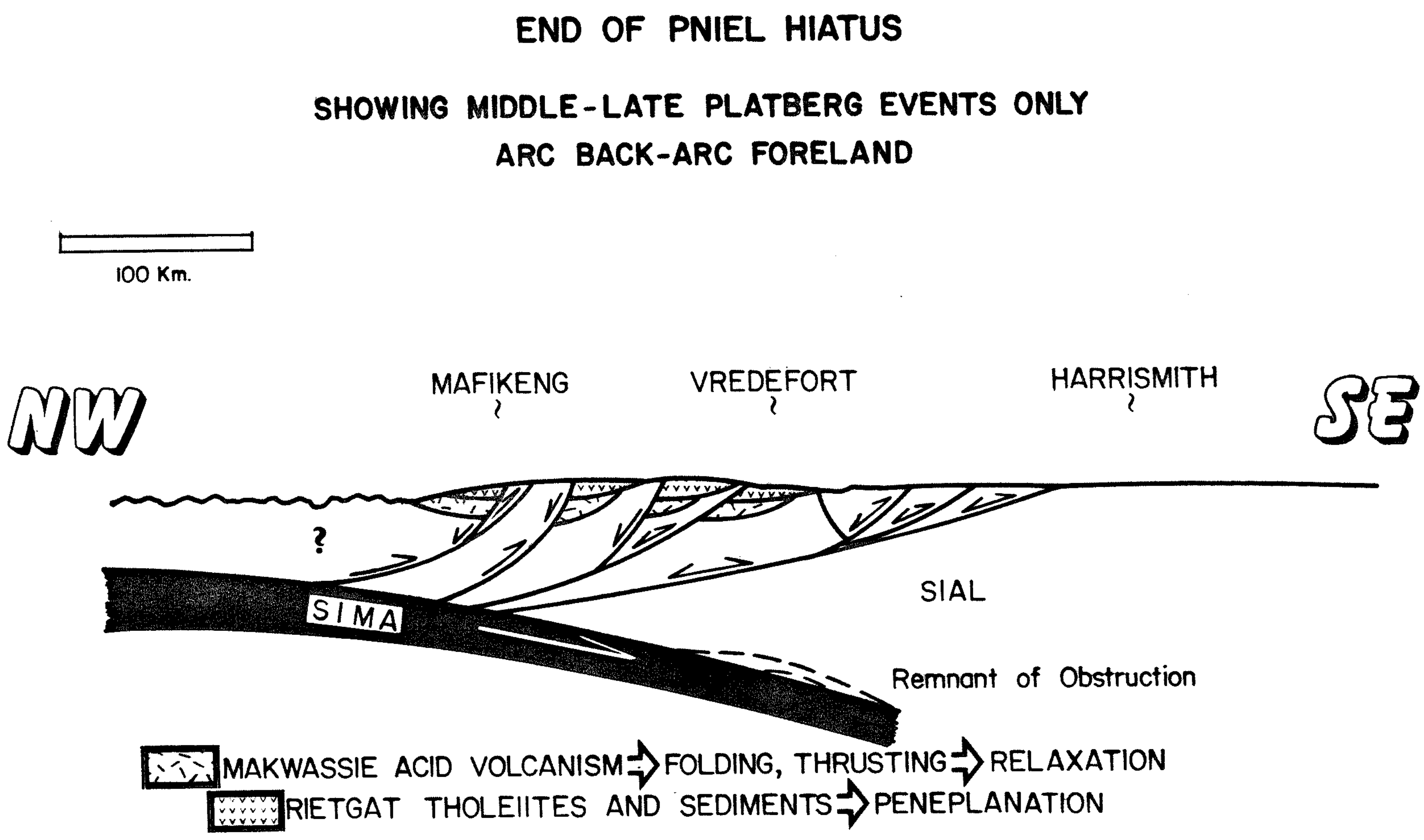


Figure 17 : *Schematic cross section of the Witwatersrand Basin at the time of the regional, Pniel unconformity.*

The cratonic history of the Kaapvaal Craton, depicting post-Pniel events and illustrating the present crustal structure, is depicted in Figures 18 and 19.

Figure 18 is a present time, schematic cross section, in the same position as before, illustrating post-Pniel geological events only. The Bothaville clastic cycle, followed by Allanridge plateau basalts of this upper Ventersdorp sequence, is environmentally a sub-basin of Transvaal sedimentation. Tectonics are interpreted as the foreland-deformation of a post-Transvaal, continent-continent collision, involving thrusting, folding, and wrench faulting. The Vredefort Dome is interpreted as a back thrust of Rocky-Mountain-foreland-uplift-type. On this scale, late-extensional displacements do not feature, nor does known, contemporaneous, extensional faulting related to flexural folding. Collision-related red-beds on the uplifted plateau are largely hidden under thin, Tertiary, Kalahari cover, whilst Late-Paleozoic Karoo rocks blanket the southeastern sector. Abundant acid volcanism and intrusions, dated at 2050-2100Ma suggest the time of collision. Final cratonization of the Kaapvaal entity followed the Waterberg-Soutpansberg, red-bed episode, at about 1650Ma.

In Figure 19 previously illustrated, major Proterozoic events are added, in the present state of deformation, to Figure 18. The complex final structural setting of the Central Rand Group is exceeded only by the effects of the Witwatersrand orogeny in the hinterland. Most of the placer gold lies within 5-25km of the subcrop of this Group. Thicknesses in steeply dipping beds are distorted, due to vertical exaggeration.

CONCLUSIONS

When modelling the contemporary events associated with Witwatersrand-Basin development, the conclusion is reached that these aspects closely resemble the features associated with Phanerozoic, cratonic, back-arc basins. Such basins are the result of an Andean type of subduction where the underthrust, oceanic plate has a flat-dipping Benioff zone. Contemporary volcanism in that situation is rare. The Witwatersrand Basin is visualized as a geosyncline, yoked to an active, fold-thrust belt in its hinterland. Adjacent to the thrust front would be a foredeep, tapering distally to a foreland-basinal facies. The foredeep and associated features would be orthogonal to the orogenic, compressional forces acting upon the sectors of the active basin margin, where such features are recognized. Contemporary warping of the basin would be dominantly parallel to the foreland. Transverse structural features are known to bound sectors or domains in the fold-thrust belts of foreland-basins and to extend their effects into the depositories.

In the case of the Witwatersrand Basin, a final, post-orogenic, molasse cycle of deposition covered the typical foreland facies, preserving the penultimate cycle and much of the earlier, marginal facies of previous tectono-stratigraphic units, within which placer gold and uranium were concentrated. The outpouring of copious volumes of Klipriviersberg tholeiitic, basaltic lavas testifies to the continuation of an extensional-tectonic regime, associated with rifting and marked, in the waning stages, by Kameeldoorns clastic wedges. The block-faulting relief was truncated by the Platberg unconformity.

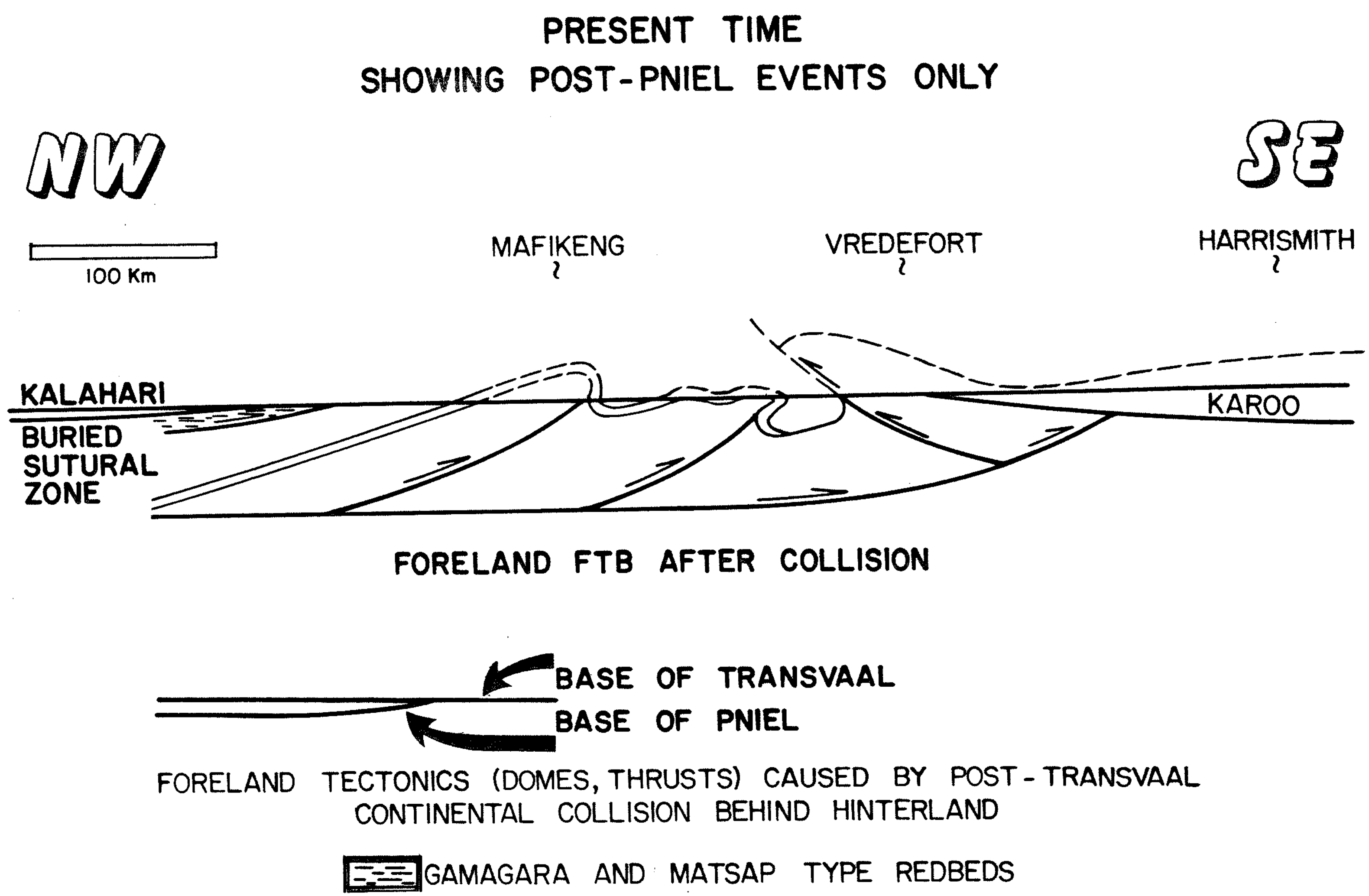
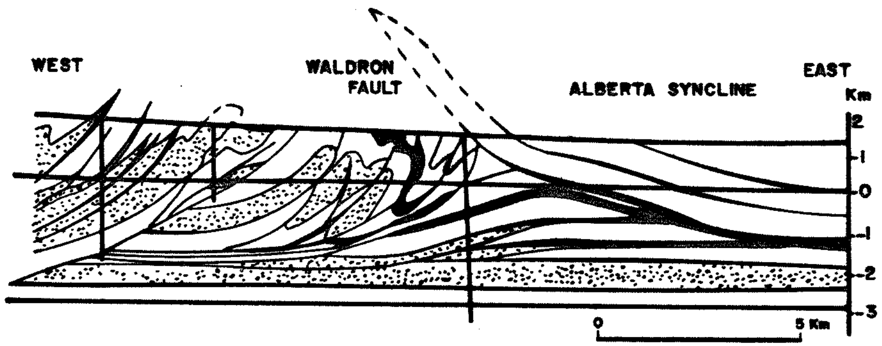


Figure 18 : *A present time schematic cross section of the Witwatersrand Basin, illustrating post-Pniel events only.*



Back thrusts developed in the frontal ranges of the Rockies. The area beneath the thrusts with opposing dip, is known as a triangle zone.

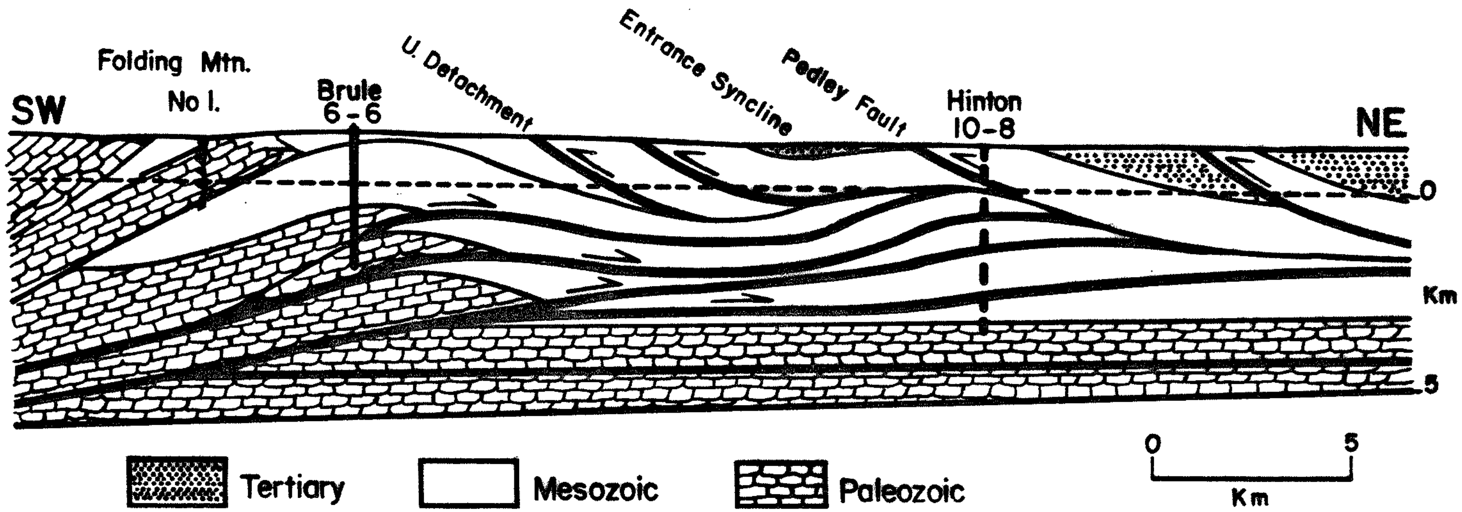


Figure 19 : *A present time schematic cross section of the Witwatersrand Basin in which previously depicted, major, Proterozoic events have been added to Figure 18.*

The tectonic cycle described above can be viewed as an orogeny, in a plate-tectonic context. A compressional event is essential to such an orogeny, but contemporary wrench and extensional tectonics are important in some regions, especially in foreland deformation (Lowell, 1983). Large-scale, Himalayan-type, wrench faulting can take place after eventual continent-continent collision, to accommodate irregularities in the continental margins. Extensional tectonic and associated volcanic periods are parts of such an orogenic cycle, which is terminated by regional peneplanation. The redefined orogeny, therefore, would have elements of geosynclinal deposition mountain building, no matter what style of tectonics dominates, and erosion.

Three compressional periods have been identified. The first two are terminated by the Platberg and Pniel unconformities, respectively, with the Black Reef truncating the third, in the eastern sector. The first orogeny is considered responsible for the Witwatersrand-Basin foreland-setting, and the other two for the basin's partial destruction. What remained of the Witwatersrand Basin was subjected to a very long period of pre-Karoo denudation and Karoo-Sequence blanketing.

ACKNOWLEDGEMENTS

The permission by Soekor to quote an unpublished report on taphrogenic sedimentation, offshore of Plettenberg Bay, is gratefully acknowledged. The generous support and backing of the Consulting Geologist, Management, and Directorship of Anglovaal Limited for this investigation, by subvention of an overseas study-visit, made this contribution possible. The author appreciates the typing, draughting, and other facilities provided by Anglovaal Limited. Professor C. Roering of the Rand Afrikaans University, is thanked for encouragement to write this report.

REFERENCES

Armstrong, R.E. (1968). Sevier Orogenic Belt in Nevada and Utah. Geol. Soc. Amer., Bull, 79, 429-458.

Bally, A.W. (1984). Structural Styles and the Evolution of Sedimentary Basins. Amer. Ass. Petrol. Geol., Short Course Notes.

Bally, A.W., Gordy, P.L., and Stewart, G.A. (1966). Structure, Seismic Data and Orogenic Evolution of the Southern Canadian Rockies. Can. Petrol. Geol. Bull., 14, 337-381.

Beloussov, V.V., Reisner, G.I., Rudich, E.M., and Sholpo, V.M. (1974). Vertical Movements of the Earth's Crust on the Continents. Geophys. Surv. 1, 245-273.

Bickle, M.J., and Eriksson, K.A. (1982). Evolution and Subsidence of Early Precambrian Sedimentary Basins. Phil. Trans. R. Soc. Lond. 305, 225-247.

Boyer, S.E., and Elliott, D. (1982). Thrust Systems. Amer. Ass. Petrol. Geol. Bull., 66, 1196-1230.

Brinn, M.C. (1982). The Structural Geology of the Buffelsfontein Gold Mine. Unpubl. M.Sc. Thesis., Univ. Natal.

Brock, B.B., and Pretorius, D.A. (1964). Rand Basin Sedimentation and Tectonics. In Haughton, S.H., (ed.), The Geology of Some Ore Deposits in South Africa, Vol. I., Geol. Soc. S. Afr., Johannesburg, 549-600.

Brown, W.G. (1984). Basement Involved Tectonics: Foreland Basins. Amer. Ass. Petr. Geol. Course Notes 26, 92pp.

Burke, K., Dewey, J.F., and Kidd, W.S.F. (1977). World Distribution of Sutures: the Sites of Former Oceans. Tectonophysics, 40, 69-99.

Burke, K., Kidd, W.S.F., and Kusky, T.M. (1985). Is the Ventersdorp Rift System of Southern Africa Related to a Continental Collision Between the Kaapvaal and Zimbabwe Cratons at 2.64Ga ago? Tectonophysics, 115, 1-24.

Butler, W.H. (1982). The Terminology of Structures in Thrust Belts. J. Struct. Geol. 4, 239-245.

Coetzee, C.B. (1960). The Geology of the Orange Free State Goldfield. Geol. Surv. S. Afr., Mem. 49.

Cross, T.A., and Pilger, R.H. (1982). Controls of Subduction Geometry, Location of Magmatic Arcs, and Tectonics of Arc and Back-Arc Regions. Geol. Soc. Amer. Bull. 93, 545-562.

Dewey, J.F. (1980). Episodicity, Sequence and Style at Convergent Plate Boundaries. In Strangway, D.W. (ed.), The Continental Crust and Its Mineral Deposits. Geol. Assoc. Can., Spec. Pap. 20, 553-573.

Dewey, J.F., and Bird, J.M. (1970). Plate Tectonics and Geosynclines. Tectonophysics, 10, 625-638.

Dickinson, W.R. (1974). Plate Tectonics and Sedimentation. In Dickinson, W.R. (ed.), Tectonics and Sedimentation. Soc. Econ. Palaeont. Miner. Spec. Publn 22, 1-27.

Dickinson, W.R., and Seely, D.R. (1979). Structure and Stratigraphy of Forearc Regions. Amer. Ass. Petrol. Geol. Bull. 63, 2-31.

Garcia, M.O. (1978). Criteria for the Identification of Ancient Volcanic Arcs. Earth. Sci. Rev., 14, 147-165.

Gilluly, J. (1971). Plate Tectonics and Magmatic Evolution. Geol. Soc. Amer. Bull. 82, 2383-2396.

Hutchison, R.I. (1975). The Witwatersrand System as a Model of Sedimentation in an Intracratonic Basin. Unpublished D.Sc. Thesis, Univ. of the Orange Free State, Bloemfontein, 255pp.

Jordan, T.E. (1981). Thrust Loads and Foreland Basin Evolution: Cretaceous, Western United States. Ass. Petrol. Geol. Bull. 65, 2506-2520.

Light, M.P.R. (1982). The Limpopo Mobile Belt: a Result of Continental Collision. Tectonics, 1, 325.342.

Lowell, J.D. (1983). Foreland Deformation. In Lowell, J.D., and Gries, R. (eds.), Rocky Mountain Foreland Basins and Uplifts, Rocky Mountain Ass. Geol., Denver, 392pp.

McCarthy, F.S., Cadle, A.B., and Horrocks, P. (1982). Thrust Faulting in Witwatersrand Rocks at Langerman's Kop, Johannesburg. Trans. Geol. Soc. S. Afr., 85, 189-202.

Molnar, P., and Atwater, T. (1978). Interarc Spreading and Cordilleran Tectonics as Alternates Related to the Age of Subducted Oceanic Lithosphere. Earth and Planet. Sci. Lett. 41, 330-340.

Nel, L.T., and Jansen, H. (1957). The Geology of the Country Around Vereeniging: An Explanation of Sheet 62 (Vereeniging). Geol. Surv. S. Afr., Pretoria.

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

Pretorius, D.A. (1981). Gold and Uranium in Quartz-Pebble Conglomerates. 75th Anniversary Volume, Economic Geology, 117-138.

Pretorius, D.A. (1984). The Proterozoic Basins of Southern Africa: Tectonic Settings, Patterns of Evolution, and Distribution of Gold Mineralization. M.Sc. Miner. Expl. Course, Course Notes, Rhodes Univ., Grahamstown, 213pp.

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

Sharpe, J.W.N. (1949). The Economic Auriferous Banket of Upper Witwatersrand Beds and Their Relationships to Sedimentation Features. Trans. Geol. Soc. S. Afr., 52, 265-300.

Shelton, J.M. (1984). Listric Normal Faults. Amer. Ass. Petrol. Geol. Bull., 68, 801-815.

Stanistreet, I.G., and McCarthy, T.S. (1984). The Tectono-Sedimentary Setting of the Ventersdorp Outlier at Kromdraai, North-West of Johannesburg. Geocongress '84, Potchefstroom, Geol. Soc. S. Afr., Abstracts.

Van Biljon, W.J. (1980). Plate-Tectonics and the Origin of the Witwatersrand Basin. In Ridge,J.W. (ed.), Proceedings 5th IAGOD Symposium, Vol. I, Schweizerbartsche, Verlagbuchhandlung, Stuttgart, 796pp.

Vos, R.G. (1975). An Alluvial Plain and Lacustrine Model for the Precambrian Witwatersrand Deposits of South Africa. J. Sediment. Petrol., 45, 480-493.

Weimer, R.J. (1970). Rates of Deltaic Sedimentation and Intrabasin Deformation, Upper Cretaceous of Rocky Mountain Region. In Morgan, J.P., and Shaver, R.N. (eds.), Deltarc Sedimentation, Modern and Ancient. Soc. Econ. Paleontol. Miner.. Spec. Publn. 15, 312pp.

Windley, B.F. (1977). The Evolving Continents. John Wiley and Sons, New York, 385pp.

Winter, H. de la R. (1964a). The Geology of the Northern Section of the Orange Free State Goldfield. In Haughton, S.H. (ed.). The Geology of Some Ore Deposits in Southern Africa, Vol. I, Geol. Soc. S. Afr., Johannesburg, 417-450.

Winter, H. de la R. (1964b). The Geology of the Virginia Section of the Orange Free State Goldfield. In Haughton, S.H. (ed.). The Geology of Some Ore Deposits in Southern Africa, Vol. I, Geol. Soc. S. Afr., Johannesburg, 507-548.

Winter, H. de la R. (1976). A Lithostratigraphic Classification of the Ventersdorp Succession. Trans. Geol. Soc. S. Afr., 79, 31-48.

Winter, H. de la R. (1983). Pre-Horizon C Stratigraphy in the Central Part of the Pletmos Basin: Block Ga. Unpubl. Intern. Rept. to Soekor, Johannesburg.

oOo