**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

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**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 Owoambo, 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.
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 tectono-stratigraphic 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 tectono-stratigraphic 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.
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 be 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.

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

<table>
<thead>
<tr>
<th>LINEAMENT</th>
<th>MAJOR FEATURES ENCOMPASSED BY THE LINEAMENT SWATH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pofadder Lineament (PFL)</td>
<td>Geologically mapped as a right lateral shear in South Africa (SA); it includes the Twelvemile Valley Shear Zone, and extends further SW as the Kudzius Mynolisk Belt; it is also part reduced from gravity and magnetic data.</td>
</tr>
<tr>
<td>Excelsior Lineament (EL)</td>
<td>Geologically mapped in the 80 x 820 km area; in part, the boundary between the Rehoboth-Summerland Zone (RSZ) and Namakas Terrane (NMT), a clear change in magnetic signature is seen across it from 1962 to 1996.</td>
</tr>
<tr>
<td>Trans-Central Kromhoek Structural Zone</td>
<td>The major structural zone is interpreted to enclose the Namakas Terrane (NMT) and in part the Port Mabula Terrane (PMT). Within a Condonian framework, the PFL has been recognized by Swart et al. (1995) as continuing into South Africa. They have linked the Ato Fissure and Ring Shear Zones westerly to the Namakas-Premiers in the Manganese Province. Corner and Swart (1995) mean of the option that the PCL was essentially rectilinearly. They involved the broader Trans-Central Kromhoek Structural Zone to encompass the Copper Province of Swart et al. (1995) as being the southern African continuation of the tectonized belt which separates the two South African provinces.</td>
</tr>
<tr>
<td>Trans-Kalahari Lineament (TKL)</td>
<td>The TKL is clearly evident in the full aeromagnetic coverage of southern Africa as an EW-transformed fault. Offshore, it displaces both the large zone and the 100 km gravity high, and the gravity high west thereof bore amplitude across it. It is evident in the Namakas magnetic data as a series of EN-orientated en echelon 12 km mountains of low 25 ms showing continuous towards Angola. Further east it terminates the Kalahari trend in the south. It feeds deep crustal sources making the southern part of the Orange River Fault structure, as well as their south of Wolwesrand and Vryheid. It displaces Wolwesrand Group strata near Wolwes and Bettfontein. It appears possible that the extensional aspect of the two structurally inverted bodies east of LIP, as well as the Karoo Central Complex structure can be included.</td>
</tr>
<tr>
<td>Noran Lineament (NL)</td>
<td>The NL is the direct NW extension of the fault zone including the Namaqua and Bophuthatswana pseudo Terrane, South Africa. It encompasses a broad array of parallel NW faults, trending NNE through the Olifantskloof and Malakite toward Vryheid and along, progressing down-slope tending into the NW. In the northern part, it appears from the increasing depth of burial of magnetic anomaly sources (within the Rehoboth-Summerland Zone). The currently active Reform fault near Senyos is the youngest manifestation of faulting on the NL.</td>
</tr>
<tr>
<td>Zonkwe/Kalahari Structural Zone (ZLS)</td>
<td>The ZLS is the western continuation of the Zonkwe fault zone in Botswana. It is interpreted from Bouguer gravity data as well as from prominent trends of the NW-orientated magnetic anomaly south of Malakite. Offshore, it is evidenced by a change in direction of the large zone and 100 km high gravity high, as well as by the displacement of the Milli uranium and associated seaward dipping reflectors.</td>
</tr>
<tr>
<td>Sandback Bay Lineament (SBL)</td>
<td>The EBZ is the northern bounding fault, approximately along latitude 23°S of major basal fault fields to the E of Rehoboth and the Namakas-Premiers border. Westward continuation is evident in high-resolution magnetic data covering the Southern Margin Zone (SMZ). It is consistent with the Bouguer gravity data.</td>
</tr>
<tr>
<td>Okahandja Lineament (OCL)</td>
<td>The NE-trending Terrance boundary between Southern Zone (SZ) and Southern Central Zone (SCZ) of the Damara Mobile Belt is well evident and documented from geological mapping and aeromagnetic interpretation (e.g. Miller 1979; Corner, 1983). In part, it is halokinetic major downdropped fault to the E, exposing magnetically anomalous lower Damara stratigraphy within the CZB to the NW.</td>
</tr>
<tr>
<td>Autsho Lineament (AL)</td>
<td>The AL includes the geologically mapped Autsho Fault, and the Oreánhosseu Thrust at the NE (e.g. Miller, 1983). It is evidenced geographically as a change in structural expression due to relative uplift of magnetically anomalous lower Mabola Group to the NE.</td>
</tr>
<tr>
<td>Otavius Lineament Zone (OLLZ)</td>
<td>The Otavius Lineament (OL) of Corner (1983) is the NE-trending terrane boundary between the magnetically anomalous lower Damara stratigraphy of the CZB and the magnetically quiet upper Damara stratigraphy of the CNZ. The OL and the parallel Autsho Lineament to its south, encompass the CNZ and are interpreted to be tectonically part of a broader structural event trended the Otavius Lineament Zone. The OMLZ contains northwestern geographical measurement of the Otavius Terrane faulting the Otavius Belt (OB). The Cape Seal, Cape Cross, Namib, Brandberg and Zizilia Complexes all as the Otavius superficial and Otavius Terrane complex all along the northern flank of the OMLZ. Offshore it half-marks the change from the NE to the north-trending branches of the Damara Orogen. Southwardward, it continues as the Walvis Fracture Zone.</td>
</tr>
<tr>
<td>Opitso Lineament (OLF)</td>
<td>Visible as folding in both aeromagnetic and geological data sets, the OLF continues offshore as the Rio Grande Fracture Zone. It is also supported by the Bouguer gravity data.</td>
</tr>
<tr>
<td>Pofadder Lineament (PFL)</td>
<td>The dextral zone, geologically recognized in the Kudzius Terrane (e.g. Miller, 1983), is also evident in the aeromagnetic data both onshore and offshore.</td>
</tr>
<tr>
<td>Welwitschia Lineament (WL)</td>
<td>The WL is located primarily on the basement of a change in the structural style in the western Central Zone where younger NNW normal fault sets are superimposed on the older NE-direction (Corner, 1983). Dykes, possibly of Carboniferous age, possibly change to the direction west of the Erosion Complex. Offshore aeromagnetic data clearly show a continuation of the WL to the SW, separating the boundary between the CZB and the SCZ.</td>
</tr>
<tr>
<td>Kidds Lineament Zone (KULZ)</td>
<td>Mesozoic displacement is seen to occur, along the EULZ, of the 200 km gravity high, the large zone and the C magnetic anomaly in the vicinity of the Kidds gas field. A series of NE-trending faults, evident in the magnetic data, are associated with its southwards in the northern portion of the Desert Island Area, and southwest of Malakite within the Rehoboth-Summerland Zone (RSZ), near Ot𝓬hocr. westward of Windhoek forming a failed south-eastern extension of the EULZ, bounding the Southern Margin Zone and the EULZ, and trending the Central Zone in that area. Initially seen only in terms of an array of these linear structures, the EULZ also appears to be the approximate location between the major linear trends identified in this study as well as two major hor (probably remnant) magnetic anomalies, i.e. the Otavius and Otavius Terrane complexes. The Otavius dome structure SE of Malakite also occurs on the EULZ.</td>
</tr>
<tr>
<td>Orasild Lineament (OWL)</td>
<td>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 part of the Otavius Complex. To the north, a prominent NNW-E fault has also emerged along it. The OWL, at its youngest age, is relatively recent and it clearly bounds, in the west, the Kudzius Terrane and northern volcanism as well as their associated free-air anomalies (Maps 3 and 4).</td>
</tr>
<tr>
<td>Alfiaho Lineament (ABL)</td>
<td>The ABL was initially identified on the basis of the early aeromagnetic data and deposition of test drilling data (Corner, 1983). Intrusions of probable late Damara age occur at its intersections with the EBZ and the OMLZ, and of early Cretaceous age (Orange Complex) at its intersection with the OLMZ. Its northern continuation may also be noted in the western boundary of the Etosha Complex.</td>
</tr>
<tr>
<td>Khomas Lineament (XHL)</td>
<td>The XHL is seen in high-resolution aeromagnetic data within the Damara. The Damara Complex has been interpreted as the intersection of the XHL, the EULZ and the NNW-trending dolerite. The Oshikoni Anomaly and OMLZ are also evident at this intersection. The former is interpreted to arise from残丘 or completely magnetic anomalies. The Skoros kimberlites may be within the south of the XHL. The XHL continues into Botswana where it continues the Kalahari trend and into South Africa where it encompasses the Luckockling Shear Structure, parallel NNW faults and a number of stratigraphic and structural Anomaly, and the Otavius Complex.</td>
</tr>
</tbody>
</table>

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.
clude 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 breakup) continental crust, occurring at the hinge zone in the region west of Walvis Bay down to Luderitz, 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. Gladzenko (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 transient faulting and mafic intrusion. The Turolian-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 southward 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 Creataceous, 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 Opwwo 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 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 TransNamaqua 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 swathe: e.g. in the northern portion of Diamond Area 1; west and southwest of Maltahohe; 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 Damara 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-Gondwanan 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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**References**


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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 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 5: NAMIBIAN DIGITAL TERRAIN MODEL AND BATHYMETRY
(Northwest apparent sun-shading)

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