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TECTONIC PROCESSES WITHIN THE KAAPVAAL CRATON DURING THE KIBARAN (GRENVILLE) OROGENY: STRUCTURAL, GEOPHYSICAL AND ISOTOPIC CONSTRAINTS FROM THE WITWATERSRAND BASIN AND ENVIRONS

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by

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ABSTRACT

A structural analysis of the Orange Free State Goldfield together with a compilation of published structural data from the Witwatersrand Basin and surrounding areas, as well as available gravity, magnetic, seismic reflection and geochronological data from the Kaapvaal Craton, indicate that northwest-directed compressional tectonics were operating within the core region of the Kaapvaal Craton during the Mesoproterozoic.

The proposed geodynamic model envisages consistent northwest/southeast-directed plate convergence to have introduced two main tectono-magmatic cycles within the interior of the Kaapvaal Craton, which were triggered by the Kibaran (Grenville)-age orogenic processes along its southern margin.
Initial orogenic activity along the southern craton margin during the time interval of approximately 1450-1250 Ma led to reactivation of major terrane boundaries within the interior of the craton and associated alkaline magmatic activity along them.
The temporally weakly constrained deformation of the Pongola Supergroup along the southern margin of the Kaapvaal Craton is interpreted to represent this initial phase of the Kibaran (Grenville) orogenic cycle.
Following a period of about 50 Ma of magmatic quiescence, the main Kibaran (Grenville) orogenic phase within the Namaqua-Natal mobile belt introduced intense northwest-directed thrust tectonics to the core of the Kaapvaal Craton, the formation of the "Pilanesberg Graben System" as a pull-apart rift orthogonal to the Kibaran (Grenville) fold and thrust belt, and the initiation of a second phase of alkaline magmatic activity, closely associated with the pull-apart graben system during the approximate time interval 1200-1000 Ma.

The proposed geodynamic model for the tectono-magmatic evolution of the Kaapvaal Craton during the Mesoproterozoic provides important economical implications, e.g. with regard to the erosion and preservation of the auriferous Witwatersrand and Pongola Supergroups, the potential occurrence of carbonatitic and kimberlitic complexes within the interior of the Kaapvaal Craton, as well as on the controls on the uranium- and coal-bearing sediments of the Karoo Sequence.
In addition, structural implications to the Vredefort impact event and its related tectonic processes, as well as implication to the temporal and kinematic evolution of the Natal Metamorphic Province, are also evident from the results of this study.

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INTRODUCTION

The formation and stabilization of the Archaean Kaapvaal Craton is viewed today to have taken place over a time, spanning approximately 1 Ga and can be subdivided into two periods (De Wit et al., 1992). The Early to Mid-Archaean (3.7-3.1 Ga) records the emergence of the first regionally extensive continental lithosphere, as a result of intra-oceanic obduction of hydrated Archaean oceanic crust and subsequent granitoid formation, terminated with a major pulse of accretion tectonics between 3.2 and 3.1 Ga (De Wit et al., 1992). The second period (3.1-2.7 Ga) is dominated by intra-continental and continental-edge processes, with the formation of intracratonic sedimentary basins (e.g. Dominion, Witwatersrand, Pongola, Ventersdorp), continuing to the Mid-Proterozoic (2.05 Ga), and continental growth due to a combination of tectonic accretion of crustal fragments and subduction-related igneous processes (De Wit et al., 1992). After the emplacement of the Bushveld Complex between 2.06-2.05 Ga, crustal growth during the successive Eburnian orogeny (2.0-1.7 Ga) and the deposition of the Soutpansberg and Waterberg formations at 1.75-1.7 Ga., a remarkable hiatus in sedimentation on the Kaapvaal Craton of approximately 1.7 Ga followed, until the deposition of the Karoo sediments between 280 and 190 Ma.

During this period, the only geological activity within the Kaapvaal Craton occurred in the interval 1.4-1.0 Ga, represented by the intrusion of a number of small carbonatite and alkaline complexes, the Premier group of kimberlites and the tholeiitic Timbavati and Trompsburg intrusions.
While the craton interior appears to have experienced a relatively inactive period, substantial tectono-magmatic and sedimentary processes occurred around its margins during the Kibaran (Grenville) cycle between 1.6 and 1.0 Ga. The Namaqua-Natal Metamorphic Province (Fig. 1) forms a segment of a global system of Grenville-age orogenic belts which amalgamated early continental fragments into the Mesoproterozoic supercontinent Rodinia at ca. 1.0 Ga (Hoffman, 1992).
In South Africa, the Kibaran cycle began with the sedimentation and volcanism at 1.6-1.3 Ga on older Eburnian basement in western and eastern Namaqualand, and in volcanic arcs on juvenile oceanic crust in east-central Namaqualand and in Natal (Eglington et al., 1989; Thomas et al., 1994). Subduction and closure of the oceanic basins led in eastern Namaqualand to the collision of the Kaapvaal and Bushmanland Cratons, and in Natal to the obduction of the Tugela ophiolite (Matthews, 1972, 1981) onto the Kaapvaal Craton and to the accretion of juvenile volcanic arcs (Eglington et al., 1989; Thomas et al., 1994).

On the basis of newly obtained and reinterpreted published structural, geophysical and isotopic data from the core of the Kaapvaal Craton, especially the Witwatersrand Basin, where an abundance of geological data exists, this paper attempts to demonstrate, that the temporal association between the Mesoproterozoic alkaline and kimberlitic magmatism on the Kaapvaal Craton and the Namaqualand-Natal orogeny are not coincidental, and that, as previously proposed by Harmer & Eglington (1994), the magmatism might have indeed been triggered by the orogenic activity along the craton margins.
Furthermore it will be shown, that the spatial distribution of the alkaline and kimberlitic magmatism is structurally controlled and that the deformational effects of the Kibaran orogeny within the interior of the Kaapvaal Craton are more dramatic and wider distributed than previously recognised.

Following a detailed structural analysis of the southern Orange Free State Goldfield, a summary and reinterpretation of previously published post-Transvaal structural data from the Witwatersrand Basin and surrounding areas, will incorporate these newly obtained data and synthesize the entire structural data set into a model for the post-Vredefort (proposed Mesoproterozoic) tectonic evolution of the central Kaapvaal Craton. The reinterpretation of new and published geophysical data, in particularly seismic reflection, gravity and aeromagnetic data available for the Witwatersrand Basin and environs, as well as for the entire region of the Kaapvaal Craton, will be utilised to complement the structural data set and to support the proposed craton-wide tectonic model.
A compilation of the available geochronological data for Mesoproterozoic igneous lithologies and time-equivalent (partial) resetting events evident within and around the Kaapvaal Craton, is used to constrain the timing of the proposed tectono-magmatic processes within the Kaapvaal Craton.

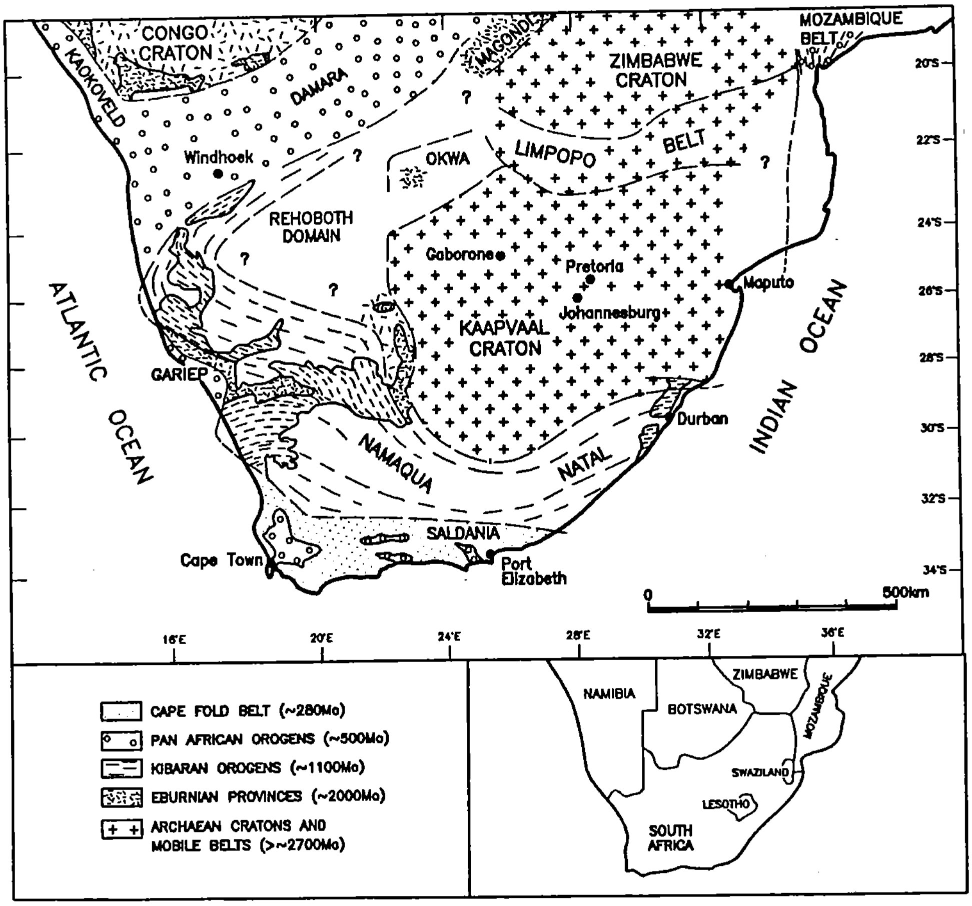


Fig. 1. Crustal architecture of southern Africa (after Thomas et al., 1993).

STRUCTURAL ANALYSIS OF THE SOUTHERN ORANGE FREE STATE GOLDFIELD

Situated approximately 270 km south-southwest of Johannesburg along the southwestern margin of the Archaean Witwatersrand Basin in the Orange Free State, the OFS Goldfield extends over 70 km between the towns of Allanridge and Theunissen in the north and south respectively. The study area covers the southern part of the goldfield between the towns of Welkom and Theunissen in the north and south respectively, and Ventersdorp and Hennenman to the east (Fig. 2).

Within the southern OFS Goldfield, the Archaean Basement is unconformably overlain by the Witwatersrand Supergroup, which forms an overall coarsening-upward sedimentary sequence of metamorphosed quartzites, conglomerates, shales and minor intercalated lava flows, and is subdivided into the lower West Rand and upper Central Rand Group.

The Witwatersrand Supergroup in turn is overlain both unconformably and conformably by volcanic and sedimentary rocks of the Ventersdorp Supergroup. The Early Precambrian rocks of the Witwatersrand and Ventersdorp Supergroups are concealed by the sedimentary (partially glacial) succession of some 300 m to 700 m of flat lying Phanerozoic sandstones and shales of the Karoo Sequence.

Within the OFS Goldfield, the Witwatersrand Supergroup is preserved in a broad, north-south trending and intensively faulted syncline, which plunges gently to the north and marks the southern closure of the basin. The goldfield is structurally further characterised by several major north to north-northwest striking faults along the western limb of the syncline, and northeast striking faults structurally dominate the eastern limb (Fig. 3). Due to the convergence of these two differently striking fault sets, a large, sigmoidal-shaped horst (De Bron Horst) of elevated West Rand Group rocks concealed by sediments of the Ventersdorp Supergroup and Karoo Sequence, divides the syncline approximately along its axis into two graben-like troughs that comprise the Welkom and Virginia sectors of the OFS Goldfield to the west and east respectively (Figs. 3&4).

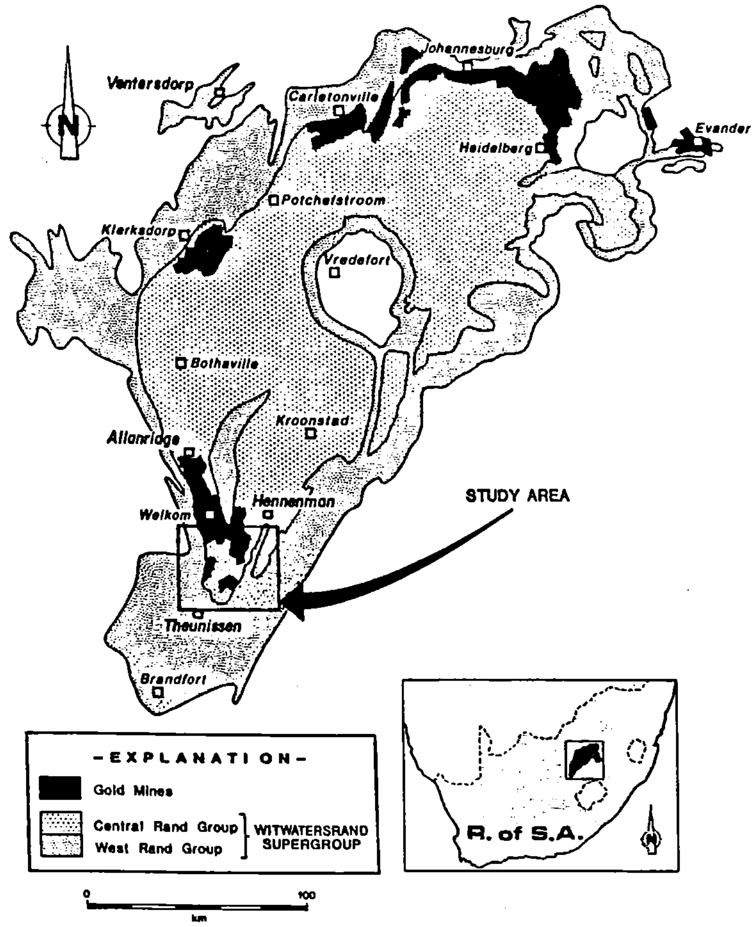


Fig. 2. Geographic location of the study area within the OFS Goldfield and the Witwatersrand Basin.

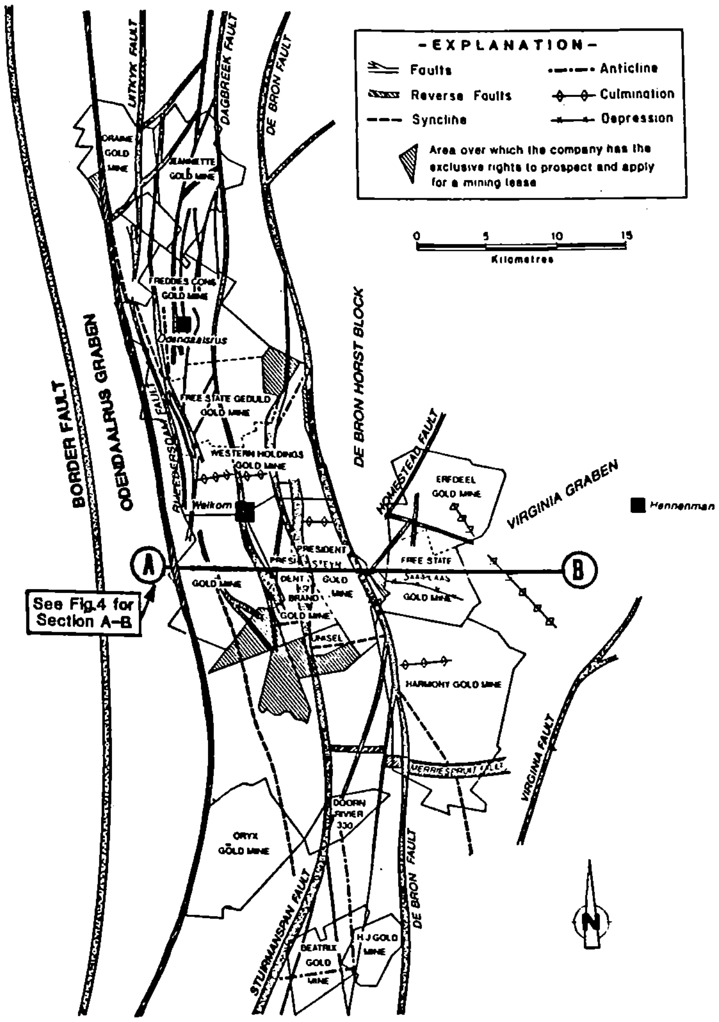


Fig. 3. Generalized structure plan of the OFS Goldfield.

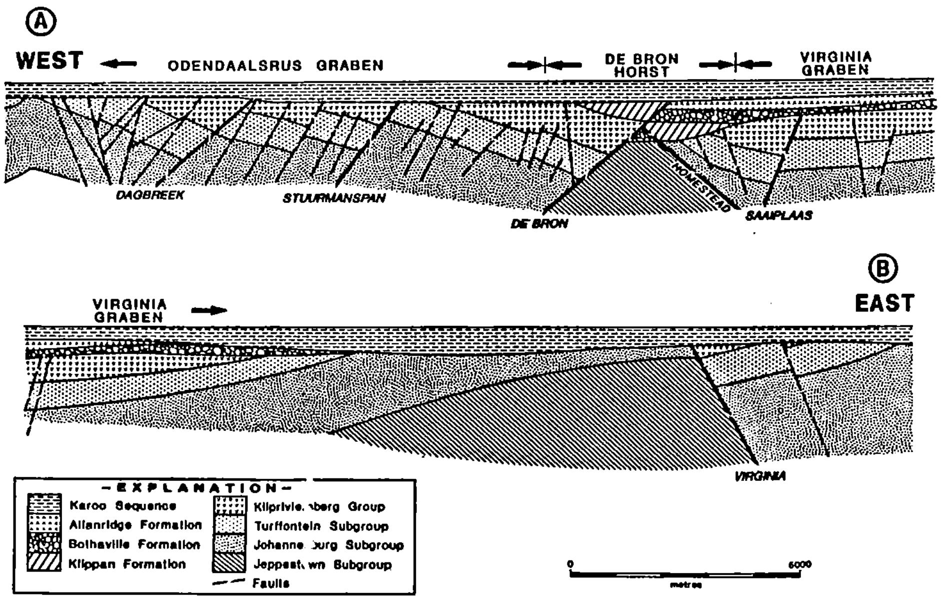


Fig. 4. East-west section across the central OFS Goldfield (after Minter et al., 1986), (see Fig. 3 for location).

The Welkom sector of the syncline forms a graben which is bounded by two major north-northwest striking faults, namely the easterly dipping Border Fault to the west of the goldfield and the westerly dipping De Bron Fault to the east. Within the graben, the Witwatersrand Supergroup strata predominantly dip steeply to the east and are intensively displaced by numerous major faults synthetic to the De Bron Fault (Figs. 3&4).
In contrast to the highly complicated structure of the Welkom sector, the eastern Virginia sector appears tectonically more stable and is characterised by shallow dips of the Witwatersrand Supergroup strata to the west. In the region of the southern closure of the syncline, the strata of the Witwatersrand Supergroup swings into an east-west strike orientation with northerly dip-directions in both sectors. The western margin of the OFS Goldfield, or rather the actual subcrop position of economical pre-Eldorado Formation strata is not delineated by the abovementioned Border Fault, but in fact by the so-called Border Structure. The term Border Structure (e.g. Winter, 1964 a/b; Olivier, 1965; Tweedie, 1986) refers to a north-northwest striking thrust zone, comprising various westerly dipping thrust faults, like the Rheedersdam and Phillipi Thrusts and others (Geol. Dept., F.S.G. Gold Mine, pers. comm.) (Figs. 3&4). Thrust-related intense folding to overfolding of Witwatersrand Supergroup strata into a monocline, situated in the footwall of the thrust zone, is evidence for syn-sedimentary compressional tectonics mainly concentrated along the western margin (Winter, 1957, 1964 a/b; Olivier, 1965; Chapman, 1969; Tweedie, 1986; Minter et al., 1986; Callow & Myers, 1986). This monoclinal flexure appears to die out to the north of the OFS Goldfield in the vicinity of Bothaville, where seismic and surface borehole data indicate easterly, shallow dipping Witwatersrand Supergroup strata.

Within the southern OFS Goldfield, five principle tectonic phases are now recognised (Friese, in prep.) and include in sequential order:-

1. a NE-SW oriented compressional event of lower Central Rand Group-age, which lead to SE-directed escape tectonics and the development of NW-SE trending, syn-depositional warping within the depository;

2. an approximately E-W oriented compressional event of upper Central Rand Group-age, which was associated with easterly verging thrusting and folding along the western margin of the goldfield, as well as syn-depositional, north-south trending, low-amplitude folding of the upper Central Rand Group depository;

3. a transtensional rift phase within a NE-SW oriented compressional stress field during Ventersdorp times, that led to the development of major N-S and NE-SW striking, initially normal and subsequently strike-slip reactivated faults, which controlled the deposition of the Klipriviersberg lavas and dyke intrusions, as well as the formation of the Platberg and Pniel Group basins;

4. a transpressional event of unknown (possibly post-Transvaal) age, which is associated with positive inversion of the entire pre-existing fault system, as well as NW- and SE-directed trusting; and

5. a possibly E-W oriented extensional phase of syn- to post-Karoo Sequence-age, which partially controlled sedimentation and the emplacement of doleritic sill and dyke intrusions.

The temporal position of the NW-directed transpressional tectonic phase (event 4) relative to the other identified deformation events is well established, but the absence of Transvaal Sequence strata within the OFS Goldfield does not allow the determination of a more precise lower age limit than that of post-Ventersdorp Supergroup, as this deformation event post-dates the deposition of the Pniel Group as well. As documented below, a correlation of the transpressional tectonic features within the OFS Goldfield with deformational structures reported from other parts of the Witwatersrand Basin and environs, that can be generated within a northwest-southeast oriented compressional stress regime, and were identified to be of post-Ventersdorp Supergroup to pre-Karoo Sequence age, was considered to assist in constraining the timing of event 4 more accurately.

Before attempting to explain this tectonic event in a spatial, genetic and temporal context within a craton-wide geodynamic model, the major findings from a structural analysis of the OFS Goldfield, especially of a kinematic analysis of the identified transpressional tectonic event (event 4), will be briefly documented:

Initial work carried out on a structural analysis of the OFS Goldfield has enabled the characterisation of the various faults into various groups, according to:

(i) the orientation of the fault plane and kinematic indicators,
(ii) the type(s) of fault rock present,
(iii) the sense of movement and amount of displacement (if possible),
(iv) the gross geometry of the fault,
(v) the continuity of the fault locally and over large distances, and
(vi) the inter-relationship of the fault with other structural discontinuities.

Based on these criteria, a classification of the various faults present in the goldfield has been carried out. Five fault categories are recognised, each representing either an individual tectonic event or a component of a single tectonic event. Data are graphically presented in Figure 5 and summarised in Table 1.

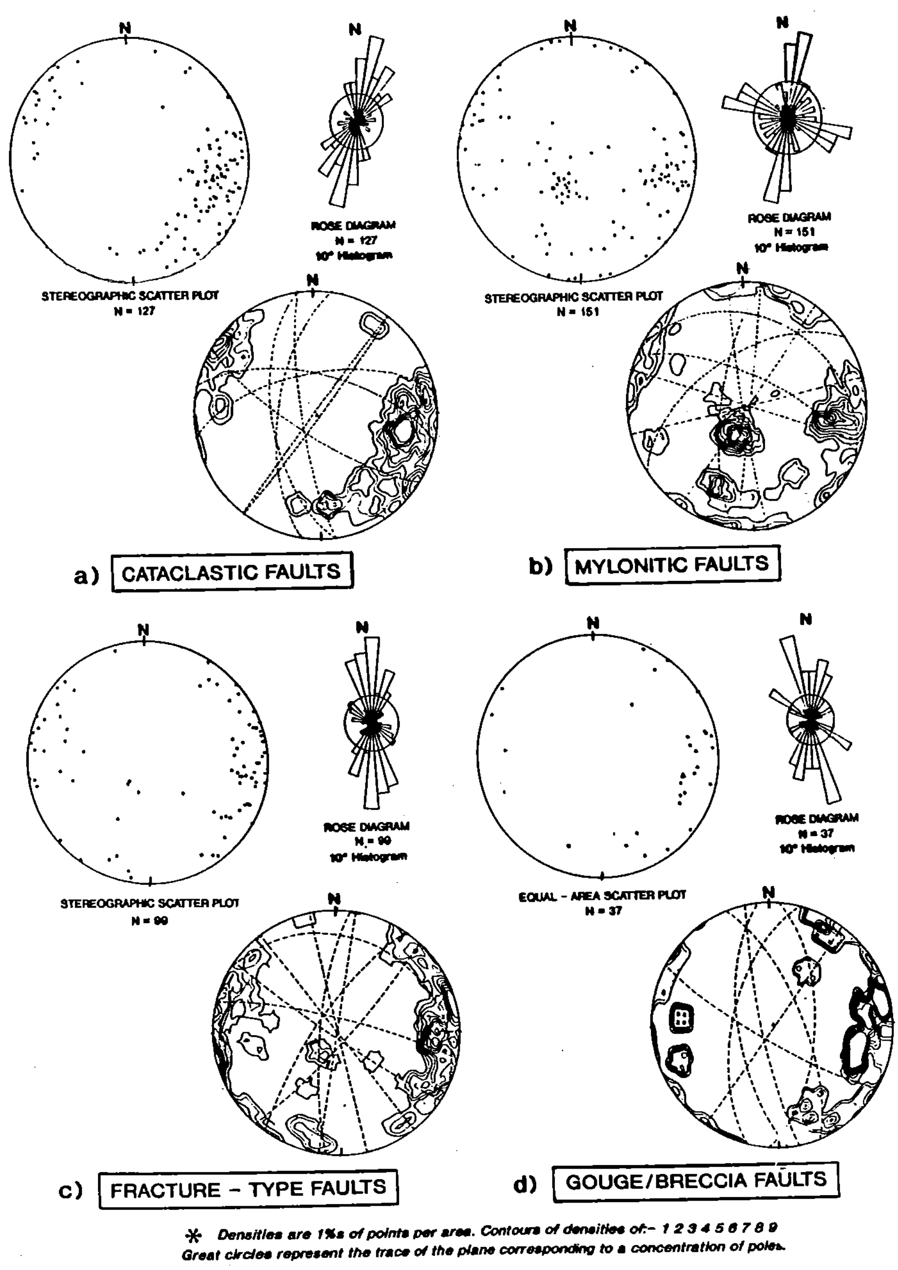


Fig. 5. Orientation diagrams for (a) cataclastic faults; (b) mylonitic faults, (c) fracture-type faults; and (d) gouge faults (Note: Group (b) mylonitic faults represents both fault category 2 & 3 of Table 1).

Table 1. Summary of pertinent characteristics for each identified fault category.

FAULT CATEGORY (GROUP 1 - 5)	TECTONITE-TYPE	ORIENTATION MAXIMUM	VECTOR ANALYSIS	GROSS GEOMETRY AND DIP-DIRECTION	INTERPRETED TEMPORAL RELATIONSHIP
1. Cataclasitic Faults (transtensional event)	Proto-, cataclasites-ultracataclasites	1. NNW/NNE - SSE/SSW	Oblique-normal and normal dip-slip	Developed as listric conjugate set; dipping with 60°-88° towards W and E.	Oldest developed fault category (due to displacement by mylonitic, fracture-type and breccia/gouge faults).
		2. NE - SW	Oblique-normal and normal dip-slip	Developed as listric conjugate set; dipping with 60°-88° towards W and E.	
		3. ENE/ESE - WSW/WNW	Oblique-normal and normal dip-slip	Dipping with 62° towards N	
		4. NW-SE	Oblique-normal and normal dip-slip	Dipping with 76° towards SW	
2. Mylonitic Faults (dextral strike-slip event)	Protomylonites	1. NNE - SSW	Dextral strike-slip	Conjugate set; dipping with 71°+89° towards W and E	First compressional event under ductile conditions (due to crosscutting-relationships with thurst faults of Group 3).
		2. NNW - SSE	Dextral strike-slip	Dipping with 86° towards W	
		3. NE - SW	Sinistral strike-slip	Conjugate set; dipping with 89° towards NW and SE	
		4. NW - SE	Dextral strike-slip	Dipping with 70° towards NE	
		5. ESE - WNW	Sinistral strike-slip	Conjugate set; dipping with 89° towards N and S	
		6. ENE - WSW	Sinistral strike-slip	Conjugate set; dipping with 89° towards N and S	
		7. NW - SE	Reverse dip- and oblique-slip	Bedding-parallel thrust faults, dipping with 29° towards NE	
3. Mylonitic Faults (sinistral oblique-slip event)	Protomylonite	1. NNW - SSW dipping ESE dipping WNW	Oblique-reverse towards NW Oblique-reverse towards SE	Same gross geometry and dip-direction as Group 2 = sinistral oblique-slip	Second compressional event under ductile conditions (due to crosscutting-relationship with thrust faults of Group 2).
		2. N - S dipping E dipping W	Oblique-reverse towards NW Oblique-reverse towards SE		
		3. NNW - SSE dipping WSW dipping ENE	Oblique-reverse towards SE Oblique-reverse towards NW		
		4. ENE - WSW dipping NNW dipping SSE	Oblique-reverse towards SE Oblique-reverse towards NW	= dextral oblique-slip	
		5. E - W dipping N dipping S	Oblique-reverse towards SE Oblique-reverse towards NW		
		6. ESE - WNW dipping NNE dipping SSW	Oblique-reverse towards ESE Oblique-reverse towards WNW		
		7. NE - SW dipping SE	Oblique-reverse to reverse dip-slip towards NW-WNW		
		dipping NW	Oblique-reverse to reverse dip-slip towards SE-ESE		
		8. NW-SE dipping NE	Oblique-normal towards N		
		dipping SW	Oblique-normal towards S		
4. Fracture-type Faults	Non-genetic	1. NNE - SSW	Combination of Group 2 and Group 3	Conjugate set, dipping with 78°-89° towards W and E.	Represent non-recognised mylonitic faults of Group 2 and Group 3.
		2. NNW - SSE		Dipping with 89° towards W and E.	
		3. NE - SW		Conjugate set, dipping with 76°-89° towards NW and SE	
		4. NW-SE		Dipping with 89° towards NE and SW	
		5. ESE - WNW		Dipping with 82° towards NNE	
		6. NW - SE		Bedding-paallel thrust faults, dipping with 25° to NE	
		7. NW - SE		Dipping with 86° towards SW	
5. Breccia/Gouge Faults (extensional event)	Fault breccia/gouge	1. NNW - SSE	Normal dip-slip	Listric, conjugate set, dipping with 66°-82° towards W and E	Latest developed fault-type (is predating all other tectonite types).
		2. NNE - SSW	Normal dip-slip	Conjugate set, dipping with 62° towards W and E	
		3. NW - SE	Normal dip-slip	Dipping with 80° towards SW	
		4. NE - SW	Normal dip-slip	Dipping with 89° towards NW and SE	

Results from a subsequently conducted stress field analysis for the various fault categories and their associated slickenside lineation population (applying the method of Aleksandrowski (1985)), indicate that faults belonging to category 1, 2 and 4 (Table 1) and their movement vectors were generated during a single transtensional rift phase, which culminated during Platberg Group time (Friese, in prep.). Almost the entire fault system present today within the goldfield was generated during this tectonic event.

Fault categories 3 and 5 are interpreted to represent tectonic phases of post-Platberg Group-age, which manifested themselves in the form of reactivation of the pre-existing "Platberg Group fault system", but not or very limited in the formation of newly generated fault sets (Friese, in prep.).
Fault category 5 is the youngest group of faults observed and is interpreted on the basis of sedimentological evidence and regional geological considerations to represent an east-west oriented extensional phase under brittle conditions of syn- to post Karoo Sequence-age. Movement vectors associated with category 4 faults (associated with the generation of semi-ductile tectonites) indicate a phase of positive inversion of the normal and strike-slip Platberg-age faults, and represent the NW/SE-oriented transpressional phase (event 4), whose age could not be constrained because of the lack of stratigraphic control within the OFS Goldfield.
This tectonic phase is mainly characterised by oblique-reverse slip movements along all pre-existing fault planes (Fig. 6) under semi-ductile conditions, which was accompanied by the generation of protomylonites. Figure 6(a) illustrates a summary slip-linear diagram of all observed oblique-slip lineations, as well as of those calculated through the cleavage and Riedel vergence method (Bell, 1981). Figure 6(b) documents all remaining lineations after excluding those with an oblique-normal component and genetically related to the transtensional rift phase during Platberg Group-time.
The resulting movement pattern derived from such an oblique-slip event is graphically illustrated in Figure 7(a), which summarises the complex movement pattern. From Figure 7(a), the following interpretations can be made:-

1. NE-SW-striking mylonitic faults with dip directions towards NW and SE are developed as reverse dip-slip or slightly oblique-reverse faults with hangingwall movements towards the northwest and southeast respectively.

2. NW-SE-striking faults with dip directions towards NE and SW occur as oblique-normal faults with movements of the hangingwall towards the north and south.

3. Faults within a NNW to NNE-striking arc (dipping in an easterly direction) show oblique-reverse movements of the hangingwall towards WNW/NW; whereas those with opposite dip directions in a westerly direction show oblique-reverse hangingwall movements towards ESE/SE.

4. Faults within an ENE to ESE-striking arc (dipping in a northerly direction) have oblique-reverse movements of the hangingwall towards SE; whereas on those with opposite dip directions in a southerly direction have oblique-reverse hangingwall movements towards NW.

5. Bedding-parallel thrust movements towards SE and NW.

6. NE-SW-striking medium-angle reverse faults (dipping towards NW) show a thrust direction towards SE.

Such a complex movement pattern can be described in a simplified way in terms of a sinistral simple shear oblique-slip model (Fig. 7(b)). The resulting regional strain ellipse for this semi-ductile oblique-slip event is illustrated in Figure 7(c), which indicates the axis of maximum principle compressive stress (σ_1) in an approximately NW-SE-orientation.
The results of a stress field analysis (Fig. 8(D1-12)) indicate, that the movement pattern during this oblique-slip event formed in a triaxial compressional stress field. This interpretation is based on the slip-movement directions and the field observation of compressional structures related to this deformational event.
All three principle stress axes appear to be oblique in their positions with the maximum principle stress axis (σ_1) in NW/SE-direction and σ_3 as minimum principle stress axis with a NE/SW-orientation. The intermediate principal stress axis (σ_2) is plunging with a moderate angle towards north (Fig. 8(D12)).
The calculated principle stress axis orientations (Fig. 8(D12)) agree with the strain ellipse resulting from sinistral simple shear oblique-slip motion (Fig. 7(c)), which had been interpreted on the basis of the observed movement pattern.

In summary, a post-Ventersdorp Supergroup transpressional deformation event has been identified within the Orange Free State Goldfield, which led to the reactivation of the entire pre-existing Platberg Group fault system in the form of oblique-reverse slip movements, bedding-parallel thrust movements towards the NW and SE, as well as to the formation of minor SE-verging thrust faults under semi-ductile conditions.

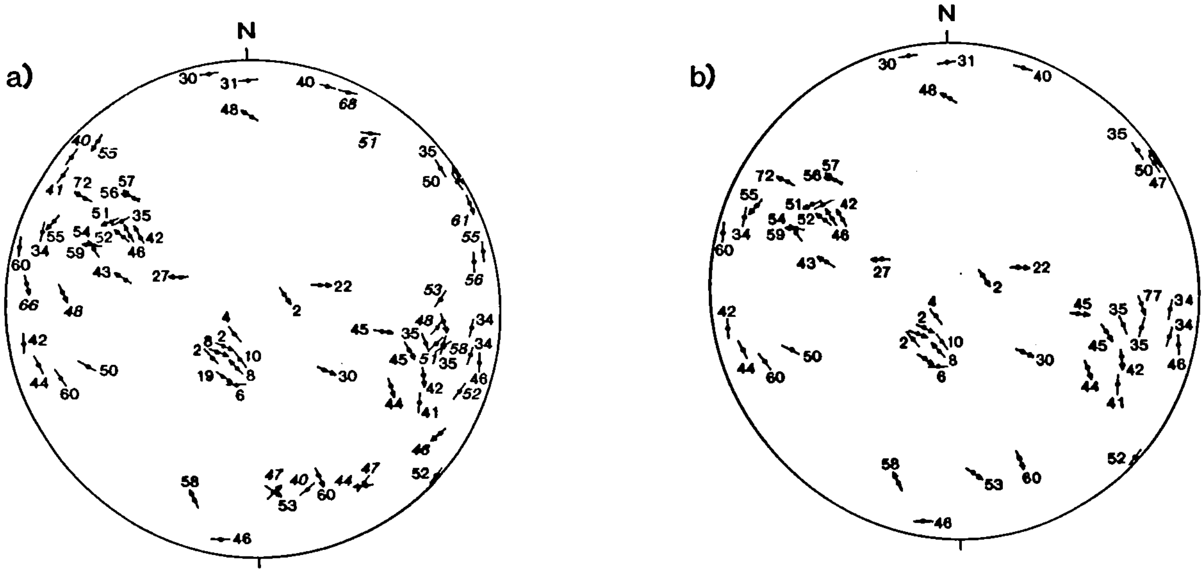


Fig. 6. a) Summary slip-linear diagram of all recorded and calculated oblique-slip lineations.
b) Summary slip-linear diagram of lineations referred as related to the post-Platberg oblique-slip event.

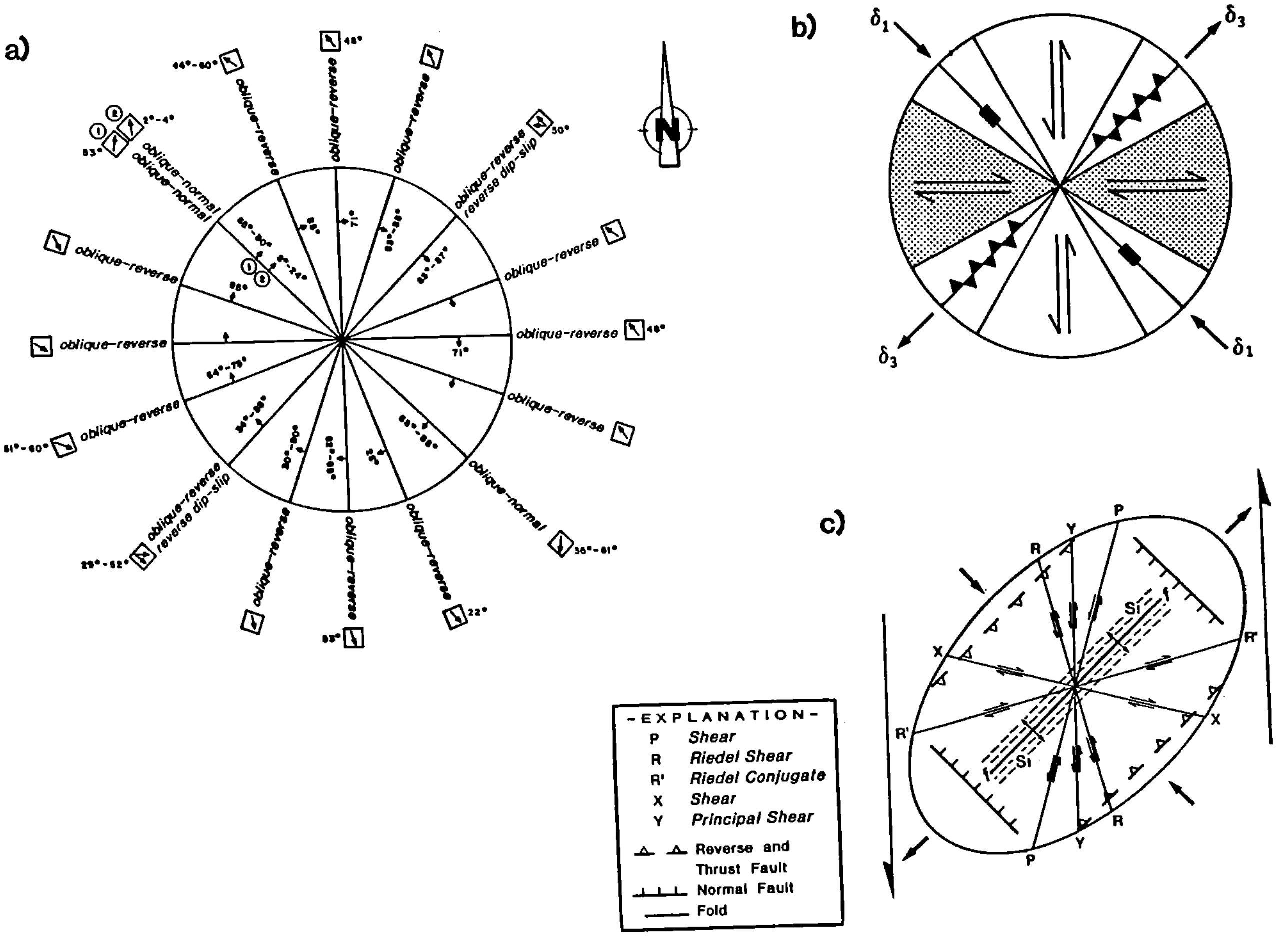


Fig. 7. a) Summary diagram of the movement pattern for an oblique-slip system, showing all existing fault trends (represented by an average strike line with dip-direction and dip-angle-spectrum) with their observed movement vector (trend and plunge of lineation is indicated by an arrow with value).
b) Sinistral simple shear oblique-slip model accommodating the observed movement pattern.
c) The characteristics of the strain ellipse resulting from sinistral simple shear oblique-slip motion.

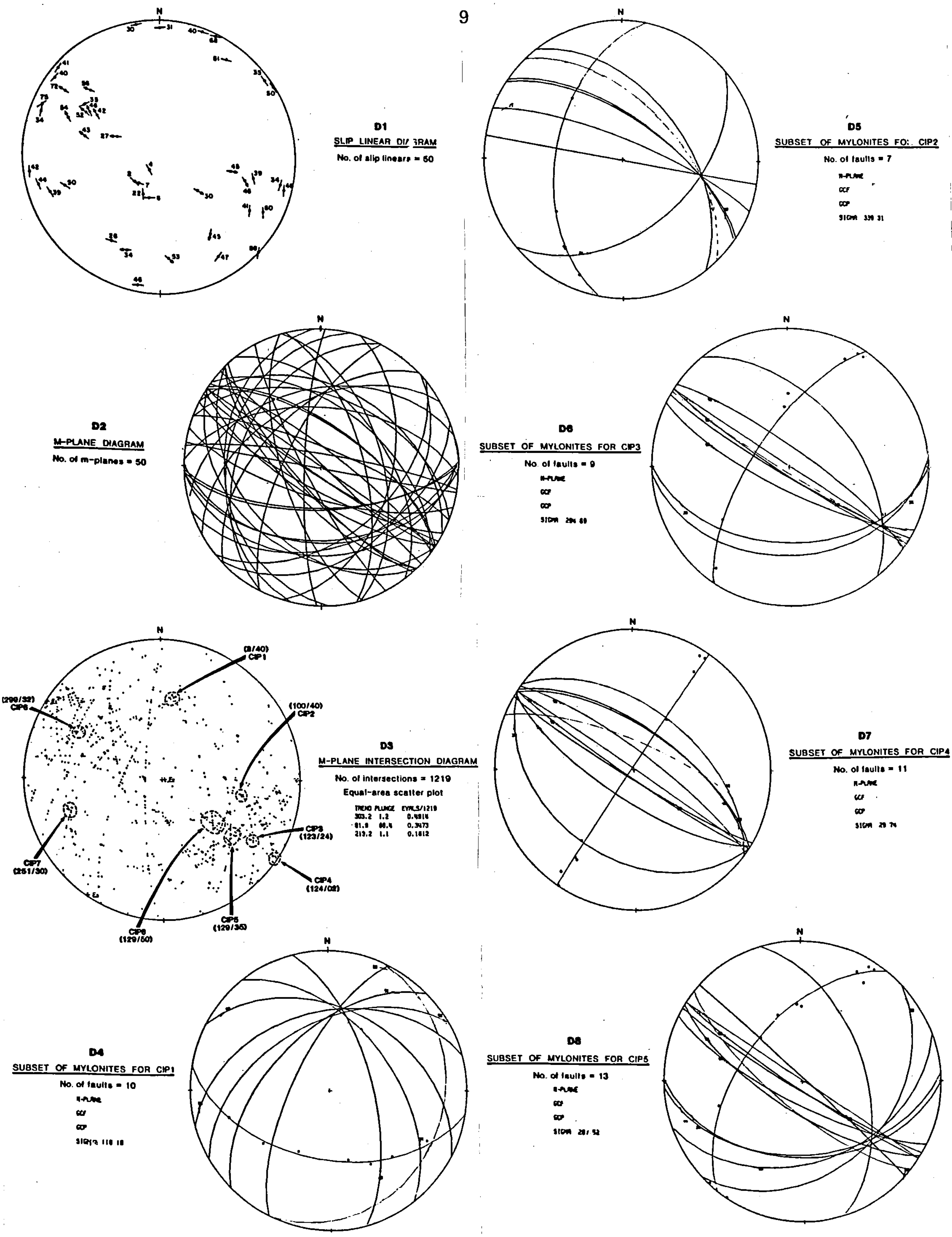


Fig. 8. Sequential illustration of a stress field analysis conducted for the identified oblique-slip event.

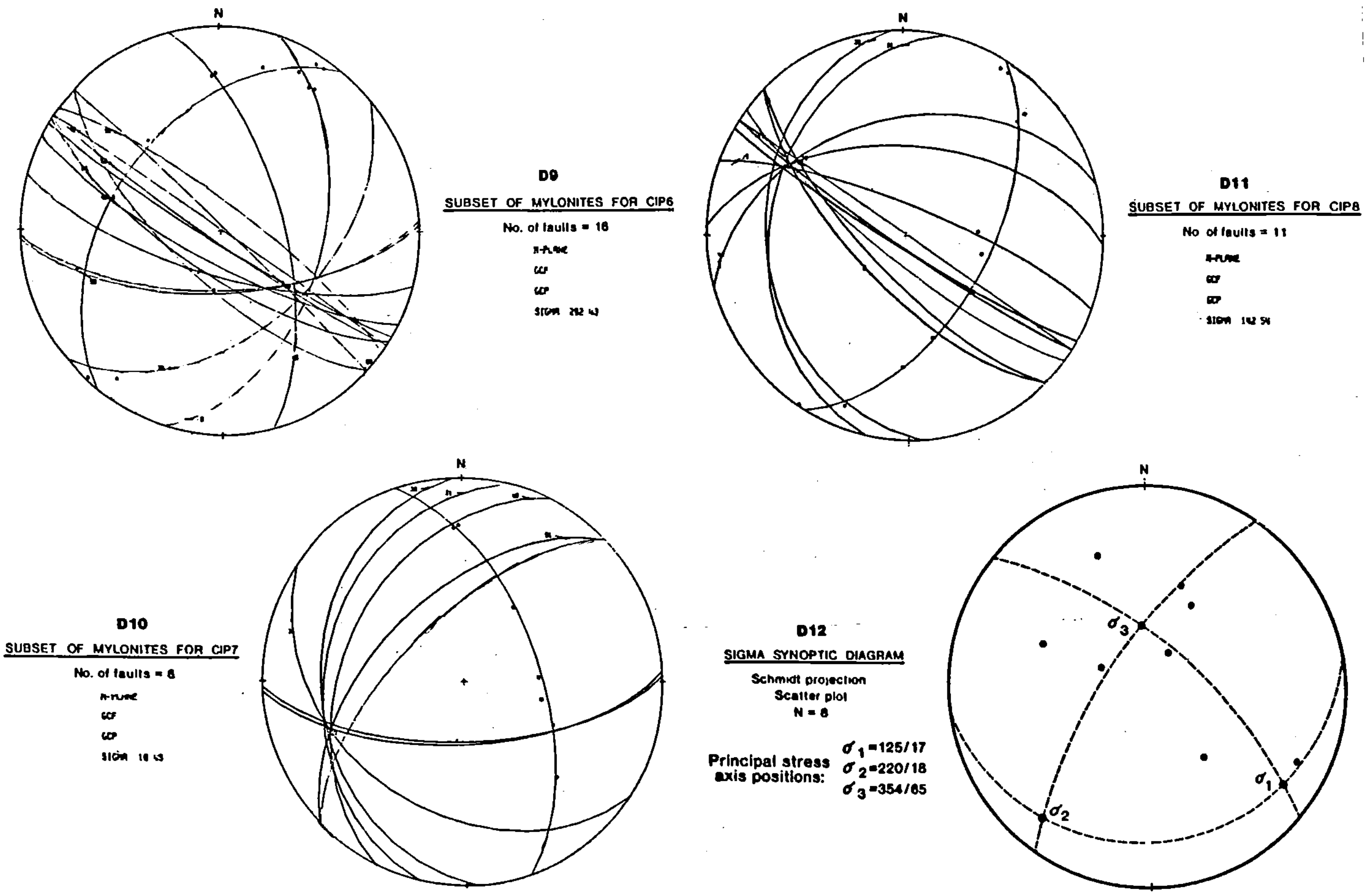


Fig. 8 (continued)

SUMMARY AND REINTERPRETATION OF PREVIOUSLY PUBLISHED POST-TRANSVAAL STRUCTURAL DATA FROM THE WITWATERSRAND BASIN

The existence of a NW/SE-oriented transpressional event during post-Ventersdorp Supergroup time in the southern Orange Free State Goldfield has been demonstrated in the previous section. A review of literature reveals that several authors have described previously structural features from the Witwatersrand Basin and environs, to be identified as or interpreted to be at least post-Transvaal in age and which were induced in a NW/SE-oriented compressional stress field:

Carletonville Goldfield

Geol. Dept. / Western of Deep Levels, East Mine:	Establishment of a geochronological tectonic history with the recognition post-Bushveld tectono-magmatic activity, in form of: - reactivation of the major ENE/WSW-striking "Big Boy" fault system by up to 170 m of dextral strike-slip translation; - Intrusion of NNE/SSW-trending, gabbroic to tholeiitic Pilanesberg-age dykes.
Vermaakt & Chunnett (1994):	Reported on the deformation history of the Bank Fault situated within the Carletonville Goldfield and identified various post-Transvaal tectonic phases, of which the youngest event being compressional, with the maximum principle stress (σ_1) oriented along a NW/SE-axis. The following structures are thought to have been generated during this event:

- Reactivational normal movements (approx. 200 m) with associated drag-folding along the north/south-striking, westerly dipping Bank Fault;
- Reactivational sinistral strike-slip movements along NE/SW-striking faults at East Driefontein Mine.

West Rand Goldfield

Killick et al. (1988): Studied the Western Areas Fault Zone, a bedding-parallel dislocation at the interface between the Ventersdorp and Witwatersrand Supergroups at Western Areas Gold Mine. They identified up to three thrust-related, compressional phases associated with the formation of mylonitic tectonites within that zone, of which the youngest event (post-Transvaal) is characterised by NNW/NW-directed thrusting.

Swartz (1989);
Swartz et al. (1991);
Swartz & Killick (1991): Established a chronological structural evolution of the eastern portion of the West Rand Goldfield, encompassing the area of Western Areas Gold Mine and Cooke Section Gold Mines.
The following post-Transvaal tectonic features were recorded:

- N/NNW-directed, bedding-parallel thrusting (mylonites) and development of open, NE/SW-folds due to ramping on thrust faults;
- NNW/NW-SSE/SE-striking normal faults (quartz cataclasites and quartz mylonites);
- Significant dextral strike-slip reactivation along E/W-striking faults (quartz-cataclasites, fracture-type faults), which formed due to a compressive stress field with o_1 along a NNW/NW-SSE/SE axis.

Parsons & Killick (1990): Reassessed the structure of the dolomite inliers southeast of Westonaria and recognised a post-Transvaal compressional event, which is characterised by:

- Development of E/W-striking, southerly dipping, flat thrust faults, E/W-trending, large-scale open folds, as well as a southeasterly dipping cleavage.

The antiformal structures are interpreted to have formed in response to large-scale ramps on the flat thrust faults as frontal hangingwall ramps. Thrusting along the E/W-striking thrust faults occurred as oblique-reverse movements towards the NW. It had not been possible for the authors to determine whether the thrusts are related to frontal compression or a transpressional regime on a larger scale.

Swartz (1991): Recognised two post-Black Reef tectonic phases in the open cast site of the South Dam Extension East Area of Lindum Reefs Goldmine, of which the younger one might have been generated under NW-SE compression:

- E-W cross-folding (large open folds, wavelength min. 200 m) of older N-S folds, as well as parasitic E-W folds;
- Approximately E/W-striking, N-verging cleavage, indicating N-directed thrusting.

Killick (1992): Analysed pseudotachylites of the West Rand Goldfield and erected a deformational history for the area. He clearly identified a tectonic phase, which post-dates the Vredefort event (associated with northward directed thrusting and the development of pseudotachylites and E/W-trending folds), and is evident in form of:

- Dominantly developed dextral strike-slip reactivation of E/W- to NW/SE-striking faults;
- Subordinately developed sinistral strike-slip reactivation of NE/SW-striking faults.

Central Rand Goldfield

Grohmann (1988): Described the evolution of faulting and dyke intrusion within the Central Rand Goldfield, and made the following observations with regard to an identified tectonic event of Pilanesberg-age:

- Emplacement of NNW/SSE-trending Pilanesberg-age dykes along pre-existing planes of detachment almost exclusively in the western portion of the Central Rand Goldfield;
- Scarce emplacement of Pilanesberg-age dykes (e.g. Syenite Dyke/Simmer and Jack Mine) in eastern half of Central Rand Goldfield;
- Two phases of Pilanesberg intrusion, an early mafic phase, and a later syenitic phase, have been recognized.

From the irregular course of the Syenite Dyke and the apparent scarcity of Pilanesberg intrusions in the eastern half of the Central Rand Goldfield, Grohmann concluded, that this area remained under compression during Pilanesberg-time and, hence was not amenable to dyke-intrusion, whereas in the western half of the goldfield, the partial relaxation of Pilanesberg-age compression allowed emplacement of Pilanesberg intrusions.

East Rand Goldfield

Pitts (1990): Erected a tectonic history for the East Rand Goldfield and recognised the following structural features, which she tentatively correlated with Bushveld emplacement:

- NW-directed bedding-subparallel thrust movements and tilting of steep NW-SE fold axes;
- initiation of steep, dextral, E-W strike-slip faulting;
- reactivation of E/W-striking, shallow southwards dipping normal faults to dextral strike-slip faults, acting as oblique ramps during the preceding NW-thrust faulting.

Evander Goldfield

Tweedie (1981): Reported on the occurrence of a few NE/SW-striking, southeasterly-dipping reverse and thrust faults within the Evander Goldfield of at least post-Ventersdorp-age.

Johannesburg Dome

Roering (1986): Reported on an earlier northward-directed thrust event of post-Transvaal-age from the northwestern margin of the Johannesburg Dome, which is clearly postdated by a set of NE-SW-striking sinistral shear zones.

Roering & Smit (1987): Recognition of north to northwesterly directed, ductile, bedding-parallel thrust movements at the northern margin of the Witwatersrand Basin (Roodeport) of unknown age.

Hilliard (1994): In his study of the structural evolution of the Johannesburg Dome, Hilliard identified the following structural features of either post-Transvaal- or unknown age:

- ENE/WSW-striking, dextral strike-slip shear zones;
- brittle, sinistral strike-slip reactivation of earlier NNW/SSE-striking, ductile, dextral strike-slip shear zones.

Courtnage et al. (1995): Identified up to four phases of pronounced ductile deformation of post-Transvaal-age in an area between the Johannesburg Dome and the Bushveld Complex. Important in this respect is the recognition of a fifth event of post-Pilanesberg Complex-time, which is evident by northerly trending sinistral and dextral strike-slip faults (up to several hundreds of metres displacement), displacing earlier folds and shear zones, as well as a NW-trending syenite dyke of Pilanesberg-age.

Vredefort Dome

Simpson (1978): In a structural analysis of the rim synclinorium of the Vredefort Dome, Simpson concluded from a study of quartz-filled veinlets, that a period of northward-directed compression postdated the formation of the rim synclinorium, the later being genetically related to the emplacement of the Vredefort Dome.

Reimold (1987 b); Reimold et al. (1986): Presented evidence for more than one generation of pseudotachylite both in the Vredefort Structure and in the Witwatersrand Basin. They showed cross-cutting relationships between an apparently older, folded pseudotachylite vein and a younger straight pseudotachylite vein in the southwestern sector of the Vredefort Structure. In the southeastern part of the structure, inclusions of pseudotachylite, showing no signs of plastic deformation, are found in pseudotachylite veins.

Similar observations of more than one pseudotachylite generation were made within the Witwatersrand Basin itself, e.g. at Elandsrand Gold Mine, where up to three generations of pseudotachylite have been recognized. Based on these observations, the authors concluded, that a significant time span may have lapsed between the formation of the two or more generations of pseudotachylite.

Radio isotope ages for the various pseudotachylite generations are documented in Table 2.

Colliston (1990): Recorded various deformation events in the basement rocks of the Vredefort Structure, of which the following features were tentatively interpreted to have been formed in post-Vredefort time:

- Second generation of pseudotachylites in post-Vredefort Structure-time;
- Proposal of a NW-trending, SE-dipping subsurface (deep crustal) ductileshear zone, which probably follows zones of metamorphic phase changes, and with its lower boundary possibly the crust-mantle interface;
- joint-fracture event.

Regional studies

McCarthy et al. (1986): Studied the deformational history of the Black Reef Formation in the vicinity of the northern portion of the Witwatersrand Basin to establish the nature of post-Transvaal Sequence structural features, potentially affecting the Witwatersrand Basin.
An analysis of their structural data, presented and interpreted by the authors to be mainly genetically related to the development of the Vredefort Structure, identifies structural features, that appear not to be genetically linkable to Vredefort-age tectonism, but rather to NW/SE-compression in post-Transvaal time:

- subordinately developed set of NE/SW-trending, large-scale, open folds within the East Rand Goldfield;
- NW- to NNW-directed, bedding-parallel thrust movements (calculated on the basis of the cleavage vergence-method after Bell (1981)) in the vicinity of the South Hills (south of Johannesburg) and Linksfield (approx. 2 km north of the Rietfontein Fault) within Witwatersrand and Ventersdorp Supergroups strata;
- subordinately developed set of NE/SW-trending, small-scale, open folds within the Klerksdorp Goldfield.

They further documented a set of post-Transvaal-age, E/W-striking dextral faults, of unknown regional significance.

Van der Merwe et al. (1988): Identified two major (both brittle) post-Transvaal events, evident along and in close proximity to the Potchefstroom Fault. The younger deformation phase was viewed as being related to the emplacement of the Vredefort Structure and records the:

- Development of several large-scale, as well as smaller scale fold structures within the Transvaal Sequence, which trend NE-SW and plunge at 10^0 to SW;
- sinistral strike-slip reactivation of the Potchefstroom Fault.

Brink, M.C. (pers. comm.): Identified in his regional mapping of the Western Transvaal and Vredefort area the existence of various NW directed thrust nappes, situated around the Vredefort Structure, immediately west of Potchefstroom, and approx. 20 km east of Fochville, which clearly post-date the Vredefort Event. These NE/SW- to E/W-striking, NW- to N-verging thrust nappes cut the dominant system of thrusts and folds, that is concentrically arranged around the Vredefort Dome and thought to be genetically related to the latter. The following thrust faults were identified as evidence for a thrusting event that post-dates the deformation related to the Vredefort Event:

- Spitskop and Frederikstad Synclines, interpreted as footwall synclines formed in response to a west- and northwest-directed thrust component of Vredefort-age along the pre-existing Potchefstroom Fault, are intersected by later north-verging thrust faults (Spitskop Thrust System).
- The overturned strata of the Witwatersrand and Ventersdorp Supergroups, as well as of the Transvaal Sequence forming the collar to the Vredefort Dome, are undoubtedly displaced by numerous thrust faults, which include the Baltespoort Thrust/Nappe 1 & 2, situated southwest of Vredefort and east of Viljoenskroon, the Annasrus thrust system and Post Office Tower Hill klippe in the Procedeerfontein area north of Parys, and three inferred nappes south of the Baltespoort Nappe.

- Several N/S- to NE/SW-striking, west- to northwest-verging thrust faults approximately 20 km east of Fochville, which displace the thrust imbricates belonging to the Fochville Thrust System of Vredefort Event-age.

Pilanesberg area

Swartz, H.G. (pers. comm.): Identified at least two phases of faulting affecting the Bushveld Complex in an area north of the Pilanesberg Complex. These comprise:

1. Pre-Pilanesberg dip-slip, cataclastic-ultracataclastic normal faults, along which some Pilanesberg-age dykes intruded. This extensional event also gave rise to the Rustenburg Fault and Brits Graben.
2. Post-Pilanesberg strike- and oblique-slip carbonate-quartz filled cataclastic and fracture-type faults.

The above summarised structural field observations within the Witwatersrand Basin and environs can be attributed to a NW/SE oriented compressional stress field, that affected at least the central Kaapvaal Craton in post-Ventersdorp Supergroup time, and will be graphically illustrated at a later stage.
The position of the various structural features is in most cases relative to the Witwatersrand Supergroup strata, except for the location of a few individual thrust nappes, which were identified by Brink (pers. comm.) within the overlying Ventersdorp Supergroup and Transvaal Sequence strata.

REINTERPRETATION OF PUBLISHED GEOPHYSICAL DATA FROM THE WITWATERSRAND BASIN

A compilation of published geophysical data, available for the Witwatersrand Basin and surrounding areas, was conducted with the aim of providing additional evidence for structural features, which might be genetically related to a NW/SE-oriented compressional deformation event in post-Transvaal time, affecting primarily the southern and central part of the Kaapvaal Craton.

Seismic reflection data from the Witwatersrand Basin

In recent years, results from seismic reflection surveys carried out in various parts of the Witwatersrand Basin, have been published and provide valuable information about the structural geometry of a particular area, as well as its tectonic evolution.
Recently published results of seismic reflection surveys over the lease area of Oryx Gold Mine (De Wet & Hall, 1994), situated in the southern Orange Free State Goldfield, as well as from the Trans-Witwatersrand vibroseis reflection survey across the northwestern and central portion of the Witwatersrand Basin (Durrheim, 1989; Durrheim et al., 1991), are presented and discussed in the following sections.
Reinterpretations of the published seismic profiles have been carried out with regard to the previously identified compressional tectonic events.

Orange Free State Goldfield

De Wet & Hall (1994) documented the results of 2-D and 3-D seismic surveys carried out across the Oryx Gold Mine, situated along the southwestern margin of the Orange Free State Goldfield (Fig. 9). The employment of these modern seismic techniques has progressively improved the understanding of the geological structure and confidence in the ore reserve estimations in this area.
The survey area is structurally complex. The Border Structure forms the main feature and represents a north/south-trending, thrust-related overturn structure of late-Central Rand Group age. The overturn is centred on the Beisa Mine area whereas the lithologies to the east (Oryx Mine area) are in normal stratigraphic order.

The interpretation by De Wet & Hall (1994) of six 2-D seismic lines, improved and refined by the results of 3-D seismic surveys, have revealed the following major structural aspects along the southwestern margin of the Orange Free State Goldfield, of which those, pertinent to the study of northwest-directed thrust tectonics within the Witwatersrand Basin, will be focused on in particular:

De Wet & Hall (1994) identified a NE/SW-striking, NW-verging thrust fault across the central lease area of Oryx Gold Mine, with up-throw of the base of the Eldorado Formation to the northwest between 200 and 50 m in the southwest and northeast respectively, subdividing the mine lease area into a northern deeper and a southern shallower area (Fig. 10). The thrust fault is seen on the 3-D seismic section of east-west lines 1130 and 1040 as a strong reflector which is correlated with a dolerite sill (6-13 m in thickness) dipping at a shallow angle to the east (Figs. 11a & 12a).

The authors interpreted the sill-filled thrust fault and similar northwest-verging thrusts (Figs. 11a, 12a &13a) to be clearly younger than a set of approximately north/south-striking, easterly verging thrust faults further to the west, and to have affected the base of the Ventersdorp Supergroup (Fig. 14). They related the formation of these younger, northwest-verging thrust faults to northwest-directed compression.

These findings were largely contradicted when they established a tectonic model for the development of the Border Structure and the Orange Free State Goldfield (Fig. 15).

In their model, De Wet & Hall view both systems of thrust faults (east- and northwest-verging) to be of the same age, with the northwesterly verging thrusts forming an integral part of the easterly verging thrust system, which drove the syn-sedimentary basement uplift and formation of the goldfield during Witwatersrand Supergroup-times. According to that model, the syn-sedimentary uplift was caused by eastward-verging thrusting of a basement wedge into West Rand Group strata at depth, along a lower sole thrust. A westward-verging thrust forms the upper surface of the wedge (Fig. 15a). The eastward-verging thrust is viewed to constitute a backthrust to the westerly verging thrust system. The tip of the wedge is located at the intersection of the sole thrust with an upper eastward-verging backthrust. The westward-verging thrusts identified in the various seismic sections, are interpreted within that model to splay of the thrust forming the upper edge of the wedge (Fig. 15b).

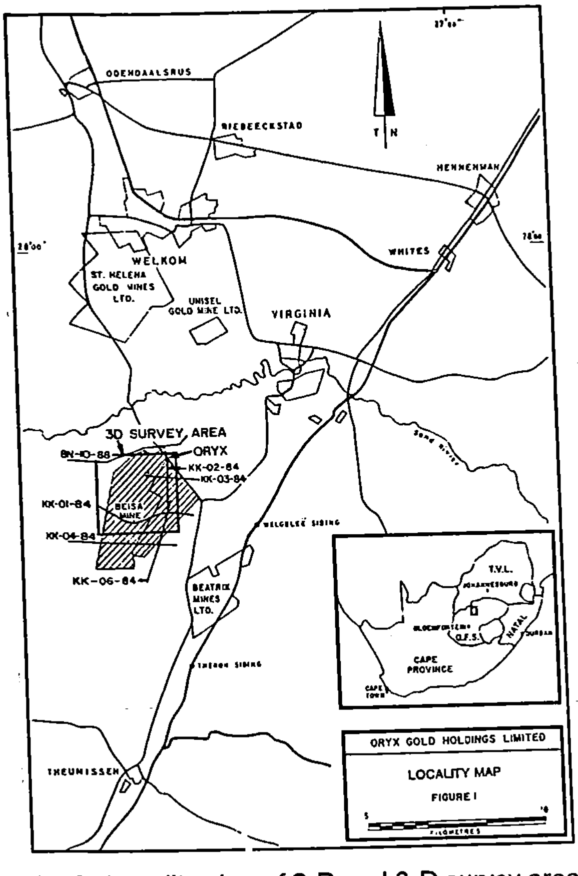


Fig. 9. Locality plan of 2-D and 3-D survey area.

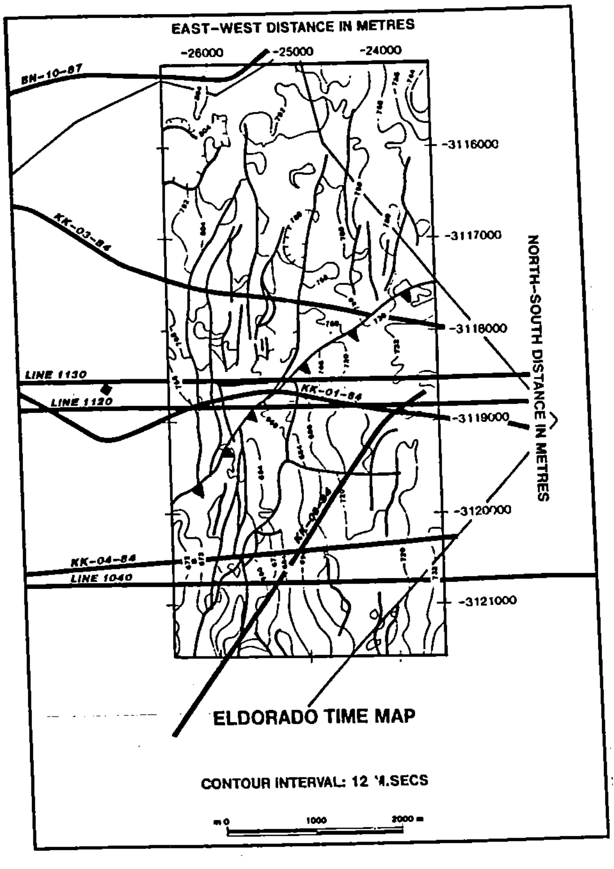
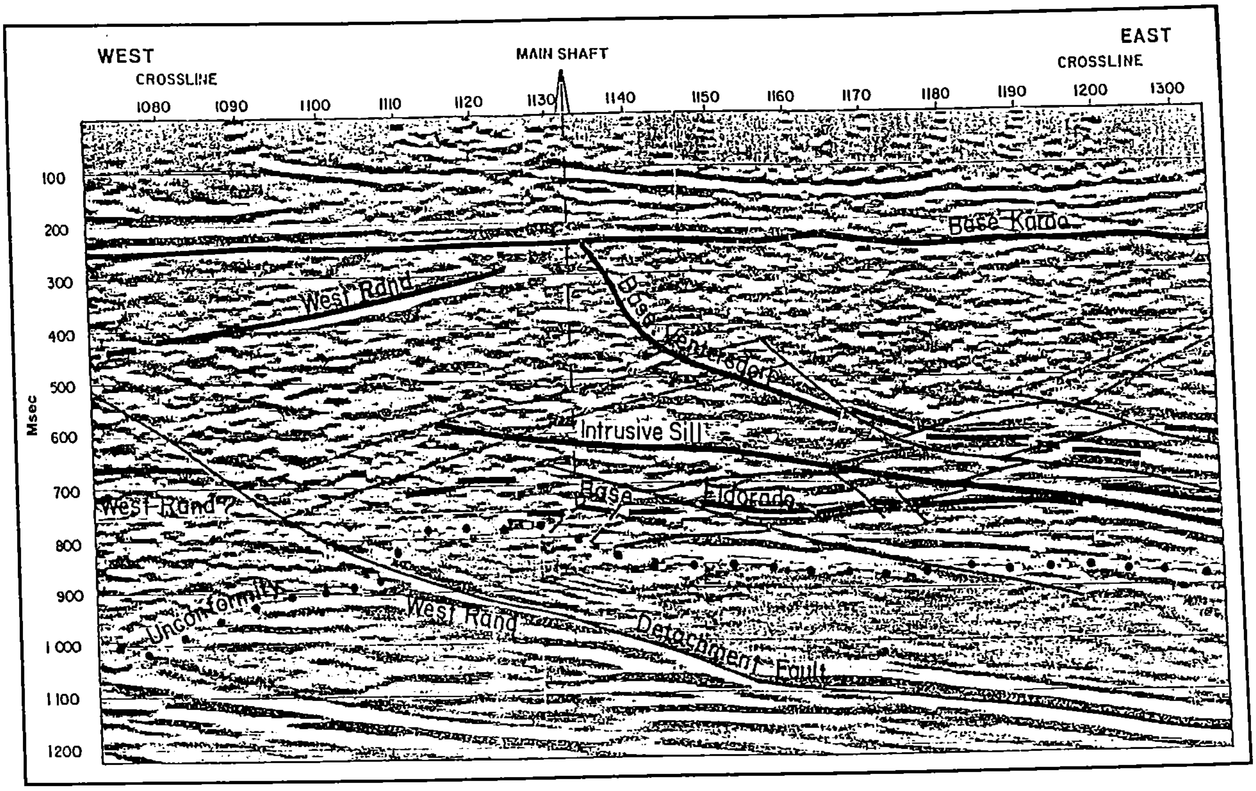


Fig. 10. Results from a 3-D survey, showing a time-depth map for the base of the Eldorado Formation (after De Wet & Hall, 1994).

a)



b)

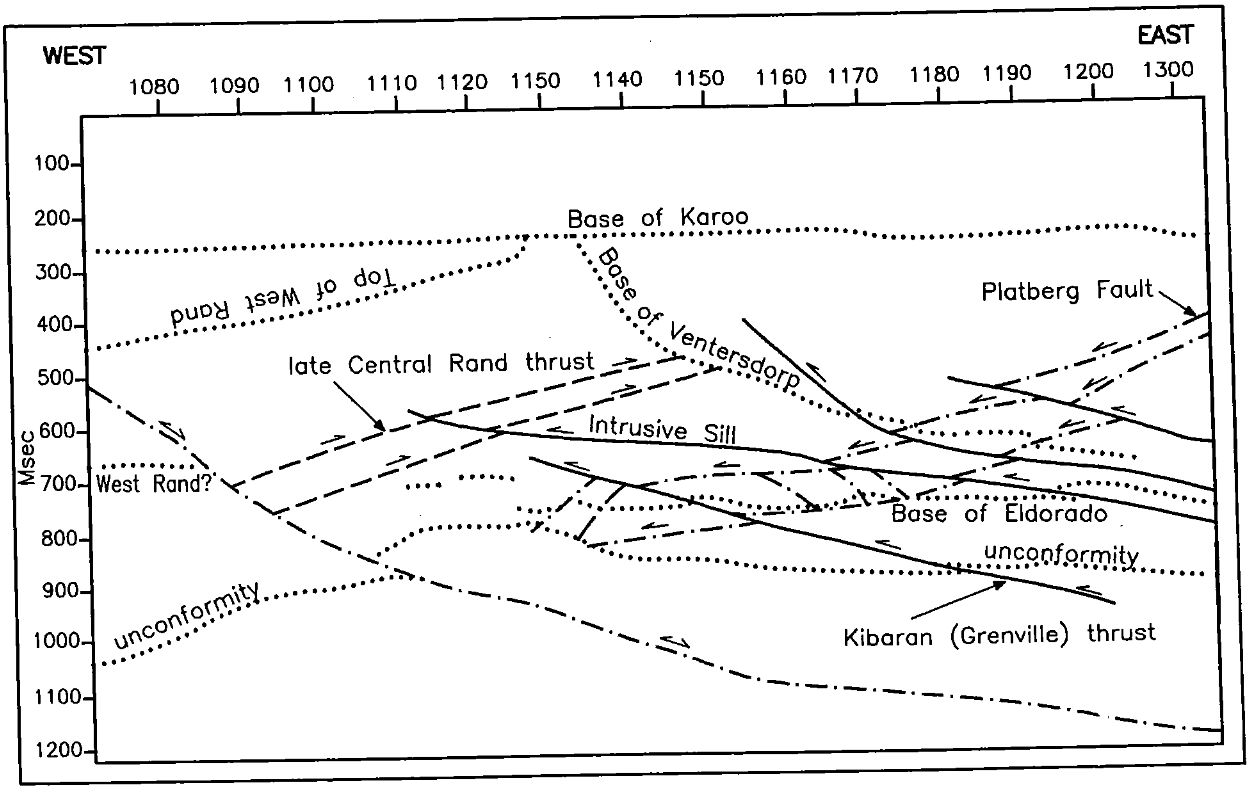
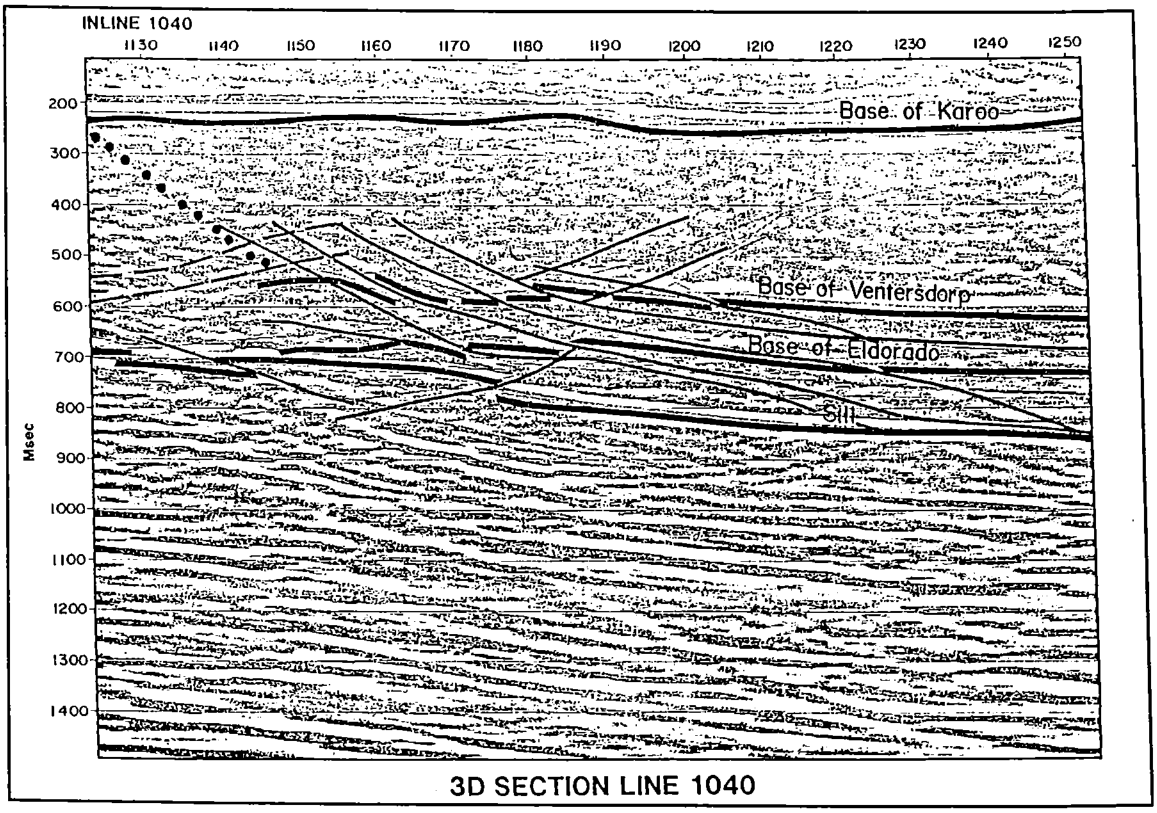


Fig. 11. a) Section through the east-west 3-D seismic line 1130 (after De Wet & Hall, 1994).
b) Reinterpretation of east-west 3-D seismic line 1130.

a)



b)

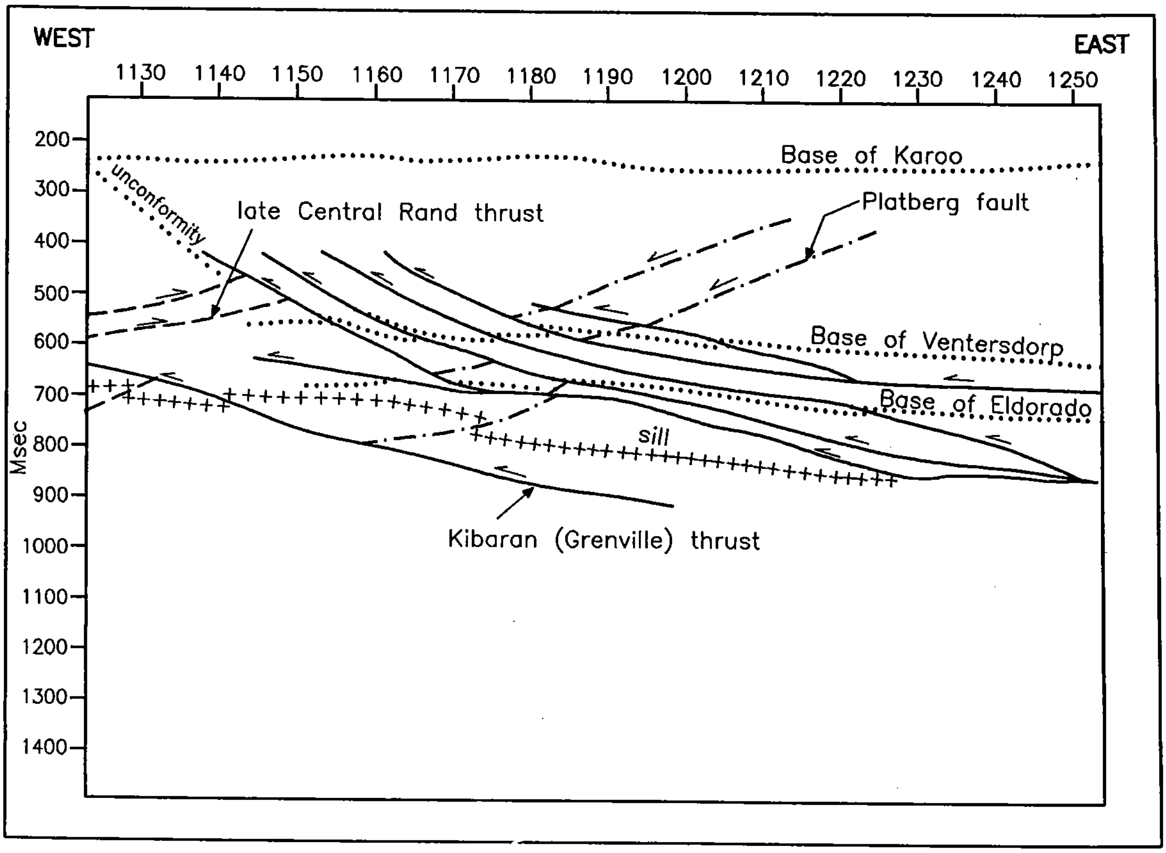
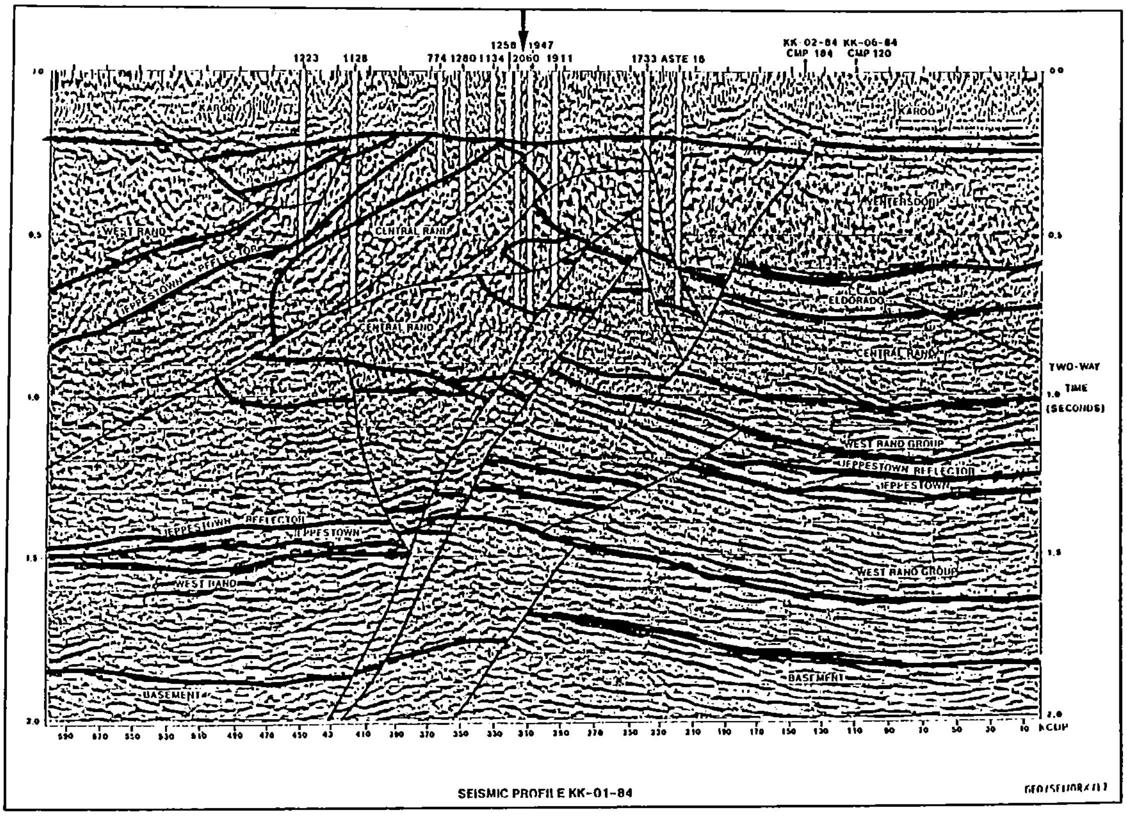


Fig. 12. a) 3-D seismic section on E-W line 1040 (after De Wet & Hall, 1994).
b) Reinterpretation of 3-D seismic section on E-W line 1040.

a)



b)

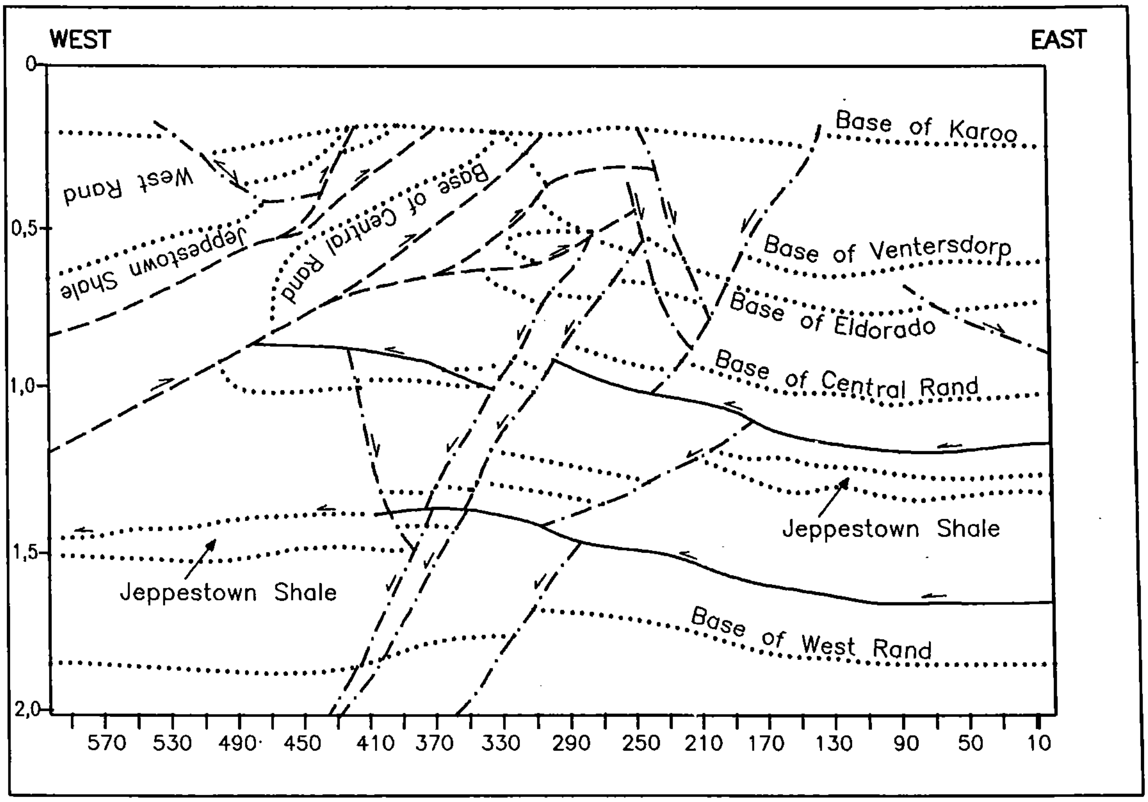


Fig. 13. a) 2-D seismic section of line KK-01-84 (after De Wet & Hall, 1994).
b) Reinterpretation of 2-D seismic section of line KK-01-84.

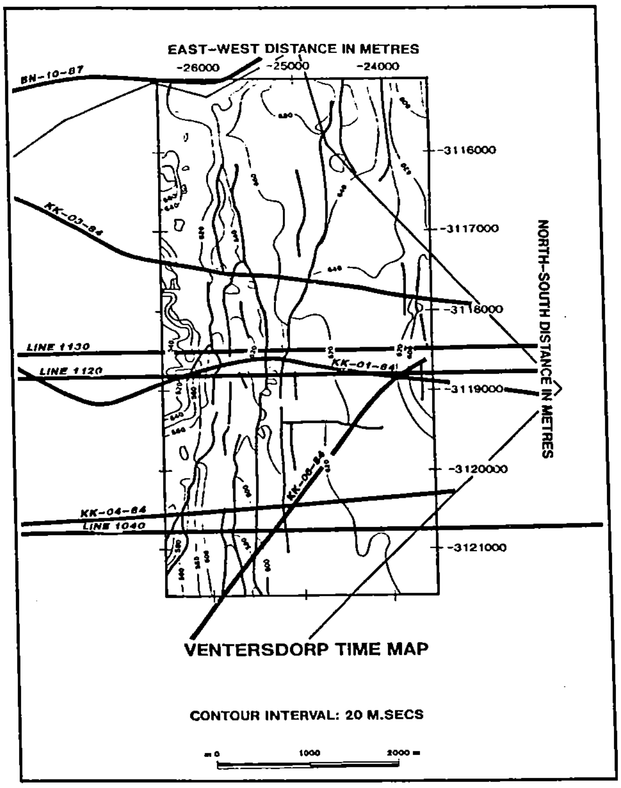


Fig. 14. 3-D time-depth map for the base of the Ventersdorp Supergroup (after De Wet & Hall, 1994).

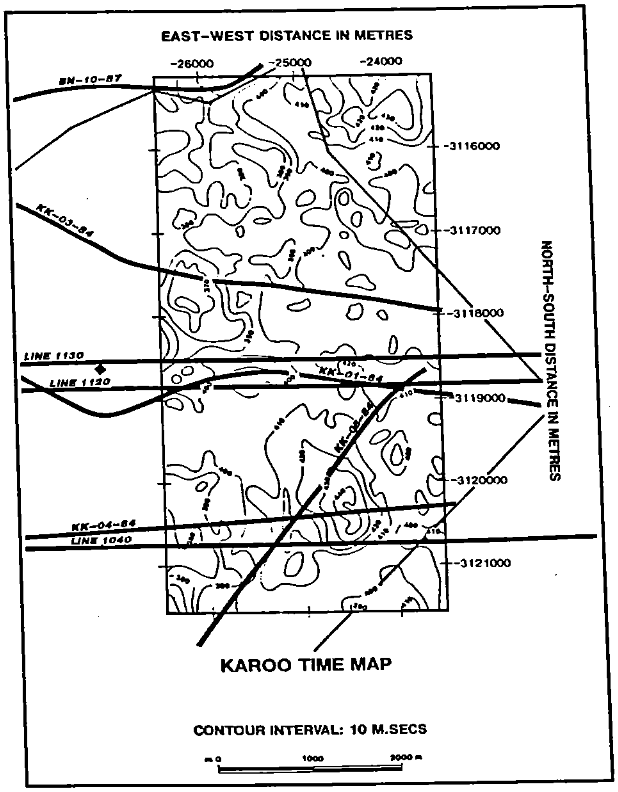


Fig. 16. 3-D time-depth map for the base of the Karoo Sequence (modified after De Wet & Hall, 1994).

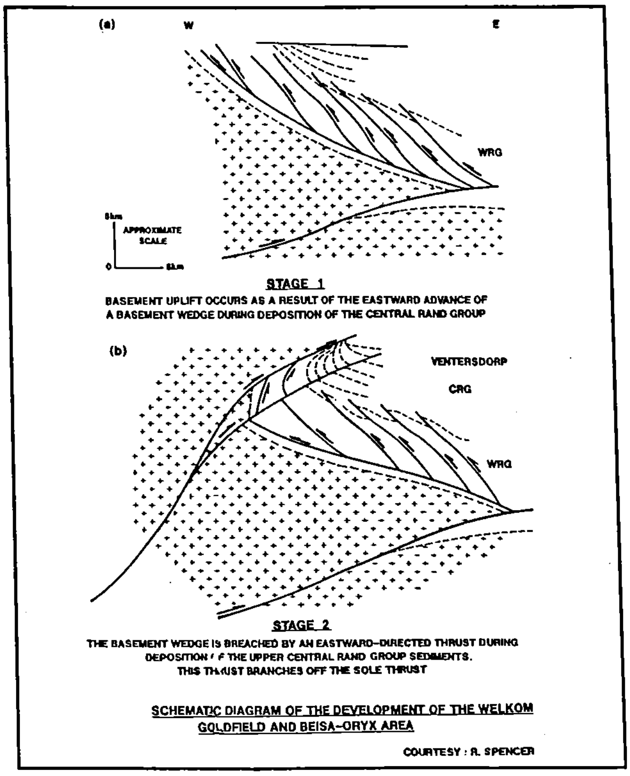


Fig. 15. Schematic diagram of the development of the OFS Goldfield and the Beisa/Oryx area (after De Wet & Hall, 1994).

It is difficult to understand, how a system of N/S-striking, east-verging thrust faults could have formed simultaneously within the same NW-directed compressional stress field, which generated a set of NE/SW-striking, northwest-verging thrusts. Regional underground observations along the western margin of the goldfield, as well as an investigation of the various 2D-seismic lines by De Wet & Hall (1994) clearly indicate, that the system of eastward-verging thrusts is of pre-Ventersdorp Supergroup age. The northwest-verging thrust system is clearly of post-Platberg Group age, as evident from displaced and rotated Platberg Group-age normal faults (Figs. 11b, 12b & 13b), which raises substantial doubts with regard to the validity of the proposed model by De Wet & Hall (1994) for the development of the Orange Free State Goldfield during Witwatersrand Supergroup-time.

In view of the somewhat contradictory interpretations by De Wet & Hall of the 2-D and 3-D seismic data from Oryx Gold Mine, the following alternative interpretation is presented:

The syn-sedimentary uplift of the basement in the area west of the Orange Free State Goldfield during the late-depositional stages of the Central Rand Group was caused by an eastward-verging fold and thrust belt (leading imbricate fan), with the most easterly developed thrust-related fold structure developed along the western margin of the goldfield, and known as the Border Structure.
Major easterly dipping normal detachment faulting in mid-Ventersdorp Supergroup-time, situated to the west of the goldfield, was accompanied by normal and subsequent strike-slip faulting within the goldfield, as well as the formation of a major roll- over anticline, causing westerly tilting of the entire western margin of the goldfield (Friese, in prep.).
NW-directed compressional stress, operating in the area of the OFS Goldfield during at least post-Platberg Group-time, was accommodated in the eastern part of the OFS Goldfield, mainly by NW-directed , bedding-parallel thrust movements predominantly along unconformities and more incompetent horizons of the moderately east dipping Witwatersrand and Ventersdorp Supergroups strata (Friese, in prep.; also see above). Due to the flattening of the strata in the crest region of the roll-over anticline, situated in the western part of the goldfield, NE/SW-striking, NW-verging thrust faults developed out of the bedding planes, to follow the Navier-Coulomb fracture angle (e.g. Fig. 13a/b).

In summary, a system of shallow-angle, NE/SW-striking, NW-verging thrust faults, which clearly post-date a set of N/S-striking, easterly verging thrusts of late-Central Rand Group-age, as well as N/S-striking, westerly dipping normal to strike-slip faults of mid-Ventersdorp-age, have been identified within the southern portion of the OFS Goldfield.
It is further interesting to note, that the major NE/SW-striking, NW-verging thrust fault appears to have experienced reactivation in syn- to post-Karoo Sequence-time, as evident by the development of two separate basins to the northwest and southeast of the inferred position of the thrust (Fig. 16).

Trans-Witwatersrand Basin vibroseis survey and extension

In 1988, a 112 km long, 16 s two-way-time (TWT) trans-Witwatersrand Basin seismic reflection profile, stretching along a NW-SE axis from the Westerdam dome, across the Potchefstroom syncline to the centre of the Vredefort dome (Fig. 17), was surveyed under the auspices of the National Geophysics Programme and the SA Geological Survey.
An unmigrated section was released on Open File by the Geological Survey of S.A. in January 1989, which was subsequently migrated at the Reflection Seismology Research Centre, Witwatersrand University (Durrheim et al, 1991).
Migration was carried out only on the upper 12 s of the section, as the difficulty of using wave equation methods to migrate deep continental data is well-known (Warner, 1987).
According to the interpretation of the trans-Witwatersrand vibroseis line by Durrheim (1989) and Durrheim et al. (1991), the crystalline basement can be divided into three zones on the basis of the seismic fabric:

Zone 1 is characterised by numerous subhorizontal reflections which occur oriented parallel to the base of the supracrustal strata in both isolated and complex packages, which mark the Conrad-Discontinuity at 3.4-4.4 s TWT (upper-middle crust transition), or the Moho-Discontinuity at 12 s TWT (crust-mantle transition), as well as sill intrusions or ductile banding (Fig. 18).

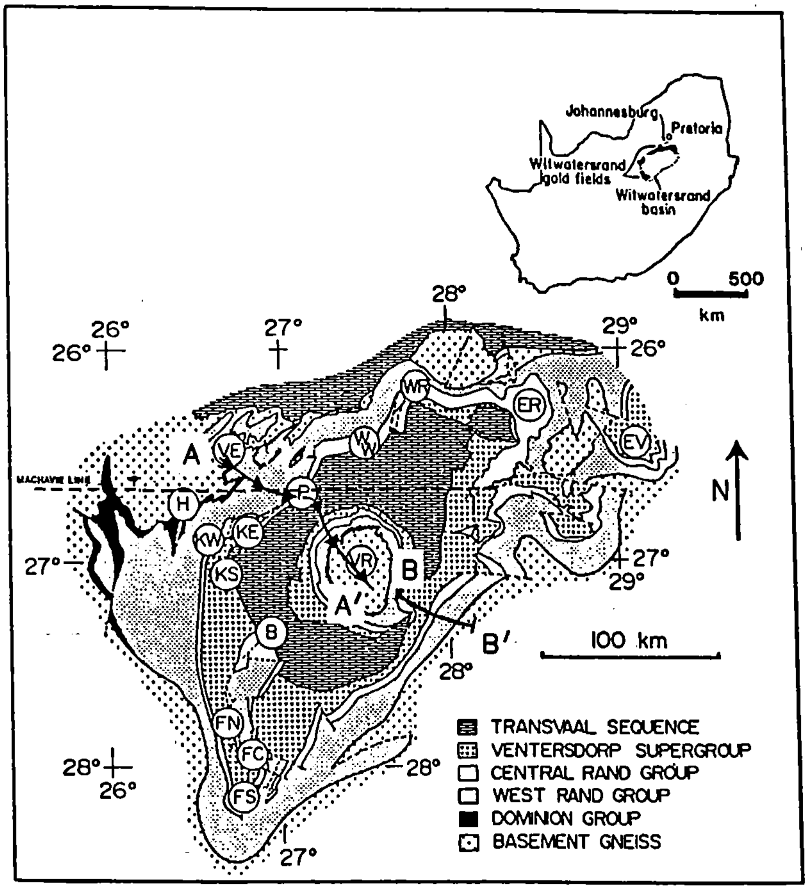


Fig. 17. Location of the seismic reflection profile and the geology of the Witwatersrand Basin with the Palaeozoic cover removed (after Durrheim et al., 1991).

Zone 2 is characterised by the complete absence of reflected energy between 6 s TWT and the base of the section at 16 s TWT (Fig. 18). Durrheim et al. (1991) interpreted the seismically transparent basement domain of Zone 2 due to structural disturbance and petrological complexity.

Zone 3 is situated within the core of the Vredefort dome and characterised by occasional inclined curved reflections, generally not more than 2 km in length, as well as the absence of a crust/mantle transition (Durrheim et al., 1991) (Fig. 18).

The boundary between Zone 1 (basement with multiple seismic reflectors) and Zone 2 (seismically transparent basement) is interpreted by Durrheim et al. (1991) to be vertical and abrupt and correlatable with the Machavie line (Corner & Wilsher, 1989) (Fig. 18). Adopting the strong evidence for an impact origin of the Vredefort Dome (e.g. Reimold & Colliston, 1994), in terms of this study, the boundary is interpreted to represent the actual margin of the transient crater, approximately 55 km in distance to the centre of the Vredefort Dome (central peak), separating a relatively undisturbed Archaean basement from a structurally highly disturbed basement within the transient crater itself.

The various lithologies(mainly granitoids of the basement and sediments/volcanics of the supracrustal cover) within the limits of the defined transient crater appear to have responded differently to the oscillating stress field (O'Keefe & Ahrens, 1995), generated at the moment of projectile penetration into the earth crust.

The relatively homogenous crystalline basement experienced intensive brecciation and fracturing, as evident from the highly fractured and with pseudotachylites intensively interspersed granitoids exposed within the Vredefort dome.

The supracrustal cover represents a unit of much higher anisotropy, when compared to the crystalline basement. Due to its long pre-existing tectono-sedimentary history, the Archaean and Proterozoic cover exhibits numerous structural and sedimentary discontinuities (faults, shear zones, joints, folds, bedding planes, unconformities etc.). Stress was therefore primarily accommodated along these zone of relative

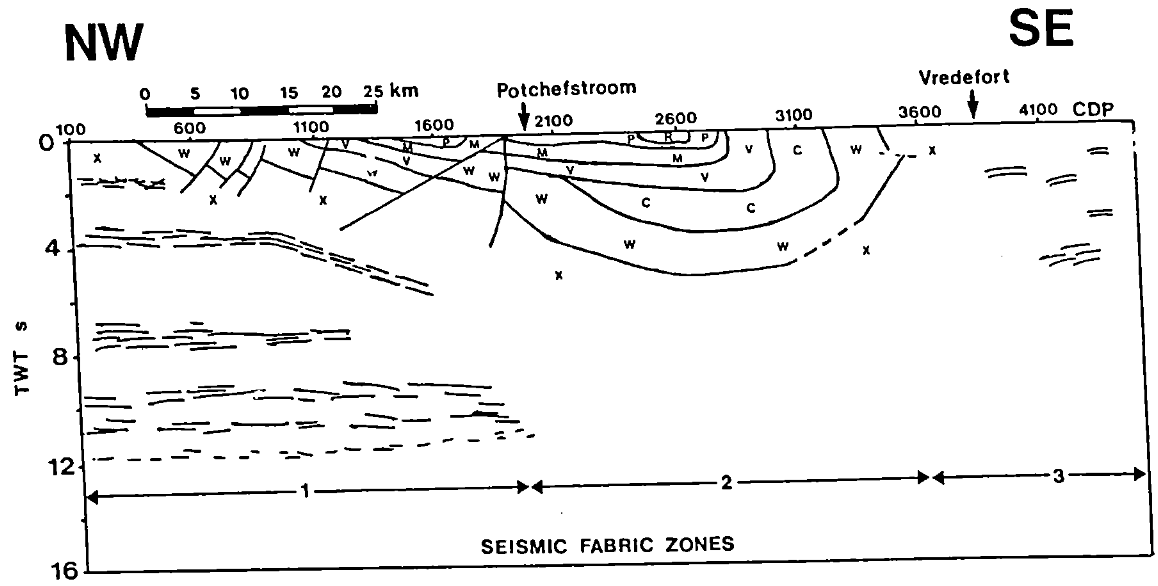


Fig. 18. Interpretation of the trans-Witwatersrand Basin seismic reflection profile (after Durrheim et al.,1991). (X=Basement, W=Dominion & West Rand Groups, C=Central Rand Group, V=Ventersdorp Supergroup, M=Black Reef Formation & Malmani Subgroup, P=Pretoria Group, R=Roodekraal Complex).

weakness, as evident by pseudotachylite formation predominantly along them. This appears to be a satisfactory explanation, how the crystalline basement could have experienced impact generated intensive structural deformation, which is not evident to such an extent in the overlying supracrustal cover.

An attempt was made, to reinterpret the trans-Witwatersrand seismic line structurally within the concept of the proposed northwest-directed, compressional tectonics of post-Vredefort impact-age.
An indication for the existence of northwest-directed thrusting, post-dating the Vredefort deformational impact event, was initially provided from the interpretation of the seismic reflection data published by Durrheim (1989) and Durrheim et al. (1991) of the northwestern collar region of the Vredefort Dome (Fig. 19). The interpretation clearly demonstrates a northwest-verging thrust fault, which displaces the overturned West Rand Group strata within the collar of the Vredefort Dome by approximately 1.5 km.
Durrheim et al. (1991) also identified a southeasterly inclined strong reflecting horizon within the Archaean

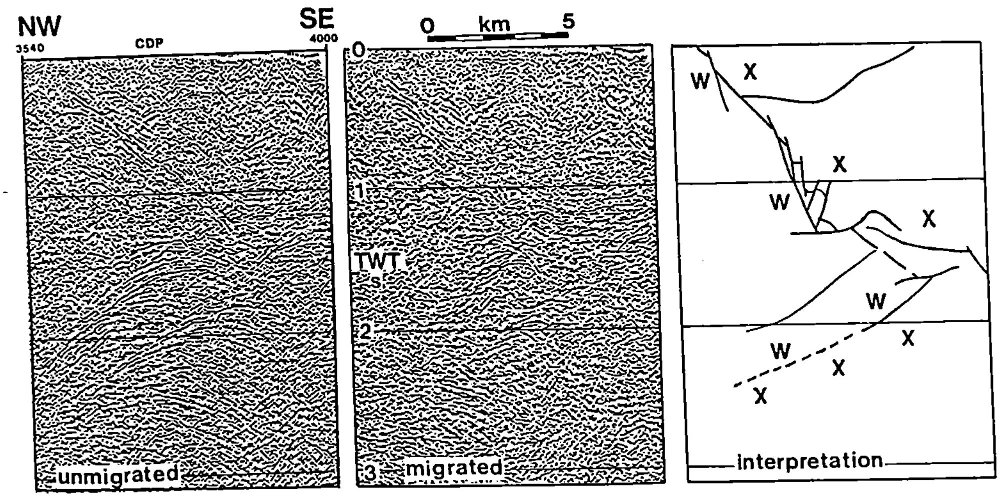


Fig. 19. Interpretation of a panel (CDP 3540-4000, for location see Fig. 18) from the trans-Witwatersrand Basin seismic reflection profile, showing the northwestern collar region of the Vredefort Dome (modified after Durrheim et al., 1991). (X=basement; W=Dominion & West Rand Groups).

basement approximately between CDP 800 and 1500 at 4-6 s TWT. Additional support for the presence of possible northwest-directed thrust faults of post-Vredefort-age was provided by previous workers, who carried out independent structural interpretations of the trans-Witwatersrand Basin seismic reflection profile. Most of these workers show northwest directed compressional tectonics as a common structural event. Colliston (1990) interpreted the subhorizontal reflectors in the early Archaean basement as NW directed thrust faults and proposed a subhorizontal crustal shear model for the origin of the Vredefort structure, as a tectonic alternative to impact, gas explosion or diapiric hypotheses.
To date, overwhelming evidence has been presented for an impact origin of the Vredefort Dome (e.g. Reimold & Colliston, 1994), but nevertheless, the identification of the subhorizontal reflectors within the crystalline basement as possible zones of ductile to brittle decollement by Colliston (1990), as well as by Durrheim (1989, 1991) and Brink (pers. comm.), supports the reinterpretation of the trans-Witwatersrand Basin seismic reflection profile presented in Figure 20, and the proposed model of NW-directed, post-Vredefort impact-age compressional tectonics.

Figure 20 presents a detailed reinterpretation of the migrated (1-5 s TWT) trans-Witwatersrand Basin seismic reflection profile, as well as of two unpublished, migrated (1-5 s TWT) seismic reflection survey lines (HB-02W-89 and HB-02E/-02EXT) (Fig. 17), which were provided courtesy of Johannesburg Consolidated Investment Co., Ltd., and represent a southeastern extension to the trans-Witwatersrand Basin seismic survey line. The reinterpretation attempts to incorporate most of the structural elements, that were previously identified from the Trans-Witwatersrand Basin seismic reflection profile by Durrheim (1989), Durrheim et al. (1991), Colliston (1990) and Brink (pers. comm.). In addition, all published geological data available from exploration drilling and surface mapping of the area to the northwest and southeast of the Vredefort Dome, as well as from underground exposures in the adjacent Klerksdorp and Carletonville goldfields, were utilized to constrain the reinterpretation of the trans-Witwatersrand Basin seismic reflection profile and of the two unpublished seismic reflection survey lines.

Based on the results from the reinterpretation of the seismic reflection profiles, the following important conclusions and interpretations, relevant to post-Vredefort impact compressional tectonics, as well as to earlier deformational events, can be made:

1. A system of northwest-verging thrust faults of post-Transvaal-age appears to be the youngest structural element identified within the profiles. This faulting is evident within and to the southeast of the Vredefort Dome, but also occurs in the area of the Westerdam Dome and the Rand Anticline to the northwest. The displacement along these thrusts ranges between approximately 500 m (e.g. Spitskop Thrust) and 1500 m (e.g. Enselspruit Thrust), indicating an apparent decrease in the displacement magnitude towards the northwest.

2. Accepting an impact origin for the Vredefort structure, Therriault et al. (1995) estimated the original dimensions of the Vredefort impact structure by assuming, that the structure was initially circular, and that its pre-deformation centre corresponds to the centre of the granitic core.
   Using current knowledge of impact cratering processes and the spatial relationship between shock metamorphic effects, the shock pressure they record, and the morphological features of the crater, as established for a number of large terrestrial craters, Therriault et al. (1995) adopted in their study a method, similar to the one given by Grieve et al. (1991) for the Sudbury Structure. By using the radial position of shock metamorphic effects and the location of the outliers of the Transvaal cover rocks at Vredefort, as well as adding a correction for the large amount of erosion of approximately 8 km implied over the Vredefort area to the transient crater dimensions estimated, Therriault et al. (1995) arrived at an estimate for the original diameter of the transient crater of the Vredefort impact structure between 114-140 km and an adjusted estimated transient cavity diameter of 125-150 km at the present level of erosion and at the time of impact cratering respectively. In detail, Therriault (1995) used the location of the limit of the shatter cone formation at 26-37 km and of shock-produced microscopic planar features in quartz at a distance of about 13 km, as well as the location of downfaulted outliers of the Transvaal cover rocks approximately 50-60 km north and west of the Vredefort structure from the outer edge of the granitic core, and derived the above mentioned maximum estimated transient crater rim diameter of less than 160 km at the present erosional level.
   The reinterpretation of the trans-Witwatersrand Basin vibroseis reflection profile (Fig. 20) indicates the Potchefstroom Fault, in relationship to the position of the Vredefort Dome, as the most northwesterly situated, southeasterly dipping normal fault of post-Transvaal age, interpreted to represent the

maximum limit of the transient crater. Support for this proposal is provided by the subdivision of the Archaean basement into three zones of different seismic fabric by Durrheim (1989) and Durrheim et al. (1991), and their identification of the boundary between Zone 1(basement with multiple seismic reflectors) and Zone 2 (seismically transparent basement) in close vicinity to the position of the Potchefstroom Fault (compare Figs. 18 and 20), as earlier outlined in detail. Consequently, the northwestern margin is not a continuous, nearly vertical line (Durrheim, 1989; Durrheim et al., 1991), interpreted by both authors to correlate with the east-west-trending Machavie line of Corner & Wilsher, (1989), but rather a southeastward curved plane (Potchefstroom Fault), which appears to be concentrically arranged around the Vredefort Dome at least to the west and northwest of the later.

Taking the position of the Potchefstroom Fault as the actual transient crater margin at the present erosional level, a transient cavity diameter of approximately 110 km is indicated. The mean estimated maximum of 114-140 km by Therriault et al. (1995) for the diameter of the transient crater, preserved at the present level of erosion, is therefore considered to be slightly to high. Thus, the results from the reinterpretation of the seismic profile confirm rather the lower estimate by the same authors of 92-114 km, based solely on the present radial position of shock metamorphic effects, like shatter cones and planar deformation features in quartz, from the outer edge of the core.

The identification of a system of major, northwest-verging thrust faults, which post-date the impact-related deformation structures (folding to overfolding and normal faulting of Archaean and Proterozoic supracrustal cover rocks concentrically around the Vredefort Dome), implies modification to the crater geometry and dimension. As most of the identified and outcropping thrust faults, situated to the west and northwest of the Vredefort Dome, display in general relatively small displacement magnitudes, as inferred from the seismic reflection profile reinterpretations and surface mapping (e.g. Brink, pers. comm.), fundamental shortening of the transient crater due to northwest-verging thrust tectonics appears to be negligible. A different scenario appears to exist east of the Vredefort Dome, where the intensity and displacement magnitude of thrust faults is apparent from the reinterpretation of the trans-Witwatersrand Basin seismic reflection profile and of its southeastern extension (lines HB-02W-89 and HB-02/-02EXT) (Fig. 20), as well as inferred from the results of gravity profile modelling across the Witwatersrand Basin (see below). Intense northwest-verging thrust tectonics to the east of Vredefort Dome are interpreted to have caused considerable reduction of the eastern sector of the transient crater. The identified asymmetry of the Vredefort Dome collar, with overturned Archaean and Proterozoic cover rocks present in an arc from the southwest to the northeast, and relatively shallow, southeasterly dipping supracrustals in the eastern sector of the dome, is interpreted to have been caused by upliftment of crystalline basement blocks in response to the proposed northwest- to north-directed compressional tectonics. A more comprehensive exposition and discussion of the proposed model will follow at a later stage.

3. The western portion of the trans-Witwatersrand Basin seismic reflection profile exhibits the presence of a system of low-angle, listric-shaped faults, displaying normal as well as reverse components of displacement. The entire fault system appears to be rooted in an almost horizontally oriented fault, which eventually climbs up through the strata by outcropping just to the west of the town of Vredefort. This entire structural domain is interpreted to represent an easterly verging imbricate thrust system of-late-Central Rand Group-age, which experienced negative inversion during a mid-Ventersdorp Supergroup rifting phase (see also Friese, in prep.).

4. A subtle indication exists for a tectonic event of post-Chuniespoort Group to pre-Pretoria Group-age, which is manifested in minor reverse movements along pre-existing, north/south-striking, late-Central Rand Group thrust faults, and normal displacements on either newly formed faults or pre-existing, north/south-striking, mid-Ventersdorp Supergroup normal/strike-slip faults (e.g. Turffontein Fault).

5. The West Rand, Central Rand and Klipriviersberg groups, preserved to the southeast of the Vredefort Dome, exhibit significantly decreased thicknesses, when compared to the area northwest of the dome.

6. The base of the supracrustal cover sequence (Dominion Group?/West Rand Group) preserved to the southeast of the Vredefort Dome is positioned at approximately 2 s TWT (6 km) and hence approximately 9 km higher than the base of the supracrustal cover sequence to the northwest of the dome at ~ 5 s TWT (~15 km) (compare with Fig. 22).

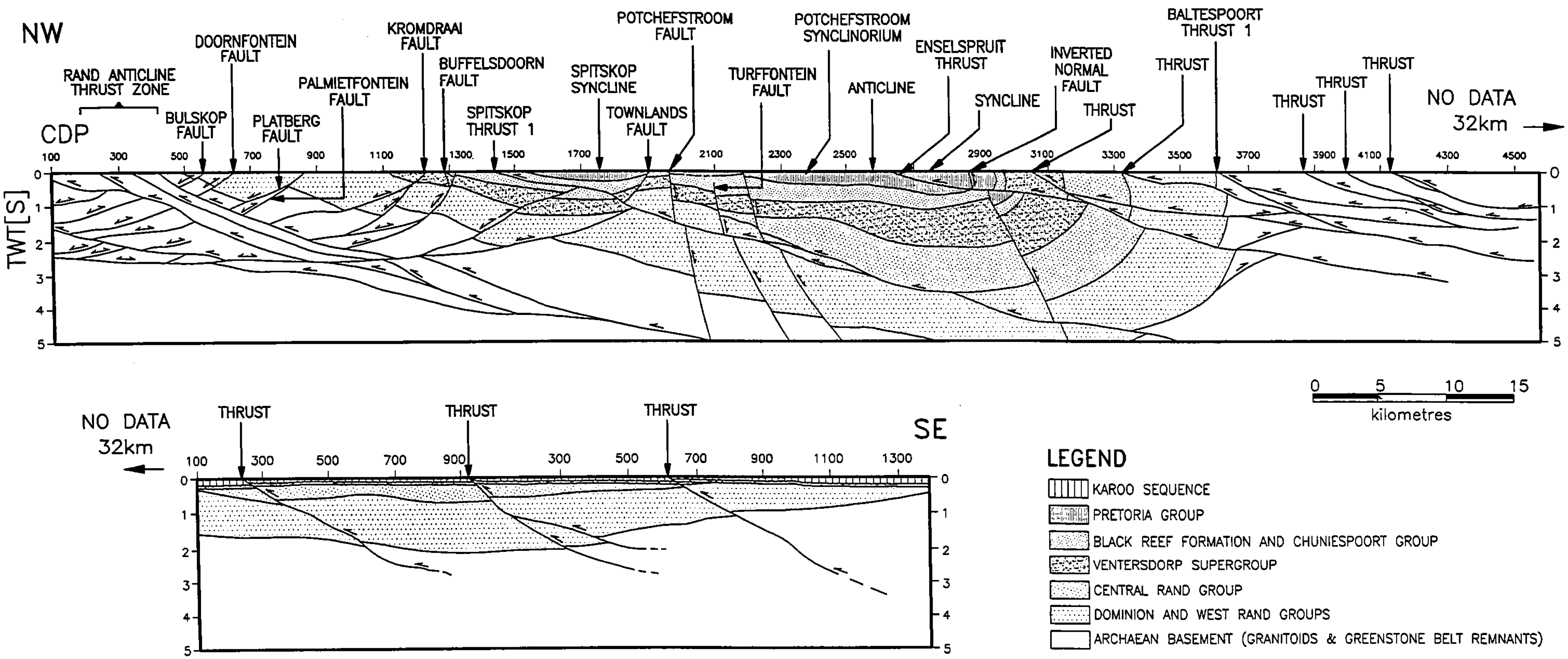


Fig. 20. Detailed reinterpretation of the trans-Witwatersrand Basin seismic reflection profile and of seismic reflection lines HB-02W-89 and HB-02E/-02 EXT (migrated to 5 s TWT). For location see Figure 17.

Gravity and aeromagnetic profile modelling across the Witwatersrand Basin

At present ongoing detailed integrated modelling of gravity and aeromagnetic data along two traverses across the Witwatersrand Basin (Fig. 21) by Henkel & Reimold (in prep.), attempts to identify the size and structural geometry of the proposed Vredefort impact crater.
For this study, in particular the preliminary results of the NW/SE-trending gravity profile modelling were utilized for a structural interpretation (Fig. 22), in order to provide in addition to the structural and seismic reflection data presented above, further implications for NW-directed compressional tectonics within the central Kaapvaal craton in post-Vredefort impact-time.

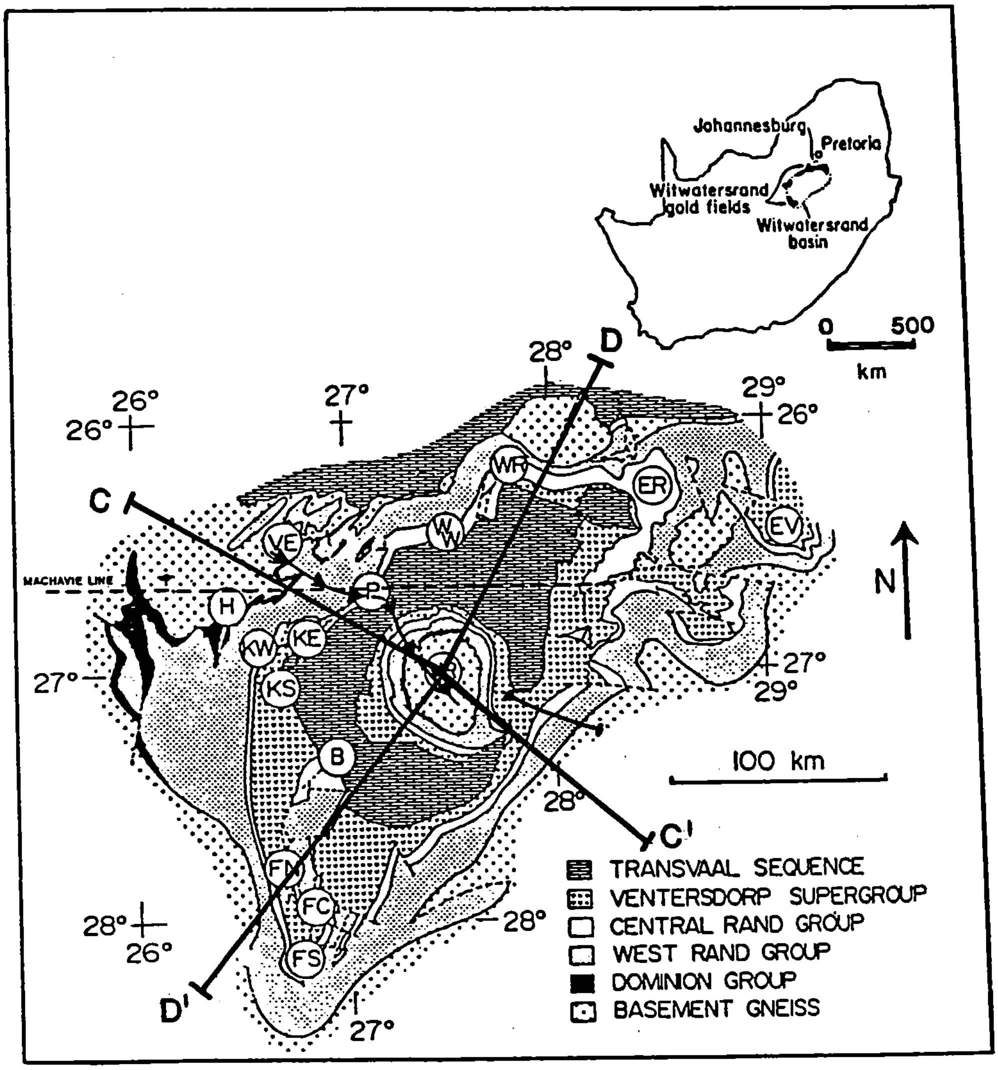


Fig. 21 Location of the modelled gravity and aeromagnetic profiles across the Witwatersrand Basin by Henkel & Reimold (in prep.), in relation to the trans-Witwatersrand Basin vibroseis line.

The structural interpretation of the gravity profile is based on the structural interpretation of the trans-Witwatersrand Basin seismic reflection profile and the seismic reflection survey lines HB-02W-89 and HB-02E/-02EXT, as well as on literature research focusing on identified post-Transvaal thrust tectonics. The interpretation of the gravity profile does not claim to be able to identify or define accurately thrust faults and their position at depth (due to the nature of gravity modelling as low-resolution method), but rather to demonstrate supportively the possibility for the existence of post-Vredefort thrust faulting within the Witwatersrand Basin.

Focusing on the structural interpretation of the preliminary NW/SE-trending gravity profile (C-C') (Fig. 22), the following conclusions can be made:

1. Several deep-crustal thrust zones within the continental crust of the central Kaapvaal Craton might exist, which could be primarily situated along major transition zones (Conrad-, Moho-discontinuity, etc.). In this respect it should be noted, that the interfaces in the gravity model, especially in the deeper crystalline crust do not necessarily correspond to lithologic boundaries. They are merely the location of the discretization intervals used in the modelling (Henkel & Reimold, pers. comm.).

2. The base of the supracrustal cover sequence preserved immediately to the southeast of the Vredefort Dome ("SE-Basin") is positioned approximately 4 km higher, than the base of the supracrustal sequence to the northwest of the dome ("NW-Basin");

3. The preserved thickness of the elevated "SE-Basin" reaches a maximum of approximately 6.5 km, consisting mainly of Witwatersrand and Ventersdorp Supergroups; compared to the "NW-Basin, with a maximum thickness of approximately 11.5 km in the area of the Potchefstroom Syncline, comprising the entire supracrustal stratigraphy of Dominion Group, Witwatersrand and Ventersdorp Supergroups and Transvaal Sequence;

4. The Archaean strata (Dominion Group, Witwatersrand and Ventersdorp Supergroups) within the "NW-Basin" appears to thin towards the Vredefort Dome;

5. No overturning of the supracrustal cover to the southeast of the Vredefort Dome exists. Instead, strata dip shallowly to the southeast, implying an apparent asymmetrical geometry to the collar;

6. Numerous southeasterly dipping, NE/SW-striking normal faults of possible Platberg-age, situated east of the Vredefort Dome, are interpreted to have experienced positive inversion during the proposed NW directed compression;

7. To the southeast of the "SE-Basin" a NW-verging, monoclinal updoming of the upper, middle and lower crust is apparent, which is interpreted as a major crustal ramp anticline (Winberg-Bethal Anticline), formed in response to the proposed Winberg-Bethal Thrust Zone;

8. Southeast of the proposed Winberg-Bethal Thrust Zone, the Archaean basement appears to be elevated by approximately 5 km and virtually no preserved remnants of Archaean and Proterozoic supracrustal cover rocks seem to exist, with deposits of the Karoo Sequence directly overlying the Archaean basement;

9. The post-impact associated dynamic rebound and uplift of the lithosphere of approximately 8-10 Km under the impact crater appears to have involve the continental crust only, with an unaffected, westerly inclined Moho-discontinuity at a depth of approximately 35 km beneath the Vredefort Dome;

10. The continental crust situated to the southeast of the Sugarbush Lineament within the Vredefort Dome, exhibits a different lithospheric structure in comparison to the northwestern counterpart, with an additional upper granitic layer within the Archaean basement, directly beneath the supracrustal cover rocks. This uppermost granitic basement unit attains an average thickness of 6 km, with maximum thickness near the centre of the Vredefort Dome and abrupt thinning to approximately 1 km thickness in the area to the east of the inferred Winberg-Bethal Thrust Zone.

It has to be stressed, that the interpretations derived from the gravity model are of preliminary nature, as the model itself represents only a preliminary stage. A refined final version is expected to be produced in due course, however only minor changes to the gravity model are expected (Henkel & Reimold, pers. comm.). Further, the general agreement between the gravity model and the refraction/reflection seismic data is by purpose as these data have been used to constrain the gravity modelling.

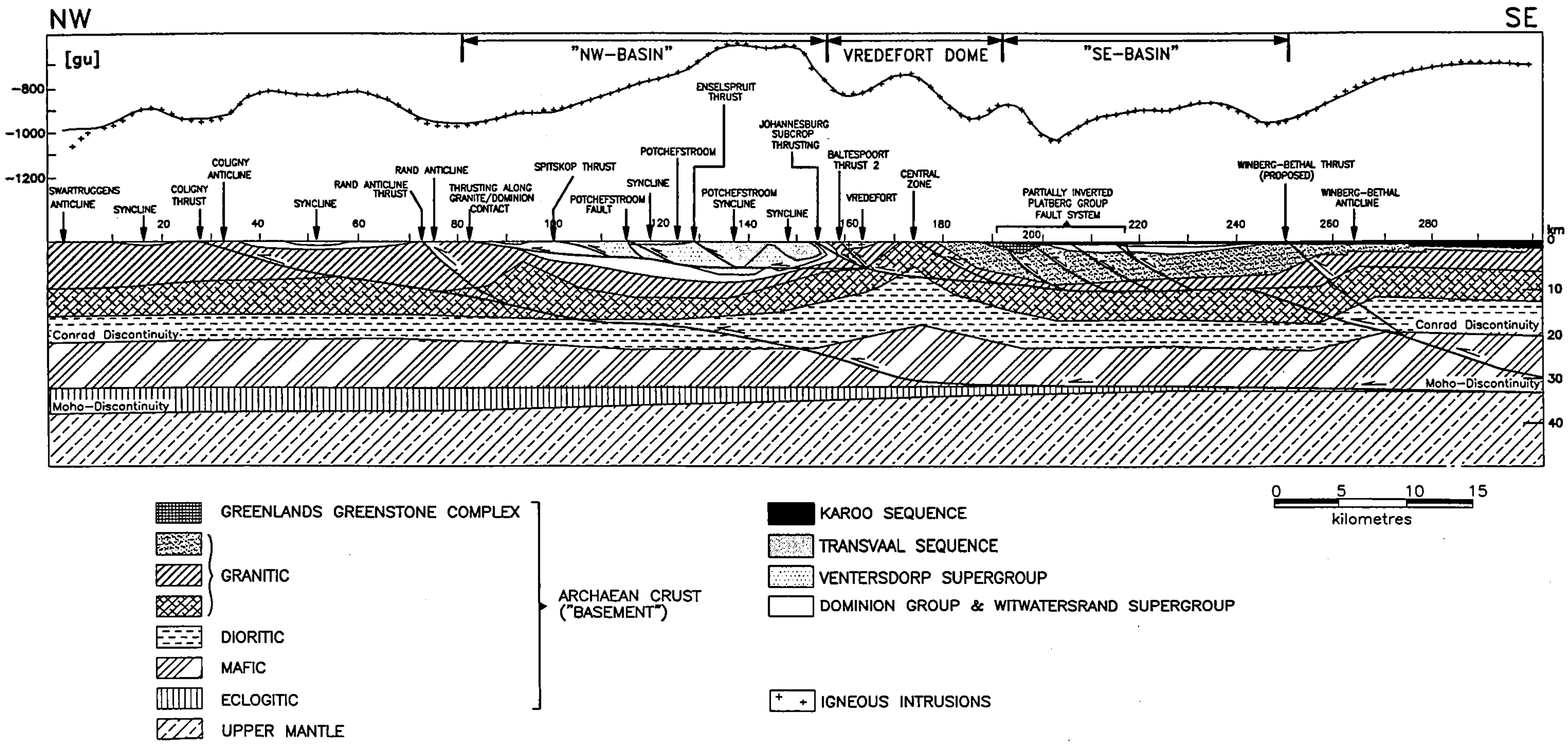


Fig. 22. Structural interpretation of the NW/SE-trending gravity profile across the Witwatersrand Basin.

GEOCHRONOLOGICAL RESETTING DATA FROM THE WITWATERSRAND BASIN AND ENVIRONS PERTINENT TO THE KIBARAN (GRENVILLE) OROGENY

As orogenic processes are commonly associated with magmato-thermal activity and related metamorphic and hydrothermal events within the lithosphere, any pre-existing isotopic systems generated during an earlier orogeny will experience disturbance or resetting during a younger orogenic phase, giving the relative age of the later.
Identified resetting ages obtained from various Archaean and Proterozoic lithologies within the Witwatersrand Basin and environs might therefore provide valuable support for younger tectono-magmatic events effecting the lithosphere of the central Kaapvaal Craton.

The following summary of available geochronological data, obtained for lithologies from the Witwatersrand Basin and environs, focuses solely on interpreted (partial) resetting ages of the time interval 1450-1000 Ma, and is tabulated below (Tab. 2), as well as diagrammatically illustrated in Figures 23a and b.

The spatial occurrence of localised partial resetting is regional within the area of the Witwatersrand Basin and appears to extends northward as far as the Bushveld Complex, and more than 100 km into the western hinterland of the Witwatersrand Basin.

With regard to the region within and around the Vredefort Dome, evidence for multiple formation of pseudotachylites (Reimold et al., 1990; Reimold et al., 1992b) was proven partially wrong (Kamo et al., 1995; Spray et al., 1995; Trieloff et al., 1994), but it is confirmed now, that in the southeastern sector of the Vredefort Dome, at the farm Broodkop, a younger generation of pseudotachylites of endogenic origin exists, which were formed between 1437 $\pm$ 9 and 1227 $\pm$ 17 Ma. Several post-Vredefort impact partial resetting events effected all lithologies within the entire area of the Vredefort Dome, with a dominantly developed phase, identified for the time interval 1450-1050 Ma.

Based on the diagrammatical illustration of (partial) resetting ages for the central Kaapvaal Craton (Fig. 23b), two main periods of increased hydrothermal resetting activity between approximately 1450-1315 Ma and 1280-1000 Ma, as well as one minor developed break of relative lower hydrothermal resetting activity within each main cycle between 1440-1415 Ma and 1200-1165 Ma are identifiable.

In the light of the summarized post-Transvaal Sequence chronological record presented above, it appears feasible to conclude the existence of two main cycles of localised magmato-tectonic activity and associated hydrothermal alteration processes throughout the central part of the Kaapvaal Craton between 1.45 and 1.0 Ga ago.

Table 2. Geochronological resetting data obtained from lithologies within the Witwatersrand Basin and surrounding areas.

	REFERENCE	LITHOLOGY / LOCALITY	AGE (Ma)	METHOD	INTERPRETATION BY AUTHOR
VREDEFORT DOME	Hargraves (1987)	Lindequesdrift intrusion	1248 ± 22	^{40}Ar-^{39}Ar; plagioclase	Thermal resetting age/event associated with igneous intrusions (e.g. Pilanesberg dikes)
VREDEFORT DOME	Reimold et al. (1990)	Pseudotachylites from widely spaced localities	1440 ± 80 1390 ± 80 1330 ± 40 1090 ± 100	^{40}Ar-^{39}Ar; whole rock	Formation or resetting ages ?
VREDEFORT DOME	Allsopp et al. (1991)	Rietfontein alkali granite	1162.6 ± 28.8, 1166.2 ± 9.7, 1441.2 ± 21.3, 1472.2 ± 10.7	^{40}Ar-^{39}Ar; hornblende, biotite, whole rock	Several partial resetting plateaux ages (repeated partial overprinting activity)
		Granophyre dyke	1206.4 ± 29.4, 1281.8 ± 18.4, 1316.9 ± 15.5, 1345.8 ± 11.7, 1415.5 ± 19.9, 1458.0 ± 8.1	^{40}Ar-^{39}Ar; biotite, whole rock	Several partial resetting plateaux ages (repeated partial overprinting activity)
VREDEFORT DOME	Spray et al. (1995)	Coesite-/ stishovite-bearing pseudotachylites / Farm Broodkop	1227 ± 17, 1337 ± 12, 1357 ± 12, 1401 + 27, 1407 ± 14, 1413 ± 22, 1437 ± 9	^{40}Ar-^{39}Ar; whole rock	Resetting ages of older pseudotachylites and formation ages of younger endogenic pseudotachylites
VREDEFORT DOME	Reimold et al. (1995)	"Epidiorites" from collar region	~1400 - 900	^{40}Ar-^{39}Ar; plag., amph.	Partial thermal resetting ages/events
OFS GOLDFIELD	Reimold et al. (1994)	Basal Reef / F.S.G. Goldmine	1035 ± 50	Xe_s-Xe_n; uraninite	Partial thermal resetting age/event
OFS GOLDFIELD	Friese (in prep.)	Platberg Group-age tectonites / H.J. Joel Goldmine	~1365, ~1200	^{40}Ar-^{39}Ar; whole rock	Partial thermal resetting ages/events
KLERKSDORP GOLDFIELD	Armstrong et al. (1991)	Crown lava Syferfontein volcanics	1066 ± 31 1201 ± 161	U-Pb; whole rock U-Pb; whole rock	Thermal overprinting age/event Thermal overprinting age/event
KLERKSDORP GOLDFIELD	Trieloff et al. (1994)	Ventersdorp Contact Reef / Vaal Reef Goldmine	~1380	^{40}Ar-^{39}Ar; whole rock	Low temperature thermal resetting age/event

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Table 2 (continued)

CARLETONVILLE GOLDFIELD	Reimold et al. (1994)	Ventersdorp Contact Reef / Kloof Goldmine	1260 ± 20	Xe_s-Xe_n; uraninite	Partial thermal resetting age/event
	Trieloff et al. (1994)	Pseudotachylites from the Ventersdorp Contact Reef / Elandsrand Goldmine	~1280	^{40}Ar-^{39}Ar; whole rock	Low temperature partial thermal resetting age/event
CENTRAL RAND GOLDFIELD	Armstrong et al. (1991)	Klipriviersberg Group lavas	936 ± 154, 1001 ± 139, 1253 ± 34	U-Pb; zircon	No interpretation given
	Reimold et al. (1994)	Main Reef / Sub Nigel Goldmine	1120 ± 50	Xe_s-Xe_n; uraninite	Partial thermal resetting age/event
BUSHVELD COMPLEX	Burger & Walraven (1977)	Upper Zone / western Bushveld	1285 ± 44	^{40}Ar-^{39}Ar; whole rock	Metamorphic overprint event
	Coertze et al. (1978)	Ferrogabbro of Upper Zone Klipkloof and Klipvoor granites	1216 ± 44 1400 ± 190	^{40}Ar-^{39}Ar; whole rock U-Pb; zircon	Partial resetting age/geol. event Controversial age - no interpretation given
	Walraven & Hattingh (1993)	Pegmatite near the upper contact between the Bushveld granites and overlying roof rocks / near Zaaiplaats and Rooiberg	~1200	Rb-Sr; potassium feldspar	Post-crystallization strong isotopic disturbance
WITS BASIN HINTERLAND	Robb et al. (1992a)	Granites from western hinterland of Witwatersrand Basin	~1089	U-Pb; zircon	No interpretation given
	Robb et al. (1992b)	Basement granites east of the OFS Goldfield near Kroonstadt	1280 ± 1	U-Pb; kerogen	No interpretation given

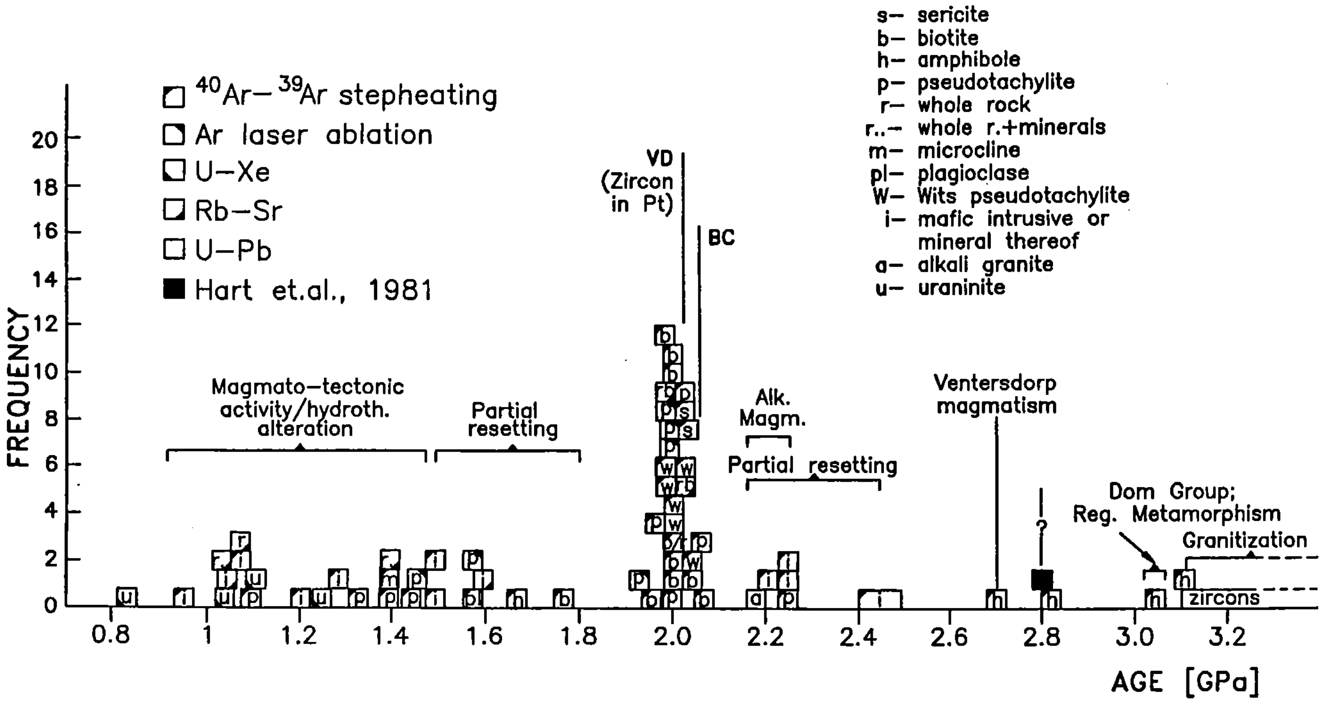

Fig. 23a. Summary of resetting ages for the time interval 1450-1000 Ma (Table 2), portrayed in comparison with other recent geochronological data obtained from the Vredefort Dome and surrounding Witwatersrand Basin (modified after Reimold et al., 1995).

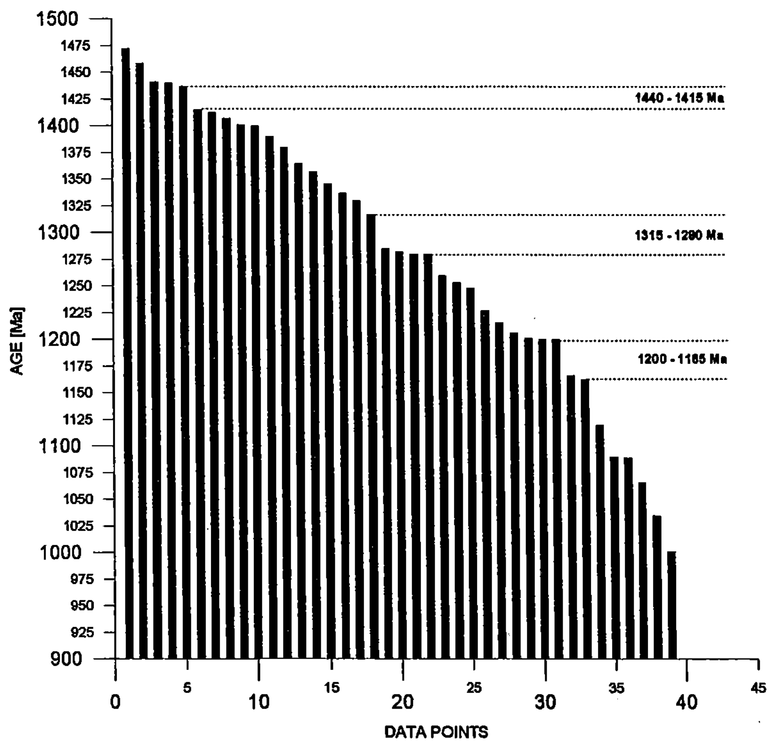

Fig. 23b. Detailed representation of the summarised resetting ages for the time interval 1450-1000 Ma (Table 2), indicating three distinct periods of relative lower resetting activity.

MESOPROTEROZOIC MAGMATIC ACTIVITY WITHIN THE KAAPVAAL CRATON

During the Mesoproterozoic, igneous activity occurred around the margins of the Kaapvaal Craton, and a number of alkaline and tholeiitic igneous intrusions were emplaced into the craton (Figs. 24 & 26). Intracratonic intrusions of tholeiitic affinity include the Timbavati gabbros (SACS, 1980; Bristow et al., 1982) and the Trompsburg intrusion (Davies et al., 1970). A suite of complexes of alkaline character, many containing carbonatite, intruded mainly in the region of the Bushveld Complex, but they also include the Glenover complex in the northwestern Transvaal, and the Stukpan complex near Bothaville in the Orange Free State (Snelling, 1963; Oosthuyzen & Burger, 1964; Verwoerd, 1967; Verwoerd et al., 1989; Nelson et al., 1988; Harmer, 1985, 1993) (Fig. 26). Also included within this Mesoproterozoic suite are the group of kimberlites near Pretoria (Kramers & Smith, 1983; Richardson, 1986; Phillips et al., 1989).
Table 3 summarises the available geochronological data of the Mesoproterozoic alkaline/peralkaline and mafic magmatic activity within and around the Kaapvaal Craton, following the deposition of the Waterberg Group sediments up to the initiation of Karoo sedimentation in the Palaeozoic.

The period 1420-1200 Ma marks the initiation and early phases of the approximately 1000 Ma Kibaran orogeny which produced the Namaqua-Natal metamorphic provinces along the southern and western margins of the Craton (e.g. Matthews, 1972, 1981; Reid, 1979; Barton & Burger, 1983; Hartnady et al., 1985; Stowe, 1986; Joubert, 1986; Eglington et al., 1989; Jacobs et al., 1993; Thomas, 1989; Thomas et al., 1994). The close temporal association between the alkaline magmatism within and along the margin of the Kaapvaal Craton and the Kibaran (Grenville) orogeny, raises the question of a possible geodynamic relationship between anorogenic alkaline magmatism within the craton and intense orogenic activity, mainly concentrated around its margin.

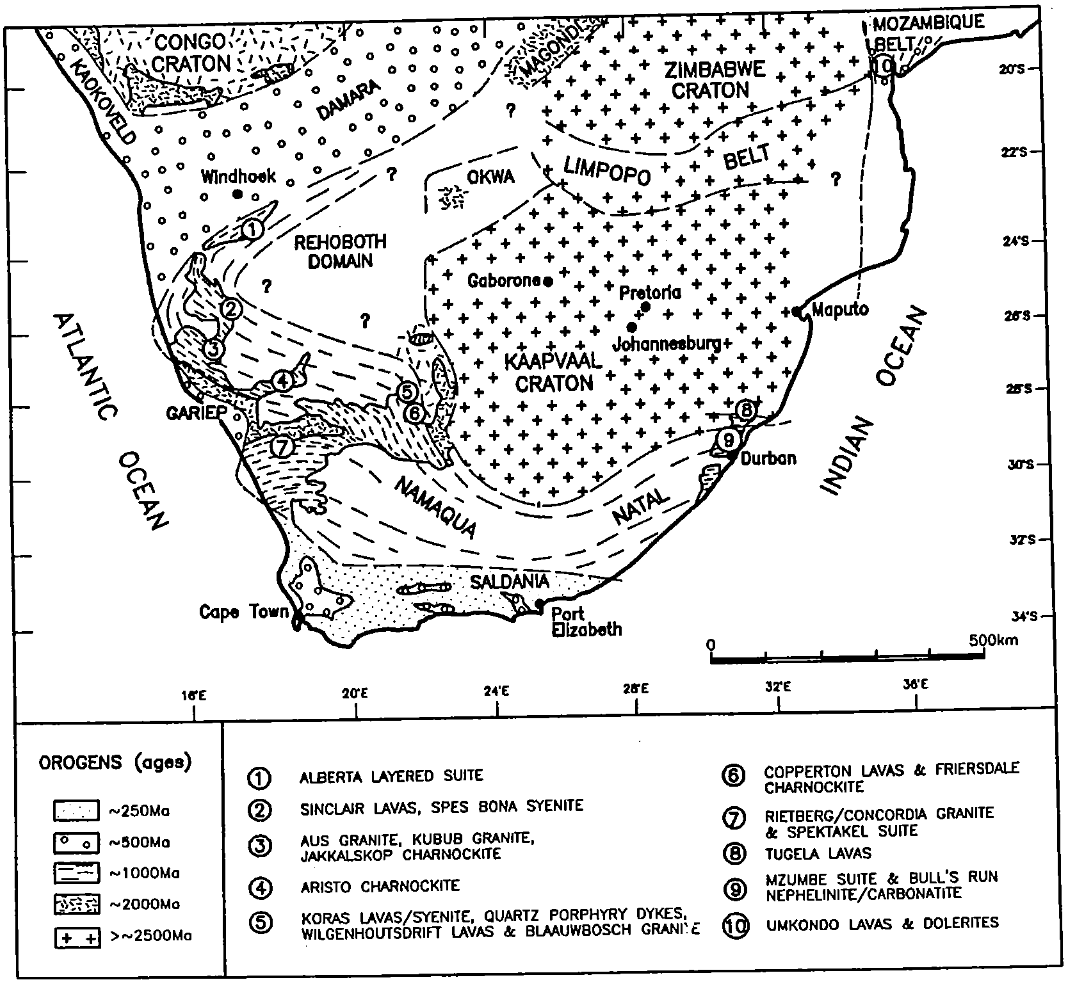

Fig. 24. Spatial distribution of Mesoproterozoic magmatic lithologies around the Kaapvaal Craton.

Table 3. Geochronological summary of Mesoproterozoic alkaline/peralkaline and mafic magmatism pertinent to the Kaapvaal Craton

COMPLEX, UNIT	AGE (Ma)	METHOD	REFERENCE
Trompsburg Complex	1372 ± 142	Rb/Sr	Davies et al. (1970)
Brandfort Gabbroid	post-Ventersdorp meso-Proterozoic	geol. interpretation geol. interpretation	Cousins (1959) Friese (this study)
Stukpan Complex carbonatite-mica	1354 ± 11 1345 ± 13	Rb/Sr Rb/Sr	Verwoerd et al. (1989) Harmer (1993)
Anna's Rust Sill gabbro	1054 ± 13 1068 ± 7	Rb/Sr Ar/Ar	Pybus et al. (1994) Reimold et al. (1995)
Premier Kimberlite Group (mineral-whole rock) (di, garn megacryst)	1198 ± 14 1202 ± 72 1180 ± 30	Ar/Ar Pb/Pb Rb/Sr, Sm/Nd	Phillips et al. (1989) Kramers & Smith (1983) Richardson (1986)
Timbavati Complex gabbro	1072 ± 4, 1123 ± 5 1454 ± 59	Ar/Ar Rb/Sr	Burger & Walraven (1979, 1980) Bristow et al. (1982)
Spitskop Complex Rietfontein nepheline syenites Ijolites Ijolites & nepheline syenites	 1326 ± 35 1357 ± 67 1341 ± 37	 Rb/Sr Rb/Sr Rb/Sr	 Harmer (1993) Harmer (1993) Harmer (1993)
Pilanesberg Complex green foyaite "foyaite" biotite	 1193 ± 98 1250 ± 60	 Rb/Sr K/Ar	 Harmer (1993) Snelling (1963)
Pienaars River Complex Leeuwfontein Leeuwkraal Rondawel Franspoort, Buffelsdrift, Klipdrift, Haakdoornfontein Roodeplaat, Saltpan Crater	 1430 ± 50 1420 ± 70 1334 ± 26 1361 ± 142 1306 ± 11 1342 ± 11	 Rb/Sr U/Pb Rb/Sr Rb/Sr Rb/Sr Rb/Sr	 Harmer (1985) Oosthuyzen & Burger (1964) Harmer (1985) Harmer (1985) Harmer (1985) Brandt et al. (in press)
Kruidfontein Complex carbonatite dykes	 1246 ± 26	 Sm/Nd	 Harmer (1993)
Goudini Complex carbonatite	 1190 ± 80	 Sm/Nd	 Nelson et al. (1988), Harmer (1993)
Glenover Complex carbonatite	 1000 ± 200	 Pb/Pb	 Verwoerd (1967)
Venterspost-Gemspost Dyke	1330 ± 80 1302 ± 78	Rb/Sr	Van Niekerk (1962) recalc. by Anhaeusser & Burger (1982)
Klerksdorp Dyke System	Pilanesberg-age	geol. interpretation	Antrobus et al. (1986), Verwoerd (1993)
Robinson Dyke	1290 ± 180 1263 ± 176	Rb/Sr	Schreiner & Van Niekerk (1958) recalc. by Anhaeusser & Burger (1982)
East Rand Dyke System	1120 ± 45	K/Ar	McDougall (1963)
Nooitgedacht, Tweerivier, Bulhoek and Derdepoort Complexes carbonatites	1269 ± 171	Sm/Nd	Harmer (1993)
Bull's Run Complex carbonatite	 1140 ± 35, 1100 ± 40	 U/Th/Pb	 Nicolaysen & Burger (1965)
Dyke swarm in SE Botswana	Pilanesberg-age	geol./geophys. interpretation	Emerman (1991)

A diagrammatical presentation of the summarised geochronological formation ages for various alkaline igneous complexes (Fig. 25), indicates three periods of relative magmatic quiescence within the Kaapvaal Craton during the time-interval 1450-1000 Ma. One predominant hiatus of approximately 50 Ma occurs between 1250-1200 Ma, and possibly two minor developed breaks occur between 1180-1140 Ma and 1420-1370 Ma where no alkaline igneous activity has been recognised.

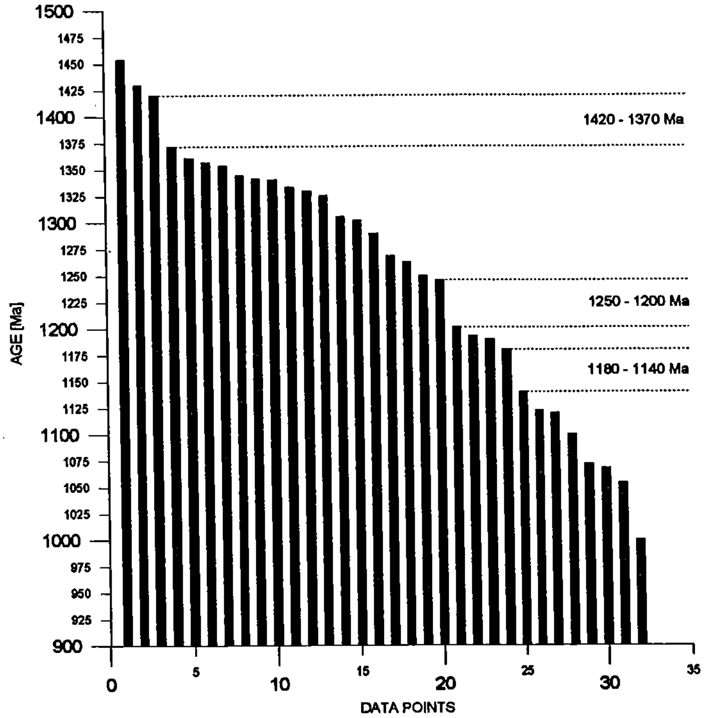

Fig. 25. Diagrammatical illustration of formation ages of various alkaline igneous lithologies within the Kaapvaal Craton, as summarized in Table 3.

Spatial distribution of the alkaline complexes and tectonic control

To date, it is widely accepted that alkaline complexes are generally related to zones of weakness within the lithosphere, corresponding in the continental environment to:

- well-defined rift zones,
- major lineaments,
- intersections of major lineaments and/or fault systems, or
- major lithospheric domes.

Woolley (1989) pointed out that less than half of the known carbonatite occurrences are situated in or near recognizable graben structures (e.g. East African Rift, Rhine Graben), with the remainder often being associated with major lineaments (e.g. mid-Zambezi-Luangwa Lineament of Zambia, Tanzania and Kenya) or lithospheric structural domes (e.g. Rungwe Dome of Angola, Richat Dome of Mauritania, Napak Dome of Uganda and Tundulu Dome of Malawi). Concentrations of alkaline magmatism occur also where lineaments and/or fault systems cross each other (e.g. Chilwa Province in Malawi).
Further, Woolley (1989) and Bailey (1993) presented evidence to show that in many cases a close temporal and spatial relationship exists between alkaline igneous complexes/carbonatite emplacement and orogenic activity and that although "few carbonatites are located within the orogenic belts themselves (e.g. Bull's Run Complex of Natal), many occur in zones, up to several hundred kilometres wide, adjacent to the belts(e.g. North Atlantic area)".
This observation is "diametrically opposed to the generally accepted view that carbonatites are characteristic of stable continental, intra-plate areas" (Woolley, 1989; p.32).

On the basis of the tectonic setting, Fitton & Upton (1987) have suggested a classification of the occurrences of alkaline igneous rocks into three categories, namely:

1. Continental rift valley magmatism (e.g. East African Rift),
2. oceanic and continental intraplate magmatism without clear tectonic control (e.g. Hawaiian islands), and
3. alkaline magmatism related to subduction processes (e.g. Trans-Pecos Province of Texas).

With regard to the Kaapvaal Craton, various authors have previously recognised a close relationship between major crustal flexures and emplacement of alkaline igneous rocks and carbonatites in southern Africa (Verwoerd, 1967, 1993; Ferguson, 1973; Cornelissen & Verwoerd, 1975, Pretorius, 1979, etc.). On the basis of this observation, these authors developed various, quite diverging structural models, with the focus on tectonic control of the alkaline magmatism.
Ferguson (1973) related Pilanesberg magmatism to a major northwest-trending Early Proterozoic antiform which included the Johannesburg Dome, the Crocodile Dome, and the Makoppa Dome.
On the other hand, Verwoerd (1967) viewed all the Transvaal carbonatites (except Glenover Complex) to follow an east-west trend. A third possible structural control of alkaline magmatism in the Transvaal is a northnortheast-trending abyssal fracture taken advantages of by the late-Archaean Great Dyke/Zimbabwe, the Bushveld Complex, and the Trompsburg Intrusive (Cousins, 1959; Ortlepp, 1959; Verwoerd, 1993).

In the discussion about the obvious tectonic control on the alkaline magmatism in general, and the Mesoproterozoic alkaline magmatism within and around the Kaapvaal Craton in particular, it is important to recognize the overall geodynamic processes operating around and within the craton at that time.
In this regard, Cooper (1990) pointed out the general and worldwide recognition, that the emplacement of a broad variety of anorogenic intrusives occurs episodically in response to crustal extension, and include mafic dyke swarms, layered mafic complexes, carbonatites, alkaline and peralkaline granitoids, and the anorthosite suite, as well as coeval volcanism.

The occurrence of Mesoproterozoic layered mafic intrusives (e.g. Timbavati, Alberta, Trompsburg complexes), mafic dyke swarms (e.g. post-Waterberg diabases, Kanye, Umkondo and Guruve dolerites), alkaline/peralkaline magmatism (Table 3), as well as major volcanic episodes (Sinclair and Koras Groups, Copperton, Wilgenhoutsdrif, Umkondo and Nuckopf Formations) in southern Africa, indicates an extensive period of major tectono-magmatic activity in the Mesoproterozoic between approximately 1450-1000 Ma within and around the Kaapvaal Craton. Within this time interval, Cooper (1990) identified two major extensional periods between approximately 1470-1360 Ma and 1180-1040 Ma.

Based on the above summarized geochronological data for resetting and magmatic events within the Kaapvaal Craton, the time intervals proposed by Cooper (1990) were slightly refined and adjusted to two major magmato-hydrothermal events within the Kaapvaal Craton, evident between approximately 1450-1250 Ma and 1200-1000 Ma.
Within these two major cycles of magmatic activity, possibly one minor developed hiatus within each of the main cycles is evident between 1420-1370 Ma and 1180-1140 Ma (Fig. 25). A comparatively similar pattern is evident from the diagrammatical illustration of resetting ages for the central Kaapvaal Craton (Fig. 23b), with the identification of two main periods of increased hydrothermal resetting activity between approximately 1450-1315 Ma and 1280-1000 Ma, and one minor developed break with a relatively lower hydrothermal resetting rate within each main cycle between 1440-1415 Ma and 1200-1165 Ma.

Comparing the position of the various periods of increased activity and relative quiescence, identified individually for magmatic and hydrothermal processes within the craton with each other, it becomes evident, that the inferred time-intervals of both groups are similar in terms of duration, but differ significantly with regard to their temporal position (Figs. 23b & 25).
In this respect, the individual periods of relatively increased/decreased magmatic activity appear to be outlasted by the identified time-intervals of relative higher and lower hydrothermal activity. This distinct trend indicates simultaneous magmatic and hydrothermal activity for most of the time, but with the hydrothermal alteration processes being time-delayed and extending beyond the periods of magmatic activity.

A temporal and spatial subdivision of the above mentioned Mesoproterozoic magmatism in southern Africa into these two major extensional events, is illustrated in Table 4.

Table 4. Two identified phases of Mesoproterozoic rifting within southern Africa, their associated magmatic lithologies, and the location of the later relative to the Kaapvaal Craton

LOCATION	EXTENSION I (1450-1250 Ma)	EXTENSION II (1200-1000)
OFF - CRATON	Copperton Lavas	Koras Lavas & Quartz-Porphyry Dykes, Koras Syenite
	Wilgenhoutsdrif Lavas	Mzumbe Suite
	Sinclair Lavas, Spes Bona Syenite	Blaauwbosch Granite
	Tugela Lavas	Bull's Run Nepheline Syenite/Carbonatite
		Kanye Dolerites
		Umkondo Lavas & Dolerites
		Spektakel Suite
		Rietberg/Concordia Granite
		Friersdale Charnockite
ON - CRATON	Trompsburg Layered Suite	Premier/National Kimberlite Group
	Alberta Layered Suite	Pilanesberg Complex
	Timbavati Gabbro	Goudini Complex
	Stukpan Complex	Glenover Complex
	Spitskop Complex	Anna's Rust Gabbro
	Pienaars River Complex	Nooitgedacht, Tweerivier, Bulhoek & Derdepoort Complexes
	Venterspost-Gemspost Dyke & Klerksdorp/Carletonville Dyke System	Post-Waterberg Dolerites
	Brandfort Gabbroid	Robinson Dyke & East Rand Dyke System
	Morokweng Complex?	Dyke Swarm in SE Botswana

It is of interest to compare the spatial distribution of Mesoproterozoic igneous lithologies within and around the Kaapvaal Craton with the position and orientation of major lithospheric lineaments.
Figure 26 illustrates the location of all above mentioned igneous lithologies (Table 4) in relationship to the fundamental tectonic grain of the craton, individually for each of the two identified extensional phases during the Mesoproterozoic time interval 1450-1000 Ma.
It is clearly evident, that magmatism during the Mesoproterozoic was concentrated along the margins of the Kaapvaal Craton, and that intracratonically, pre-existing, deep-rooted major lineaments represent primarily reactivated zones of weakness for ascending alkaline magmas.
The major lithostratigraphic lineaments (Fig. 26) are interpreted as palaeosuture zones between individual Archaean terranes or subdomains within the craton (De Wit et al., 1992; Friese, in prep.).

Another centre of anorogenic, intracontinental alkaline magmatism within the Kaapvaal Craton, namely the carbonatitic dykes and alkaline complexes of the Pilanesberg Province and East Rand area, is closely associated with a NW trending system of graben-forming faults (e.g. the Rustenburg Fault, Brits Graben, etc.), situated within the western sector of the Bushveld Complex, as well as with a major lineament (Pilanesberg Lineament), cross-cutting the "Pilanesberg Graben System" in a NE/SW-trending direction.

In addition, within the Carletonville and Klerksdorp goldfields, to the south of the Pilanesberg Alkaline Province, an older system of north-south trending carbonatite dykes (e.g. Venterspost-Gemspost Dyke) appears not to be closely associated with any pre-existing fault systems within the Witwatersrand Basin, but might be related to the Stukpan Complex (Fig. 26) or an unexposed alkaline-carbonatitic complex of the same age group (Verwoerd, 1993). The older age of approximately 1300-1330 Ma for the Venterspost-Gemspost dyke system relative to the magmatism within the "Pilanesberg Graben System" is confirmed by the fact, that the dyke system experienced a finite sinistral strike-slip displacement of up to 10 km along the Rustenburg Fault (Geol. Sheet 2626 West Rand, 1:250000; Vermaakt & Chunnett, 1994, p. 118).

The temporal separation of the Mesoproterozoic alkaline magmatic complexes on the Kaapvaal Craton into two groups (Table 4) finds further support by the fact, that the older generation (1450-1250 Ma) is exclusively situated along the proposed major lineaments, whereas the younger group (1200-1000 Ma) appears to be closely associated with the "Pilanesberg Graben System".
An exception to this recognized trend are the sill- and dyke-like gabbros of the Timbavati Complex, situated parallel to the eastern margin of the Kaapvaal Craton and which cross-cut several major easterly trending lineaments (Fig. 26), as well as the Anna's Rust sill-like gabbro that outcrops within the Vredefort Dome. The Anna's Rust Complex belongs to the younger group of alkaline intrusives, which occur outside the "Pilanesberg Graben System", but in close vicinity to the Sugarbush Lineament (Fig. 26).

A circular magnetic feature approximately 70 km in diameter, situated near Morokweng in the North West Province, the so-called Morokweng Ring Structure (Fig. 27), has been interpreted by Andreoli et al. (1995) as the relic of a large Mesoproterozoic meteorite impact structure. The Structure is composed of a suite of charnockitic rocks, predominantly charnoenderbite and jotunite (Andreoli et al., 1995).
The position of the structure directly along a major interpreted lineament (Marokweng Lineament; Friese, in prep.), the close spatial relationship to a major dome structure (Ganyesa Dome), as well as obtained Rb/Sr whole rock-errorchron and Sm/Nd model ages for five charnoenderbite borehole samples, yielding 1.4 $\pm$ 0.2 Ga and a range between 3.0 Ga (T_{chur}) and 3.2 Ga (T_{DM}) respectively (Andreoli et al., 1995), support an alternative interpretation that the Morokweng Ring Structure is an Archaean igneous complex with a Mesoproterozoic alkaline magmatic component.

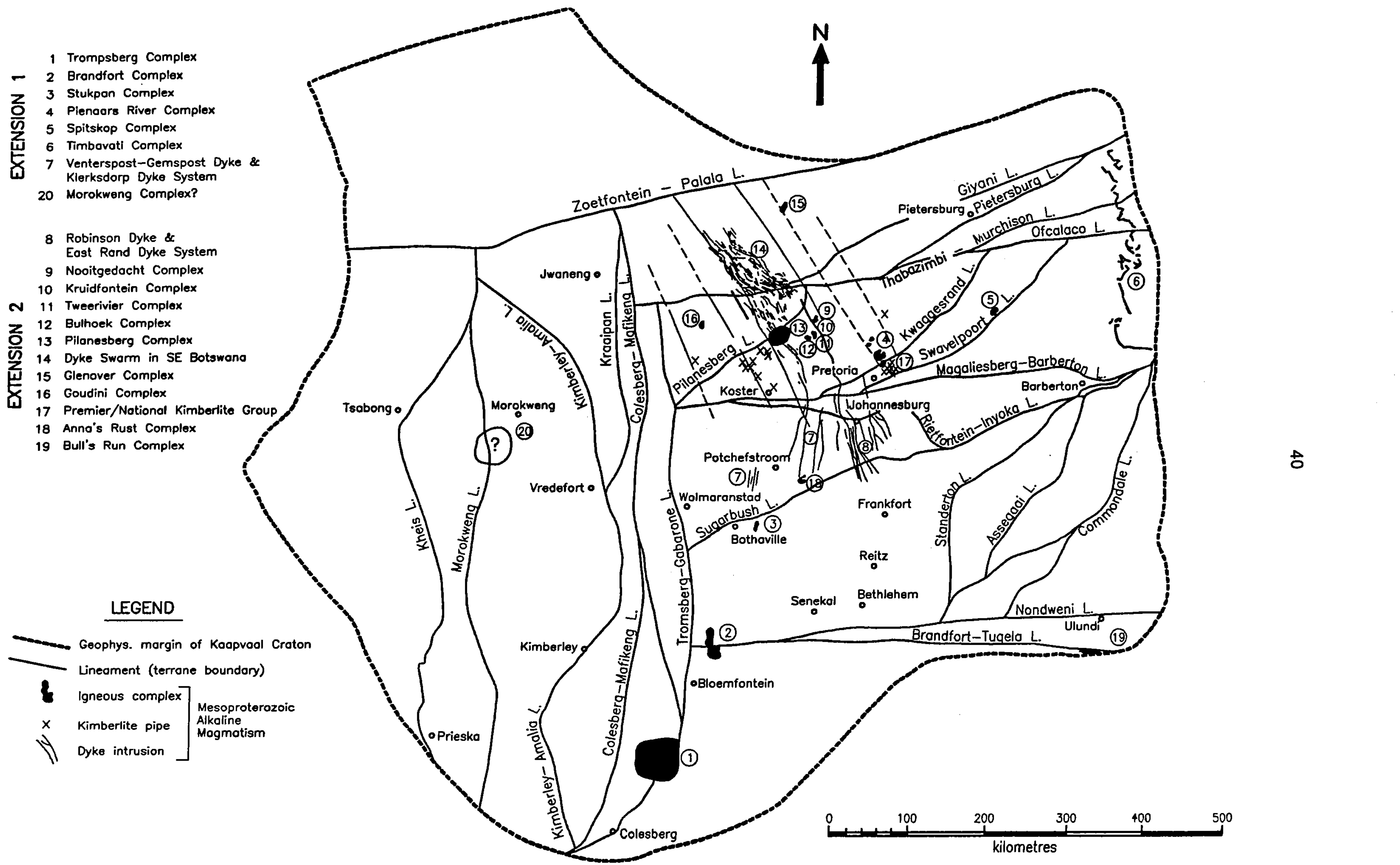

Fig. 26. Spatial distribution of Mesoproterozoic magmatism during two separate extensional phases at 1450-1250 Ma and 1200-1000 Ma, evident within the Kaapvaal Craton, and in relationship to the inferred position of Archaean crustal subdomains (terranes) and suture zones within the craton (after Friese, in prep.).

Petrogenesis of alkaline magmatism

To date, it is universally accepted that kimberlites, carbonatites and other volatile-rich alkaline magmas are products of deep-mantle plumes, either derived directly by partial melting (Dawson, 1971; Michell & Crockett, 1971; Mysen & Boetcher, 1975) of a metasomatised mantle and lower crust (Woolley & Jones, 1987; Bailey, 1987), or through differentiation in form of fractional crystallization or liquid immissibility processes which operated on a mantle-derived magma at higher levels in the crust (O'Hara & Yoder, 1967; MacGregor, 1979; Macdonald, 1987). Additional processes considered to date to have produced the diversity of compositions in these saturated and undersaturated magmas, are crustal contamination of mantle derived magmas and magma mixing (Macdonald, 1987; Downes, 1987).

World-wide observations and the above documented findings from the Kaapvaal Craton have clearly shown, that in most cases the sites of intracontinental anorogenic alkaline magmatic activity is governed by pre-existing lines of intracrustal weakness (e.g. Watson, 1986; Bailey, 1993), and not simply the rise of mantle plumes (Fitton & Dunlop, 1985).

Cooper (1990) proposed that the occurrence of mantle plumes and continental hot spots seem to be a consequence (Hamilton, 1988) rather than the cause of lithospheric extension (Burke & Dewey, 1973). Support for this interpretation is provided by the lower-order periodicity of volcanism in continental rifts (Baker et al., 1972) because constraints imposed by heat conduction make episodic behaviour in mantle diapirs unlikely (Gass, 1975).

Accepting tectonic activity within the lithosphere to be the controlling factor for these mantle processes, Bailey (1993) raised the question, that either melts are omnipresent near the base of the lithosphere and simply await for channel openings to appear, or that melt generation is triggered by stress release in the overlying lithosphere. Since melt generation cannot be initiated by local heating, and the fact, that episodic magmatism along pre-existing zones of crustal weakness is widely scattered across the African plate during the same time interval, led Bailey (1993) to the conclusion, that the crucial factor in magma genesis is the focusing of fluid release from the deep mantle, whenever old lesions are re-opened through the lithosphere (decompressional melting). This indicates minimal inertia in the magma generating systems which is revealed in the ready response to plate-wide triggering (and shut-down) mechanisms.
In summary, magmatology, the lithospheric regime, episodicity and repetition of magmatic activity, thus form a coherent pattern consistent with periodic reactivation of the plate by external forces (Bailey, 1993).

With regard to the Mesoproterozoic alkaline magmatic activity on and around the Kaapvaal Craton, it can be concluded on the basis of the above spatial, temporal and petrogenetic considerations, that the magmatism was not controlled by deep mantle plumes impinging on the base of the lithosphere, but rather by craton-wide operating lithospheric processes, which in turn were triggered by the Kibaran (Grenville)-age orogenic activity along the western and southern craton margins.
The collisional and accretional processes along the craton margin manifested themselves in form of two individual major rifting events, which effected the entire region of the Kaapvaal Craton during the time-intervals 1450-1250 Ma and 1200-1000 Ma, as evident by the substantial regional extent of magmatic activity on and off the craton during these two time-intervals.

Support for the proposal of two distinct generations of alkaline magmatism within the craton during the Mesoproterozoic is provided by the following aspects:

1. Sr and Nd isotopic data differ markedly between the silicate and carbonatite components of the Spitskop Complex. These data are not compatible with models which derive carbonatites as late stage differentiates of a carbonated silicate magma or through liquid immiscibility from nephelinitic or phonolitic melts (Harmer, 1993). Further, new data from the Pilanesberg Suite complexes show that carbonatites from most of the complexes have isotopic compositions which are similar to the variations established for world carbonatites, with the exception of the carbonatites from the Spitskop and Stukpan complexes, deviating from this field (Harmer, 1993).
   It therefore seems likely that separate and different parent magmas were involved in the formation of both, Stukpan and Spitskop complexes, compared to the younger generation of alkaline igneous rocks emplaced during the second extensional phase between approximately 1200 and 1000 Ma.

2. Differences with regard to the tectonic style between the two extensional events and associated alkaline magmatism is evident, with the first extensional phase being characterised primarily by the reactivation of pre-existing intracratonic suture zones and the emplacement of alkaline igneous complexes along or in close vicinity to them. Whereas the younger rifting event saw the formation of the major "Pilanesberg Graben System" and accompanying igneous activity, situated in the northern portion of the Kaapvaal Craton.

3. A more speculative, but possible difference and similarity between both age groups of alkaline magmatism might exist in terms of total chemical composition and compositional trend respectively.
   Both alkaline magmatic groups seem to be characterised mainly by olivine-gabbros, pyroxenite ijolites, nepheline syenites/foyaites (phonolites), gabbros, anorthosites/syenites (trachyte) and carbonatites, but with the younger age group exhibiting, in addition, kimberlites and a relatively higher proportion of carbonatites.
   Also throughout the entire time interval of each age group, as well as within each individual alkaline complex itself, there appears to exist a common general compositional trend, from initially ultramafic/mafic magmas to more felsic composition at a later stage, or else from undersaturated to saturated igneous lithologies.

4. The similar periodicity of episodes with relative increased or decreased magmatic activity compared to hydrothermal activity within the Kaapvaal Craton (Figs. 23b & 25), supports the interpretation of two major magmato-hydrothermal episodes within the craton between approximately 1450-1250 Ma and 1200-1000 Ma. These two magmatic episodes are separated by a major hiatus of about 50 Ma, and both internally interrupted by an additional minor period of relative quiescence between 1420-1370 Ma and 1180-1140 Ma, respectively.

It is stressed, that the interpretations and conclusions with regard to the Mesoproterozoic tectono-magmatic evolution within and around the Kaapvaal Craton documented above, are based on the available geochronological data set. As age reliability is a crucial issue to any geological modelling, in this study especially with regard to the validity of the identification and separation of the Mesoproterozoic alkaline magmatic activity into two major individual age groups, more precise age determinations on a greater variety of lithologies are necessary.
Nevertheless, combined geophysical and geological studies alone provide enough evidence to justify the interpretation that the Mesoproterozoic anorogenic alkaline magmatism on the Kaapvaal Craton evolved during two individual phases, both extending over a period of approximately 200 Ma and separated by possibly 50 Ma of relative magmatic quiescence.

GEODYNAMIC MODEL FOR KIBARAN (GRENVILLE)-AGE TECTONO-MAGMATIC PROCESSES WITHIN THE CENTRAL KAAPVAAL CRATON

The identification of north- to northwest-directed compressional tectonics within the central Kaapvaal Craton from an analysis of structural, isotopic and geophysical data, that are available for the Witwatersrand Basin and surrounding areas, requires a synthesis of the entire data set into a time-constraint geodynamic model. The model has to be applicable to the entire region of the Kaapvaal Craton, as geochronological data have provided conclusive evidence for craton-wide magmato-thermal activity during the mid-Proterozoic, indicating the involvement of large-scale lithospheric and asthenosperic processes at that time.
Further, due to the time-equivalence of the Mesoproterozoic magmato-thermal activity within the Kaapvaal to the collisional and accretional tectonic activities during the Kibaran (Grenville) orogeny along the southern margin of the Kaapvaal Craton (Namaqua-Natal mobile belt), the model must have also the prime objective, to incorporate the relevant structural and kinematic features observed within the Witwatersrand Basin and environs, with those evident in the Namaqua-Natal orogenic belt itself, in order to provide a satisfactory explanation for the timing and spatial distribution of the accompanying magmato-thermal activity within and around the Kaapvaal Craton.

In this study, emphasis has been placed on the correlation of compressional tectonics evident within the Witwatersrand Basin, with those related to accretional tectonics primarily within the eastern sector of the

Namaqua-Natal mobile belt (Natal Metamorphic Province), due to the apparent orientational and temporal compatibility of structural features within both regions.
Nevertheless, reference will also be made to the time-equivalent tectono-magmatic events evident from the western Namaqualand Province, but are not envisaged to have had a significant influence on the region of the central Kaapvaal Craton, primarily referred to in this study.

Before arriving at a proposed craton-wide geodynamic framework, a tectonic model for the Witwatersrand Basin will be outlined, which attempts to combine all reported kinematic and structural features with the results from seismic, gravimetric and aeromagnetic surveys available for this area, and reported earlier.

Tectonic model for the Witwatersrand Basin and environs

Structural features, identified in various areas of the Witwatersrand Basin to be post-Transvaal Sequence in age, and interpreted to have formed in response to a northwest-southeast oriented compressional stress field, were summarised above and are graphically illustrated in Figure 27. In addition, the results from a reinterpretation of geophysical data were included in Figure 27.
On the basis of this data set alone, it is possible to divide the area of the preserved Witwatersrand Basin into three individual main structural domains, each exhibiting a contrasting tectonic style (Fig. 28).

Within the southwestern and northeastern sectors of the basin, namely the area covering the Orange Free State Goldfield, as well as the entire northern and northeastern basin margin extending from the Carletonville Goldfield and West Rand to the Evander and South Rand goldfields, transpressional tectonics dominate. In these two structural domains, ductile oblique-reverse to strike-slip movements are evident primarily on pre-existing fault and bedding planes.
Despite a common transpressional environment, both structural domains display opposite kinematic vectors. The southwestern domain (OFS Goldfield) is characterised by the development of transpressional structures activated in a north/south-trending sinistral shear zone. The northeastern domain predominantly shows kinematic vectors generated in an east/west-trending dextral transpressional environment.
Within both domains, the transpressional reactivation of pre-existing fault and bedding planes occurs as the dominant structural style. In addition, within both domains, north- to northwest-directed thrusting is subordinately developed.
In complete contrast to these two structural domains, the central part of the Witwatersrand Basin is structurally dominated by the occurrence of northwest- to north-directed thrust tectonics. Thrusts occur mainly in the form of ductile bedding-parallel movements or by the generation of new thrust zones, and characterise the central part of the Witwatersrand Basin as a separate tectonic domain (Fig. 28). The pre-existing fault system within this domain experienced reactivation in form of ductile sinistral or dextral oblique- to strike-slip movements, depending on the strike orientation of the pre-existing faults.

The following basin-wide tectonic model is proposed in an attempt, to explain the orientational divergence of the kinematic vectors within all three structural domains, generated simultaneously during a single tectonic event:

In response to a Kaapvaal Craton-wide northwest-southeast oriented compressional stress field, a mid-basin frontal-ramp system and two oblique-ramp systems, situated at the northeastern and southwestern edge of the frontal-ramp, developed within the area of the presently preserved Witwatersrand Basin.
The generation of oblique-ramp areas during northwest-directed compression, which are characterised by transpressional tectonics along the northern and southern margin of the Witwatersrand Basin, is envisaged as a consequence of the overall pre-existing structural geometry or structural grain of the Witwatersrand Basin:
Representing the erosional remnants of a structural basin, the Witwatersrand Basin exhibits predominantly east-west and north-south trending fault systems in the north and south respectively, which were formed as early as during the deposition of the Witwatersrand Supergroup. Some of them (e.g. Rietfontein and Sugarbush lineaments) may have existed even prior to that. Consequently, this fundamental tectonic grain experienced repeatedly tectonic reactivation, and controlled throughout time the overall tectonic framework of the Witwatersrand Basin and its response to craton-wide changing stress fields.

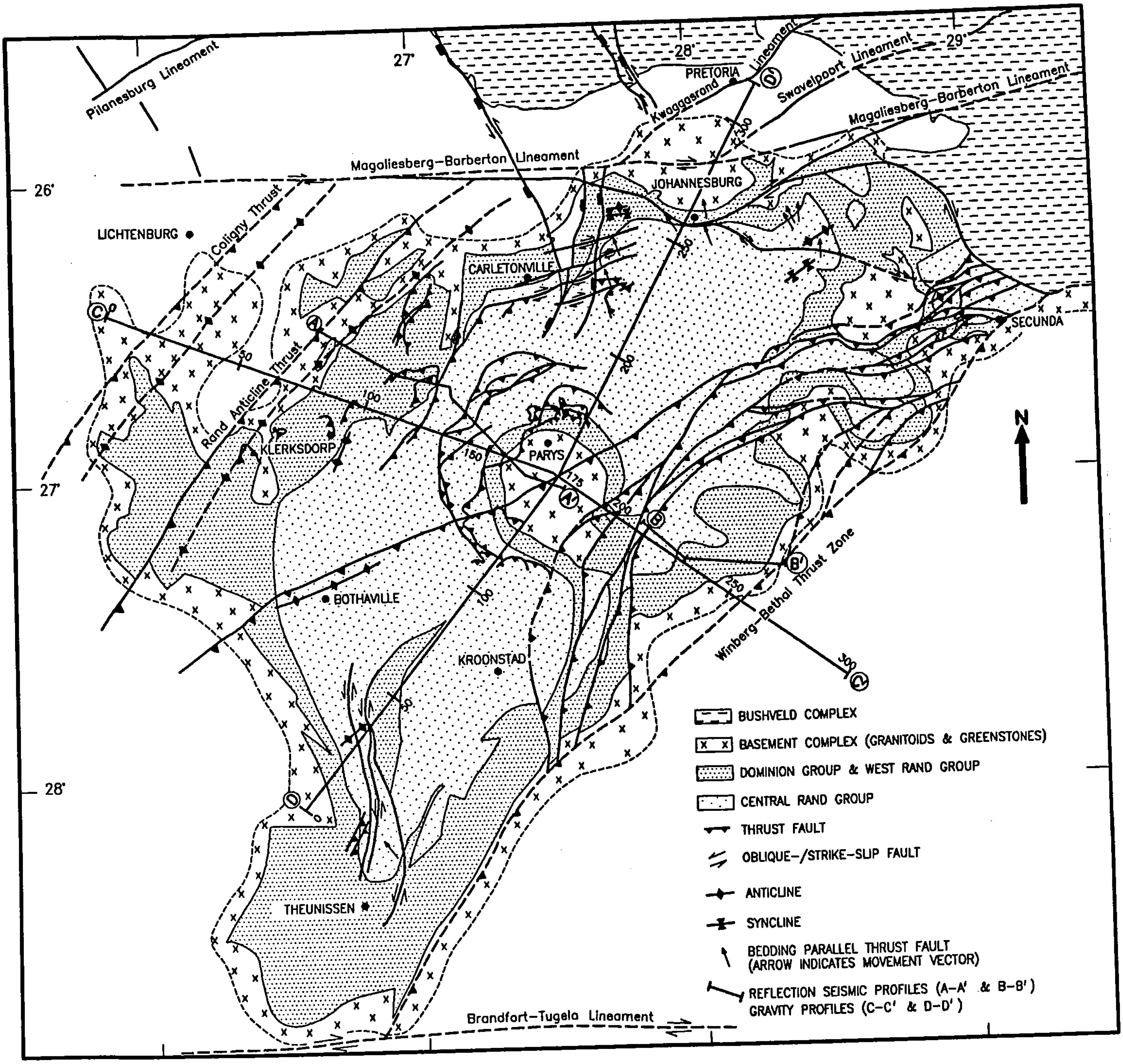

Fig. 27. Graphical illustration of structural features (obtained by field observations and interpretation of geophysical data) within the Witwatersrand Basin of at least post-Transvaal age, interpreted to have formed in response to a NW directed compressional stress field, operating within the central part of the Kaapvaal Craton. The position of the trans-Witwatersrand vibroseis reflection survey line (A-A'), an extension seismic reflection survey line (B-B'; provided with courtesy of JCI Co., Ltd.), and of two gravity modelling traverses (C-C', D-D') is indicated.

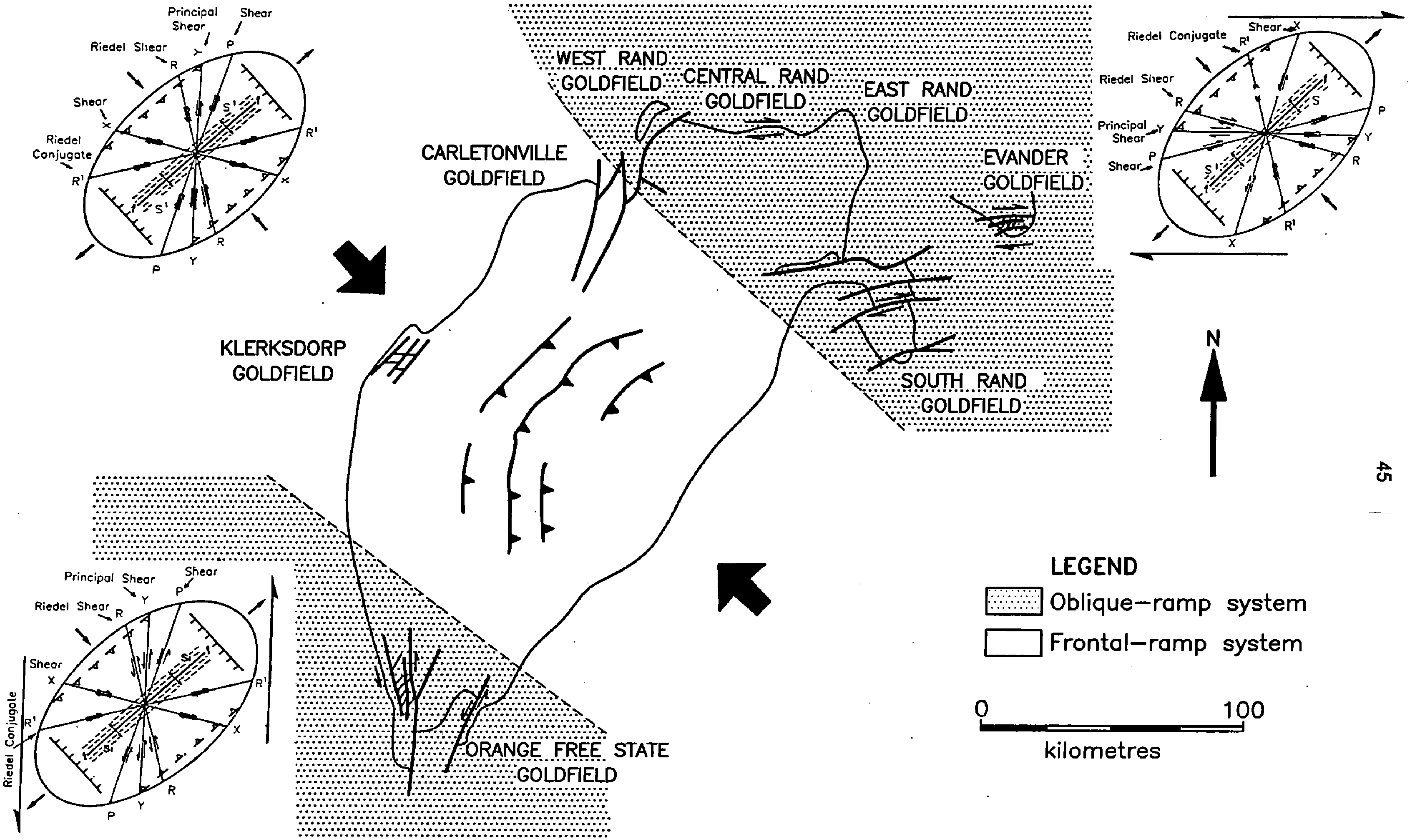

Fig. 28. Schematic diagram illustrating the position of three individual tectonic domains within the limits of the preserved erosional remnant of the Witwatersrand Basin, as well as their identification and function as frontal- and oblique-ramp systems during northwest-directed craton-wide compression in Mesoproterozoic time.

This model would explain satisfactorily the simultaneous generation of transpressional tectonics activated in a north-south trending sinistral shear zone in the Orange Free State Goldfield, those activated in an east-west trending dextral shear zone at the northern margin of the Witwatersrand Basin, as well as predominantly north- to northwest-directed thrusting within the mid-basin frontal-ramp area.

The proposed tectonic model for the Witwatersrand Basin, with the recognition of oblique- and frontal ramp areas in response to northwest-directed compression, can be viewed as a microcosm for the deformation of major parts of the Kaapvaal Craton during this tectonic event, as documented below. In this respect, any steeply inclined, pre-existing east/west and north/south-striking fault plane will have experienced dextral or sinistral strike-slip reactivation, respectively.

Geodynamic model for the Kaapvaal Craton

Based on structural, geophysical and isotopic data from the Kaapvaal Craton, clear evidence is provided for a major, post-Vredefort impact deformational event of northwest-directed compressional and transpressional tectonics, operating at least intra-cratonically within the region of the Witwatersrand Basin and environs. Mesoproterozoic alkaline magmatism, closely related to the structural development during this tectonic phase, as well as associated regional hydrothermal activity, causing widespread partial resetting of formation ages within the core of the Kaapvaal Craton, constrain the temporal position of this event to the time interval 1450-1000 Ma.

Taking into account the contemporaneous Kibaran (Grenville)-age orogenic activities along the southern margin of the Kaapvaal Craton (Namaqua-Natal mobile belt), the main constraints to the development of a craton-wide geodynamic model are the findings from the southern margin of the Kaapvaal Craton and the Namaqua-Natal-Dronning Maud Land mobile belt itself, especially with regard to the kinematic evolution of these areas.

Namaqua-Natal mobile belt

The ~1.1 Ga (Late Kibaran) Namaqua-Natal mobile belt forms a high-grade tectonic province adjacent to the southern and western margins of the Archaean Kaapvaal Craton, which extends from southern Namibia through Namaqualand and eastward, under Phanerozoic cover, to Natal.

The Natal Province comprises three shear zone-bounded tectono-stratigraphic terranes, namely from north to south the Tugela, Mzumbe and Margate Terranes (Thomas, 1989). The Tugela Terrane comprises layered mafic metavolcanics which erupted at ~1.2 Ga (Barton, 1983; Barton & Burger, 1983) in an oceanic setting (Matthews, 1972) and were subsequently intruded by granites, mafic-ultramafic complexes, and serpentinites (Matthews, 1972), as well as by a number of alkaline-peralkaline granitoids (Scogings, 1989). The terrane has been interpreted as an ophiolite complex which was obducted northwards onto the Kaapvaal Craton as four major flat-lying thrust nappes during the Kibaran (Grenville) orogeny (Matthews, 1972), resulting in isotopic resetting of minerals up to 25 km north of the southern margin of the Archaean craton (Eglington, pers. comm.). The southern Mzumbe and Margate Terranes comprise arc-related, felsic to mafic metavolcanic supracrustal gneisses with subordinate paragneisses no older than ~1.3 Ga. These rocks were intruded at ~1.2 Ga by arc-related, calc-alkalic tonalitic orthogneisses and by syn-, late-, and post-kinematic granitoids between ~1.1 and 1.0 Ga (Eglington et al., 1989; Thomas et al., 1990a, 1992b, 1993). The development of the southern terranes has been interpreted in terms of growths of a volcanic arc(s) associated with subduction of the Tugela ocean (Thomas & Eglington, 1989). The Natal Province has been interpreted as a totally juvenile orogen, since no older basement has been identified (Eglington et al., 1989; Thomas & Eglington, 1990).

In comparison, the Namaqualand Province comprises Paleoproterozoic (Eburnian) basement rocks in the west (Richtersveld Terrane) and east (Kheis Province), as well as Kibaran (Grenville)-age rocks subdivided into two major subprovinces, within which a number of tectono-stratigraphic terranes are recognized (Hartnady et al., 1985; Joubert, 1986; Colliston et al., 1990). These terranes comprise ~1.6-1.3 Ga old (Reid et al., 1987; Cornell et al., 1990) early sequences of typically metasedimentary and calc-alkalic metavolcanic supracrustal gneisses similar to the Natal Province (e.g. Moen, 1988), which were deposited

on older Eburnian basement in western and eastern Namaqualand (Kakamas, Bushmanland, Kaaien Terranes), but in volcanic arcs on juvenile oceanic crust in east-central Namaqualand (Areachap Terrane). These subduction-related rocks were intruded at ~1.2 Ga (Walraven et al., 1982) by calc-alkalic batholiths (Geringer et al., 1988; Hoal et al., 1989) and later at ~1.1-1.0 Ga (Burger & Walraven, 1980; Walraven et al., 1982) by megacrystic granites and charnockites (Joubert, 1986). Magmatism ceased by ~1.0 Ga with the intrusion of pegmatoids and microgranites (Burger & Walraven, 1980). In eastern Namaqualand and southern Namibia, syn-Kibaran (Grenville), ~1.2-1.15 Ga old, low-grade volcano-sedimentary sequences (Koras, Sinclair, Ghansi Sequences) were deposited in fault-bounded pull-apart grabens (Botha et al., 1979; Borg, 1988; Hoal et al., 1989; Hoal & Heaman, 1994).
Kibaran (Grenville) kinematic evolution in Namaqualand is interpreted in terms of early northeast and/or southwest-directed thrusting, during the earliest collision phase, followed by pervasive, northwest-southeast-striking dextral shearing and steepening/reactivation of the earlier thrusts due to continued convergence and crustal thickening (e.g. Coward & Potgieter, 1983; Stowe, 1986; Humphreys & Van Bever Donker, 1987; Harris, 1988; Van Bever Donker, 1991; Jacobs et al., 1993; Thomas et al., 1994; Van der Merwe, 1995).

Recently, Jacobs et al. (1993) and Thomas et al. (1994) have proposed a plate tectonic model to describe the crustal evolution of the orogenic belt as a whole, including the Western Dronning Maud Land belt (East Antarctica). According to these authors, the evolution of the belt can be interpreted in terms of a complete Wilson Cycle model, from early extension and rifting, leading to fragmentation, ocean basin formation, and hence to plate convergence, subduction, and oblique collisional orogeny.
With regard to the kinematic evolution of the belt, the model envisages the Kaapvaal Craton to have acted as a southwest-directed indenter during a prolonged period of consistent northeast/southwest-directed plate convergence along the southern edge of the Kaapvaal Craton. In the entire belt, early northeast- and southwest-directed thrusting during initial accretionary orogenic activity progressed to transcurrent shearing (NW/SE-trending dextral in Namaqualand, E/W-trending sinistral in Natal) and the generation of the Koras and Sinclair-Ghansi-Rehoboth pull-apart grabens in the Namaqualand sector.

However, this model does not account for the fact, that the thrust directions and fold axis orientations, observed by several workers (e.g. Matthews, 1972, 1981a/b; Charlesworth, 1981) within the Natal sector, are generally northward-directed, as well as east/west-trending, respectively.
The fact also, that the southerly inclination of the Natal thrust belt and the underlying Ntingwe strata increases progressively from 10-20^0 in the west to 46-60^0 in the eastern part of the thrust belt, indicates, when viewed in combination with the general E to ENE structural trend of the Natal thrust belt (Matthews, 1981a), oblique collision and accretion (transpression) due to NW/SE-directed plate convergence, which contradicts the proposal by Jacobs et al. (1993) and Thomas et al. (1994) of NE/SW-directed plate convergence.
Further, the geodynamic model proposed by the later authors envisages transcurrent sinistral and dextral shearing within the Natal and Namaqualand provinces respectively, to represent a progressive deformational stage to the initial northeast- and southwest-directed thrusting within both provinces, and hence to be part of the major orogenic phase during the Kibaran (Grenville) event.
Jacobs et al (1995) provided clear evidence, that the sinistral transcurrent shearing along the margins of the three Natal tectonostratigraphic terranes and within the Mzumbe and Margate terranes, are not part of the main compressional orogenic phase, but represent rather late-stage, post-collisional adjustment features, as young as approximately ~950 Ma, and are therefore part of the post-orogenic relaxation phase.

In addition, the proposal of northeast- and southwest-directed trusting during an initial accretionary orogenic phase, followed by northwest-trending dextral transcurrent shears as a result of progressive deformation by northeast/southwest-oriented plate convergence in the Namaqua Metamorphic Province, is not in agreement with studies by various other workers (e.g. De Beer & Meyer, 1984). These authors have identified predominantly dextral strike-slip tectonics across the Namaqua Province-Kaapvaal Craton boundary, and southeast- and northwest-directed thrusting to be only subordinately developed. This is in sharp contrast with the dominantly developed thrust and obduction tectonics apparent in the Natal Metamorphic Province. The different kinematic evolution of both provinces is not explainable within the plate tectonic model, proposed by Jacobs et al. (1993) and Thomas et al. (1994), for the entire Namaqua-Natal mobile belt.

Southern margin of the Kaapvaal Craton

Studies on the tectono-thermal evolution of the Late-Archaean Pongola Supergroup by Matthews (1990) indicate, that the Pongola Supergroup has been subjected to a sequence of five episodes of deformation, of which one event (D_4) is clearly post-depositional and compressional in nature.
This post-Pongola compressional event is viewed by the author to have caused the northward emplacement of the extensive Nsuze Nappe from the south, with the development of a complex internal imbricate structure of folded lower Pongola (Nsuze) strata. Matthews (1990) views gravitational gliding from an up-arched region at least 20 km south of the present southern domain of the Pongola Supergroup, as the principle nappe transport mechanism. Subsequent east/west-trending, open folding of the Nsuze Nappe, and at lower structural level, buckling of the pre-existing Emome and Mhlatuze half-graben structures is envisaged by the same author to be the consequence of northward propagation of lateral compression, and thus representing a progressive phase of this post-Pongola Supergroup, but pre-Ntingwe Formation deformational event (D_4).
According to Matthews (1990), the apparent absence of lithologies older than ca. 1500 Ma within the Natal sector of the mobile belt, rules out the possibility that compressional deformation of the Pongola Sequence along the southern margin of the craton was caused by a continent-continent collision (Wilson cycle), or a continent-island arc collision or a Cordilleran-type orogeny.
Consequently, the author proposed, that the initial tectono-depositional development and subsequent tectonic deformation of the Pongola Supergroup along the southern margin of the Kaapvaal Craton, together comprising a period of approximately 1500 Ma during the interval from about 3000 to 1500 Ma, took place when this region was situated along part of a transform plate boundary with a major ocean basin.
With regard to a possible plate tectonic setting of the Pongola Supergroup, Matthews (1990) envisaged the entire sequence of deformational events (all pre-Ntingwe Formation in age and thus pre-dating the Kibaran (Grenville) orogeny) within the framework of a transform continental margin, where along the southern margin of the Kaapvaal Craton, short intervals of a laterally moving oceanic plate adjacent to the south, caused intermittent transpressional and transtensional tectonics. The proposal of intermittently occurring transtensional and transpressional tectonics due to lateral movements of an oceanic plate, relative to the southern margin of the Kaapvaal Craton along a long-lived transform boundary, also takes into account geological and geochronological evidence for a remarkable 1500 Ma hiatus across the southern boundary of the Kaapvaal Craton with the Natal sector of the Proterozoic mobile belt, as the juxtaposition of progressively younger segments of oceanic crust relative to the southern craton margin along the transform boundary, would result in an apparent time-gap across this boundary (Matthews, 1990).

A comparison between the pre-Ntingwe transpressional tectonic phase (D_4) and the oblique-collisional/ -accretional phase during the Kibaran (Grenville) orogeny (post-Ntingwe Formation), exhibits remarkable similarities in terms of tectonic style and kinematic vectors (east-west trending, north-verging folds with westerly plunging fold axes, and north-verging thrust faults), as well as in the limited amount of crustal shortening involved during both tectonic events, suggesting a similar tectonic setting and orientation of plate convergence.

The suggestion of a similar tectonic setting of both pre- and post-Ntingwe Formation deformation events, is confirmed by the independent proposal of a transpressional regime for both tectonic events by Matthews (1990), as well as by Jacobs et al. (1993) and Thomas et al. (1994).
With regard to the direction of plate convergence during both transpressional events, no specific movement direction of the oceanic plate other than oblique to the southern edge of the Kaapvaal Craton was proposed by Matthews (1990) for the pre-Ntingwe Formation event, and disagreement exists in the literature about the direction of plate convergence during the Kibaran (Grenville) orogeny.
Whereas Matthews (1990) considered generally southward subduction and hence north/south-directed convergence of the oceanic plate and the southern margin of the Kaapvaal Craton, Jacobs et al. (1993) and Thomas et al. (1994) envisaged consistent NE/SW-directed plate convergence the driving force during the Kibaran (Grenville) orogeny along the southern margin of the Kaapvaal Craton. However, the progressive increase of the southerly inclination of the Natal thrust belt and the underlying Ntingwe strata from 10-20^0 in the west to 45-60^0 in the eastern part of the thrust belt, as well as the E to ENE structural trend of the Natal thrust belt (Matthews, 1981a), is indicative for a transpressional environment as mention above and implies rather NW/SE-directed oblique convergence of the two plates.

As the remarkable similarities between the pre-Ntingwe deformation and the Kibaran (Grenville) orogenic event in terms of kinematic evolution suggests a close relationship of both deformational events to each other, similar NW/SE-directed plate convergence along an inferred transform boundary can be anticipated during the pre-Ntingwe tectonic event.

In conclusion, although Matthews (1990) considered the tectonic development of the southern domain of the Pongola Supergroup to have occurred long before the evolution of the Namaqua-Natal mobile belt, it is now alternatively proposed that both, pre- and post-Ntingwe Formation compressional events affecting the southern margin of the Kaapvaal Craton, occurred due to a prolonged period of consistent NW/SE-directed plate convergence, hence are transpressional in nature and represent two individual deformational phases of the Kibaran (Grenville) orogenic cycle in this area.

Dronning Maud Land mobile belt/East Antarctica

The anticipated NW/SE-directed plate convergence during the Kibaran (Grenville) orogeny is strongly supported by geophysical studies of the area south of the Kaapvaal Craton and the western Dronning Maud Land (East Antarctica). Five major generally east-west trending, long-wavelength magnetic anomalies within the Namaqua-Natal mobile belt to the south of the Kaapvaal Craton, namely from north to south the Empangeni, Durban, Amanzimtoti, Beattie and Mbashe anomalies , correlate partially with the three major terranes identified in the Natal sector (e.g. Thomas et al., 1994), and appear related because they occur sub-parallel to one another and their causative bodies are similarly shaped (Du Plessis & Thomas, 1991). A number of major magnetic anomalies (Kirwan anomalies) in the western Dronning Maud Land (East Antarctica), portraying signatures, shapes and dimensions remarkably similar to the Beattie-set of anomalies in southern Africa (Futterer, 1989), were identified by aeromagnetic and geological field data as individual polymetamorphic and deformed granite-gneiss terranes, representing mafic to felsic volcanic and volcaniclastic rocks formed during Mesoproterozoic arc-related magmatism or arc-derived crust, that are bounded by low-angle, northwest-verging thrust faults (Hodgkinson, 1990; Corner, 1995; Grantham et al., 1988; Jackson, 1995; Harris, P.D & Knoper, M.W. pers. comm.).
To date, both sets of anomalies in southern Africa and western Dronning Maud Land are interpreted to represent individual allochthonous, polymetamorphic and deformed, magnetic terranes, that are bounded by mainly low-angle southeasterly dipping thrust faults (Maher & Pitts, 1989; Du Plessis & Thomas, 1991; Hodgkinson, 1990; Grantham et al., 1988; Corner, 1995), which acted as conduits for magnetite-enriched metamorphic fluids (Corner, 1989). These terranes together represent juvenile Mesoproterozoic crust, that was metamorphically and tectonically modified during the Kibaran (Grenville) orogeny and thus forming today the preserved extend of the Namaqua-Natal-Heimefrontfjella mobile belt (Jacobs et al., 1993). The protolith, extending laterally at least from the western Dronning Maud Land (East Antarctica) to the southern margin of the Kaapvaal Craton, experienced collisional and accretional tectonics due to its convergence with a northern Archaean-Proterozoic supercontinent (Piper, 1976, 1982, 1983) during the mid-Proterozoic. As the movement direction of low-angle thrust faults is identical with respect to the Kaapvaal Craton in both the southern African and East Antarctic cases, i.e. dipping away from the craton and thus indicating northwest-directed thrusting toward the craton (Corner, 1989), NW/SE-directed plate convergence during the Mesoproterozoic is indicated between the Archaean-Proterozoic supercontinent and oceanic plate, situated to the south.

Proposed model

Based on these considerations and constraints, as well as the findings from the central Kaapvaal Craton summarized above, the following geodynamic, plate-tectonic model for the tectono-magmatic evolution of the Kaapvaal Craton during the Mesoproterozoic is proposed:

Following the proposal by Matthews (1990), the southern margin of the Kaapvaal Craton is envisaged to have been positioned since the onset of Pongola Supergroup deposition (~3 Ga) until the Mesoproterozoic along part of an extensive transform margin of a proposed Archaean-Proterozoic supercontinent (Piper, 1976, 1982, 1983) with a major ocean basin. Repeated lateral movements of the southern oceanic plate, relative to the southern margin of the supercontinent along this long-lived transform plate boundary, caused intermittent transpressional and transtensional tectonics, which led to the entire sequence of depositional and deformational events, reported to have effected the southern margin of the Kaapvaal Craton in pre-Ntingwe Formation-time (Matthews, 1990).

In response to NW/SE-directed plate convergence during the Mesoproterozoic time interval 1450-1250 Ma, initial Kibaran (Grenville)-age orogenic, transpressional tectonics were induced to the southeastern (Natal) and western (Namaqualand) sectors of the Kaapvaal Craton's southern margin, documented in the Natal sector by the pre-Ntingwe deformation of the Pongola Supergroup within the southern structural domain. The area between these two transpressional sectors, in the following referred to as the Lesotho frontal ramp sector, experienced instead northwest-directed compression (Fig. 29). Compared to relative limited amounts of crustal shortening within the transpressional Natal and Namaqualand provinces, the Lesotho frontal ramp sector is envisaged to have experienced major crustal thickening and shortening due to northwest-, cratonward-directed thrust tectonics.
Despite the fact, that Karoo Sequence strata cover much of the southern margin of the Kaapvaal Craton, an indication for elevated, highly magnetic or non-magnetic granitic basement up to 150 km craton-inward from the craton margin, is provided by regional magnetic and gravity anomalies, trending approximately parallel to the geophysical interpreted southern margin of the Kaapvaal Craton (Corner, 1986b, 1987, 1989, 1990, 1992; Corner & Wilsher, 1989), and hence are related to the Beattie-set of anomalies as part of the Namaqua-Natal-Dronning Maud Land mobile belt (Fig. 29).
Analogous to the study results of the Beattie-set of anomalies in Southern Africa and related ones in the western Dronning Maud Land (De Beer & Meyer, 1984; Maher & Pitts, 1989, 1991; Du Plessis & Thomas, 1991; Pitts et al., 1993; Hodgkinson, 1990), the anomalies within the Lesotho frontal ramp sector are interpreted as both, thrust-bounded, by northwest-directed thrusts elevated crustal segments of the granitic Archaean basement (non-magnetic, further craton-inward anomalies), or as individual Mesoproterozoic terranes, up to 30 km northwesterly obducted onto the southern margin of the Kaapvaal Craton (highly magnetic anomalies along the craton margin).
The latter interpretation appears to be strongly confirmed by Cretaceous kimberlites in northern Lesotho, situated north of the southern margin of the craton and containing xenoliths of crustal material. Xenoliths with preserved amphibolite grade assemblages provide Archaean model neodymium dates, whereas those with granulite grade assemblages provide Proterozoic model ages (Rogers & Hawkesworth, 1982; Hawkesworth et al., 1983, 1986; Van Calsteren et al., 1986). These data may indicate Proterozoic mafic material, that has been metamorphosed to granulite grade and thrusted over the Archaean crust.
In response to these initial orogenic activities, occurring along the southern margin of the Kaapvaal Craton during the approximate time interval 1450-1250 Ma, major lineaments (terrane boundaries), representing the fundamental tectonic grain of the craton (Friese, in prep.), experienced renewed reactivation in form of sinistral and dextral strike-/oblique-slip movements, depending on their orientation relative to the induced NW/SE-oriented stress field (Fig. 29). Displacement along these deep-rooted shear zones is envisaged to have led to the opening of the latter, propagation of pressure release, channelling of volatiles and consequently to partial melting, which resulted in an initial phase of alkaline magmatism within the interior of the Kaapvaal Craton (Table 3), hereby exploiting predominantly this reactivated system of major lithospheric lineaments.

Following a period of approximately 50 Ma of relative orogenic quiescence with sedimentation and (back?) arc volcanism on juvenile oceanic crust to the south of the Kaapvaal Craton, renewed NW/SE-directed plate convergence initiated the main Kibaran (Grenville) orogenic phase along the southern craton margin, forming the Namaqua-Natal mobile belt in the time interval 1200-1000 Ma.
The migration of a major northwest-directed foreland fold and thrust belt from the southern margin to the interior of the Kaapvaal Craton, resulted in significant uplift and southeast-directed tilting of extensive Archaean crystalline basement segments, and subsequent erosion of overlying Archaean and Proterozoic supracrustal strata. Hereby, individual thrusts appear to have developed between two major east-west trending shear zones, the Brandfort-Tugela and Rietfontein-Inyoka lineaments in the south and north respectively, acting as lateral ramps to the northwest-directed thrust tectonics (Fig. 29).
While the Rietfontein-Inyoka Lineament represented the northern limit to the fold and thrust belt, a contemporaneous induced extensional stress regime further north led to the development of the NW/SE-trending "Pilanesberg Graben System", and its exploitation as zone of relative lithospheric weakness by a second phase of alkaline magmatism (Table 3), mainly in form of individual carbonatitic and kimberlitic complexes, and a major northwest-striking dyke system (Fig. 29). The graben forming process is viewed to have occurred in two stages, with initial normal dip-slip movements, followed by sinistral strike-slip displacements (up to 10 km) along the earlier normal faults, thus indicating a late-stage pull-apart setting

for the "Pilanesberg Graben System". The evolution of the Tertiary Rhinegraben/Germany within the northern foreland of the Alpine orogen (Illies & Greiner, 1978; Illies & Baumann, 1982; Bergerat, 1987) might represent an analogue example of intra-continental rifting ahead of a fold and thrust belt and in response to compressional stresses, that originated from contemporaneous orogenic activity along the continental margin, several hundred kilometres in distance to the centre of rift development.

A northwest/southeast-trending gravity profile across the eastern and central Kaapvaal Craton (Swazi Subprovince) (Fig. 30) indicates the position of major lineaments (terrane boundaries), previously refered to in Figures 26, 27 & 29.

DISCUSSION

In view of the study results, implications with regard to the Vredefort impact event and its related tectonic processes, as well as to the Kibaran (Grenville) Orogeny especially along the southern margin of the Kaapvaal Craton (Natal Metamorphic Province), appear to exist in terms of timing, kinematic evolution and tectonic modelling.

Vredefort impact structure

The nature, intensity and relative age of the identified thrust faulting, arranged concentrically at least in an clock-wise arc from southwest to northeast around the Vredefort Dome, as the central peak of the Vredefort impact crater, has to be assessed within the light of the new evidence for Mesoproterozoic compressional tectonics within the central part of the Kaapvaal Craton.
From the evidence gathered in this study it can be concluded, that the deformation related to the Vredefort impact crater was confined to intense overfolding, as well as relatively low-amplitude, open folding of the supracrustal cover concentrically around the central peak. The intensity of folding decreases radially with distance to the Vredefort Dome. The maximum radial extent of the folding can only be speculated on, as fold structures, matching in their orientation the concentric fold pattern of Vredefort impact-age, could have been generated by a different deformation event. However, estimates of the final rim diameter of the Vredefort Crater by Therriault et al. (1993, 1995) range between 175-300 km, 206-285 km, and 200-263 km, depending on the method applied for the calculation, and might give an indication of the maximum area effected by impact-related folding.

With regard to the question of the nature and intensity of possible thrust faulting generated during the various stages of impact crater formation, it must be stressed that to date no studies on other terrestrial impact structures have revealed any evidence for significant thrust faulting of that kind, observed within the Archaean basement and supracrustal cover rocks surrounding the Vredefort Dome.
The current knowledge of the sequential development and the various processes involved during impact crater formation, indicates an initial main compressional phase at the moment of projectile impact with the generation of the transient cavity, followed by a main decompressional/collapse phase characterised by tensile stresses and the modification to the transient crater and surrounding area.
As the formation of an impact crater during these two main phases is proposed to occur within a time scale of less than 30 minutes (Stoeffler et al., 1994), high to ultra-high strain deformation within the target rocks is envisaged, leading to the formation of pseudotachylites mainly during the initial compressional phase, and the remainder subsequently during the recovery/modification stage (Thompson & Spray, 1994).
The fact, that pseudotachylite occurrences within the Vredefort impact crater are concentrated predominantly along bedding planes and unconformities within the supracrustal cover rocks, and along fracture zones within the underlying crystalline basement, indicates stress accommodation within the supracrustal cover mainly in form of bedding-parallel movements.

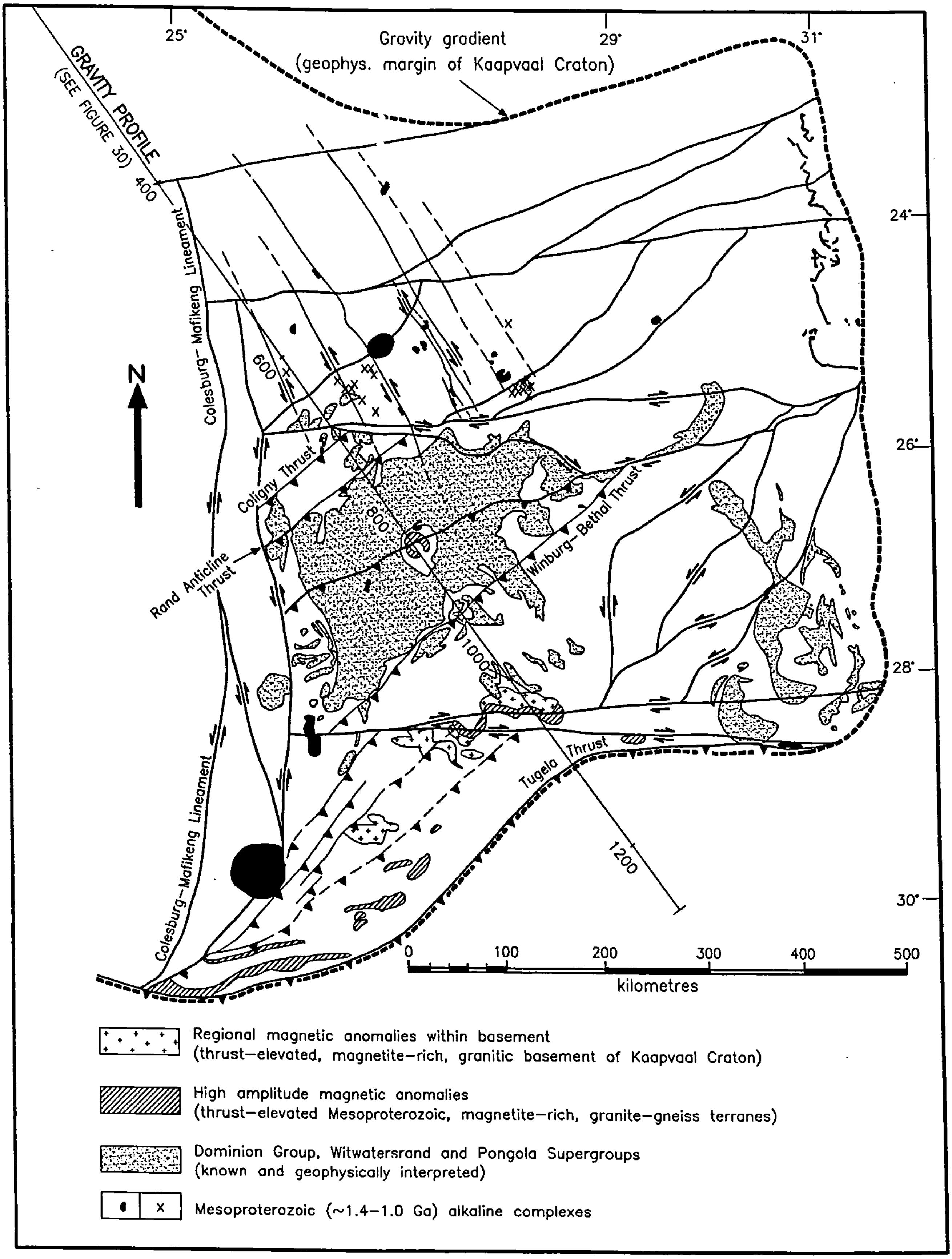

Fig. 29. Proposed geodynamic model for the Mesoproterozoic tectono-magmatic evolution of the central and eastern Kaapvaal Craton.

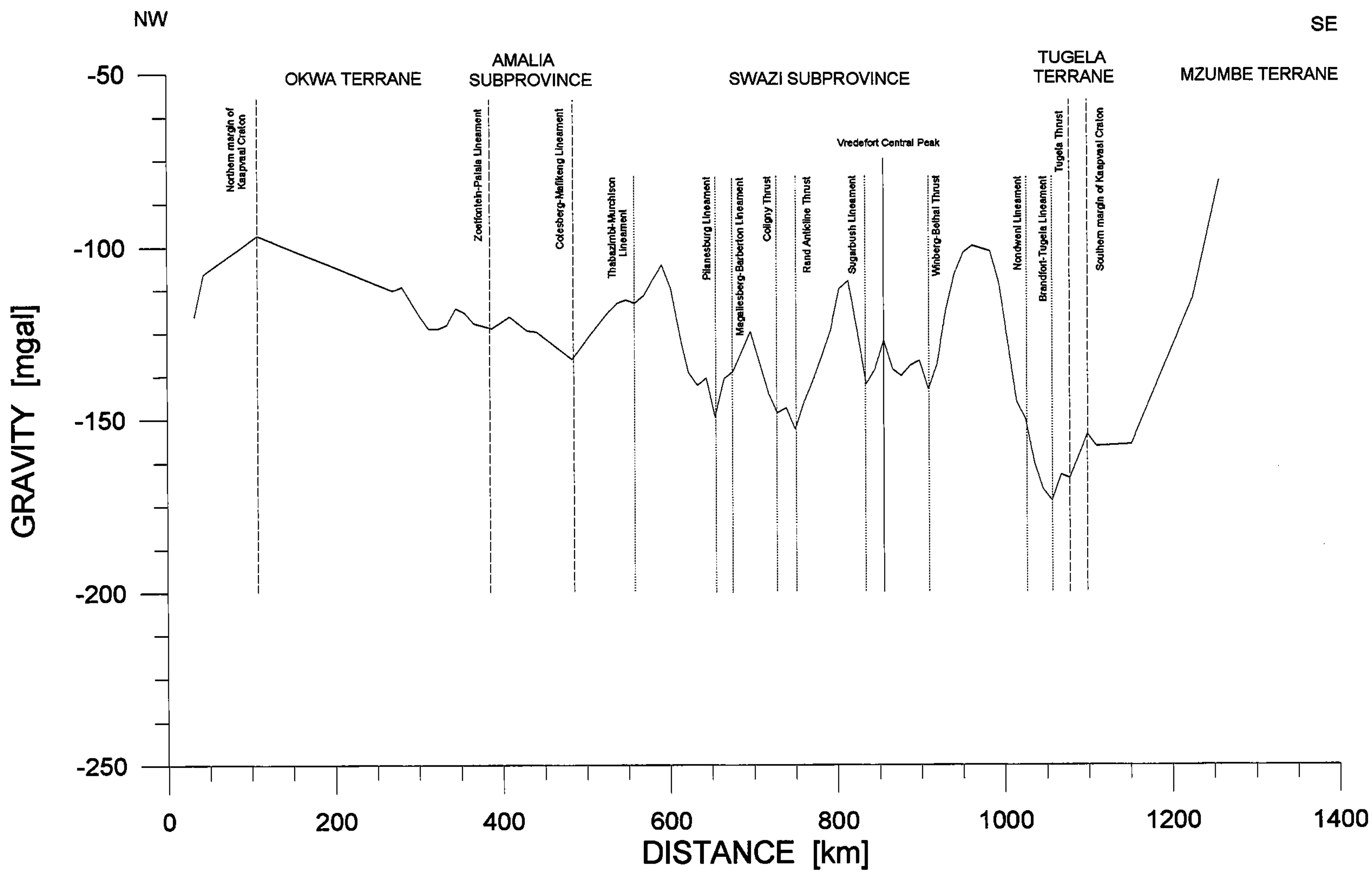

Fig. 30. NW/SE-trending gravity profile across the Kaapvaal Craton.

It is therefore concluded, that compressional and tensile stresses, induced during the initial compression phase at the moment of impact and during the subsequent rebound phase respectively, caused rapid outward movements of the target rocks over the transient crater rim , followed shortly by downward and inward movements of the same material towards the central peak under the influence of gravity, in both cases mainly accomplished along bedding planes.
Thus, thrusting related to the formation of the Vredefort impact structure must be envisaged rather as a process of rapid outward and inward movements of the Archaean and Proterozoic cover rocks, marked by multiple generations of bedding-parallel pseudotachylite (e.g. evident within the Klerksdorp and Carletonville goldfields).
The thrusting observed within the area around the Vredefort Dome is associated with the formation of mylonites, hence indicating much lower strain rates and deformation under rather ductile conditions.
Further, the thrusting is not entirely concentrated along bedding planes, but also characterised by various thrust planes, that cut through the Archaean and Proterozoic strata in a northwesterly to northerly direction and clearly post-date the impact-related overfolding of the supracrustals within the collar region of the Vredefort Dome.

Another important aspect with regard to the nature of the observed thrust tectonics is the fact, that the gravitational inward movements caused by thermal subsidence of the cooling central peak region during the rebound phase, represent the final stage of the impact crater formation process, and hence no additional compressional forces and associated outward thrusting can be expected at a later stage.
Consequently, any reverse-slip components along bedding planes or possible thrust faults, that were generated during the initial compressional phase at the moment of meteorite impact, will be entirely inverted to a normal net slip during the following rebound phase, and further enhanced due to the mass deficit within the central peak region, caused by the vaporisation and displacement of the target rock.

In summary, previous interpretations, which regarded the observed thrust tectonics within the Archaean and Proterozoic cover rocks as being concentrically arranged around the Vredefort Dome, and hence genetically related to the formation of the dome, must now be called in question.
Based on the findings of this study with regard to the recognition of considerable compressional tectonics within the central Kaapvaal Craton during the period of the Kibaran (Grenville) Orogeny, northwest- to north-directed thrusting observed within the supracrustal lithologies and the Archaean crystalline basement is now considered to form part of a major compressional event, that effected major parts of the Kaapvaal Craton and formed in response to the orogenic activity mainly along the southern margin of the craton during the Mesoproterozoic.

Namaqua-Natal mobile belt

To date, the evolution of the Mesoproterozoic Namaqua-Natal mobile belt is envisaged to have occurred within a complete Wilson cycle during the time-interval 1400-1000 Ma, involving one main orogenic phase between 1200-1000 Ma (Jacobs et al., 1993; Thomas et al., 1994).
Within the Natal sector of the mobile belt, the Kibaran cycle began at approximately 1400 Ma with early extension/rifting and ocean basin formation, accompanied by sedimentation and volcanism in volcanic (back?) arcs on juvenile oceanic crust. Subduction and closure of the Tugela oceanic basin between 1200 Ma and 1040 Ma led to accretion and obduction of the juvenile volcanic arcs onto the Kaapvaal Craton in form of three terranes, polyphase deformation and high-grade metamorphism, as well as to syn-, late-, and post-kinematic emplacement of granitoids until ~950 Ma (Thomas et al., 1994).

As the Mesoproterozoic alkaline magmatism within the Kaapvaal Craton is envisaged to have been triggered by the orogenic activities within the southern part of the Namaqua-Natal mobile belt, the here presented model proposes, that the Kibaran (Grenville) orogeny along the southern margin of the Kaapvaal Craton occurred during the time-interval 1450-1000 Ma in two separate main cycles between approximately 1450-1250 Ma and 1200-1000 Ma. Further, each cycle exhibits possibly at least two episodes of increased orogenic activity and associated tectonomagmatic processes, between 1450-1420 Ma and 1370-1250 Ma during the first cycle, and between 1200-1180 Ma and 1140-1000 Ma during the second main orogenic cycle.

This proposal is based on a geochronological data set, summarising partial resetting and formation ages of alkaline magmatism within the Kaapvaal Craton during the Mesoproterozoic, as well as supported by structural, sedimentological and geochronological data available from the southern margin of the Kaapvaal Craton. In this regard, the following important aspects are:

- Lithologies of the Natal nappe complex are polymetamorphic and have been affected by at least three major phases of deformation (east-west folding, northward thrusting) (Matthews, 1981), which are kinematically indistinguishable and hence different stages within a single protracted, progressive deformation episode.
  A correlation appears to be possible between the identified two phases of increased alkaline magmatic activity between 1200-1180 Ma and 1140-1000 Ma predominantly along reactivated 'suture' zones (terrane boundaries) within the Kaapvaal Craton during the time-interval 1200-1000 Ma and the contemporaneous polymetamorphic and -deformational evolution of the Kibaran (Grenville) mobile belt in the Natal sector.

- The co-linearity between the deformation within the Natal Metamorphic Province and the older pre-Ntingwe deformational event, evident within the southern structural domain of the Pongola Supergroup, might not be conclusive evidence, but allows for the speculation, that both deformation periods are related and hence part of the Kibaran (Grenville) orogenic cycle within the Natal sector of the mobile belt.
  The proposal, that the pre-Ntingwe deformation event represents an initial phase within the evolution of the Mesoproterozoic orogenic belt along the southern margin of the Kaapvaal Craton, might be supported by the possibility, to correlate the two successive phases of deformation evident during the pre-Ntingwe compressional event (Matthews, 1990), with the identified two episodes of increased alkaline magmatism at 1450-1420 Ma and 1370-1250 Ma in the interior of the Kaapvaal Craton.

- The time for the commencement of the Kibaran cycle within the Natal sector in form of sedimentation and volcanism is to date not constrained precisely enough.
  Whereas Eglington et al. (1989) and Thomas et al. (1994) both estimated a lower age limit of approximately 1400-1300 Ma, Barton (1983) and Barton & Burger (1983) envisaged an age of ~1200 Ma for the eruption of the mafic metavolcanics of the Tugela terrane. As there are no radiometric ages available for lithologies of the Ntingwe Formation, which is interpreted to represent para-autochthonous transgressive continental shelf deposits of the Mesoproterozoic Tugela oceanic basin (Cain, 1975; Matthews, 1972, 1981), the beginning of the main Kibaran cycle in form of sedimentation and volcanism could have occurred as late as ~1250 Ma, after the cessation of a proposed earlier orogenic cycle between 1450-1250 Ma, representing an initial phase of the Kibaran (Grenville) orogeny, which led to the deformation of the Pongola Supergroup within the southern structural domain.

In conclusion, the recognition of northwest-directed transpressional and compressional tectonics within the Kaapvaal Craton during the Mesoproterozoic, represents a further contribution to the understanding of the temporal and kinematic evolution of the Namaqua-Natal-Dronning Maud Land mobile belt.
The kinematic data obtained from the interior of the Kaapvaal Craton are conform with those, reported from the Dronning Maud Land sector and Natal sector of the Namaqua-Natal belt, suggesting a prolonged period of consistent NW/SE-plate convergence.
The geodynamic model proposed here incorporates not only the kinematic features observed within the Natal Metamorphic Province and the Dronning Maud Land belt (East Antarctica), but also the pre-Ntingwe compressional deformation (D_4; Matthews, 1990) of the Pongola Supergroup, the identified north- to northwest-directed thrust tectonics within the central Kaapvaal Craton, time-equivalent alkaline magmatism within and around the Kaapvaal Craton, as well as the generation of northwest-striking pull-apart graben structures in the northern part of the craton.

In comparison to these findings, the kinematic model proposed by Jacobs et al. (1993) and Thomas et al. (1994) for the crustal evolution of the Namaqua-Natal-Heimefrontfjella mobile belt as a whole, suggesting the Kaapvaal Craton to have acted as a southwest-directed indentor under consistent NE/SW-plate convergence during the Kibaran (Grenville) orogeny, exhibits fundamental discrepancies between the suggested and by their model expected kinematic features within various areas of the belt, and the actual structures observed, particularly in the Natal Metamorphic Province and the Dronning Maud Land segment of the Kibaran (Grenville) mobile belt.

CONCLUSIONS

The recognition of north- to northwest-directed compressional tectonics and associated alkaline magmatism within major parts of the Kaapvaal Craton, in response to Kibaran (Grenville)-age orogenic activities particularly along the southern margin of the craton, forming the Natal Metamorphic Province, entail the following important economic and geological implications:

Economic implications:

1. As carbonatites and kimberlites are a major economic source of Nb, phosphate, rare earth elements, as well as of diamonds, the potential location or likely occurrence of these alkaline complexes beneath Phanerozoic cover is predictable with a relatively high percentage of confidence. According to the findings of this study and the concept of the proposed tectonic model, potential areas with a higher incidence of alkaline magmatism and its associated economic mineralization, would be situated primarily along the inferred terrane boundaries within the Kaapvaal Craton. As secondary target areas might qualify the Kibaran (Grenville) orogenic belts along the western, southern and eastern margins of the Kaapvaal Craton, as well as major graben structures in the northern portion of the craton analogue to the "Pilanesberg Graben System".

2. Based on the proposed model and tectonic framework for the Kaapvaal Craton, potential areas with a greater likelihood for preservation or erosion of the economical important, auriferous Witwatersrand Supergroup strata, are now thought to be identifiable with greater confidence.
   Generally it can be stated, that the inferred thrust tectonics within the central Kaapvaal Craton during the Kibaran (Grenville) Orogeny had a rather negative effect on the preservation of the Witwatersrand Supergroup, as uplift of various basement blocks led to increased exposure and erosion of Archaean strata. In particular the proposed so-called Winberg-Bethal Thrust Zone along the southeastern margin of the Witwatersrand Basin is seen to have had the most severe modificational influence to the basin, with uplift, tilting and intense erosion to the east of it. Erosional remnants, mainly correlatives to the Dominion, West Rand and lower Central Rand Groups (e.g. Pongola Supergroup) are evidence for an originally much greater Witwatersrand Basin, which appears to have been tectonically modified and reduced erosionally to more than 50% of its initial size.
   Hence, the Witwatersrand Basin (sensu stricto) can be envisaged as being preserved and situated within an imbricate system of major northwest-directed thrust faults, namely the inferred Winberg-Bethal and Rand Anticline thrust zones along the southern and northern margin of the basin respectively, which would explain the present geometry of this Archaean structural basin.

3. The pattern of erosion and preservation of the coal- and uranium-bearing sediments of the Karoo Sequence on the Kaapvaal Craton appears to be structurally controlled. Hereby, the identified major east/west-striking 'suture' zones (e.g. Brandfort-Tugela, Sugarbush, Magaliesburg-Barberton, Thabazimbi-Murchison, and Zoetfontein-Palala lineaments, etc.), as well as the Winberg-Bethal and Rand Anticline thrusts (Figs. 26 & 29) seem to have functioned as main controlling structures, due to their reactivation by predominantly normal movements at least in post-Karoo Sequence-time and probably related to taphrogenesis during the break-up of Gondwana.
   Isopach maps constructed for the Karoo Sequence within the Orange Free State Goldfield (Visser & Kingsley, 1982; Friese, in prep) and for various formations of the Karoo Sequence within the southeastern part of the Kaapvaal Craton (Cadle, 1979), as well as the evidence for reactivation of northwest-directed thrusts within the OFS Goldfield (De Wet & Hall, 1994) in syn-Karoo Sequence time, indicates negative inversion of pre-existing major structural features as early as during deposition of the Karoo Sequence, and probably related to orogenic activities to the south of the presently preserved Karoo basin during the Cape Orogeny.

Geological implications:

1. Vredefort Impact Event

   Previous interpretations, which regarded the observed thrust tectonics within the Archaean and Proterozoic cover rocks as being concentrically arranged around the Vredefort Dome, and hence genetically related to the formation of the dome, must now be called in question.
   Based on the findings of this study with regard to the recognition of considerable compressional tectonics within the central Kaapvaal Craton during the period of the Kibaran (Grenville) Orogeny, northwest- to north-directed thrusting observed within the supracrustal lithologies and the Archaean crystalline basement is now considered to form part of a major compressional event, that effected major parts of the Kaapvaal Craton and formed in response to the orogenic activity mainly along the southern margin of the craton during the Mesoproterozoic.
   In this regard, the apparent asymmetrical geometry to the collar of the Vredefort Dome is envisaged to have been caused by tectonic modification during the Kibaran (Grenville) compressional event. Uplift and erosion of the southeastern collar region due to northwesterly directed thrusting, resulted in relative shallow, southeasterly dipping supracrustal strata in the east of the dome and the preservation of their impact-related overturned orientation in an arc from southwest to northeast.

2. Mesoproterozoic tectono-magmatic evolution of the Kaapvaal Craton and Namaqua-Natal Orogeny

   Based on a structural analysis of the Orange Free State Goldfield, a compilation of published structural data from the Witwatersrand Basin and surrounding areas, as well as available gravity, magnetic, seismic reflection and geochronological data from the Kaapvaal Craton, northwest-directed compressional tectonics have been identified to have operated within the core of the Kaapvaal Craton during the Mesoproterozoic.
   Triggered by the Kibaran (Grenville)-age orogenic processes along the southern margin of the Kaapvaal Craton, the proposed geodynamic model for the Kaapvaal Craton envisages consistent northwest/southeast-directed plate convergence to have introduced two main tectono-magmatic cycles within the interior of the craton.
   Initial orogenic activity along the southern craton margin during the time interval of approximately 1450-1250 Ma led to reactivation of major terrane boundaries within the interior of the craton and associated alkaline magmatic activity along them.
   The temporally weakly constraint deformation of the Pongola Supergroup along the southern margin of the Kaapvaal Craton is interpreted to represent this initial phase of the Kibaran (Grenville) orogenic cycle.
   Following a period of about 50 Ma of relative magmatic quiescence, the main Kibaran (Grenville) orogenic phase within the Namaqua-Natal mobile belt introduced intense northwest-directed thrust tectonics to the core of the Kaapvaal Craton, the formation of the "Pilanesberg Graben System" as a pull-apart rift ahead of the Kibaran (Grenville) fold and thrust belt, and the initiation of a second phase of alkaline magmatic activity, closely associated with the pull-apart graben system during the approximate time interval 1200-1000 Ma.

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