REPUBLIC OF NAMIBIA
Department of Water Affairs
DWA
Windhoek

FEDERAL REPUBLIC OF GERMANY
Federal Institute for
Geosciences and Natural Resources
Hannover

TECHNICAL COOPERATION

PROJECT NO. 89.2034.0

GERMAN-NAMIBIAN GROUNDWATER EXPLORATION PROJECT

FOLLOW-UP REPORT VOL. 3

Calculated configuration and relative magnetisation of the basement rocks in the Kuiseb Dunes helicopter survey area

Bundesanstalt für Geowissenschaften und Rohstoffe

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Calculated configuration and relative magnetisation of the basement rocks in the Kuiseb Dunes helicopter survey area

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6. CD-ROM with all Enclosures and this report as PDF files,
including Adobe® Acrobat® Reader for various platforms.

1. Introduction

In 1992, BGR conducted a helicopter-borne geophysical survey in the hyper-arid Kuiseb Dunes area, as part of the German-Namibian Groundwater Exploration Project (GNGEP).

The location of the 5312-km² survey area is shown in **Fig. 1**. The magnetic, electromagnetic (AEM), and radiometry methods were applied over a total flight-line distance of 12,346 line-km. The positions along the flight-lines were determined by GPS and Doppler in combination with barometric and radar altimeters. The technical details are described in Project Report Vol. A-I (SENGPIEL et al. 1995a).

This report presents a description and the results of a novel interpretation procedure for airborne magnetic data based on variogram analysis, developed by S. Maus (MAUS, 1999a, MAUS et al., 1999b). The algorithm has two output parameters:

a) the depth of the magnetic basement below the magnetometer sensor and
b) an estimate of the rock magnetisation, called "logarithmic intensity".

Values of the anomalous magnetic field intensity ΔT are input for the algorithm. A boxcar window is moved over the data in the survey area. The calculated depth and intensity values are assigned to the midpoint of this window (see chapter 2). One advantage of the method is its straight-forward application to a quite general model, namely a sedimentary, nearly non-magnetic sequence overlying bedrock with some magnetisation. It is assumed that this type of geologic model applies to the Kuiseb Dunes survey area.

The geology of the area is summarised in Project Report Vol. D-1 (LENZ et al., 1995). The basement consists mainly of Precambrian rocks of the Damara sequence (metagreywackes, mica schists, quartzites and marbles), as well as syntectonic and post-tectonic granites. The bedrock is overlain by up to 100 m of reddish quartzose sandstone of the Tertiary Tsondab Formation. A fine-grained, recent dune sand up to 100 m thick covers the Tsondab Sandstone or directly overlies the bedrock [the bedrock crops out north of the lower Kuiseb River].

A number of paleochannels of the Kuiseb are inferred from the AEM results (**Fig. 2**) and subsequent drillings. These paleochannels are incised into the Tsondab Sandstone or the crystalline basement (SENGPIEL et al., 1995b). It was not possible to trace the main channels all the way to the coast, probably due to a very thick sand or sandstone cover. These channels are assumed to be potential fresh-water reservoirs. However, on the basis of the results of hydraulic modelling, G. Schmidt (1995) came to the conclusion that the yield of the paleochannel system would be small and not economical.

As an alternative for meeting the increasing demand for drinking water in the Walvis Bay region, a desalinisation plant has been considered by the Namibian authorities. The plant would be supplied with saline or brackish groundwater from a coastal well field instead of using sea water. These wells were to be located preferably in an area of maximum sedimentary thickness over the basement.

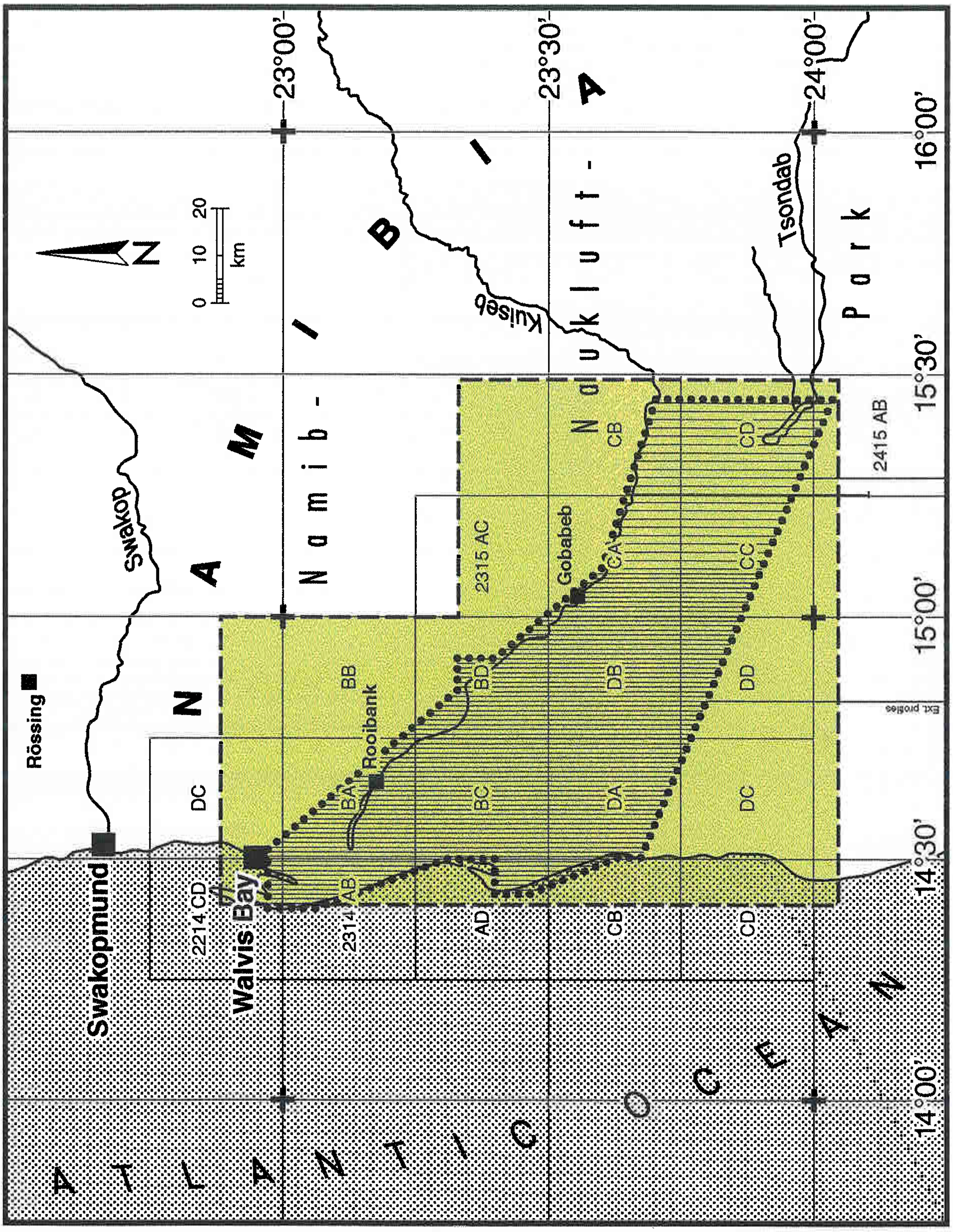


Fig. 1: *Location map of the Kuiseb Dune helicopter survey area of BGR (1992). The area of the overview map sheets used in this report is marked by yellow shading.*

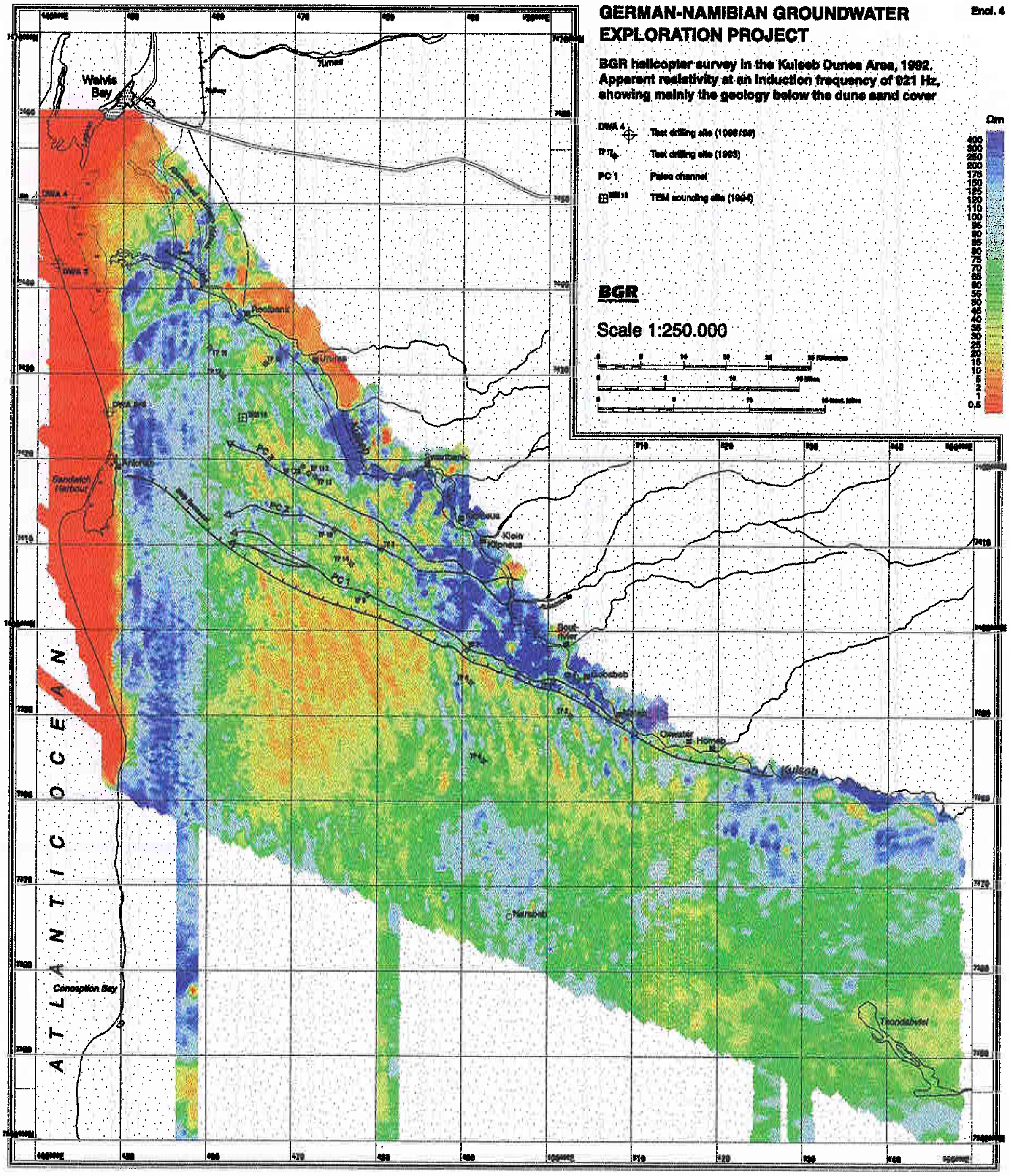


Fig. 2: *BGR helicopter survey in the Kuiseb Dunes Area, 1992. The half-space resistivity at an induction frequency of 921 Hz reflects the geology below the dunes and sandstone cover and indicates the main paleochannels of the Kuiseb river (PC 1, 2, & 3) and the seawater intrusion along the coast (red). From Sengpiel et al., 1995b.*
This is a copy of Encl. 4 at reduced scale (1:750,000)

BGR suggested that the Maus variogram analysis method for determining the depth to the magnetic basement be applied not only in the coastal area, but in all of the Kuiseb Dunes area in order to extend the AEM results to greater depths. During a meeting at BGR on November 19, 1996, both DWA and BGR agreed to this plan. DWA was represented by Mr. P. Heyns.

Fig. 3 illustrates the magnetic anomalies ΔT in the Kuiseb Dunes area resulting from the BGR helicopter survey. These data were used in the variogram analysis.

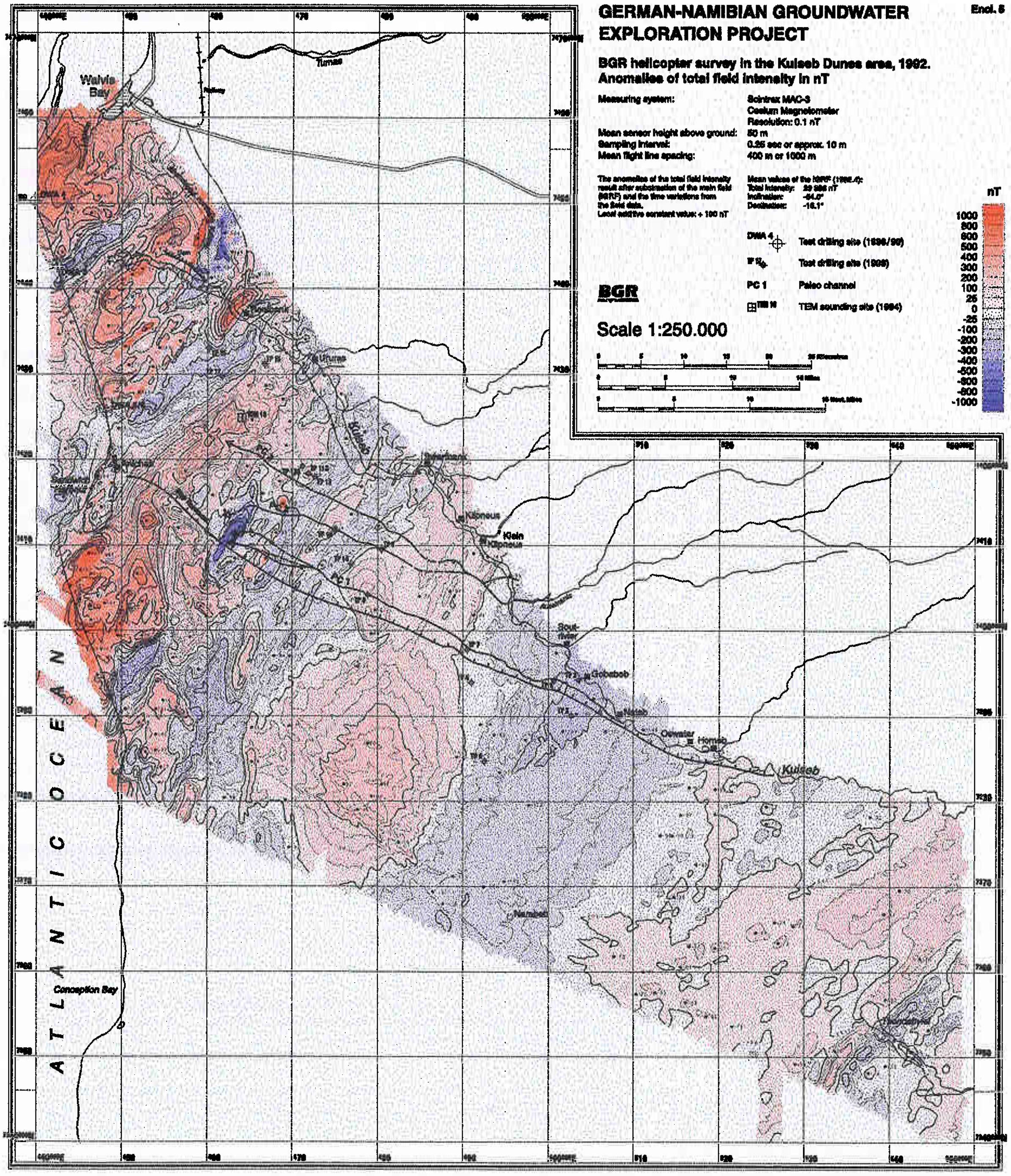


Fig. 3: *Magnetic anomaly distribution in the Kuiseb Dunes survey area (Sengpiel et al., 1995a). This is a copy of Encl. 5 at a reduced scale 1:750,000.*

2. Data processing

2.1 Data pre-selection

Prior to any further processing, the magnetic flight-line data have to be inspected for noise. High-frequency noise is misinterpreted by the variogram analysis method as shallow basement. Hence, a single noisy track can lead to poor depth estimates. The following noisy sections were identified and removed:

line 1,	UTM-Y 7460000 to end
line 33,	UTM-Y 7411800 to 7437000
line 66,	UTM-Y 7413000 to 7418000
line 67,	UTM-Y 7391000 to 7400000 and 7417000 to 7419000
line 161,	UTM-Y 7365300 to 7365900
line 162,	completely
line 163,	UTM-Y 7377800 to 7378400
line 164,	UTM-Y 7372500 to 7373000

2.2 Variogram Analysis

The magnetic flight-line data of the Kuiseb helicopter survey was analysed using the variogram analysis method developed by Maus. A data window is moved over the data set. For each window position, the variogram of the magnetic data within the window is computed. The variogram is then compared with model variograms for a half-space with fractal susceptibility distribution. The best-fitting model variogram provides an estimate of the depth to the top of the magnetic basement and the intensity of basement magnetisation. Subtraction of the estimated depth from the mean sensor altitude above m.s.l. gives an estimate of the basement level relative to m.s.l. for each window position. Moving the window over the whole survey area yields a picture of the relief of the magnetic basement. Generally speaking, shallow depth causes the magnetic profile to have a jagged appearance, whereas the greater the distance between magnetic sensor and magnetic basement the smoother the magnetic profile is. The smoothness of the field increases quite dramatically with depth, as illustrated for a region with shallow basement in **Fig. 4** and a region with deep basement in **Fig. 5**.

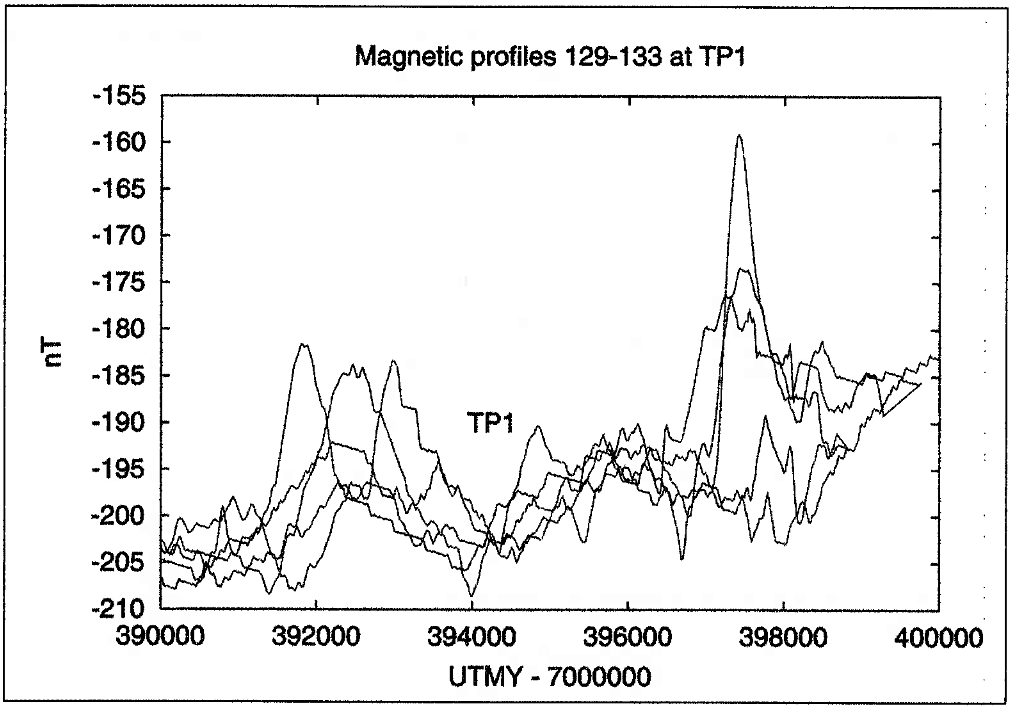


Fig. 4: *Five adjacent magnetic profiles over an area with shallow basement (depth below terrain around 40 m). The proximity of the basement is reflected by the jagged appearance of the magnetic profiles.*

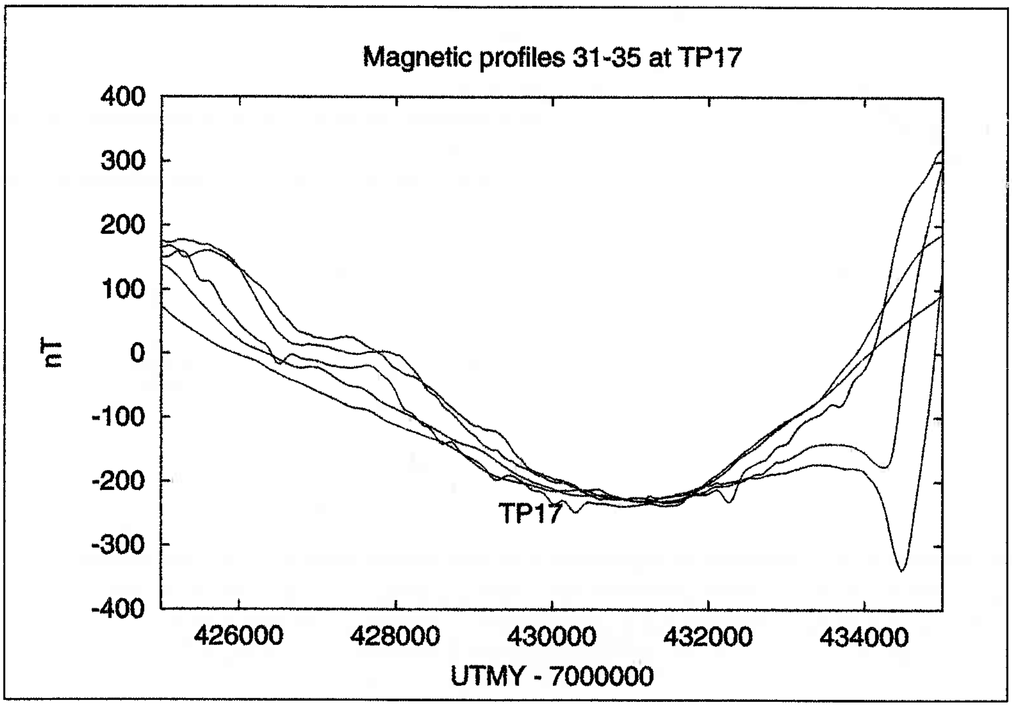


Fig. 5: *Five adjacent magnetic profiles over an area with deep basement (depth below terrain around 100 m). The large distance between source and observation plane leads to a smooth magnetic profile.*

2.3 Computation of depth

Since depth is estimated from fractal distribution of the magnetic field, a rather large data window is required for each depth estimate. The larger the window, the more accurate the depth estimate. On the other hand, the smoothness of the resulting basement relief increases with the window size. Hence, there is a trade-off between better resolution of the basement relief and the accuracy of the depth values. For this survey, the optimum window size is approximately 6 × 6 km. To centre the depth estimates in the window, the magnetic data is weighted inversely to its distance from the centre of the window. These weights are also used for calculating the mean sensor altitude and mean ground elevation within the window.

2.4 Computation of the intensity of the basement magnetisation

As a by-product of the depth estimate an estimate of the intensity of the basement magnetisation is also obtained. However, due to the large data window required for depth estimation, these intensities would appear smoothed. To enhance structural features, the magnetic flight-line data are reprocessed using a much smaller data window in the variogram analysis. Each flight line is processed separately using a window length of only 500 m. Due to the exponential distribution of intensities, it is recommended to plot them logarithmically.

2.5 Comparison of the inversion result with drilled basement levels

The true and estimated basement elevations, with absolute and relative errors, are compared in **Table 1**. With a few exceptions, depth estimates are in good agreement with drilling results. Large discrepancies occur for TP4, TP7 and TP16. This is probably due to pronounced small-scale features in the basement relief that cannot be resolved with the variogram analysis method. It is also possible that basement rocks with a low magnetisation, like some granites, overlie a strongly magnetised basement.

Table 1: *True and estimated basement levels (m a.s.l.)*

	true base	est. base	abs. error	rel. error
TP 1	356 m	362 m	6 m	6 %
TP 2	414 m	412 m	-2 m	3 %
TP 4	318 m	375 m	57 m	52 %
TP 6	343 m	318 m	-25 m	23 %
TP 7	237 m	328 m	91 m	49 %
TP 8	205 m	210 m	5 m	3 %
TP 9	198 m	211 m	13 m	8 %
TP 10	139 m	119 m	-20 m	10 %
TP 11a	143 m	114 m	-29 m	18 %
TP 12a	121 m	111 m	-10 m	6 %
TP 13	138 m	118 m	-20 m	12 %
TP 14	176 m	169 m	-7 m	4 %
TP 15	101 m	91 m	-10 m	8 %
TP 16	24 m	76 m	52 m	31 %
TP 17	62 m	58 m	-4 m	3 %

mean absolute error: 23 m.
mean relative error: 16 %; 100 % = sensor altitude above true basement (including radar altimeter altitude).
bias: 6 m; when bias > 0 = estimated depths are too shallow.

2.6 Sources of error

The main limitation of the method is the averaging effect of the window. Since each basement depth value is in fact the mean depth value of the basement in a 6 × 6 km area, considerable disagreement with drilling results can occur, particularly in the presence of small-scale basement features, such as narrow paleochannels.

Moreover, errors in the depth estimates are likely to occur in areas with a low magnetic signal. The reason for these errors is that the magnetometer has noise levels of around 1 nT. This noise is difficult to eliminate or to model, since it varies considerably in amplitude. In areas with a low magnetic signal, the noise is misinterpreted as due to shallow sources, leading to shallow depth estimates. Such a situation is probably at least partly responsible for the deviation at TP7, as demonstrated in **Fig. 6**.

The topographic elevations determined from the helicopter altitude records (barometric and radar) can vary within ±16 m. This does not apply to the "true base" values in **Table 1,** which were determined at the drilling sites using triangulation.

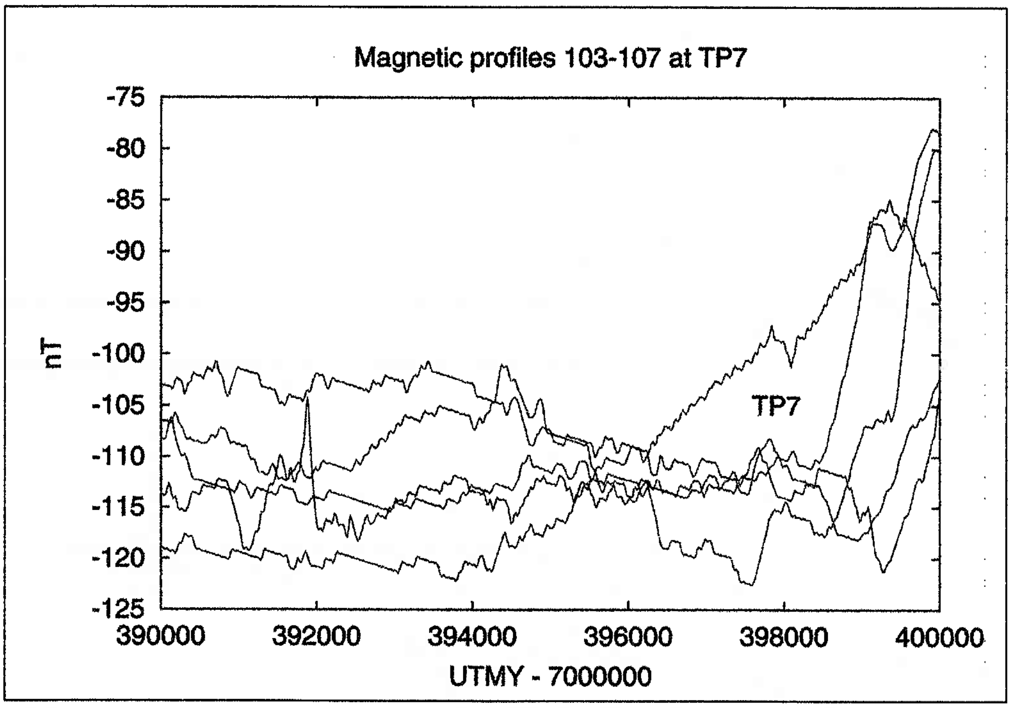


Fig. 6: *Example of an area with low-amplitude magnetic signal and high noise (in the order of several nT). At short to intermediate wavelengths the noise is stronger than the signal, which leads to depth estimates that are too low (true depth = 118 m, estimated depth = 27 m).*

2.7 Output data set

The results of a variogram analysis are assigned to the centre co-ordinates of the moving window and are then projected onto the flight line at the centre of the window. To obtain a consistent data set for plotting maps, the estimated depths and intensity values were merged with the original magnetic data set in GEOSOFT xyz-format. Each depth and intensity estimate was shifted to the site of the nearest neighbouring magnetic measurement. The combined data-set was stored in an xyz-format compatible with GEOSOFT [x, y, mag, topo-alt, sensor-alt, basement-alt, log10 (intensity), topo-alt minus basement-alt, fid, scan] with data points spaced 100 m along the flight-line.

3. Results

3.1 Representation of the results

The results of the variogram analysis of the aeromagnetic data are included with this report in form of three 1:250,000 maps (Enclosures 1 to 3). These maps represent

Encl. 1: the magnetic basement configuration in m above m.s.l.,
Encl. 2: the magnetic basement configuration in m below ground level, and
Encl. 3: the logarithmic intensity c_s (a function of the magnetisation) in arbitrary units. These maps also contain relevant topographic elements.

Small-scale (1:750,000) representations of **Encls. 1 to 3** are included in this report as **Figs. 7, 8,** and **9**. For comparison with earlier results, we have added the following enclosures:

Encl. 4: a 1:250,000 map of the apparent resistivity, equivalent to **Fig. 2** (half-space resistivity at 921 Hz),
Encl. 5: a map of the anomalous total magnetic intensity ΔT (equivalent to **Fig. 3**), and
Encl. 6: a sketch from Barbour (1990) based on a report of Van Zijl and Huyssen (1967) showing the main bedrock structures resulting from a seismic refraction survey in 1965/66 along several dune valleys (1:250,000), equivalent to **Fig. 10**.

Encl. 6 is a transparent sheet, which can be used to compare the seismically inferred highs and lows of the bedrock with the magnetic basement on **Encl. 2**. A CD-ROM containing **Encls. 1 to 6** and this report, with all figures and tables, is also enclosed with this report.

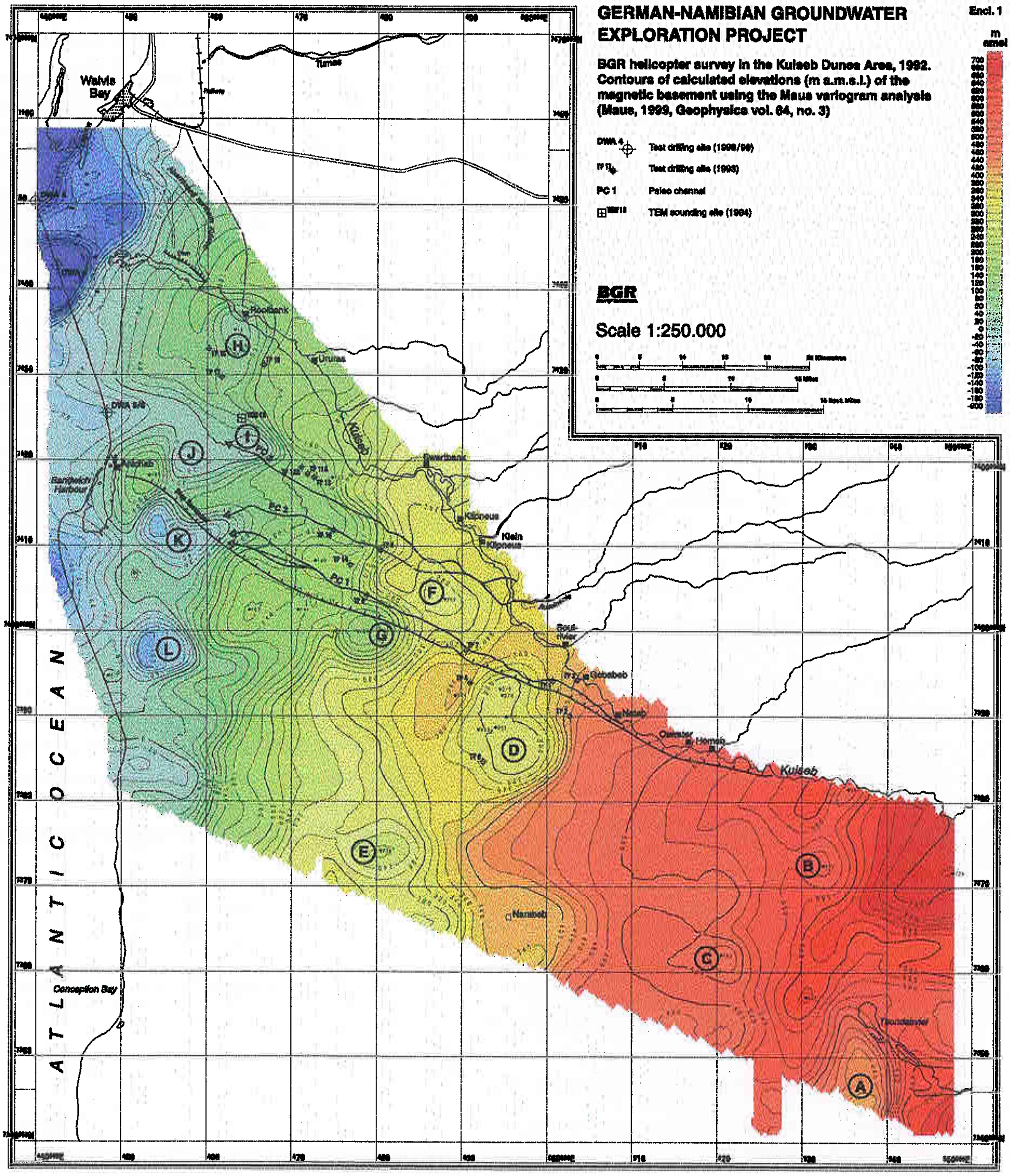


Fig. 7: *Calculated magnetic basement levels (m above mean sea level). Partially closed basins are marked by letters A to L. This is a copy of Encl. 1 at reduced scale (1:750,000).*

3.2 Discussion of results

3.2.1 Basement configuration relative to sea level

The elevation contours of **Encl. 1** and **Fig. 7** are strongly biased by the relatively steep E–W slope of the landscape within the survey area. The elevation drops from about 780 m in the E to sea level in the W. Taking into account that narrow features in the magnetic basement may not be resolved, and that the magnetic basement may not always coincide with the crystalline basement, **Encl. 1** and **Fig. 7** should generally indicate the lower boundary of the sedimentary aquifer. Storage of groundwater can be expected in basins without an outlet towards lower altitude. Such type of potential basins are marked with capital letters A, B, C, ... from E to W, beginning S of Tsondabvlei (A). The bottoms of basins I, J, K, and L are below sea level; therefore, at least their deeper parts can be filled with saltwater. It is recommended that the groundwater potential of these basins be investigated by the Namibian authorities (see Chapter 4). The enormous depth of the magnetic basement in the northernmost part of the survey area, S of Walvis Bay, was not confirmed by recent drilling by DWA (see section 3.2.2).

Earlier hydrogeologic research in the present-day Kuiseb Valley (Barbour 1990) came to the conclusion that this river loses water along 22 km of its course between a point 8 km W of Swartbank and Rooibank. The basement configuration shown in **Encl. 1** strongly supports this assumption as there is no significant high in the basement which could prevent the seepage of Kuiseb River water.

3.2.2 Basement depths below ground level

Encl. 2 and **Fig. 8** show the magnetic basement depths below ground level. This map was generated by subtracting the basement levels of **Encl. 1** from the topographic elevations recorded along the flight-lines during the helicopter survey (based on the barometric and radar altimeter records). The absolute error of the topographic elevation values can be up to 10 m for several reasons. Small-scale topographic features, like narrow valleys, are correctly reproduced by the altimeters, but not necessarily by the calculated basement configuration data mentioned above. Both types of error can lead to negative depth values. These values are represented in **Encl. 2** by a brownish colour.

This type of map indicates the average thickness of non-magnetic material over the magnetic basement and is not biased by the regional slope of the topography from E to W. There are four major areas, denoted I, II, III and IV in **Encl. 2** and **Fig. 8,** where the coverage well exceeds 100 m. Comparison of this map with that in **Encl. 1** and **Fig. 7** shows these areas correlate with the following basins or group of basins:

area (I):	basin A (S of Tsondabvlei)
area (II):	basin D (SW of Gobabeb)
area (III):	basins G, H to L (S of Rooibank)
area (IV):	unlabeled basin south of Walvis Bay.

Basin area I is filled with non-magnetic material (sediments?) of considerable thickness (>250 m). It is possible that this basin is recharged with fresh water from the Tsondab River. Therefore, it should have a high storage potential for fresh water, unless there is a water outlet further south, i.e., beyond the survey area.

Encls. 1 and **2** also show the courses of the main paleochannels of the Kuiseb River deduced from the BGR airborne EM data. These paleochannels are labeled PC 1, PC 2, and PC 3.

Basin areas II and III are apparently in contact with these paleochannels and possibly receive (or may have received) water from them: basin area II from PC 1, the center basin area III from PC 1 and PC 2, and the northern part of this area, not only from PC 3 but also from the Kuiseb seepage area between Swartbank and Rooibank. It should be noted that the main paleochannels lead to major basins.

None of the test boreholes (marked TP in the Enclosures/Figures) were drilled into the deeper parts of the basin structures. Nevertheless, the deepest basement depths were observed at TP 13 (122 m), TP 12A (104 m), and TP 10 (121 m), close to PC 2 and PC 3. These drilling locations are clearly within basin area III. All three wells provided fresh water and the highest yields of the 1993/95 test drilling program:

TP 13:	TDS = 400 mg/L;	yield = 8.1 m^3/h
TP 12A:	TDS = 800 mg/L;	yield = 7.4 m^3/h
TP 10:	TDS = 910 mg/L;	yield = 5.6 m^3/h.

A search for more information on these basins led to the Time Domain Electromagnetics (TEM) survey reported by G. Schaumann (1994). The soundings along the so-called H-Line, in a dune valley that is accessible to motor vehicles, are of special interest. One of the southernmost sounding sites was no. 18, which is marked in the enclosures and figures as TEM 18. It is not far from basin I of **Encl. 1 (Fig. 7),** which is the northernmost basin of area III of **Encl. 2 (Fig. 8)**. The TEM inversion results for a three-layer ground were

$\rho_1 = 890\ \Omega m$; $d_1 = 39$ m,
$\rho_2 = 39\ \Omega m$; $d_2 = 100$ m,
$\rho_3 = 2700\ \Omega m$ $(d_3 = \infty)$,

i.e., the basement appears at 139 m depth, somewhat less than in **Encl. 2**, where the magnetic basement is indicated at ~160 m. Both EM methods (AEM and TEM) yield resistivities around 40 Ωm below the resistive sand cover, which can be attributed to rather fresh water.

Recently (1998/99), DWA drilled two more test boreholes (WW 37492, WW 37493) about 5 km N of Anichab at the western margin of basin area III. They encountered about 20 m of freshwater and penetrated the basement at 23.2 and 25 m. The two sites were selected on the basis of recommendations in the Kuiseb Dunes area interpretation report (SENGPIEL et al., 1995b: Sandwich Harbour freshwater lenses). The locations of these test boreholes is marked in the enclosures/figures as DWA 5 and 6.

DWA has also recently drilled four more test boreholes within basin area IV south of Walvis Bay, where the variogram analysis yielded a magnetic basement depth of up to 250 m. Two of the drilling sites are marked on our maps as DWA 3 (WW 37055B) and DWA 4 (WWW 37151). The depths to the crystalline basement (here granite) were found to be only 78 m, and 91 m, respectively. An explanation of the discrepancy to the calculated depths may be that this granite is poorly magnetised and overlies the magnetic basement with a thickness on the order of 150 m. In any case, the SE margin of basin area IV coincides perfectly with the margin of the well-known fresh water Dorop aquifer, which is underlain by salt water.

It is interesting to compare the results of the earlier seismic refraction study, summarized in **Encl. 6** and **Fig. 9,** with the magnetic basement depths in **Encl. 2**. There is at least rough agreement between the two results: In the N, along the final seepage area of the Kuiseb River, there is a bedrock high in **Encl. 2** which is much broader than in the seismically deduced data. The bedrock low of **Encl. 6** follows more or less the northern margin of basin III of **Encl. 2**. There is also agreement between the magnetic and seismic data at Anichab and from there towards the east, where both methods indicate a bedrock high. However, the eastern part of this high is clearly located further north in **Encl. 2** than in **Encl. 6**. South of this high another bedrock low is inferred by both methods and the groundwater flow postulated in **Encl. 6** follows roughly the course of PC 1. Thus, both results agree in the sequence of bedrock highs and lows, but these structures differ in a number of details. It should be mentioned that the old seismic survey was conducted under difficult conditions in the dune valleys and with stations about 2 km apart.

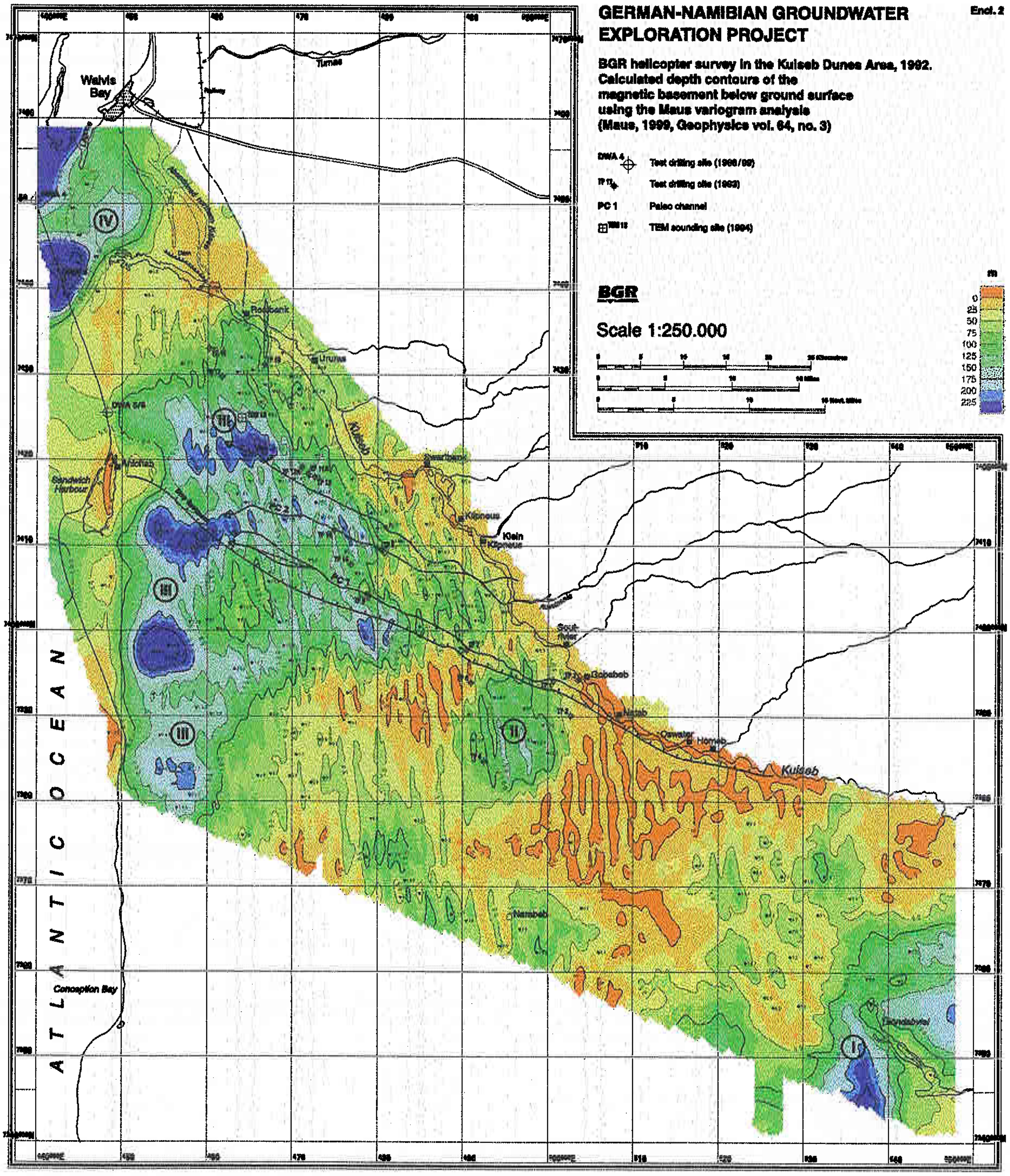
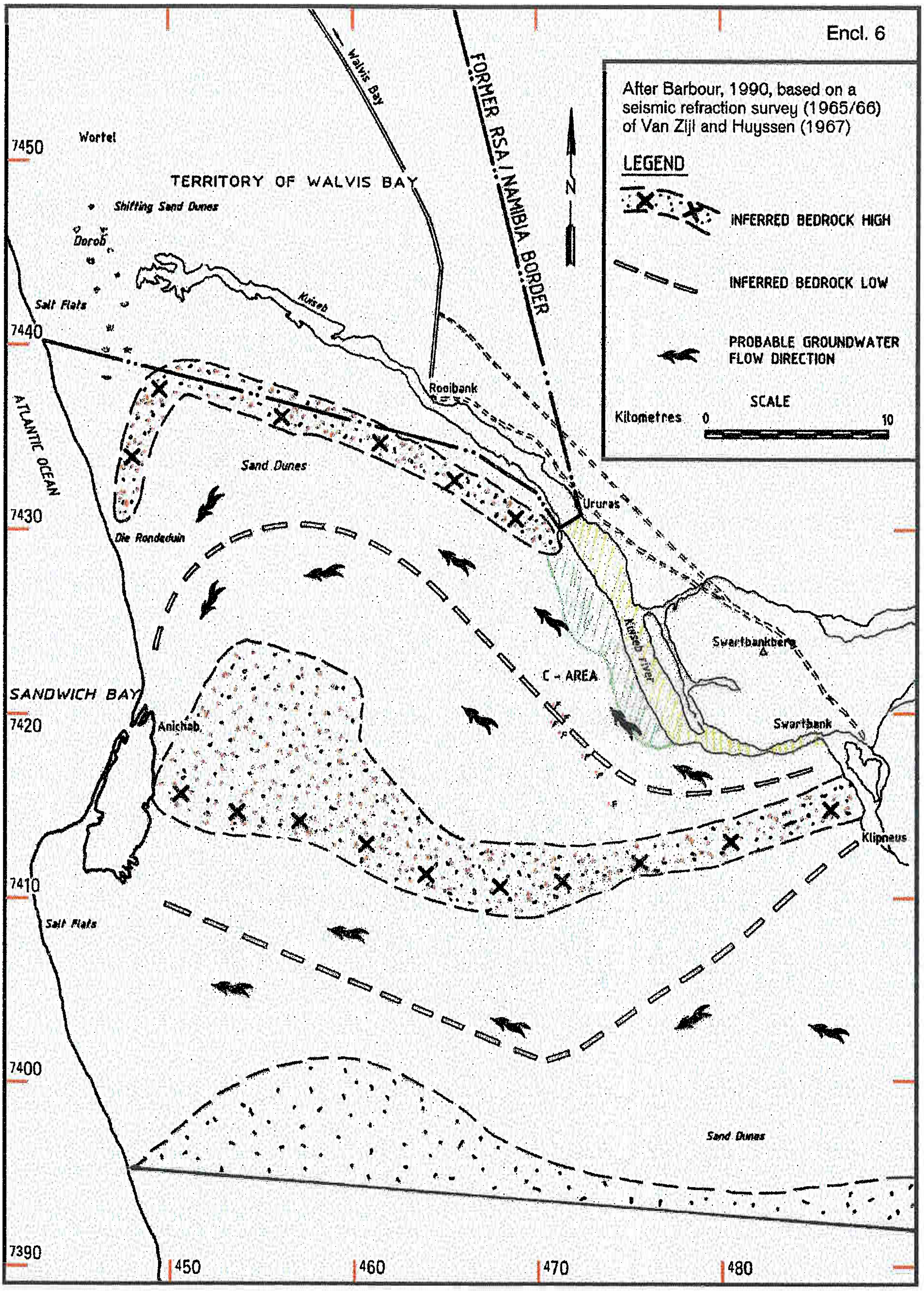


Fig. 8: *Calculated basement depths below ground surface. Major areas of thick non-magnetic cover are marked (I, II, III, IV). This is a copy of Encl. 2 at reduced scale (1:750,000).*


Encl. 6

After Barbour, 1990, based on a seismic refraction survey (1965/66) of Van Zijl and Huyssen (1967)

Fig. 9: *Sketch of bedrock relief based on a seismic refraction survey (1965/66) by Van Zijl and Huyssen (1967), after Barbour, 1990. This is a copy of Encl. 6 at a slightly reduced scale.*

3.2.3 Basement magnetisation (logarithmic intensity)

A particular useful feature of the Maus variogram analysis is the fact that it provides a measure of the local magnetisation, or – more specificly – the small-scale variance of the local magnetisation, as shown in **Encl. 3** and **Fig. 10**. Using the smaller box car window – as mentioned in 2.4 – ensures that this magnetisation value is correlated with the upper parts of the magnetic basement. Since basement rocks crop out north of the Kuiseb River valley, the different geologic formations can be traced from there further to the SW, i.e., below the sand cover, using **Encl. 3**. This tracing can – in principle – also be done on the basis of the ΔT distribution given by **Encl. 5** (and **Fig. 3**). However, it turns out that **Encl. 3** is better suited for that: Small linear magnetic structures, probably the well known dolerite dikes, are clearly indicated in **Encl. 3** but are only barely detected in **Encl. 5**. Moreover, the relative magnetisation values do not change sign as the total magnetic field does over a magnetised body. Thus, the magnetisation values facilitate outlining the boundaries of geologic units of different magnetisation.

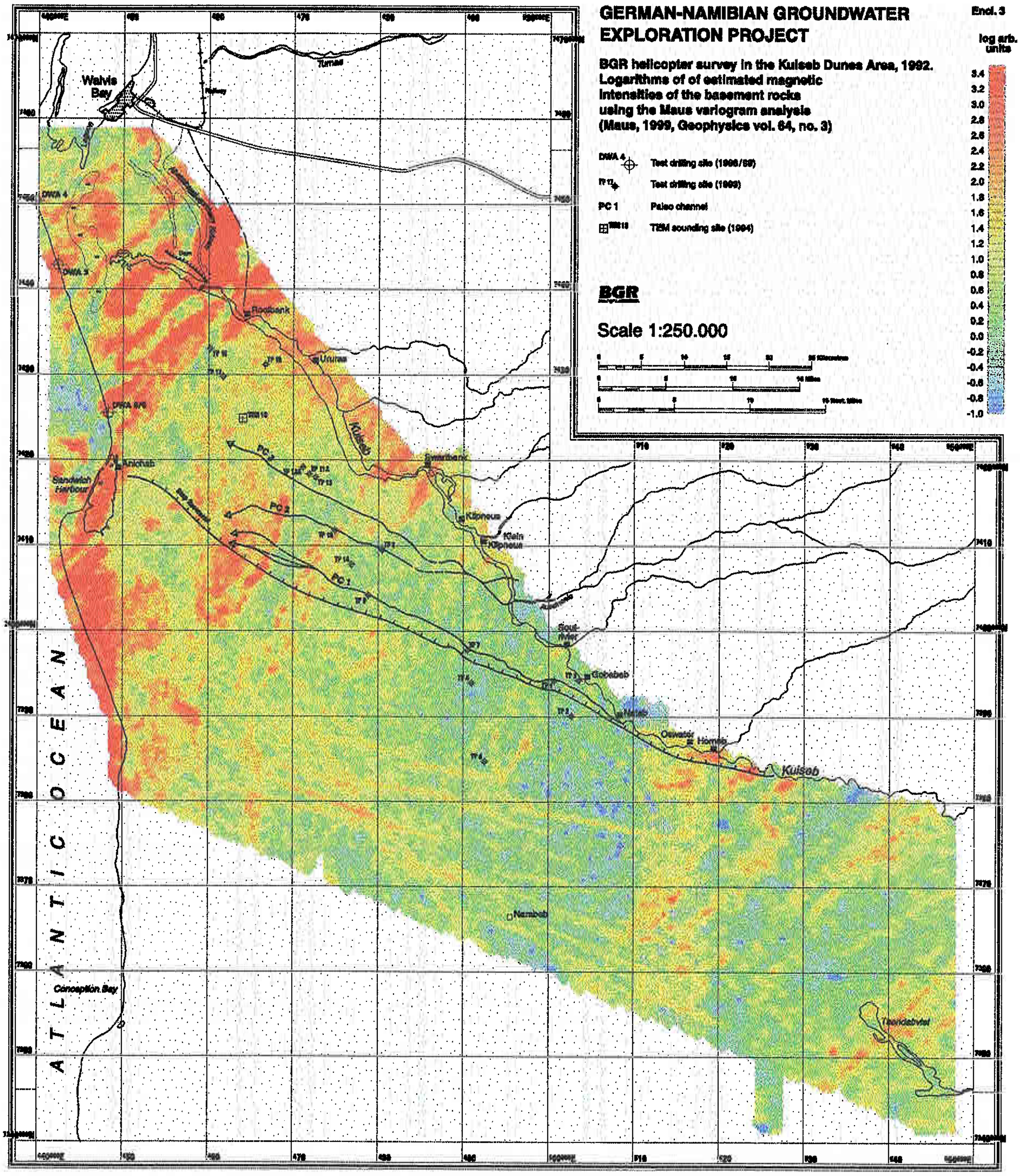


Fig. 10: *Local variance of the magnetisation of the bedrock calculated using the Maus variogram analysis. This is a copy of Encl. 3 at reduced scale (1:750,000).*

4. Recommendations

The Maus variogram analysis results have provided useful new information on the general basement configuration in the Kuiseb Dunes survey area. A number of unexplored basin structures were revealed; some of them appear to be in hydraulic contact with the Tsondab River (area I) or the Kuiseb River (area III) or with the main paleochannels of the latter (areas II and III). It is certainly not only of scientific interest to investigate the deepest part of these basins further, starting with TEM soundings to verify whether the resisitivity of the sedimentary cover can be attributed to fresh, brackish, or saline water. The resistivity ($\rho_2 = 39\ \Omega$m) of the second layer at site TEM 18 (Schaumann, 1994) indicates an aquifer of 100 m thickness, probably filled with fairly fresh water. If feasible, the most promising TEM results should be followed up by drilling.

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