Crustal framework of Namibia derived from magnetic and gravity data

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The National aeromagnetic and gravity data sets covering Namibia and its offshore areas, merged with satellite-derived offshore gravity data and ship-track magnetic data, provide an invaluable basis for mapping regional crustal structure. This study represents an interpretation of these potential field data sets, facilitating the compilation of a more cohesive map of the crustal framework of Namibia. A number of new structural features, both lineaments and ring structures, are identified. Merging with the offshore data has also facilitated the mapping of the extensions offshore of the major tectono-stratigraphic domains and associated domain boundaries. Major intrusions and intrusive complexes are shown in relation to the mapped structures and a number of intrusions have been newly identified. The mapped structural framework provides an important basis for mineral exploration thinking and strategy. In particular, the ring structures, major lineaments and lineament zones, and their associated intrusions, could provide the conduits for and sources of mineralising fluids respectively.

" It was difficult to understand why their (zebra close by) clear, bright eyes didn't spot me. . . . . The explanation must therefore lie in an inability to interpret what the eye saw. But wasn't interpretation the essential prerequisite of recognition . . . and also a form of judgment?"

The Sheltering Desert
Henno Martin, 1983

Introduction

The regional aeromagnetic data set of Namibia, acquired mostly at a 1 km line spacing, has been significantly enhanced in recent years in two respects, i.e. firstly, by the ongoing National programme of the Geological Survey of Namibia to improve the resolution to a 200 m line spacing and, secondly, by the addition of an offshore data set extending 250 km out to sea. The latter was acquired at a square-grid line spacing of 25 km under contract to the National Petroleum Corporation of Namibia (Pty) Ltd (Namcor). The onshore data set is discussed by Eberle *et al.* (1995), who also outline its contribution to crustal evolution and mineralisation distribution. Onshore gravity coverage is much more sparse in terms of data density. Nevertheless, it provides valuable regional structural information when combined with the offshore satellite-derived gravity data. The above data sets provide an excellent basis for mapping both regional crustal structure as well as for more focused mapping in the case of the higher resolution surveys.

The present study is directed towards the geophysical mapping of the regional crustal framework of Namibia, including the offshore continental domain. Onshore emphasis is placed on the identification of large-scale structures, including major faults, lineaments and ring structures, many of which have escaped attention in past studies of the potential field data. Henno Martin's experience (excerpt above) with the zebra, which failed to see him at close range, is a fitting analogy of what may escape the eye when studying the earth using geophysical data. The identified structures are tied in with the tectono-stratigraphic domains as delineated by Petzel and Schreiber (1999). Much of what is presented in this study is, in the first instance, observational, identifying many new features and thus laying a basis for further research on the nature, genesis and implications of the lineaments and ring structures. An analysis of the geological nature of the tectono-stratigraphic domains is not part of the scope of this study. The interested reader is referred to Miller (1983) for an overview of the Damaran terranes.

A number of transformations and filters have been applied to the above data sets in order to enhance features of interest. These transformations include pole-reduction, analytical signal, first vertical derivative and trend removal. Real-time imaging (apparent sun-shading and colour palette rotation) of these data sets is applied in order to facilitate identification of structures. Emphasis is placed, firstly, on mapping major faults and crustal lineaments, incorporating those mapped in previous studies in the adjacent Kaapvaal craton (Corner, 1998) where relevant to Namibia; secondly, on identifying the continuity, where evident, of these structures into the offshore domain; thirdly, on identifying crustal boundaries such as the Congo craton, and the onset in the offshore region of extended continental crust; and, lastly, on the disposition of the younger basins in relation to the identified regional lineaments, e.g. the Owambo, Nama and offshore basins. The magnetic and gravity data are interpreted in the offshore areas together with marine seismic data to facilitate understanding of key offshore structural and lithological features.

Data sets

The continental and offshore data sets (sources acknowledged on each map) that have been selected for presentation here are included as the following maps.

Map 1: Continental aeromagnetic data merged with the offshore aeromagnetic and ship-track data.
Map 2: Continental Bouguer gravity data merged with the offshore satellite-derived Bouguer gravity

data; both with a first-order trend removed so as to largely filter out the steep gradients associated with the continental margin.

Map 3: Merged continental and offshore Free Air gravity data sets; the former being included particularly to illustrate the state of isostatic compensation in Namibia (by comparison with Map 5).

Map 4: Merged continental aeromagnetic and offshore Free Air data sets. This data combination best illustrates the continuity of many of the Pan-African and Irumide lineaments into the offshore domain. The major lineaments are overlain on this map so as to assist the reader in locating these directly on the images.

Map 5: Digital terrane model for the Namibian topography juxtaposed against the bathymetric data.

It should be stressed that the above maps are presented here at a highly reduced scale of 1:5 000 000 for the sake of economy in this volume. Also, the presented images reflect only one sun-shaded direction and one colour palette. Thus many of the features, which helped identify certain of the lineaments and ring structures, may not necessarily be easily seen.

Interpretation

In the interpretation map, presented as Map 6, the identified lineaments, major faults, ring structures, and intrusions are shown with respect to major tectonostratigraphic domains. The latter are taken from the preliminary map of Petzel and Schreiber (1999), but are simplified in that fewer sub-zones are shown. Also, the terrane boundaries are modified slightly in places, based on the present mapping of the locality of the major structural boundaries. Certain terranes are extended offshore in this study on the basis primarily of their magnetic signatures. It became apparent that many of the known intrusions lie along, and thus appear to be controlled by, the mapped lineaments or major structures. These intrusions, as well as some newly interpreted ones, are also included in Map 6.

The distinction between a major fault and a lineament is subjective, based in part on the strength or subtlety of their appearance in the images, in part on their continuity over large distances (signifying crustal scale disruption), or in part whether they occur as domain boundaries. The concept of a lineament as spoken of geophysically needs to be clarified here. It often happens that what is seen geophysically as a clear linear or curvi-linear array of deformation patterns, small-scale faulting or intrusive activity may not always manifest itself everywhere along its length at outcrop level. The magnetic and gravity images reflect anomalous sources and their deformation in a range of depths from surface to 3 km or more depending on the size of the causative body and its physical property contrast. This is in contrast to surface data which are the essence of geological mapping, and from which extrapolations are made, for example, by dip inference. A lineament seen geophysically may be considered as a broad linear zone along which an array of continuous or discontinuous structural disruption is seen, as well as possible intrusive activity in places within its swath.

It is important to note that what is shown as a lineament in Map 6, for presentational simplicity, is a line representing only the approximate central locus of a lineament's swath. Broader lineaments are referred to as lineament zones in this text, as (subjectively) distinct from lineaments which appear to have narrower swaths, and from major faults which denote distinct, well focused structures.

Mapping of faults and lineaments has been conducted independently prior to this study, both by the author (unpublished confidential exploration mapping), by Eberle *et al.* (1995) and by Wackerle (1999). The map by Wackerle (1999) shows many, but not all, of the lineaments presented in Map 6, and *vice versa*, as well as many small scale faults which are not the emphasis of the present study. The differences between the Wackerle map and that presented here reflect, in part, the subjectivity of mapping lineaments from geophysical data as well as the availability and use of different data sets and filtered products thereof, e.g. Wackerle did not have the benefit of the offshore data which have played a significant role in the present study. A further difference in emphasis between the two interpretation maps is that Wackerle has subdivided the region into magnetically evident domains, in contrast to Map 6 in which subdivision is based on geologically mapped tectonostratigraphic domains. Thus the scope of two maps is somewhat different and should be viewed in that light. Andritzky (1996) has produced a map of fracture zones, interpreted from satellite data, co-located with mineral deposits and magmatic features. Space constraints here do not allow a comparison of his mapped structures with the results of Map 6, but many correlations between mineralisation and the geophysically mapped lineaments have been noted.

Fundamentally important is that the timing of the mapped structures is often difficult if not impossible to ascertain from geophysical data alone. However, what has become apparent, in this study and that of Corner and Swart (1997), is that many of the known Irumide and Pan-African structures (Map 6) such as the Pofadder Lineament (POL), the Excelsior Lineament (EL), the Welwitschia Lineament (WL), the Autseib Lineament (AUL) and the Omaruru Lineament Zone (OMLZ) have been active as recently at least as the late Mesozoic. This is interpreted from the structural displacement of the offshore magnetic and gravity anomalies of this age. No unique age can therefore necessarily be ascribed to a lineament nor to associated intrusions, but rather activation age limits.

Table 1: Summary list of major features which make up the identified lineaments (abbreviations as in Map 6)

LINEAMENT	MAJOR FEATURES ENCOMPASSED BY THE LINEAMENT SWATH
Pofadder Lineament (POL)	Geologically mapped as a right lateral shear in South Africa (SA), it includes the Tantalite Valley Shear Zone, and extends further WNW as the Kuckaus Mylonite Belt; it is in-part also interpreted from gravity and magnetic data.
Excelsior Lineament (EL)	Geologically mapped in the SE it forms, in part, the boundary between the Rehoboth-Sinclair Zone (RSZ) and Namaqua Terrane (NQT); a clear change in magnetic signature is seen across it from 16°E to 19°E.
TransGondwana Konkiep Structural Zone	This major structural zone is interpreted to encompass the Namaqua Terrane (NQT) and in part the Port Nolloth Terrane (PNT). Within a Gondwana framework, the POL has been recognised by Tankard *et al.* (1995) as continuing into South America. They have linked the Alto Paraguay and Rio de la Plata cratons tectonically to the Namaqua Province in the Mesoproterozoic. Corner and Swart (1997) were of the opinion that the POL was somewhat restrictive laterally. They invoked the broader TransGondwana Konkiep Structural Zone to encompass the Gordonia Province of Tankard *et al.* (1995) as being the southern African continuation of the tectonised belt which separates the above two South American cratons.
Trans-Kalahari Lineament (TKL)	The TKL is clearly evident in the full aeromagnetic coverage of southern Africa as an EW crustal-scale fault. Offshore, it displaces both the hinge zone and the 100-km gravity high, and the gravity high west thereof looses amplitude across it. It is evident in the Namibian magnetic data as a series of EW truncations east of the Klinghardt mountains (north of Witputz) continuing toward Obobogorap in SA. Further east it terminates the Kalahari Trend in the south. It faults deep crustal sources making up the southern portion of the Morokweng Ring structure, as well as those south of Wolmaranstad and Vryburg. It displaces Witwatersrand Group strata near Welkom and Bethlehem. It is possible that the emplacement of the two remanently magnetised bodies east of 18°E as well as the Aukam Complex are related to the TKL.
Nama Lineament (NL)	The NL is the direct NW extension of the fault zone including the Brakbos, Doornberg and Strydenburg faults near Prieska in South Africa. It encompasses a broad array of parallel NW faults, trending NW through Keetmanshoop and Maltahöhe toward Walvis Bay. Along it, progressive downfaulting to the NE into the Nama Basin is seen from the increasing depths of burial of magnetic anomaly sources (within the Rehoboth-Sinclair Terrane). The currently active Hebron fault near Sesriem is the youngest manifestation of faulting on the NL.
Zoetfontein Lineament (ZL)	The ZL is the westward continuation of the Zoetfontein fault zone in Botswana. It is interpreted from Bouguer gravity data as well as from the termination of the NW-trending magnetic anomaly south of Maltahohe. Offshore, it is evidenced by a change in direction of the hinge zone and 100-km gravity high as well as by the displacement of the M11 anomaly and associated seaward-dipping reflectors.
Sandwich Bay Lineament (SBL)	The SBL is the northern bounding fault, approximately along latitude 23.5°S, of major basalt fields to the SE of Rehoboth and straddling the Namibian/Botswana border. Westward continuation is evident in high-resolution magnetic data covering the Southern Margin Zone (SMZ). It is consistent with the Bouguer gravity data.
Okahandja Lineament Zone (OKLZ)	This NE-trending Terrane boundary between Southern Zone (SZ) and Southern Central Zone (CSZ) of the Damara Mobile Belt is well evidenced and documented from geological mapping and aeromagnetic interpretation (e.g. Miller, 1979; Corner, 1983). In part, it hallmarks major down-faulting to the SE, exposing magnetically anomalous lower Damaran stratigraphy within the CSZ to the NW.
Autseib Lineament (AL)	The AL includes the geologically mapped Autseib Fault, and the Otjihorongo thrust to the NE (e.g. Miller, 1983). It is evidenced geophysically as a change in magnetic signature due to relative upliftment of magnetically anomalous lower Nosib Group to the NW.
Omaruru Lineament Zone (OMLZ)	The Omaruru Lineament (OL) of Corner (1983) is the NE-trending terrane boundary between the magnetically anomalous lower Damaran stratigraphy of the CSZ and the magnetically quiet upper Damaran stratigraphy of the CNZ. The OL, and the parallel Autseib Lineament to its north, encompass the CNZ, and are interpreted to be tectonically part of a broader structural zone here termed the Omaruru Lineament Zone. The OMLZ continues northeastwards as the Mesozoic to Cretaceous Waterberg fault bounding the Waterberg Basin (WB). The Cape Seal, Cape Cross, Messum, Brandberg and Paresis Complexes as well as the Otjiwarongo Massif and Grootfontein Mafic Complex all lie along the northern flank of the OMLZ. Offshore it hallmarks the change from the NE- to the north-trending branches of the Damara Orogen. Southwestwards, it continues as the Walvis Fracture Zone.
Opuwo Lineament (OPL)	Evident as faulting in both aeromagnetic and geological data sets, the OPL continues offshore as the Rio Grande Fracture Zone. It is also supported by the Bouguer gravity data.
Purros Lineament (PUL)	This shear zone, geologically recognised in the Kaoko Terrane (e.g. Miller, 1983), is also evident in the aeromagnetic data both onshore and offshore.
Welwitschia Lineament (WL)	The WL is recognised primarily on the basis of the onset of a change in structural style in the western Central Zone where younger NNE directed fold axes are superimposed on the older NE direction (Corner, 1983). Dykes, possibly of Karoo age, have taken advantage of this direction west of the Erongo Complex. Offshore aeromagnetic data clearly show a continuation of the WL to the SW, demarcating the boundary between the CSZ and the SZ.
Kudu Lineament Zone (KULZ)	Major displacement is seen to occur, along the KULZ, of the 100-km gravity high, the hinge zone and the G magnetic anomaly in the vicinity of the Kudu gas field. A series of NNE-trending faults, evident in the magnetic data, are associated with its swath: in the northern portion of Diamond Area 1; west and southwest of Maltahöhe within the Rehoboth-Sinclair Zone (RSZ); near Gibeon; east of Windhoek forming a faulted south-eastern margin of the Southern Margin Zone and the RSZ; bounding the Steinhausen Anomaly in the east; and traversing the Central Zone in that area. Initially seen only in terms of an array of these linear structures, the KULZ also appears to be the approximate locus of the series of major ring structures identified in this study as well as of two major low (probably remanent) magnetic anomalies, i.e. the Steinhausen and Omatako Anomalies. The Hatzium dome structure SE of Maltahöhe also occurs on it.
Owambo Lineament (OWL)	The OWL is seen, in both the regional data and a number of higher resolution data sets, to manifest itself as a series of faults extending from the northern border southward to Oranjemund. In the north, a prominent N-S dyke has also intruded along it. The OWL, at its youngest age limit, is relatively recent as it clearly bounds, in the west, the Khomas Hochland and southern escarpment as well as their associated Free Air anomalies (Maps 3 and 5).
Abbabis Lineament (ABL)	The ABL was initially identified on the basis of the early aeromagnetic data and disposition of basement exposures (Corner, 1983). Intrusions of probable late Damaran age occur at its intersection with the SBL and the OKLZ, and of early Cretaceous age (Erongo Complex) at its intersection with the OMLZ. Its northern continuation may hallmark the western boundary of the Congo craton.
Khoisan Lineament (KHL)	The KHL is seen in high-resolution aeromagnetic data straddling 20°S. The Daneib Complex has been emplaced on the intersection of the KHL, the KULZ and the NNW-trending dyke swarm. The Omatako Anomalies and OMRS are also evident at this intersection. The former are interpreted to arise from remanently or reversely magnetised intrusions. The Sikereti kimberlites may lie within the swath of the KHL. The KHL continues into Botswana where it clearly faults the Kalahari Trend, and into South Africa where it encompasses: the Morokweng Ring Structure; parallel NNW faults and intrusions south and SW of Vryburg; the Kimberley, Koffiefontein and Jagersfontein kimberlite fields; and the Trompsburg Complex.
Note: Reference is made to local place names in Table 1 which are too numerous to include in Map 6. They are nevertheless provided so as to assist other interpreters in locating features using larger format maps.	

Discussion

The interpretation presented in Map 6 contains numerous structures and intrusions. Certain of these features have become evident for the first time, both onshore and as a result of the recent availability of the offshore data (Corner and Swart, 1997). In the experience of the author, regional-scale lineaments as defined above and which potentially traverse hundreds of kilometres can be very real features. However, this view may not always shared by other workers. In order to assist the reader in understanding the basis for drawing the lineaments, a reference table (Table 1) has been compiled which lists and locates the major structural components making up each lineament. Reference is made to local place names in Table 1 which are too numerous to include in Map 6. They are nevertheless provided so as to assist other interpreters in locating features using larger format maps. The major features are discussed individually below. Abbreviations used for these are also given in Map 6. It is worthy of mention that the concept of structural analysis of co-registered onshore and offshore data sets is becoming increasingly of interest in hydrocarbon exploration. A topical example of similar scope to the present study is that of Smethurst (2000), in which tectonic links between the onshore and offshore of western Norway and the North Sea have been studied using magnetic and gravity data.

Offshore continental margin

The margin of the unextended (by Gondwana break-up) continental crust, occurring at the hinge zone in the region west of Walvis Bay down to Lüderitz, falls sharply into focus in the offshore aeromagnetic data set (Maps 1 and 6). East of the hinge zone the offshore trend of the Damara orogeny is clearly seen for the first time. The data have allowed the offshore extensions of the Northern Central-, Southern Central-, and Southern-Zone Terranes to be mapped (Map 6).

Offshore semi-linear gravity highs

At least four major coast-parallel gravity highs are seen in the offshore data. These are structurally disrupted along seaward extensions of major fault lineaments identified in the onshore data, signifying either later reactivation of these lineaments or control by these early lineaments of the architecture of the extended crust. More likely, a combination of both of these scenarios prevailed. The most prominent of these gravity highs lies approximately 100 km offshore and continues along the entire length of the Namibian coastline (referred to here as the 100 km high, see Map 6). Light *et al.* (1992) first reported this anomaly, detected at that time by relatively sparse marine gravity profiles. They favoured a model in which the anomaly arises from a continuous mantle wedge displacing less dense continental material. They did not however discount the possibility of an intrusive or extrusive source. Gladczenko (1994) however proposed that this gravity high represents the shelf edge, particularly in view of a close correlation with the 500m bathymetric contour defining the shelf edge. This does not however explain the other linear gravity highs and cannot be maintained by forward modelling (Corner and Swart, 1999).

In their studies, Corner and Swart (1999) have shown through forward modelling of both the high magnetic and gravity anomalies, using depth-converted interpreted seismic sections as a basis, that the 100-km gravity high is caused primarily by the onset of a major package of seaward dipping reflectors (SDR) defining the hinge zone. The 100-km high is also clearly seen to be associated with the "G" magnetic anomaly along the entire length of the hinge zone. The suboutcrop locality of the SDR's at the hinge zone is delineated in this study from the seismic profiles and is interpreted to be that of a major sequence of basalts (Corner and Swart, 1999). The modelling further suggests that the basalts are interlayered with sediments. The 100-km gravity high occurs either sympathetically over the hinge zone or immediately down dip, as the basaltic sequence starts to thicken. It however loses amplitude completely further seaward as the overlying low-density sedimentary pile neutralises the gravity high due to the basalts, which are nevertheless still seen in the seismic sections at depth. A similar origin is invoked for the gravity highs further out to sea, i.e. correlating with further pulses of basalt extrusion.

This interpretation is in contrast to that of Watts and Fairhead (1999) who have applied a process orientated approach to modelling "edge effect" anomalies such as the 100-km gravity high. The processes which they consider include rifting, sedimentation, and magmatic underplating. By quantifying these they are able to model the edge effect anomalies. These authors do not, however, consider the effect of the basaltic seaward-dipping reflectors, nor do they take cognisance of the associated magnetic anomalies. The modelling of Corner and Swart (1999) clearly shows that the 100-km gravity high, and the associated magnetic anomaly, can be generated in the first order by these basalts. However, in their modelling the regional gravity field has been removed in part. It is this long-wavelength component which is likely to be associated with magmatic underplating. The solution thus probably lies in a combination of both the Corner and Swart (1999) and Watts and Fairhead (1999) models.

Offshore magnetic anomalies

The extension-related magnetic anomalies mapped by a number of previous workers (e.g. Rabinowitz and LeBrecque, 1979; Gladzenko, 1994) as the G, M11, M4 and M2 anomalies are readily evident in the recent offshore data and are thus now more definitively positioned in Map 6. Of major significance are the newly identified trends of M2 and M4 which are seen to converge toward the northern Namibian and Angolan coastlines, in contrast to their earlier placement much further out to sea. This has potential major implications for the relative ages of the northern and southern offshore sedimentary sequences, for relative rates of extension from the southern to northern offshore areas (Corner and Swart, 1997) and for rotation about the Tristan hotspot at this time (Reeves, pers. comm., 2000).

The above results imply that, within the confines of the offshore area bounded by the M2 anomaly in the west, at least, clear oceanic crust cannot be seen within the present data as responses are masked by the SDR's in all data sets. More likely, the region constitutes extended continental crust.

Phoenix Volcanic Province

A major linear, northeast-trending series of gravity highs is seen to flank the Walvis ridge in the north, immediately south of the Rio Grande Fracture Zone (Maps 4 and 6), and is interpreted to be associated with transcurrent faulting and mafic intrusion. The Turonian-Cenomanian Phoenix volcano (PV) (Holtar and Forsberg, 2000) lies where this trend intersects the 100 km offshore gravity high, forming one of a number of intrusions constituting a local volcanic province, here termed the Phoenix Volcanic Province.

Offshore regional-scale faulting

A significant result of this study is that the mapped Mesozoic gravity and magnetic anomalies have been clearly offset along the offshore continuations of a number of Pan-African and Irumide lineaments, e.g. including inter alia the Autseib (AUL), Omaruru (OMLZ), Welwitschia (WL), Transkalahari (TKL), and Pofadder Lineaments (POL). This suggests that these late Proterozoic to early Palaeozoic structures not only determined the architecture of the extended crust but were probably reactivated during the late Mesozoic. Recent to present-day movement has occurred along the seismically active Hebron fault which forms part of the Nama Lineament (NL). An important implication arising from these conclusions is that these structures may have provided potential pathways for the larger drainage systems and hence the focus of major offshore sedimentation, thus controlling the evolution of the offshore basins.

Omaruru and Autseib Lineaments

The Pan-African Omaruru Lineament (Corner, 1983) and the Autseib Lineament (Miller, 1983) are interpreted in this study to be associated parallel features, constituting a broader Omaruru Lineament Zone (OMLZ). The OMLZ, probably the largest regional structure seen to extend from the onshore into the offshore domain, is also clearly evident in the gravity data as the southern boundary of a major linear regional gravity high (Maps 2 and 3). Major structural change is seen across the OMLZ offshore, e.g. the Damaran domains extend further seaward to its south and it hallmarks the change in regional Damaran structural direction from the NE branch to the NNW, coast-parallel branch. The 100-km gravity high and the G and M11 magnetic anomalies show right lateral displacement across the OMLZ. The left lateral displacement of the M4 and M2 anomalies along the OMLZ appears to be of smaller scale and may reflect a later event. The OMLZ is clearly seen in the shiptrack data (beyond the western border of Map 6) to continue southwestward as the Walvis Fracture Zone (WFZ). This phenomenon is interpreted to arise from the likelihood that the Pan-African lineaments constituted a favourable direction at the time of break-up, initiating the WFZ transform fault as the continents moved apart. The WFZ in turn reactivated the Autseib and Omaruru Lineaments as recently as the Cretaceous, as is evidenced in part by the Waterberg Fault which bounds the Waterberg Basin (Map 6). Clemson *et al.* (1997) in their study of basement structure of the Namibian passive margin also note the evidence from offshore seismic data that the Omaruru and Autseib Lineaments were active in post-Karoo times. A similar structural relationship is considered to apply between the Rio Grande Fracture Zone (Walvis Ridge) and the onshore Opuwo Lineament.

The well known line of intrusive complexes, Brandberg, Messum, Cape Cross, and the complex to the southwest of Cape Cross, newly identified in this study and here named the Cape Seal Complex, all lie along the northern flank of the OMLZ (Autseib Lineament, Map 6). Further north-eastward, the Paresis Complex (PC), the Otjiwarongo Massif (OM) and the Grootfontein Mafic Complex (GMC) also lie along the OMLZ.

The intrusive complex, evident offshore of Walvis Bay as a major gravity and magnetic anomaly (Corner and Swart, 1997) and named here the Walvis Bay Complex (WBC), as well as the Erongo Complex (EC), both occur along the southern flank of the OMLZ. These two complexes are interpreted to be similar in that both are capped by Karoo basalts. Evidence for a major confined Karoo basin being located above the WBC is seen in the offshore seismic data (R. Swart, pers. comm. 2000, see schematic outline in Map 6). In both cases the presence of cross cutting lineaments may have played an important role in the emplacement of the intrusions, i.e. the Nama and Abbabis Lineaments respectively.

The Abbabis Lineament

The Abbabis Lineament (ABL, Map 6) was initially identified on the basis of the early aeromagnetic data and disposition of basement exposures in the Damaran Central Zone (Corner, 1983). Intrusions of probable late-Damaran age occur at its intersection with the Sandwich Bay Lineament (SBL) and the Okahandja Lineament Zone (OKLZ). Similarly, early Cretaceous intrusions (Erongo Complex) occur at its intersection with the OMLZ. Its continuation northward is interpreted here as the approximate western margin of the Congo craton.

The Owambo Lineament and major dyke swarms

The approximate limits of the two major dyke swarms in northern Namibia are shown in Map 6. The first, the WNW-trending swarm which traverses the subcontinent, has been interpreted by a number of workers as a Karoo-age failed rift (e.g. Reeves, 1978). The second is a fan-like array of dykes symmetric about the Owambo Lineament (OWL) and bounded in the east by the Tsumeb dyke (TSD). Although some dykes do occur outside the limits shown, their frequency is much less. The origin of the fan-like swarm, and why its apex should coincide with the Paresis Complex, is uncertain. It can be said however that in large part the Owambo basin is encompassed by these dykes suggesting that the dyke swarm responded to significant crustal extension and subsidence at least since Karoo times. The OWL in itself is quite a remarkable feature as it is seen, from both analytical signal data and a number of higher resolution data sets, to manifest itself as a series of faults extending from the northern border southward to Oranjemund. In the north a prominent NS dyke, within the fan-like swarm, has intruded along it. The OWL is assumed at its youngest age limit to be relatively recent, as it clearly bounds the Khomas Hochland and southern escarpment in the west, as well as their associated NS Free Air anomalies (Maps 3 and 5). A number of topographic features are in fact controlled by north-south, post-break-up faulting, e.g. the Windhoek and Onganja grabens.

The TransGondwana Konkiep Structural Zone

Corner and Swart (1997) have termed the zone, flanked by the Pofadder (POL) and Excelsior (EL) Lineaments, as the TransGondwana Konkiep Structural Zone. It encompasses the Namaqua Metamorphic Terrane (NQT) and part of the Port Nolloth Terrane (PNT). Within a Gondwana framework, the Pofadder Lineament has been recognised by Tankard *et al.* (1995; their Tantalite-Valley-Pofadder Lineament Zone) as continuing into South America. They have linked the Alto Paraguay and Rio de la Plata cratons tectonically to the Namaqua Province in the Mesoproterozoic. Corner and Swart (1997) were of the opinion that the Tantallite Valley-Pofadder Lineament Zone was somewhat restrictive laterally. They thus invoked the broader TransGondwana Konkiep Structural Zone, encompassing the Namaqua Terrane in Namibia (Gordonia Province of Tankard *et al.*, 1995), as being the southern African continuation of the tectonised belt which separates the above two South American cratons.

The Nama Lineament

The northwest-trending Nama Lineament (NL) signifies the locus of a series of major parallel faults in which progressive downfaulting to the northeast, into the Nama Basin, is seen from the increasing depths of burial of sources of magnetic anomalies within the Rehoboth-Sinclair Zone (RSZ). The NL is the direct NW extension of the fault zone including the Brakbos, Doornberg and Strydenburg faults near Prieska in South Africa.

Mapping of the more obvious intrusions and intrusive complexes from magnetic data shows extensive intrusive activity in the region encompassed by the TransGondwana Konkiep Structural Zone and the Nama Lineament (NL), e.g. the Aukam Complex (AC) named here, and others shown in Map 6, as yet unnamed.

The Kudu Lineament Zone

This lineament zone (KULZ) has been recognised for some time by the author and others in the mineral exploration community. Offshore, in the vicinity of the Kudu gas field, major apparent right lateral displacement is seen to occur of the 100-km gravity high, the hinge zone and the G magnetic anomaly along the KULZ. A series of NNE-trending faults, evident in the magnetic data, are associated with its swath: e.g. in the northern portion of Diamond Area 1; west and southwest of Maltahöhe; within the Rehoboth-Sinclair Zone (RSZ), east of Windhoek, forming the faulted southeastern margin of the Southern Margin Zone and the RSZ; bounding the Steinhausen anomaly in the east; and traversing the Central Zone in the latter area.

Initially seen only in terms of an array of these linear structures, the KULZ is recognised in this study as also being the approximate locus of the series of major ring structures discussed below and shown in Maps 4 and 6. In view of its parallelism to the Welwitschia Lineament (WL; Corner, 1983), the KULZ is interpreted to be of similar age, at least at its earliest limit, i.e. late Damaran, as it cuts across the northeast Damaran trend. This direction has proved to be important for mineralisation within the Damara (unpublished exploration results).

Regional-scale ring structures and remanent anomalies

The ring structures indicated in Maps 4 and 6, recognised for the first time in this study through real-time imaging of the magnetic and gravity data sets and their transformations, and major low (probably remanent) magnetic anomalies, are seen to lie along the KULZ. These features were not used in any way to identify the KULZ, but their disposition to and possible control by the KULZ is clear from Map 6, perhaps also being influenced by cross-cutting lineaments.

Starting in the south, arcuate structures are seen in the offshore area, flanking the Kudu gas field, in gravity, magnetic and seismic data (see Map 6). These are seen in the magnetic data to form part of a ring structure continuing onshore and encompassing the Marmora (MT) and Port Nolloth (PNT) Terranes. This feature is here named the Chameis Bay Ring Structure (CBRS, Map 6). The origin thereof is uncertain but it correlates with the locality of a long-lived mantle plume proposed by Frimmel *et al.* (1996) and may arise from deep-seated plutonism associated therewith. The question may be asked whether it is coincidence that the Kudu gas field is situated on, or close to, the CBRS and KULZ structures or whether these structures aided the thermal regime required for hydrocarbon maturation.

At least three major ring structures are seen further NNE along the KULZ, named here the Naukluft Ring Structure (NRS), the Rehoboth Ring Structure (RRS) and the Omatako Ring Structure (OMRS). They appear to be associated with possible intrusions as interpreted from the magnetic data and its derivative products. An interesting observation is that both the NRS and RRS encompass major nappe structures, i.e. the Naukluft (NNS, Map 6), Rostock and Naos Nappe Complexes in the case of the NRS, and the Tsebris, Lichtenstein-Auas Nappe Complexes as well as the Rietfontein Basement Complex in the case of the RRS.

Also situated on the KULZ, in a linear array with the above ring structures, are two major low (remanent) magnetic anomalies here named the Steinhausen Anomaly (SA) and the Omatako Anomaly (OMA). The latter, together with an annular zone of high magnetisation surrounding it (the Omatako Ring Structure, OMRS), is one of the most singular regional magnetic anomalies within southern Africa. The OMRS occurs on the intersection of other major lineaments, i.e. the Khoisan Lineament (KHL) (previously the Morokweng-Trompsburg Lineament, Corner 1998), the Gam Lineament (GL), the Omaruru Lineament in part, and it falls within the region of the WNW-trending dyke swarm crossing the subcontinent. The SA appears as a positive anomaly in the Analytical Signal data and therefore is interpreted to be a remanently or reversely magnetised intrusive complex. A similar origin may be invoked for the OMA although it is probably more deeply buried beneath basalts. Sited on the intersection of the Gam (GL) and Khoisan (KHL) Lineaments, within the OMRS, is a prominent localised magnetic anomaly interpreted to be an intrusion, here called the Daneib Complex.

The origin of the ring structures remains enigmatic, although a cue could be taken from similar features observed on a smaller scale associated with hydrothermal activity, i.e. where granitoid or mafic intrusive complexes are seen it is often the case that arcuate or ring structures are seen to be associated with them. Cooling of the intrusion is followed by ring fractures which act as conduits for hydrothermal fluids. These ring fractures are often seen in magnetic, and particularly radiometric data. It is thus concluded that the CBRS, NRS, RRS and OMRS are manifestations of deep-seated plutonism partly affecting local structural style, and may be associated with hydrothermal activity and intrusives. The phenomenon of ring structures and associated mineralising fluids, although new to Namibia, is not new globally. O'Driscoll has published extensively on the subject with respect particularly to Australian mineral deposits (e.g. O'Driscoll and Campbell, 1997).

Isostatic compensation in Namibia

When Map 3, showing the Free Air data for Namibia, is compared to the Namibian topographic data in Map 5, a clear correlation is seen in the first order between the elevated regions of Namibia and the positive Free Air anomalies. This implies that the high topographic features are either supported by the elastic strength of the crust or are uncompensated by root zones and are therefore relatively young features, i.e. post-Gondwana break-up. An interesting major east-west change in Bouguer gravity amplitude is seen in the offshore data roughly along latitude 21°S. This possibly also signifies isostatic disequilibrium in the extended crust offshore.

Conclusions

The study presented in this paper represents an interpretation of Namibian potential field data sets, incorporating recently acquired or compiled offshore gravity and magnetic data. Whereas the onshore data have been available for some time, this interpretation has revealed many newly identified structural features, both lineaments and ring structures. Merging with the offshore data has facilitated the compilation of a more cohesive map of the crustal framework of Namibia, as well as the offshore extensions of the major tectono-stratigraphic domains. The spatial relationship of intrusions and intrusive complexes to the mapped structures is apparent and a number of intrusions are newly identified.

Much of this study is based on observational analysis, identifying many new features which will lay the basis for future research on the nature, genesis and implications of the lineaments and ring structures. It is concluded that the mapped structural framework provides an important basis, in part at least, to mineral exploration thinking and strategy. In particular, the ring structures, major lineaments and lineament zones, and their associated intrusions, could provide the conduits and source of mineralising fluids respectively.

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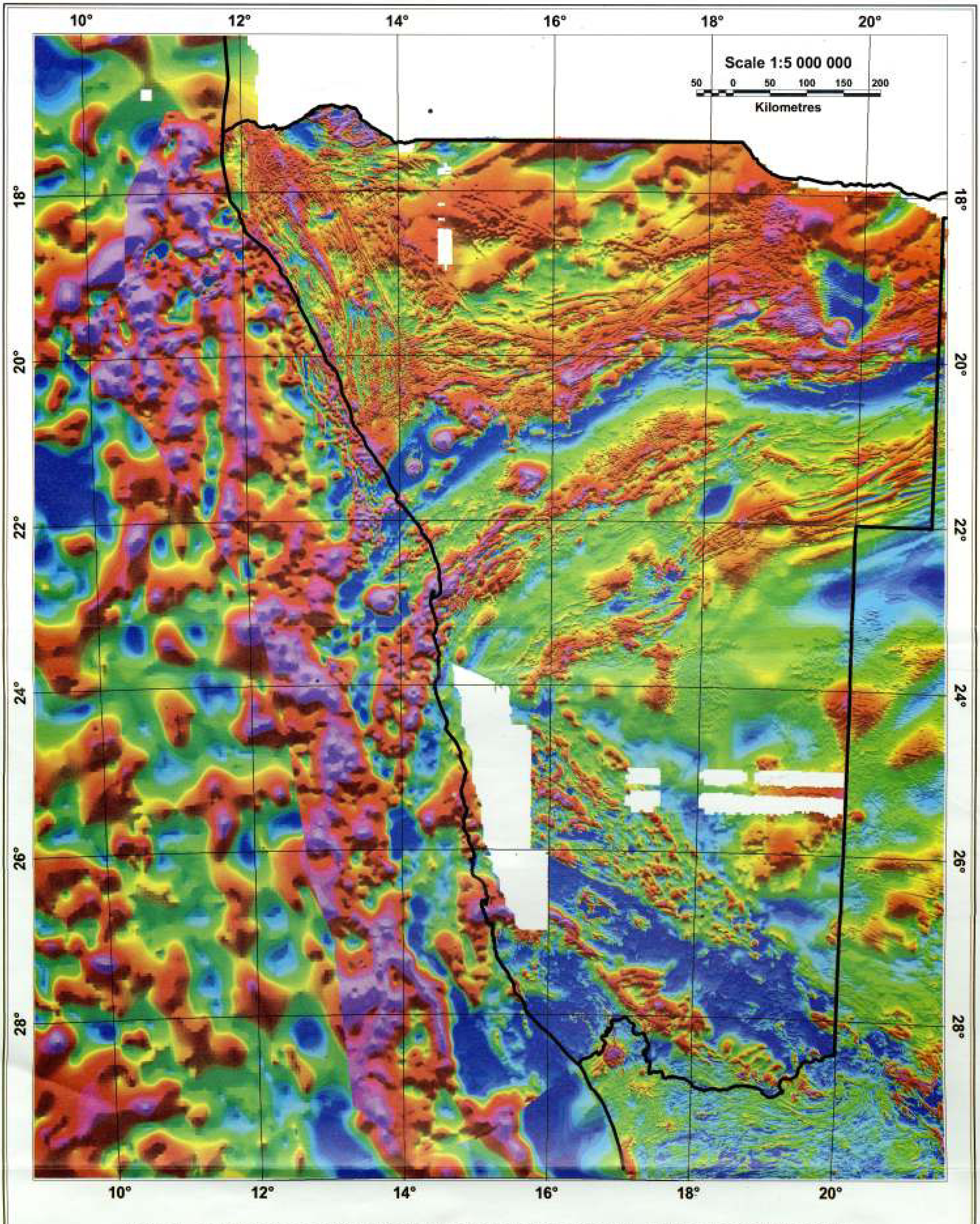
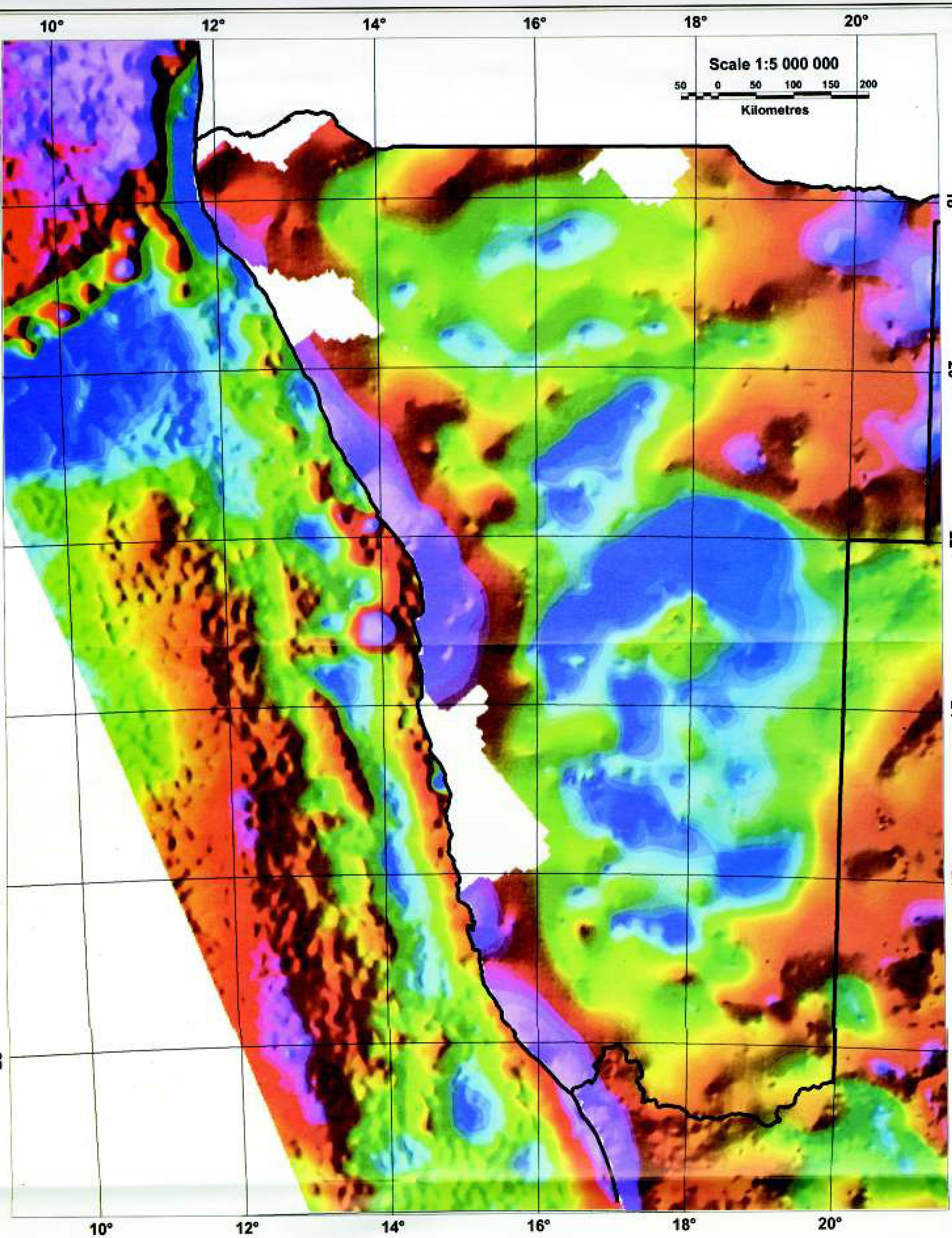


MAP 1 : NAMIBIAN CONTINENTAL AND OFFSHORE TOTAL-FIELD MAGNETIC DATA

(northwest apparent sun-shading)

Data sources: Continental - Geological Survey of Namibia, Fugro/Geodass (Pty) Ltd; Offshore aeromagnetic - NAMCOR; ship-track - World data Center, USA

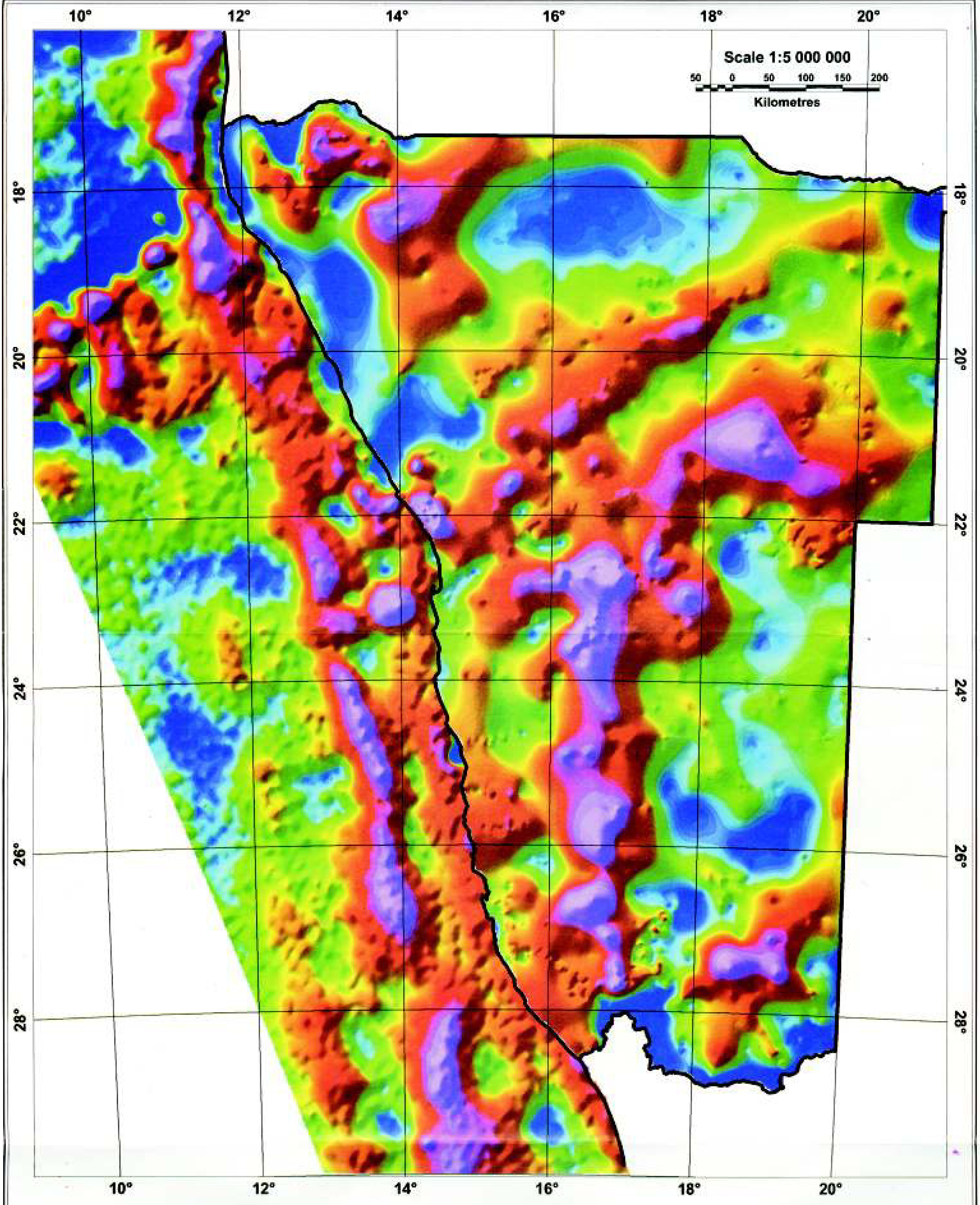
(Note the change in resolution of the three data sets)



MAP 2 : NAMIBIAN CONTINENTAL AND OFFSHORE BOUGUER GRAVITY DATA

(First-order trend removed; northwest apparent sun-shading)

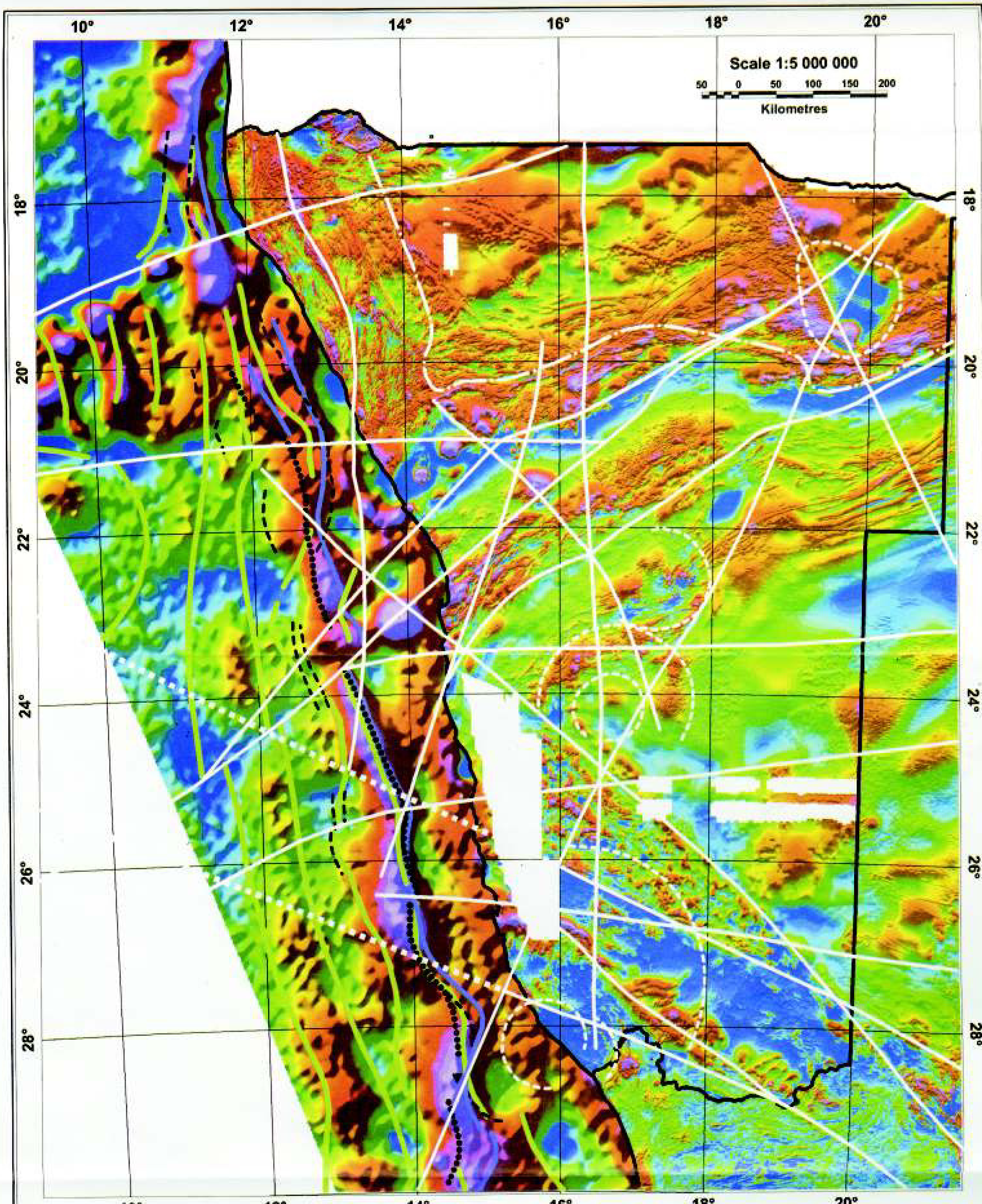
Data sources: Continental - Geological Survey of Namibia, Fugro/Geodass (Pty) Ltd; Offshore satellite-derived - NAMCOR



MAP 3 : NAMIBIAN CONTINENTAL AND OFFSHORE FREE-AIR GRAVITY DATA

(Northwest apparent sun-shading)

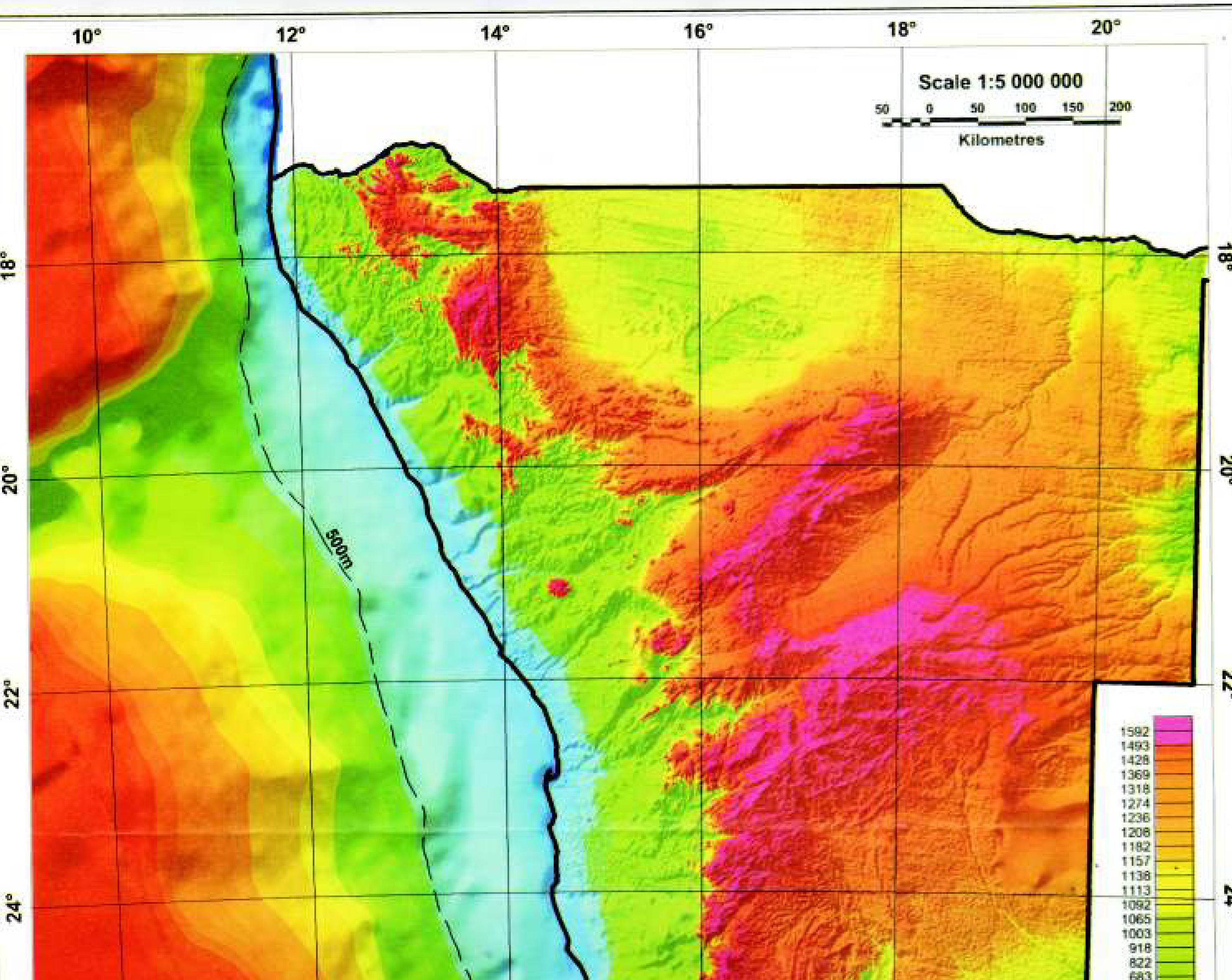
Data sources: Continental - Geological Survey of Namibia; Offshore satellite-derived - NAMCOR



MAP 4 : NAMIBIAN CONTINENTAL AEROMAGNETIC AND OFFSHORE FREE-AIR GRAVITY DATA

(Major interpretation features are overlayed - see Map 6 for key)

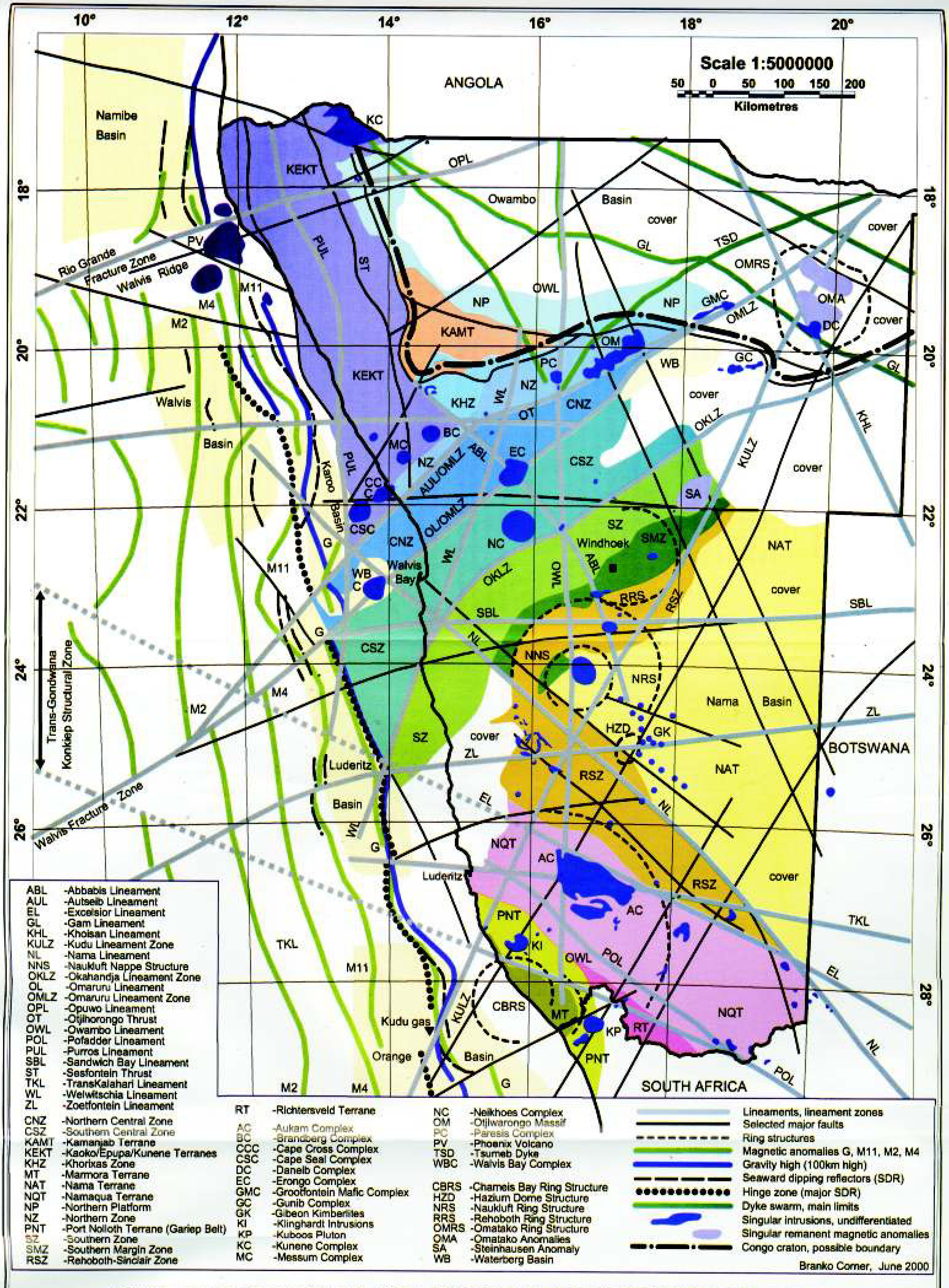
Data sources: Continental aeromagnetic - Geological Survey of Namibia, Fugro/Geodass (Pty) Ltd; Offshore Free-Air - NAMCOR



MAP 5 : NAMIBIAN DIGITAL TERRAIN MODEL AND BATHYMETRY

(Northwest apparent sun-shading)

Data sources: Continental DTM- Geological Survey of Namibia (USGS); satellite-derived bathymetry - NAMCOR; ship-track bathymetry - World Data Center, USA



MAP 6: MAJOR STRUCTURAL AND LITHO-STRATIGRAPHIC ELEMENTS OF NAMIBIA

TECTONO-STRATIGRAPHIC DOMAINS ARE SIMPLIFIED AND MODIFIED AFTER PETZEL AND SCHREIBER, GEOLOGICAL SURVEY OF NAMIBIA