ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

THE KALAHARI FORELAND, ITS MARGINAL TROUGHS AND OVERTHRUST BELTS, AND THE REGIONAL STRUCTURE OF BOTSWANA

by

D. A. PRETORIUS

INFORMATION CIRCULAR No.169

UNIVERSITY OF THE WITWATERSRAND

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ABSTRACT

The two core-components of the Southern African Craton are the Rhodesia and Kaapvaal stable blocks, separated by the Limpopo Mobile Belt. The Rhodesia Block extends southwestwards, under the Kalahari formations, into Botswana and the Kaapvaal Block northwestwards. Where Precambrian strata emerge, in South West Africa, from beneath the Kalahari cover, the basement of the terrane is constituted by mobile-belt assemblages, much younger in age than the basements of the Rhodesia and Kaapvaal blocks. The key to understanding the extent and configuration of the Southern African Craton, at least as it existed at the close of Precambrian times, clearly lies beneath the Kalahari of Botswana.

In South Africa, it has been well established that the Natal Mobile Belt has been thrust northwestwards over the Kaapvaal Block and the Namaqualand Mobile Belt northeastwards. In South West Africa, the Damara Mobile Belt is overthrust southeastwards onto a basement, the origins of which still have to be determined. There is evidence of overthrusting in the Limpopo Mobile Belt, northwestwards onto the Rhodesia Block. The Mocambique Mobile Belt has been transported westwards and the Zambezi Mobile Belt southeastwards onto the Rhodesia Province.

A study of the computed depth to the magnetic basement under Botswana suggests that the limits of the Rhodesia and Kaapvaal blocks take the form of typical marginal overthrust belts : imbricated folded nappes, with relatively elevated magnetic basements; foreland-fold basins or marginal troughs, with deeply-depressed magnetic basements; hinge-zones, serving as loci for igneous activity, with moderately-deep magnetic basements; and foreland platforms, with relatively shallow magnetic basements. In northern and northwestern Botswana, the northeastwards-striking Gobabis-Gantsi-Maun-Livingstone front thrusts Rehoboth-Sinclair-Kgwebe-Ghanzi-Muva formations over the Zambezi Marginal Trough, in which the magnetic basement reaches a maximum depth in excess of 15 000 metres below surface in the Passarge Basin. The hinge-zone, marked by the Xade positive magnetic anomaly and its extensions, follows the 2 500-metre-depth contour. In western Botswana, the overthrust-front lies outside the territory, somewhere between the Botswana-South West Africa border and a line through Mariental and Keetmanshoop, while the axis of the Gemsbok Marginal Trough cuts across the border, with depths to the magnetic basement in excess of 15 000 metres occurring in the Ncojane and Nosop basins. The hinge-zone also follows the 2 500-metre-depth contour and can be traced along the Tshane positive magnetic anomaly. Between the hinge-zones and the exposures of Precambrian rocks in northeastern, eastern, and southeastern Botswana, the platform of the Kalahari Foreland has been deformed into a series of regional upwarps and downwarps which trend northwestwards. The distance between the axes of the warps is 170-230 kilometres. The most conspicuous of these regional structures, which plunge off the Rhodesia and Kaapvaal stable blocks into the Zambezi and Gemsbok marginal troughs, is the Francistown Re-entrant

running from the Limpopo-Shashi confluence, through the Makgadikgadi Pans, towards the Okavango Delta. To the northeast, this upwarp is flanked by the Wankie Embayment in Zimbabwe. To the southwest, the flanking Kweneng Embayment is succeeded by the Werda Re-entrant, and this, in turn, by the Gemsbok Embayment.

Overthrusting of the Natal, Namaqualand, and Damara-Katanga terranes onto the Rhodesia and Kaapvaal provinces was associated with centripetally-directed forces which elevated the circumscribing mobile-belt nappes and depressed the foreland marginal troughs, platforms, and stable-block cores. The platforms and blocks consequently remained essentially negative regions of the crust for most of the Precambrian, thereby providing the mechanism which favoured the remarkable degree of preservation of Proterozoic basins in the eastern and central segments of Southern Africa. Compensatory elevation of the depressed Kalahari Foreland probably commenced only in Mesozoic times, after the break-up of Gondwanaland, and is still taking place.

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THE KALAHARI FORELAND, ITS MARGINAL TROUGHS AND OVERTHRUST BELTS, AND THE REGIONAL STRUCTURE OF BOTSWANA

Magnetic Trends and Regimes and the Structure of Botswana

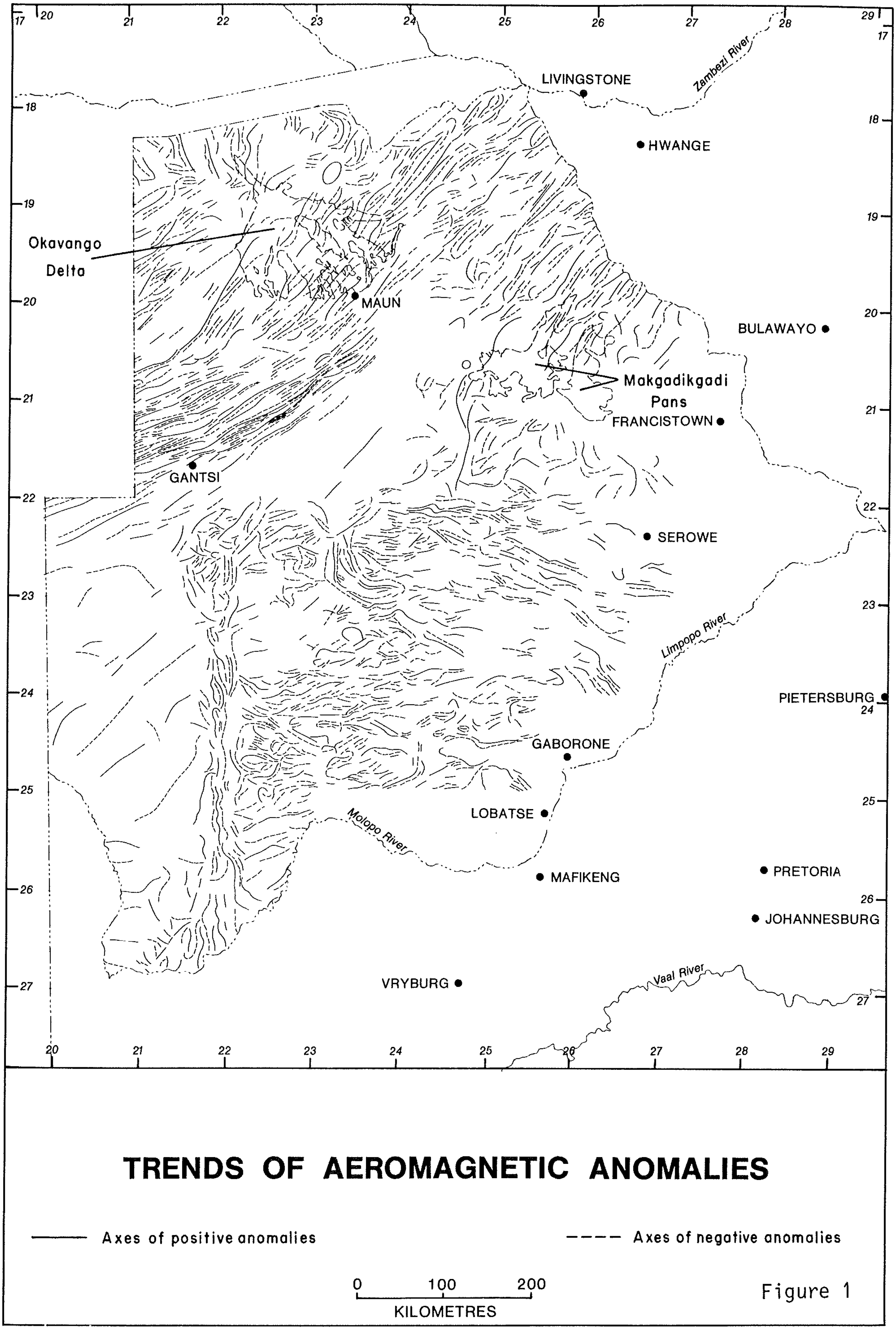
At the conclusion of the early assessments of the results of the regional aeromagnetic survey of Botswana, Pretorius (1978) stated that : "The major part of the areal extent of Botswana constitutes one of two large tracts of Southern Africa still remaining relatively unexplored in regard to the potential for mineralization in Precambrian rocks .... Therefore, as a basis for encouraging mineral exploration in Botswana, the first two essential operations are : (i) the determination of the areal variations in thickness of the Phanerozoic cover, and (ii) the decipherment of the nature, extent, and structure of the Precambrian formations which underlie the central, northern, southern, and western parts of the country". Since then, an appreciable volume of new data has become available on the possible structure of that terrane beneath the Kalahari cover, as a result of follow-up drilling operations in Botswana and of geological mapping of the regions of exposed Precambrian strata in surrounding territories. Justification, therefore, seemed to exist for attempting to advance structural knowledge through a re-examination of the original geophysical data, in the light of some of the novel concepts put forward by several workers in the field of structural geology. Because of its more intense coverage of the Kalahari region, emphasis was placed on re-looking at the results of the aeromagnetic survey, rather than on the results of the gravimetric studies. Heed was paid to Reeves's (1978) remark that "..... it is certain that the full potential of the aeromagnetic survey and interpretation has not yet been realized ......".

The trends and patterns in the contoured aeromagnetic data are portrayed in Figures 1 and 2. In the former, the strikes of the axes of positive and negative anomalies have been abstracted, and, in the latter, the distribution and extent of the different regimes of varying magnetic intensity have been depicted. The significance and possible origin of these features in the magnetic field have been discussed by Reeves (1978; 1979), Pretorius (1978; 1979), Hutchins and Reeves (1980), and Reeves and Hutchins (1982). All of these investigators agreed that the following broad-scale variations can be seen in the aeromagnetic maps of Botswana :

(1) the pattern of the magnetic field in northern and northwestern Botswana is quite different to that in the western, central, southern, eastern, and northeastern portions of the territory;

(2) in the northern and northwestern regions, two subdivisions can be recognized — a northwesterly one of low-intermediate magnetic intensity associated with the presence of Damara-age rocks close to the surface and a southeasterly one of intermediate-high magnetic intensity over the Kgwebe and Ghanzi formations of the Sinclair Sequence;

(3) the boundary between the two subdivisions is along, or just to the south of, a narrow zone of very high magnetic intensity striking northeastwards through the central portion of the Okavango Delta;



TRENDS OF AEROMAGNETIC ANOMALIES

—— Axes of positive anomalies

- - - - Axes of negative anomalies

Figure 1

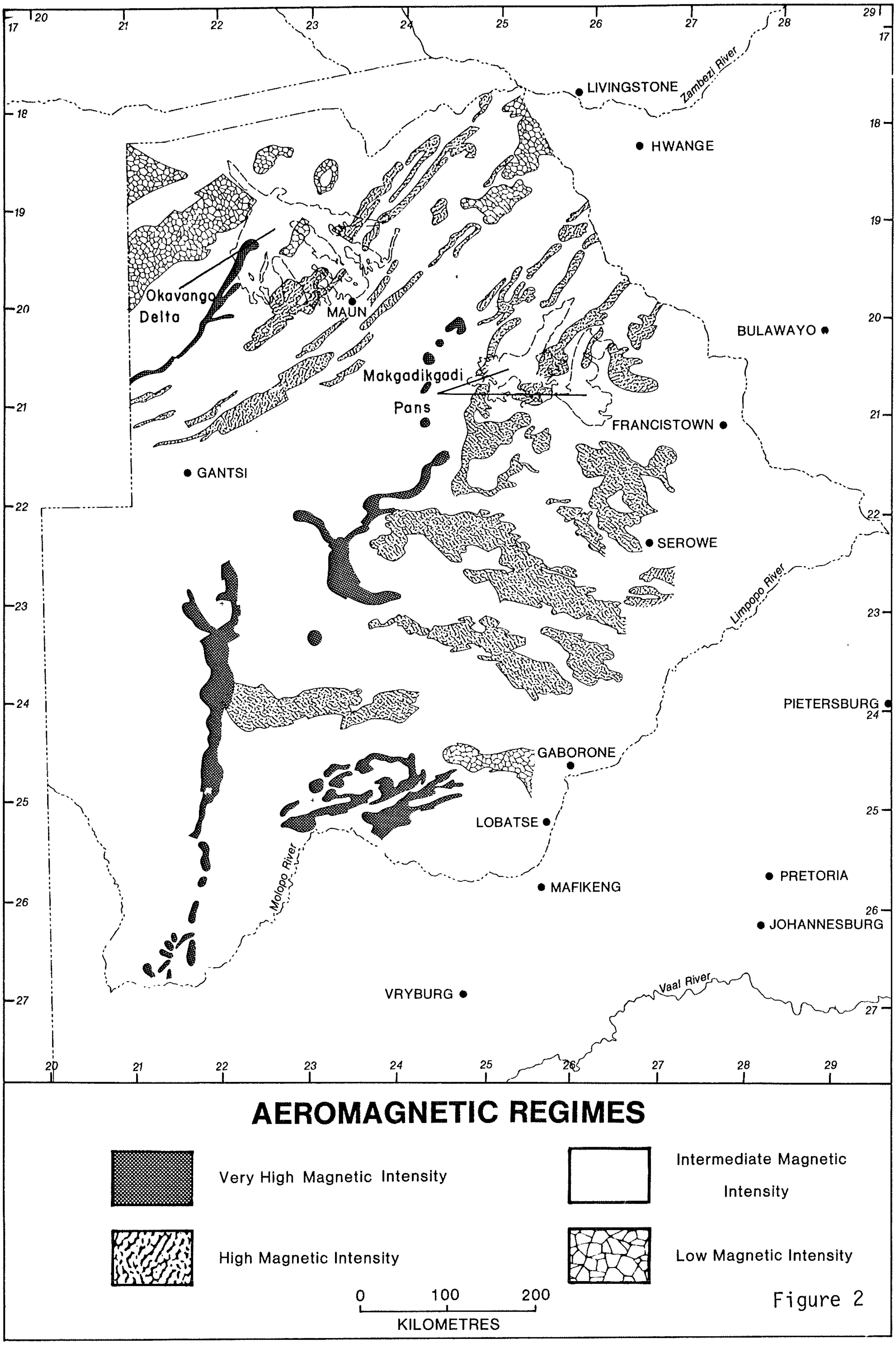

LIVINGSTONE
Zambezi River
HWANGE
Okavango
Delta
MAUN
BULAWAYO
Makgadikgadi
Pans
FRANCISTOWN
GANTSI
SEROWE
Limpopo River
PIETERSBURG
GABORONE
LOBATSE
Molopo River
MAFIKENG
PRETORIA
JOHANNESBURG
VRYBURG
Vaal River
AEROMAGNETIC REGIMES
Very High Magnetic Intensity
Intermediate Magnetic Intensity
High Magnetic Intensity
Low Magnetic Intensity
0
100
200
KILOMETRES

Figure 2

(4) the positive and negative anomalies are more closely spaced over the Kgwebe and Ghanzi rocks, and the closures of some of the anomalies point to tight folding in the Gantsi-Chobe Fold-belt which stretches northeastwards from Gobabis, in South West Africa, through Gantsi and Maun, towards Livingstone, in Zambia;

(5) there is a very abrupt termination of the Gantsi-Chobe trends and patterns along a southwest-northeast line which is located south of Gantsi and Maun;

(6) in the large region southeast of the Gantsi-Chobe Fold-belt, there are six conspicuous regimes of very high magnetic intensity — (a) an arc of small isolated anomalies between Maun and the Makgadikgadi Pans; (b) an irregular, sinuous belt south of Maun and southeast of Gantsi, containing the prominent Xade positive anomaly (Reeves, 1978); (c) an isolated, circular anomaly, south-southeast of Gantsi and southwest of the Xade anomaly, named the Tsetseng feature (Reeves, 1978); (d) a U-shaped anomaly south of Gantsi; (e) a long, relatively straight anomaly trending slightly east of north from the Molopo River to the U-shaped anomaly south of Gantsi, and containing the conspicuous Tshane sub-anomaly (Reeves, 1978); and (f) the large, ellipsoidal anomaly north and northeast of the big bend in the Molopo River, west of Lobatse, which is developed over the Molopo Farms basic igneous complex (Reeves, 1978);

(7) the remainder of the region southeast of the Gantsi-Chobe Fold-belt is characterized by alternating belts of intermediate and high magnetic intensity associated with the Archean basement and its Proterozoic cover, composing the Rhodesia and Kaapvaal structural provinces;

(8) there is a belt of intermediate magnetic intensity, with few anomalous features, trending northeastwards and lying between the Gantsi-Chobe Fold-belt and the three zones of very high magnetic intensity south of Gantsi and southeast of Maun; and

(9) there is a wide belt of intermediate magnetic intensity, with no sharply-defined anomalous features, striking north-south between the South West African border and the Tshane anomaly.

The Major Lineaments Observable in the Aeromagnetic Field

Reeves (1978) postulated three major lineaments as being revealed within the magnetic data and as being confirmed, to a certain degree, by the results of the gravimetric survey :

(1) the Makgadikgadi Line, extending from the southern end of the U-shaped positive anomaly, south of Gantsi, through the Xade anomaly, and along the line of discontinuous, very-high-intensity anomalies west of the Makgadikgadi Pans;

(2) the Kalahari Line along the Tshane positive anomalies, located between the Molopo River and the southern end of the U-shaped anomaly; and

(3) the Zoetfontein Fault, running from the South African border, north-east of Gaborone, west-southwestwards, past the northern limit of the Molopo Farms Complex, to the middle section of the Kalahari Line.

The Makgadikgadi Line was interpreted by Reeves (1978) as the linear boundary between the Irumide-age folds, as exemplified in the Gantsi-Chobe Fold-belt, to the northwest, and the older cratons of Southern Africa. Hutchins and Reeves (1980) regarded this lineament as a tectonic front "separating the more recently tectonised rocks of the northwest from the stable cratonic regions of southern and eastern Botswana", and Reeves and Hutchins (1982) believed it to be the front of the Proterozoic metamorphism and tectonism which is readily observable in the northwestern sections of Botswana.

The Kalahari Line, according to the conclusions of Reeves (1978), separates basements of a fundamentally different nature on the west and the east, and he considered the lineament to be a possible obduction zone, marking a suture along the line of collision of a block of possibly oceanic material to the west and a block of continental material to the east. Reeves (1979) offered the interpretation that "the Kalahari Line is marked by a transition from a high magnetic level with deeply-seated magnetic features in the west, to an average magnetic level with a multitude of shallow magnetic features in the east". Reeves and Hutchins (1982) regarded the Tshane anomaly, on the Kalahari Line, as indicating an ophiolite suite obducted onto a continental block at a convergent plate boundary and concluded that the lineament defined the western limit of the Archean rocks of the Kaapvaal Province.

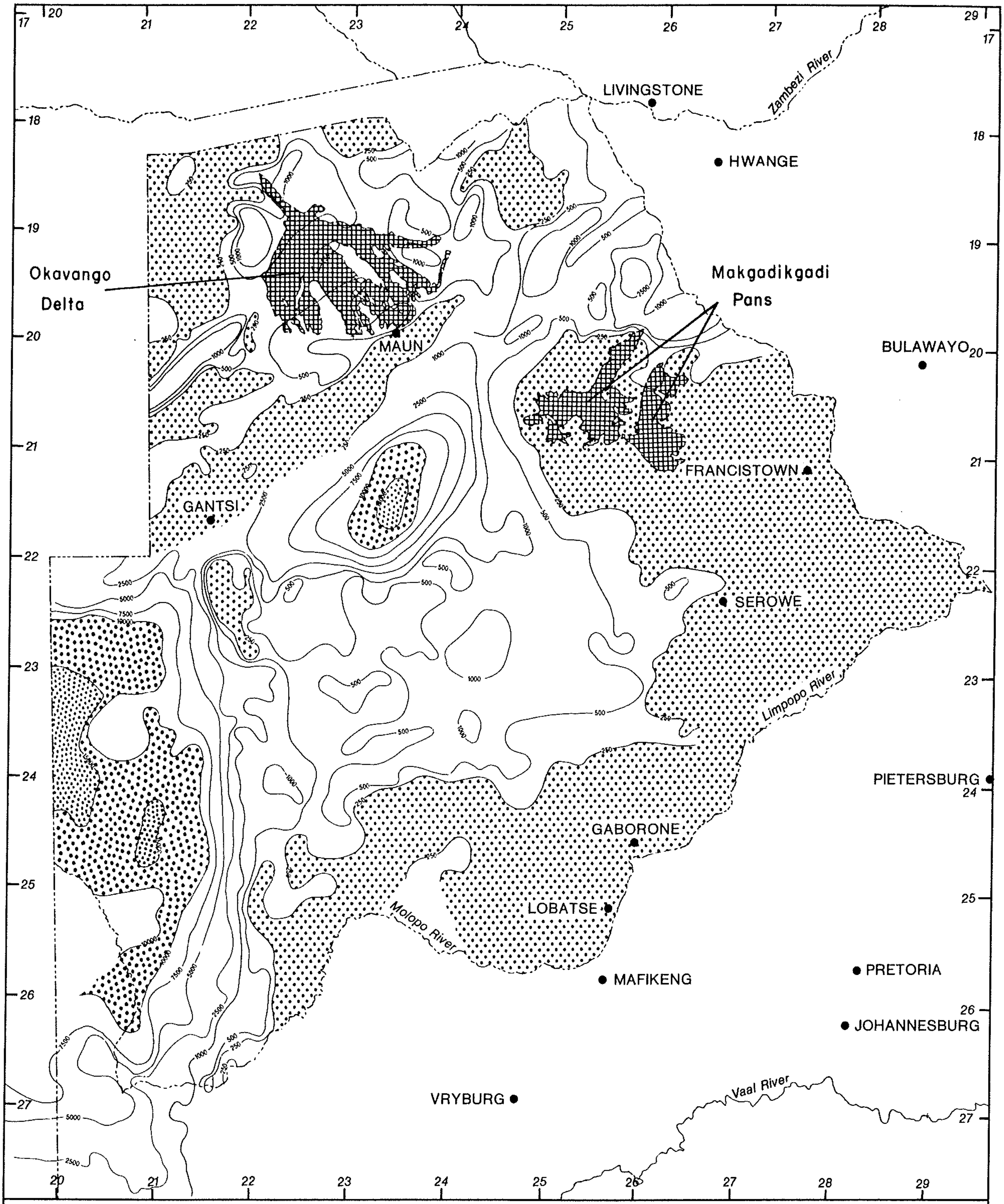
The northern limit to the Kaapvaal Block was considered by Reeves (1978) to be along the Zoetfontein Fault which is a normal dislocation, with a downthrown side to the north. This fault was also regarded as defining the southern limit of preservation of almost all the Karoo rocks in Botswana.

Although recognizing the obvious presence of the Kalahari Line and the Zoetfontein Fault, Pretorius (1978; 1979) did not identify the linear Makgadikgadi Line in his interpretation of the aeromagnetic data. Instead, he proposed that the boundary between the main magnetic regimes in northwestern Botswana is represented by a linear, northeast-southwest feature extending from Livingstone to Gantsi, located between 100 and 200 km northwest of the Makgadikgadi Line. This lineament was thought to connect with the Deka Fault in northwestern Zimbabwe. Pretorius (1978; 1979) also described another major linear feature running from Walvis Bay, in South West Africa, to the southern region of Zambia. In northwestern Botswana, this lineament passes through the centre of the Okavango Delta, connecting the Okahandja Lineament of South West Africa with the Mwembeshi Dislocation Zone of Zambia. The boundary between the Damara and Gantsi-Chobe fold-belts was seen as lying along, or close to, this lineament.

The Morphology of the Surface of the Magnetic Basement

The most revealing information on the sub-Kalahari regional structure is that provided by the contour-map of the estimated depths to the magnetic basement (Figure 3). Any interpretation of the possible configuration of the Precambrian formations has to take cognizance of the following features which are displayed on the contour-map :

(1) the region northwest of a line between Gantsi and Livingstone is characterized by a basement at a depth of less than 2500 metres below surface,



ESTIMATED DEPTHS TO MAGNETIC BASEMENT

> 15 000 metres   10 – 15 000 metres   < 250 metres   Delta and Pans

0   100   200
KILOMETRES

Figure 3

with about 50 per cent of the area being very shallow, at less than 250 metres depth; the region can be classified, in general terms, as having a shallow magnetic basement;

(2) the peripheral region of Botswana, along the northeastern border with Zimbabwe and the eastern border with South Africa, has a very shallow magnetic basement, over which the depth does not exceed 250 metres;

(3) the central region, contained between Gantsi, Maun, Serowe, and Gaborone, has a shallow-intermediate basement, over which the depths range from 250 to 2500 metres;

(4) the strip of country along the Kalahari Line, from south of Gantsi to the Molopo River, is characterized by depths of 250-1000 metres, indicating a shallow basement;

(5) the area east of Gantsi and south of Maun is underlain by a conspicuously-deep magnetic basement, with estimates of more than 15000 metres having been made;

(6) the region between the South West African border and the Kalahari Line has an equally-deep magnetic basement, with depths in excess of 15000 metres also being recorded;

(7) the axes of inflection in the configurations of the depth-contours trend southwest-northeast to the northwest of the Gantsi-Livingstone line, but are aligned south-north and southeast-northwest to the southeast of this line;

(8) the southern axes of inflection are developed along a series of alternating re-entrants and embayments defined by northwestwards convexities and concavities, respectively, in the sinuous disposition of the depth-contours;

(9) from southwest to northeast, across Botswana, the succession of regional upwarps and downwarps is — (a) the Gemsbok Embayment, the deepest parts in Botswana of which are the Ncojane and Nosop basins (Reeves, 1978; Jones, 1979; Hutchins and Reeves, 1980); (b) the Werda re-entrant, striking from east of the big bend in the Molopo River to south of Gantsi, with its northern extremity constituted by the very shallow Okwa basement (Reeves, 1978); (c) the Kweneng Embayment, extending from between Lobatse and Serowe to between Gantsi and Maun, the deepest segment of which is the Passarge Basin (Reeves, 1978, 1979; Hutchins and Reeves, 1980); (d) the Francistown Re-entrant, on which the Makgadikgadi Pans are developed and along which a wide and extensive post-Karoo dyke-swarm has been intruded from the Limpopo valley, through Francistown and the Makgadikgadi Pans, to beyond the Okavango Delta (Reeves, 1978, 1979); and (e) the Wankie Embayment, extending from Bulawayo northwestwards to Livingstone;

(10) the northwesterly-trending downwarps, two of which are represented by the Kweneng and Wankie embayments had an influence on Karoo sedimentation, since the preferential siting of coal deposits in Botswana is along the former and in Zimbabwe along the latter; and

(11) the axes of the embayments and re-entrants and the patterns of the depth-contours around the Passarge, Ncojane, and Nosop basins terminate

abruptly against the southeastern boundary of the Gantsi-Chobe Fold-belt; clearly, there is a major structural discontinuity along this boundary, with a substantially-more-elevated magnetic basement on the northwest and a very much deeper basement on the southeast; to this discontinuity has been given the name 'Tsau Fault-zone', since Reeves (1978) noted that the boundary between the Gantsi-Chobe Fold-belt and the Passarge Basin could be placed along he Great Tsau Hill; previously, the discontinuity was considered to be marked by the Botletle Fault and the southwestwards extension of the Deka Fault (Pretorius, 1979).

In his first report on the interpretation of the results of the aeromagnetic survey, Reeves (1978) described the Passarge Basin, 200 km east of Gantsi, as occurring over the deepest magnetic basement, and as containing a very thick accumulation of non-magnetic sediments represented by non-tectonized equivalents of the Ghanzi Formation and, possibly, some younger Nama rocks. He added : "The Ghanzi-Chobe fold belt is separated from the eastern and central basement by a strip within which, for the most part, the magnetic basement is interpreted as very deep. The southeast boundary to this strip is coincident with the Makgadikgadi Line .....". No interpretation was offered as to the structural nature of, or the tectonic factors responsible for, the Passarge Basin. The structure of the deep Ncojane and Nosop basins also was not explained. In a further consideration of the subsurface geology of the Kalahari, as determined from the results of the aeromagnetic investigations, Reeves (1979) depicted, in a northwest-southeast section through the Passarge Basin, the deep magnetic basement as underlying a syncline containing Ghanzi and Nama formations below a Karoo cover. To the northwest, this syncline is followed by an anticline, with an elevated crystalline basement of possible Irumide age, and, then, another syncline, containing Kgwebe and Ghanzi formations of the Gantsi-Chobe Fold-belt. To the southeast, the Passarge syncline is separated from the eastern and central Archean basement by the Makgadikgadi Line. A west-east section through the Nosop Basin (Reeves, 1979) showed the thrusting of possibly-Proterozoic sediments over a syncline of Kheis rocks on the edge of the Archean basement of the Kaapvaal Province. Two westwards-dipping faults, possibly listric in their geometry, were included as part of the Kalahari Line. Reeves (1979) again left the tectonics of the Passarge, Ncojane, and Nosop basins unexplained.

Hutchins and Reeves (1980) referred to tectonic fronts, without defining their nature and genesis, as separating the Damara Fold-belt from the Irumide-age Gantsi-Chobe Fold-belt, and the latter from the Rhodesia and Kaapvaal blocks. Tectonic fronts were also mentioned as forming the boundaries between the Cape Fold-belt and the Namaqua metamorphic terrane and between the Natal-Namaqua assemblage of metamorphic rocks and the Kaapvaal Province. The observation was also made that the structural provinces showed progressive younging towards the northwest, in the case of the former two fold-belts, and towards the southwest with respect to the Natal-Namaqua and Cape belts. The only tectonic front specifically described was the Makgadikgadi Line, "separating the more recently tectonised rocks of the northwest from the stable cratonic regions of southern and eastern Botswana". By favouring the Kalahari Line as indicating the presence of a zone of obduction, Reeves and Hutchins (1982) implied that overthrusting had taken place along this particular tectonic front.

Jones (1979) put forward a positive interpretation of the structure responsible for the regions of deep magnetic basement in Botswana : "A medial rift separates the craton areas from the Damarides and in northwest Botswana this widens to a substantial region. Within this graben the basement is depressed in several areas to depths well in excess of 10km". This medial rift, striking southwest-northeast between the Gantsi-Chobe Fold-belt and the Makgadikgadi Line, was reported as being 30 km wide in the northeast and 200 km wide in the southwest. An intimation that a possible rift structure might be present over the deep magnetic basement was given by Reeves (1978) in stating that the feature projected northeastward into the Lake Kariba area of Zimbabwe, where rift-faulting has been observed by other investigators. The Deka Fault was considered to be co-linear with the margin of the central and eastern basement. The very deep magnetic basement in the southwestern segment of Botswana was thought by Jones (1979) to be associated with a north-south branch, hosting the Ncojane and Nosop basins, of the medial rift containing the Passarge Basin. Pretorius (1979), in his interpretation of the mechanism of formation of the Passarge Basin stated : "The fact that the magnetic basement is very deep ..... adjacent to the Botletle-Deka fault zone ..... might well be the product of considerable drag of supracrustal formations downwards on the southeastern, upthrown side of the zone", but no opinion was offered as to whether the drag was the result of normal faulting or overthrusting.

The First-Order Structures of Botswana

The sub-Kalahari structure of Botswana, as deduced from the first interpretations of the results of the gravimetric and aeromagnetic surveys of the territory by Reeves (1978; 1979), Pretorius (1978; 1979), Jones (1979), Hutchins and Reeves (1980), and Reeves and Hutchins (1982), is portrayed in Figure 4, which represents a northwest-southeast section from the Caprivi Strip to the area between Serowe and Gaborone. A Bouguer anomaly profile and the various magnetic regimes along the section are also shown. Within this generalized section, the following components have been identified, but not all included in Figure 4 :

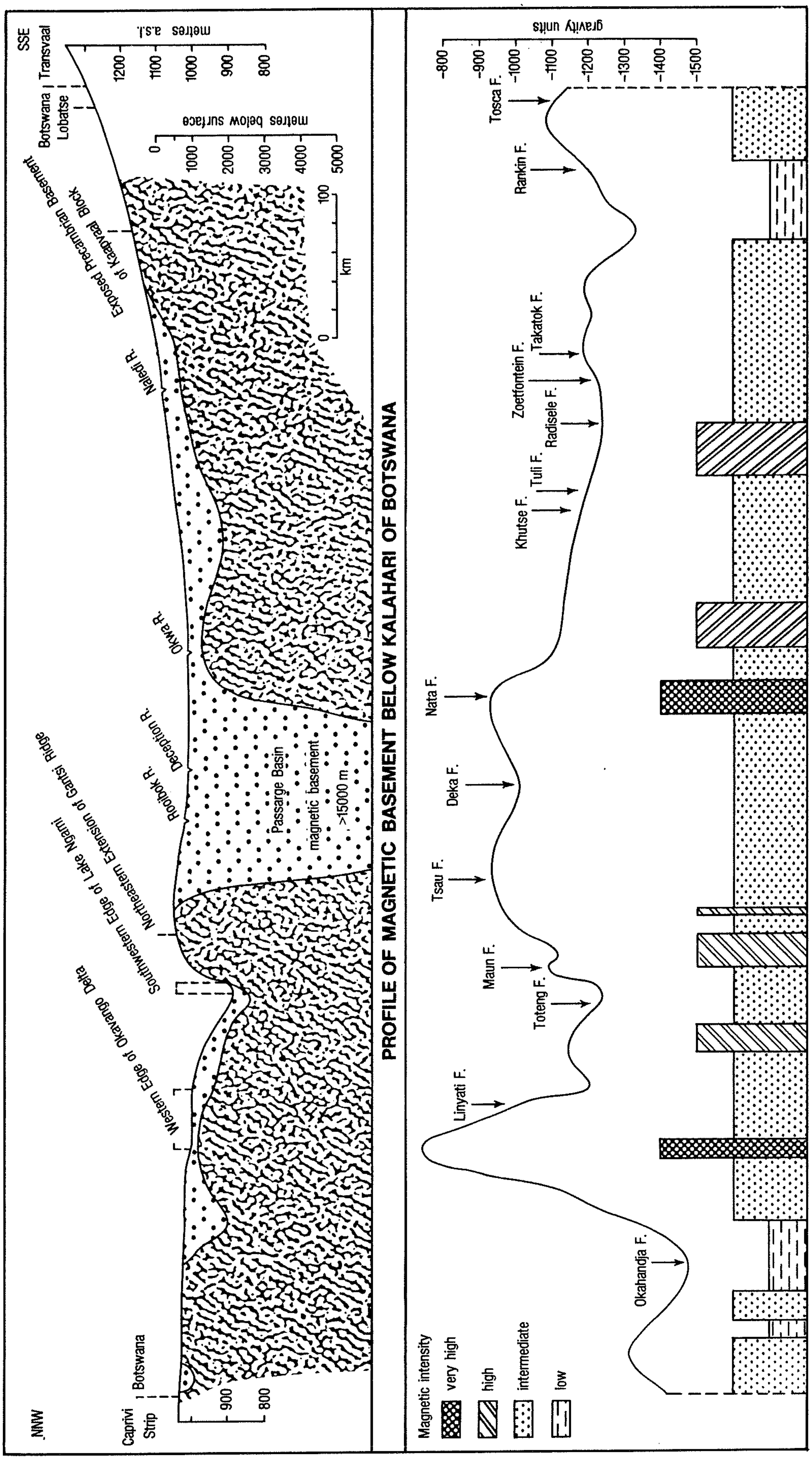
(1) a most-northwesterly region of shallow Damara-Katanga formations;

(2) the Okahandja-Mwembeshi Fault-zone, with an apparent downthrow to the southeast — a tectonic front between the Damara belt and the Irumide belt (Hutchins and Reeves, 1980); a suture zone (Pretorius, 1979);

(3) the Gantsi-Chobe Fold-belt, with a shallow-intermediate basement — originally, a product of the Irumide orogenic episode, refolded during Damaran deformation (Reeves, 1979);

(4) the Tsau Fault-zone, with an apparent downthrow to the southeast — the Botletle-Deka Fault-zone of Pretorius (1979), postulated as the boundary between Late Proterozoic and Archean-Early Proterozoic formations; not recognized by Reeves (1979; 1980), Hutchins and Reeves (1980), and Reeves and Hutchins (1982);

(5) the Passarge Basin, with a deep-very deep magnetic basement — a syncline (Reeves, 1979); a graben (Jones, 1979); a downdrag on the Tsau Fault-zone (Pretorius, 1979);



PROFILE OF MAGNETIC BASEMENT BELOW KALAHARI OF BOTSWANA
NNW
SSE
Caprivi Strip
Botswana
Botswana
Transvaal
Lobatse
metres a.s.l.
1200
1100
1000
900
800
metres below surface
0
1000
2000
3000
4000
5000
0
100
km
Exposed Precambrian Basement of Kaapvaal Block
Nata R.
Okwa R.
Deception R.
Rooibok R.
Northeastern Extension of Gantsi Ridge
Southwestern Edge of Lake Ngami
Western Edge of Okavango Delta
Passarge Basin
magnetic basement
>15000 m
BOUGUER ANOMALIES AND SMOOTHED AEROMAGNETIC INTENSITY
gravity units
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
Tosca F.
Rankin F.
Takatok F.
Zoetfontein F.
Radisele F.
Tuli F.
Khutse F.
Nata F.
Deka F.
Tsau F.
Maun F.
Toteng F.
Linyati F.
Okahandja F.
Magnetic intensity
very high
high
intermediate
low

Figure 4

(6) The Makgadikgadi Line, delineated by a magnetic signature of very high intensity, as exemplified by the Xade anomaly — tectonic front between the Irumide-age orogenic belt and the Rhodesia and Kaapvaal cratons (Reeves, 1978, 1979; Hutchins and Reeves, 1980); Reeves and Hutchins, 1982); not recognized by Pretorius (1978; 1979).

(7) the Kweneng Embayment, with an intermediate-depth basement — the central basement of Reeves (1978);

(8) the Zoetfontein Fault, with an apparent downthrow to the northwest — a tectonic front marking the northwestern limit of the Kaapvaal craton (Reeves, 1978, 1979); and

(9) a most-southeasterly region of shallow Archean-Early Proterozoic basement.

A structural section along a southwest-northeast line, approximately at right-angles to the one described above, between the extreme southwestern corner of Botswana and Francistown would reveal the following features :

(1) the Gemsbok Embayment of deep basement, with the deepest portion being the Ncojane and Nosop basins — a southerly branch of the medial rift (Jones, 1979);

(2) the Kalahari Line, delineated by a signature of very high magnetic intensity, as exemplified by the Tshane anomaly — tectonic front marking the western limit of the Kaapvaal craton (Reeves, 1978, 1979; Hutchins and Reeves, 1980; Reeves and Hutchins, 1982); collision zone-suture line between oceanic material to the west and continental material to the east (Reeves, 1978); thrust-front with westwards-dipping listric dislocations (Reeves, 1979); obduction zone with an ophiolite suite at a convergent plate boundary (Reeves, 1978; Reeves and Hutchins, 1982);

(3) the Werda Re-entrant, with a shallow basement — the southern basement of Reeves (1978);

(4) the Zoetfontein Fault;

(5) the Kweneng Embayment of intermediate-depth basement;

(6) the Francistown Re-entrant, with a shallow basement — uplifted and collapsed, failed third arm of a triple junction, with a post-Karoo dyke-swarm trending N117°W over a width averaging 100 km (Reeves, 1979); and

(7) the Wankie Embayment of intermediate-depth basement.

An Alternative Interpretation of the First-Order Structures

That the above interpretations of the structure of Botswana can bear re-examination has a basis in the statements of Pretorius (1978) : "..... Botswana must have a distinctive structural setting. The central and western parts are underlain by the conjunction of at least five of the six domains which (are disposed around) the territory. In the absence of Precambrian exposures, it has not been possible to ascertain ..... how far into Botswana each of the metallo-tectonic domains penetrates, nor what form the boundaries between the various crustal fragments take ..... The regional structure would appear to be more in the nature of a mosaic of very large fault-blocks, across which continuity of geological formations once existed, than of discrete cratons or tectonic provinces, each with its own individual history of evolution", and Pretorius (1979) : "Six different groupings of faults and other major lineaments have been identified from the results of the aeromagnetic survey. The more persistent of these strike northeast and north-northwest".

(a) *The Passarge Deep Basement*

The most conspicuous of the northeasterly faults is the Tsau dislocation, delineating the northwestern limit to the Passarge Basin. According to Jones (1979), this fault is the one boundary of the medial rift, the other wall being the Makgadikgadi Line (Reeves, 1978). It is believed that the true nature of the Tsau Fault-zone can be ascertained by examining the geological structures along the northeastern and southwestern projections of the alleged medial graben.

In the Zambezi Valley, the southeastern limit of the Muva-age gneisses and granites to the northwest of Lake Kariba is co-linear with the southeastern limit of the Gantsi-Chobe Fold-belt (Reeves, 1978). The gneisses have long been regarded as having been tectonically transported by thrusting southeastwards from Zambia, in a manner similar to that in which the Damara rocks were moved southeastwards in South West Africa (Martin and Porada, 1977b). The Urungwe Klippe, on the southern foreland of the Zambezi Fold-belt, has been compared by Martin and Porada (1977a) as occupying the same tectonic setting as the Naukluft Klippe in South West Africa, adding weight to the argument that the Irumide orogenic belt of Zambia has been thrust over the foreland of Zimbabwe. Coward (1980) concluded that the Rhodesia Block, as a whole, has moved southwestwards between the thrusts of the Zambezi and Limpopo fold-belts. Further support for the conclusion that the Zambezi Fold-belt had been thrust southwestwards over Zimbabwe has been provided by Coward and Daly (1984).

If the southeastern limit of the Irumide-age fold-belt in Zambia and Zimbabwe is an overthrust-zone, then it is logical to assume that the southeastern limit of the Gantsi-Chobe Fold-belt, co-linear with the former limit (Reeves, 1978), might also be represented by an overthrust dislocation, by which the Kgwebe and Ghanzi formations of the Sinclair Sequence, of post-1500-Ma age have been moved over the Archean and Lower-Middle Proterozoic rocks, of pre-1500-Ma age, of the Rhodesia Block and its southwestwards extension into central Botswana. The Passarge deep basement would then be underlying, not a medial rift or graben, but a marginal trough on the foreland side of a thrust-front.

Even more convincing evidence of the nature of the Tsau Fault-zone is displayed along the southwestwards extension of the feature, where good exposures of pre-Karoo rocks and detailed mapping in South West Africa have revealed the presence of several thrusts, affecting both Damara and Sinclair formations and the basements on which these rest. The Geological Survey of South West Africa (1982), in its explanation of a geological map of the territory, stated that the Damara Sequence terminates in "an intensely thrusted southern margin". Martin and Porada (1977a) reported that the Damara Fold-belt showed, in a southwards direction, a progressively more-intense imprint of overfolding, shearing, and thrusting, with slices of basement involved in the thrusting. Still farther southwards, the Naukluft Klippe is the remnant of a large nappe complex of Damara rocks. Coward and Daly (1984) concluded that the major strike-faults of the central part of South West Africa were originally left-lateral wrenches, but were later re-activated as overthrusts verging to the southeast. The southern limit of the Sinclair and Rehoboth formations is covered by Nama and Karoo strata, so that there is only a small amount of geological evidence, visible on outcrop, pointing to the continued development of thrust-fronts to the south of those delineating the termination of the Damara rocks. However, the patterns in the gravity field over the area between Windhoek, Gobabis, and Mariental (Figure 5) indicate a discontinuity in the inflection-axes of Bouguer trend-lines as abrupt and as unequivocal as that between the Gantsi-Chobe Fold-belt and the Passarge Basin, southwest, south, and east of Gantsi.

The above considerations favour the conclusion that there is but little evidence for the presence of a graben, of a size suggesting considerable crustal extension, in a region where compression seems to have been dominant. The tectonic fabrics of both South West Africa and Zambia indicate appreciable thrusting, to the southeast, of Irumide and Pan-African tectono-metamorphic belts. There might well be signs of extensional tectonics, but the data from Zimbabwe and Botswana, particularly, support the deduction that such crustal stretching was essentially post-Karoo. On the basis of the observed structures, the gravimetric field, and the interpreted tectonics of the territories adjacent to Botswana, it is put forward that the structural section presented in Figure 4 can be reconstructed to take the form depicted in Figure 6, illustrating the following points :

(1) the deeply-depressed magnetic basement under the Passarge Basin could be the bottom of an underthrust marginal trough of the Kalahari Foreland to the Rhodesia and Kaapvaal stable blocks;

(2) the Gantsi-Chobe Fold-belt, with a basement of Rehoboth-age (1300-1600 Ma) and Sinclair-age (1000-1300 Ma) rocks, could have been thrust over, along the Maun and Tsau fault-zones, the Rhodesia or Kaapvaal blocks in the first, more-obvious episodes of compressional tectonics; the age of this thrusting could be post-Rehoboth (equivalent to the 1300 Ma-age Kibaride episode) and post-Sinclair (equivalent to the 1000 Ma-age Irumide, Namaquide, Natalide episodes);

(3) thereafter, the Damara Fold-belt, with a 1000 Ma-age basement, could have been thrust over the older Gantsi-Chobe Fold-belt, with dislocation along more than one thrust, producing more than one folded nappe; the age of this thrusting would then be Pan-African (500 Ma); further movement more-than-likely took place on the Tsau and Maun fault-zones, when the Linyati and Okahandja fault-zones were at their most active;

(4) the Zambezi Marginal Trough, at the leading edge of the Tsau thrust-front, could have started filling with molasse-type sediments from the end of Rehoboth times; therefore, it could contain Rehoboth-, Sinclair-, and Damara-age erosional debris below the unexpectedly thin Karoo cover which has been indicated by geophysics and drilling over the Passarge Basin;

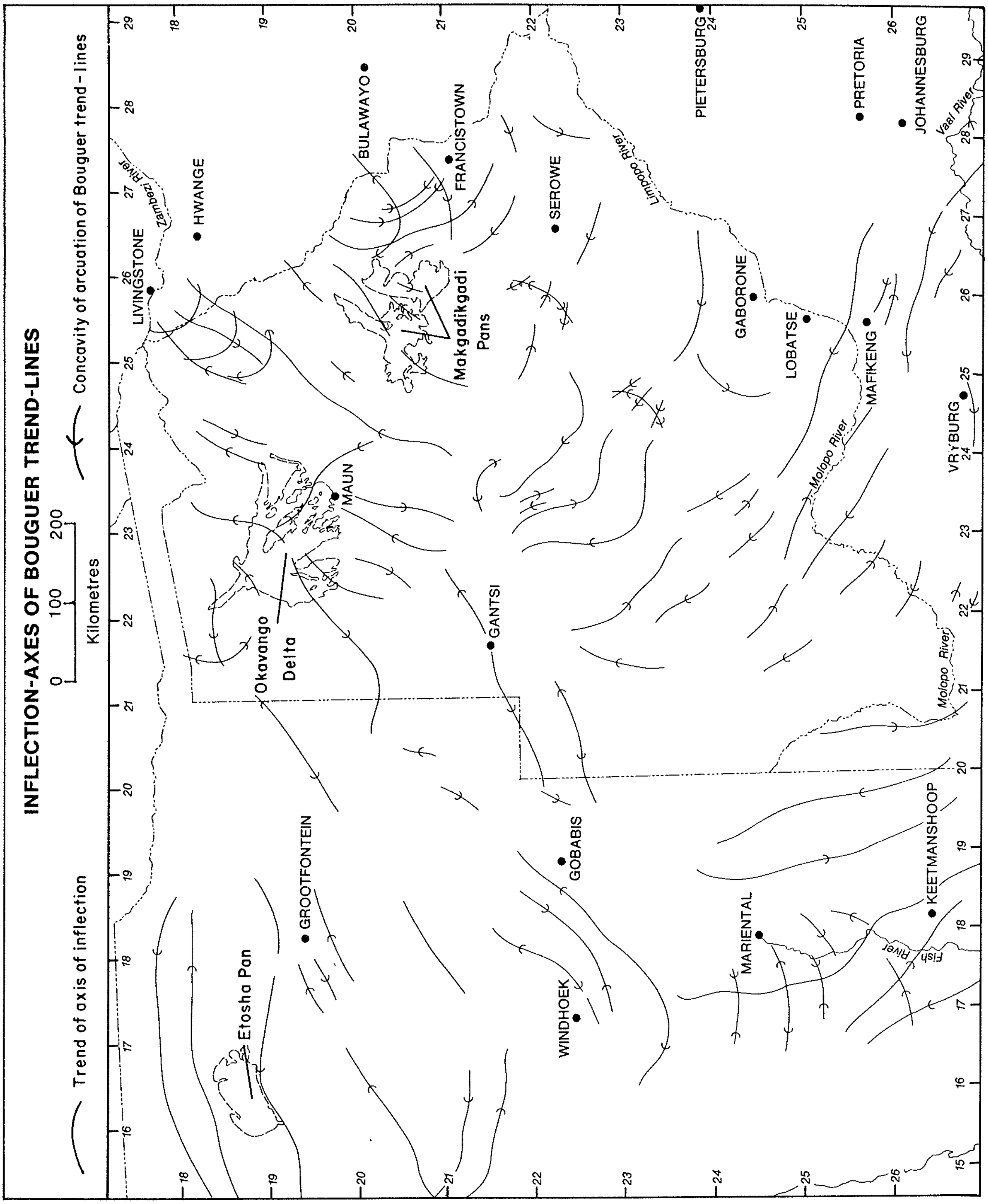
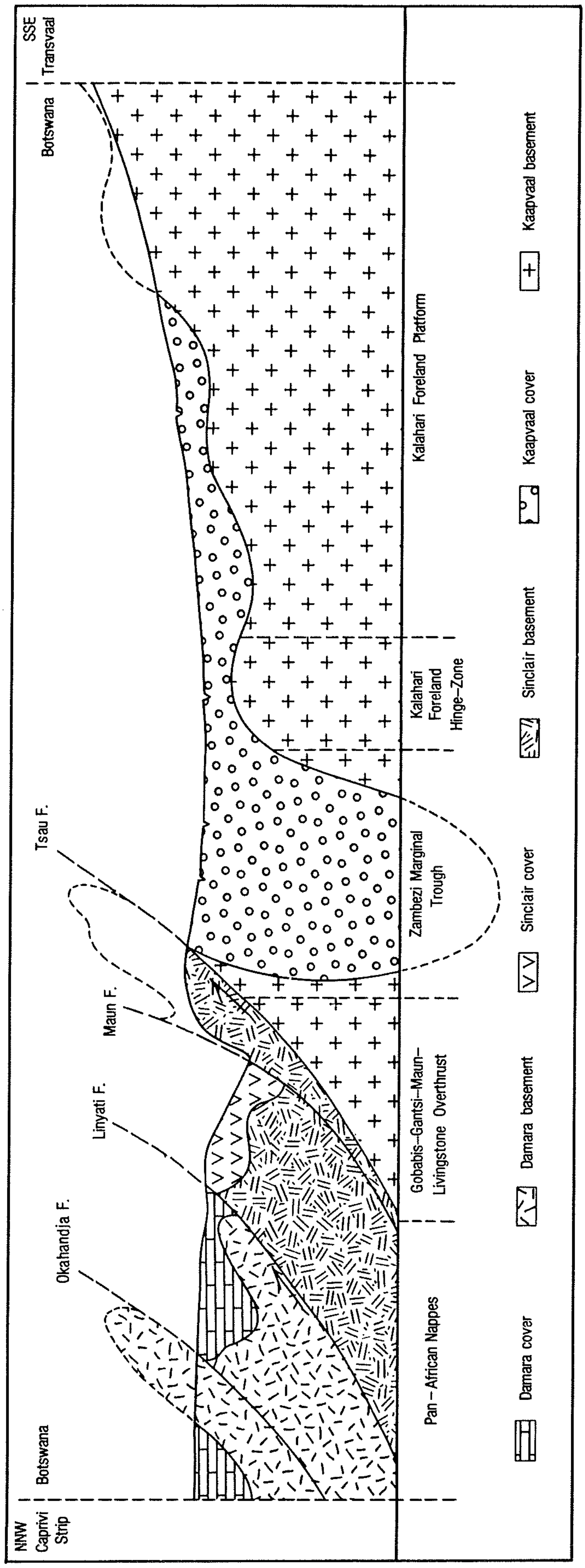

INFLECTION-AXES OF BOUGUER TREND-LINES
Trend of axis of inflection
Concavity of arcuation of Bouguer trend-lines
0
100
200
Kilometres
LIVINGSTONE
HWANGE
BULAWAYO
FRANCISTOWN
SEROWE
PIETERSBURG
PRETORIA
JOHANNESBURG
GABORONE
LOBATSE
MAFIKENG
VRYBURG
Makgadikgadi Pans
MAUN
Okavango Delta
GANTSI
GOBABIS
WINDHOEK
GROOTFONTEIN
Etosha Pan
MARIENTAL
KEETMANSHOOP
Zambezi River
Limpopo River
Molopo River
Vaal River
Fish River

Figure 5



PROFILE ACROSS THE DAMARA-SINCLAIR OVERTHRUST AND THE KALAHARI FORELAND

Figure 6

(5) if overthrusting has taken place on the Maun and Tsau thrust-zones, then the Lake Ngami and Okavango Delta areas, to the northwest, could be underlain by underthrust formations of the Rhodesia or Kaapvaal provinces;

(6) sections through overthrust belts and underthrust terranes throughout the world show the thrust-front side of the marginal trough to be steeply-dipping and the platform-side to be less so, with considerable flattening of the dip over a hinge-zone separating the marginal trough from the foreland; hinge-line zones are characterized by flexuring and crustal extension, with the conditions of tension frequently favouring the emplacement of igneous intrusions;

(7) the hinge-zone between the Zambezi Marginal Trough and the Kalahari Foreland Platform contains a conspicuous positive magnetic anomaly, following a sinuous trace and containing the very prominent Xade feature; drilling has disclosed the presence of noritic quartz gabbro under the Xade anomaly (Meixner and Peart, 1983); and

(8) the Kalahari Foreland Platform, which would include the central and eastern basements of Reeves (1978), shows a progressive thinning south-eastwards of the Phanerozoic cover, until Proterozoic and Archean formations are exposed in the region straddling the border between Botswana and the Transvaal.

(b) The Ncojane and Nosop Deep Basements

An alternative explanation, to its being the southern branch of the medial rift proposed by Jones (1979), for the development of the deep magnetic basement below the Gemsbok Embayment might lie in the application of a similar thrust-front-marginal-trough model to the southwestern segment of Botswana. Only a part of the Gemsbok Marginal Trough would then occur in Botswana, an unknown proportion being situated in the eastern and south-eastern regions of South West Africa. Basins other than the Ncojane and Nosop depressions could be anticipated within the embayment. Unfortunately, the well-developed cover of Kalahari, Karoo, and Nama formations and the non-availability of magnetic data render it impossible, at this stage, to define the complete geometry of the Gemsbok trough.

The depth-contours of Figure 3 point to the Gemsbok structure as being of about the same length as the Passarge trough, but much wider. A westward projection of a section through the Nosop and Ncojane basins could place the thrust-front somewhere in the vicinity of a line between Mariental and Keetmanshoop. Some support for this suggestion is contained in Figure 5 which shows a persistent inflection-axis in the trends of the Bouguer anomalies as running from east of Keetmanshoop to west of Mariental. This north-northwesterly axis which, from the direction of arcuation of the Bouguer trend-lines, would appear to be along a zone of uplift, terminates abruptly against the Tsau discontinuity in the gravity trends. Five other inflection-axes, between the Fish and Molopo rivers, parallel the Mariental-Keetmanshoop feature, and the whole assemblage might be considered as constituting a broad zone of thrusting on the transport side of the Gemsbok trough, in the same manner as all the faults between the Okahandja and Tsau thrusts form part of the overthrust terrane on the northwest side of the Zambezi Marginal Trough.

Farther to the west of the postulated thrust-front zone, the Gariep formations, of an equivalent age to the Damara rocks, have been thrust eastwards (Geological Survey of South West Africa, 1982). The coastal belt of southwestern South West Africa and western Namaqualand has been identified by Kröner and Jackson (1974) as an "imbricated, eastward-directed thrust-front". Later, Martin and Porada (1977b) confirmed that, south of Lüderitz, the re-entrant of Gariep formations is thrust eastwards and northeastwards over the Namaqualand Mobile Belt. Davis and Coward (1982) also viewed the Gariep arc as representing an obducted mass overthrust, in imbricate slices, southeastwards and eastwards over the undeformed foreland.

The shallowing of the basement along Reeves's (1978) Kalahari Line can be interpreted as marking the position of the hinge-zone between the Gemsbok Marginal Trough and the Kalahari Foreland Platform. The zone of very high magnetic anomalies, containing the Tshane feature, could then be regarded as the product of intrusion of basic igneous bodies into the rifted terrane over the hinge-zone. Drilling has encountered the presence of noritic quartz gabbros under the magnetic anomalies, these igneous rocks being very similar to those found under the hinge-zone flanking the Zambezi trough (Meixner and Peart, 1983). In the Gemsbok hinge-zone, the magnetic anomalies are relatively straight, whereas in the Zambezi hinge-zone they are sinuous and highly folded, the axes of the deformations trending in a north-northwesterly direction, perhaps significantly parallel to the strike of the thrust fronts postulated on the western side of the Gemsbok trough. This interpretation of the Kalahari Line as being part of a hinge-zone displaying extensional tectonic responses, between a thrust-front-marginal trough and a foreland platform contrasts strongly with Reeves's (1978) conclusions that the Line marks a compressive zone of obduction of oceanic floor from the west onto continental cratonic crust on the east.

In summary, it might be stated that, in the light of well-documented evidence of overthrusting, at about 500 Ma, of Damara-equivalent rocks eastwards over the southwestern portion of South West Africa, it is not unreasonable to assume that another major thrust-front lies to the immediate west of the Gemsbok marginal trough. If so, then the Namaqualand metamorphic terrane could have been thrust over formations of possible Rehoboth and Sinclair age at about 1000 Ma. A west-east section through southern Botswana would then look very similar to the northwest-southeast one through central Botswana (Figure 6). The Gemsbok Marginal Trough, at the leading edge of a possible 1000-Ma thrust-front, would be the equivalent of the Zambezi trough in front of the Tsau overthrust, also of an age of possibly 1000 Ma. The hinge-zone containing the Tshane positive magnetic anomalies of the Kalahari Line, associated with gabbroic intrusions, would be the equivalent of the hinge-zone containing the Xade positive magnetic anomalies, also correlated with gabbroic bodies. The foreland lying to the east of the hinge-zone containing the Kalahari Line, and believed to be underlain by Archean and Proterozoic formations of the Rhodesia and Kaapvaal blocks, would be the equivalent of the foreland situated to the southeast of the hinge-zone containing the Makgadikgadi Line and also thought to be composed of Precambrian formations of the Rhodesia and Kaapvaal provinces.

Implications for the Tectonics of Southern Africa

The interpretation of the regional structure of Botswana presently proposed has the southwestern extension of the Rhodesia Province overthrust from the northwest by post-1500 Ma rocks of the Gantsi-Chobe and Damara fold-belts and the northwest extension of the Kaapvaal Province overthrust from the west by the post-1500 Ma formations of the Namaqua and Gariep fold-belts. For the regions lying to the northwest, west, and southwest of Botswana, the structural relations of the Namaqua, Gariep, Rehoboth, Sinclair, and Damara belts have been discussed in arriving at the new conclusions concerning the structure of the Kalahari Foreland and its flanking marginal troughs and bounding overthrust-fronts. To fit Botswana into the crustal architecture of the sub-continent, it is necessary to consider the other tectonic fronts which have been identified and described to the south, east, and northeast of the territory.

The boundary between the Namaqua metamorphic terrane and the Kaapvaal Block has been described by Botha and Grobler (1979) as hosting isoclinal folds, overturned to the east, with their axes oriented in a north-south direction. Although no thrusts were observed, they considered the possibility that the signs of earlier thrusting could have been destroyed by later folding. Coward and Potgieter (1983) reported that the Namaqua belt was "involved in major thrusting to the NE followed by strike-slip movement along shear zones parallel to the orogenic front" and that the Doornberg and other faults have the form of a series of thrust sheets with vergence to the southeast and northeast.

The tectonic front to the Natal metamorphic terrane, marking the boundary with the Kaapvaal Block, was recognized, in the pioneering work of Matthews (1972), as a southerly-dipping zone of dislocation in which "a series of thrust-sheets and large imbricate slices have been transported northwards in an ascending sequence, towards the stable foreland".

In the southeastern portion of Zimbabwe, Coward (1980) observed that thrusting from the southeast has taken place along a major fault-zone defining the northwestern limit of the Limpopo metamorphic belt. The gneisses of the mobile belt have been transported over the Archean granites and greenstones. Further thrusting towards the northwest was also described as occurring within the Limpopo Fold-belt (Coward and Daly, 1984), suggesting that the Rhodesia stable block is separated from the Kaapvaal stable block by two or more thrust-slices developed in, and on the edge of, the Limpopo belt.

The boundary between the Mocambique metamorphic terrane and the Rhodesia stable block contains three structural domains, all with a westerly vergence, which collectively are responsible for the Mocambique belt's being overthrust westwards onto Late Proterozoic strata lying on the Rhodesia Block (Johnson and Vail, 1965). Later, Coward and Daly (1984) confirmed that the younger metamorphic terrane has been thrust westwards or west-northwestwards.

The tectonic front to the Zambezi metamorphic belt has been mentioned previously as a thrust-zone, marking the boundary with the Rhodesia Province. Martin and Porada (1977b) reported that the Zambezi terrane has been deformed during southerly-directed tectonic transport, in a manner similar to that observed in the Damara belt. Coward and Daly (1984) supported this conclusion in their statement that the Zambezi orogenic belt has been thrust southwards over Zimbabwe.

As a synthesis of these observations and deductions, Figure 7 has been prepared, in which eleven structural provinces are proposed as constituting the Southern African Craton. Ten tectonic fronts, represented by overthrust-zones, form the boundaries between the provinces. In some of the provinces, hinge-line zones, defined by flexuring, keystone-graben formation, and the intrusion of substantial volumes of basic igneous material, with lesser amounts of felsic rocks, are recognized. Similar hinge-zones, originally developed in the other provinces, possibly have been obliterated by later thrusting and metamorphism associated with the successive generation of younger overthrusts.

From the directions of tectonic transport recorded for each sub-continental-scale dislocation, overthrusting would appear to be centripetally oriented towards the Rhodesia Block. The ages of successive thrust-fronts young radially away from the Rhodesia Province, a pattern which offers confirmation of previous conclusions that the Rhodesia stable block constitutes the nucleus, core, or shield region, of the Southern African Craton (Pretorius, 1973; 1979) and that there is an appearance of continental 'accretion' outwards from this nucleus. This 'accretion' now takes the form of originally more-distal segments of the craton being moved to more-proximal positions, relative to the shield region, by centripetal overthrusting.

The overthrust-fronts and the circum-platform marginal troughs are not considered to be subduction zones produced by plate tectonics in pre-Mesozoic times. Martin and Porada (1977a) have produced evidence to permit a conclusion that the southern margin of the Damara Fold-belt cannot be regarded as a collision-suture and that no good case can be made out for a plate-tectonic model of the Damara Mobile Belt. The Zambezi tectonic front is viewed by Martin and Porada (1977b) as containing tectonically- and thermally-reconstituted Archean basement, and they doubted whether any structures are present which would indicate a continent-continent collision-suture. Similar conclusions were drawn by Martin and Porada (1977b) for the Mocambique Mobile Belt. Botha and Grobler (1979) were disinclined to identify a subduction-zone as occurring along the tectonic front between the Namaqua metamorphic terrane and the Kaapvaal Province. Coward (1980) stated that none of the major shear zones, thrust or wrench, in the Precambrian crust of Southern Africa represents a suture between two plates and that no collision-zones can be found to account for the various mobile belts.

The present re-interpretation of the broad structure of Botswana and surrounding segments of the sub-continent serves to reinforce the deduction of Pretorius (1978) : "The regional structure would appear to be more in the nature of a mosaic of very large fault-blocks, across which continuity of geological formations once existed, than of discrete cratons or tectonic provinces, each with its own individual history of evolution .. ... the structural fabric ..... has continued to re-activate itself repeatedly through geological time". Botha and Grobler (1979) drew a similar conclusion to the effect that most, if not all, Precambrian mobile belts were originally ensialic and evolved through extensive reworking of older stable block areas, this concept invalidating the postulate of

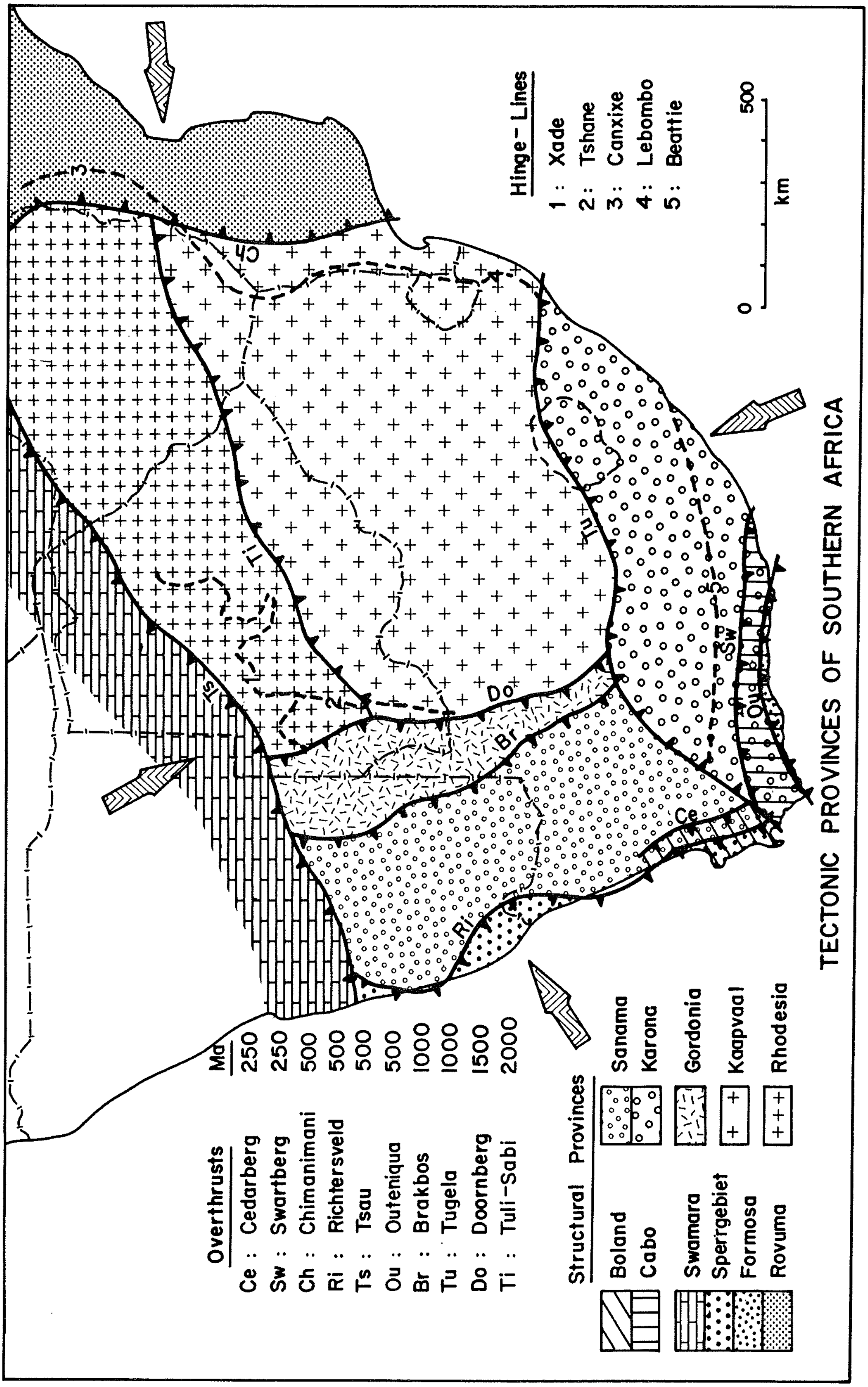

TECTONIC PROVINCES OF SOUTHERN AFRICA
Hinge - Lines
1 : Xade
2 : Tshane
3 : Canxixe
4 : Lebombo
5 : Beattie
0
500
km
Overthrusts
Ma
Ce : Cedarberg 250
Sw : Swartberg 250
Ch : Chimanimani 500
Ri : Richtersveld 500
Ts : Tsau 500
Ou : Outeniqua 500
Br : Brakbos 1000
Tu : Tugela 1000
Do : Doornberg 1500
Ti : Tuli-Sabi 2000
Structural Provinces
Boland
Cabo
Sanama
Karona
Swamara
Sperrgebiet
Gordonia
Formosa
Kaapvaal
Rovuma
Rhodesia
Ce
Sw
Ch
Ri
Ts
Ou
Br
Tu
Do
Ti

Figure 7

successive cratonization and continental growth, but implying successive episodes of destruction of an originally-large continental proto-shield.

It is possibly of significance that three of the four compressional directions depicted in Figure 7 can be accommodated within the post-Mesozoic configuration of plate tectonics. Compression from the west-southwest can be related to the southern Atlantic Ocean spreading ridge, from the south-southeast to the southwestern Indian Ocean spreading ridge, and from the east to the central Indian Ocean spreading ridge. Compression from the north-northwest might indicate that the Damara belt was formed in an aulacogen, as suggested by Martin and Porada (1977a), spreading open both to the southeast, with consequent overthrusting onto the Southern African Craton, and to the northwest, resulting in overthrusting onto the Central African Craton.

Centripetal overthrusting might offer an explanation for the high degree of preservation of Proterozoic-basin assemblages in the Kaapvaal Block and, to a lesser extent, on the Rhodesia Shield. Figure 8 suggests that the over-riding of the Natal nappes northwestwards and the Pan-African nappes southeastwards would have tended to elevate, relatively, the younger strata on the overthrust sides and to depress, relatively, the older rocks on the underthrust sides. Thrusting within the Limpopo belt might also have contributed to further depression of the provinces with the oldest Archean basements. Repeated overthrusting episodically through Precambrian time, at least, would have accentuated the depression of the segments of the Southern African Craton lying closest to the centre of the centripetal configuration. Only after the break-up of Gondwanaland would the formerly-depressed provinces have started rising in response to some form of isostatic compensation, so that uplift and erosion must be of relatively recent age, accounting for the apparently small proportion of Proterozoic sequences stripped away. The Rhodesia Shield might well have risen at a faster rate than the Kaapvaal Block, so that there is a less-impressive state of preservation over the former. Had centripetal overthrusting not been the dominant mode of crustal deformation, then the eastern portion of Southern Africa would have been characterized by large expanses of Archean granite-greenstone basement terrane, with a minimal preservation of the original Proterozoic cover, in which so many of the large and important ore-deposits are to be found.

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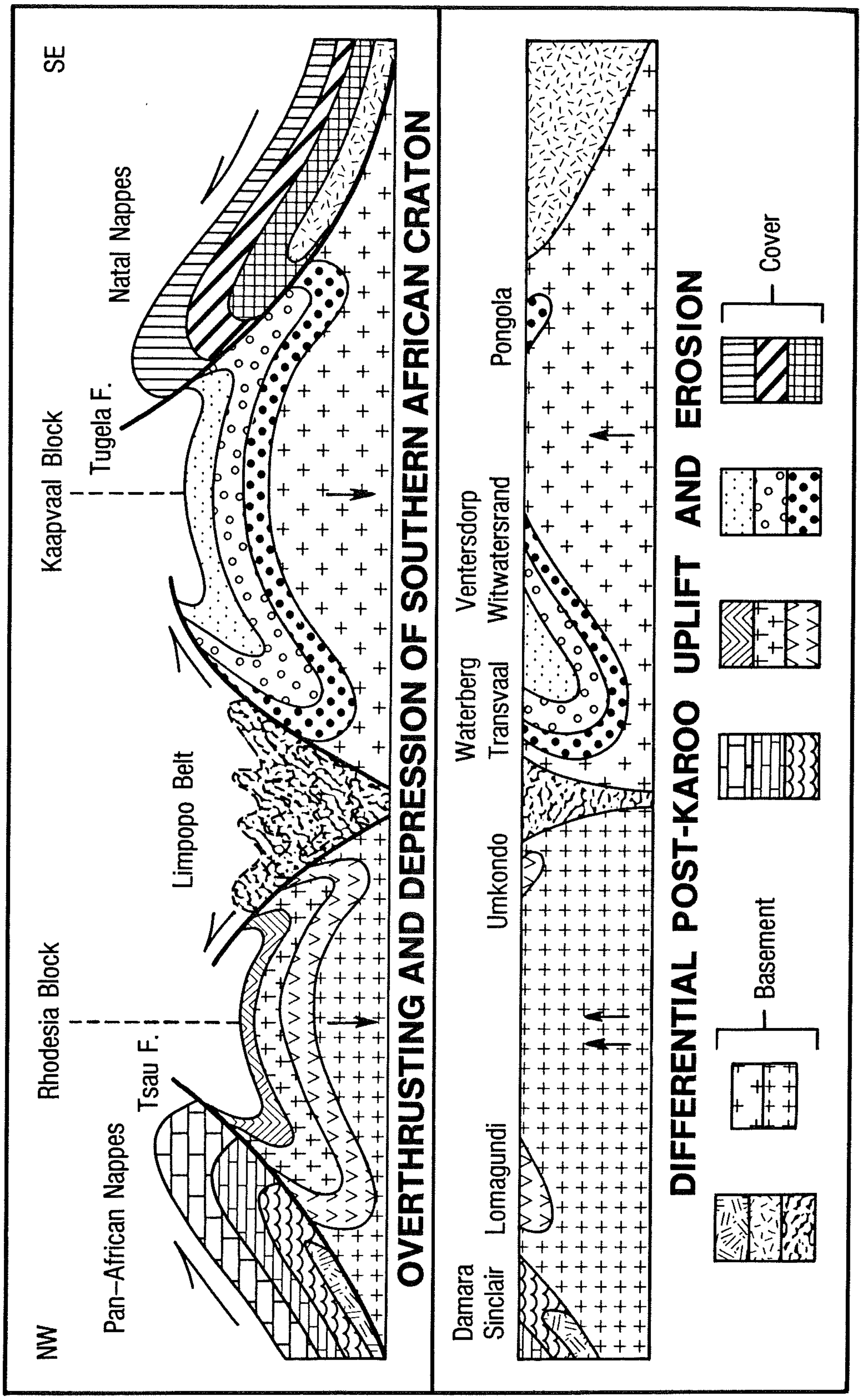
NW
SE
Pan–African Nappes
Rhodesia Block
Tsau F.
Limpopo Belt
Kaapvaal Block
Tugela F.
Natal Nappes
OVERTHRUSTING AND DEPRESSION OF SOUTHERN AFRICAN CRATON
Damara
Sinclair
Lomagundi
Umkondo
Waterberg
Transvaal
Ventersdorp
Witwatersrand
Pongola
DIFFERENTIAL POST-KAROO UPLIFT AND EROSION
Basement
Cover

Figure 8

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