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Geophysical profile of the Roter Kamm impact crater, Namibia

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Abstract–New gravity and magnetic data were obtained along ground profiles across the Roter Kamm impact crater in the southern Namib desert of Namibia. As the traverses of previous studies did not extend sufficiently beyond the crater rim, it had not been possible to adequately determine the regional background values. The gravity results of this study are similar to those obtained by Fudali in 1973, in that a negative, near-symmetrical anomaly was obtained over the crater center. This anomaly conforms to the results expected for a sediment and impact breccia-filled, simple bowl-shaped crater. The magnetic results of this study, however, are different to those previously reported, which is most probably as a result of the longer profiles used in this new study. A slight positive magnetic anomaly was obtained over the crater interior. Short-wavelength, high-amplitude anomalies observed in the vicinity of the crater rim reflect magnetization contrasts that are probably related to brecciation and block rotation. Modelling of the positive magnetic anomaly indicates the possibility of a small magnetic body or lining at the crater floor-breccia interface in the interior of the crater. Also presented is a 10 m contour digital elevation model of the crater and its environs.

INTRODUCTION

Roter Kamm Crater, a confirmed impact structure (Reimold and Miller, 1989), was formed ~3.7 Ma ago (Koeberl *et al.*, 1993; Reimold *et al.*, 1994). The well-preserved crater is located at E16°18' and S27°46' in the Namib Desert of southern Namibia (Fig. 1). Figure 2a–c shows the near circularity of the crater. The rim to rim diameter of Roter Kamm is ~2.5 km. Eolian sands are pervasive both inside and outside of the crater. The only exposures of Precambrian granitoid rocks (granitic-granodioritic orthogneisses) are found along the partially sand covered rim (Reimold and Miller, 1989). The crater occurs in gneisses and granite of the Namaqualand Metamorphic Complex, for which metamorphic ages between 900 and 1200 Ma have been determined. Inclusions of arkose, amphibolites, and aplite occur within the Namaqualand gneisses (Reimold and Miller, 1989). Reimold and Miller (1989) noted that quartz veins and quartz-feldspar pegmatites are a common lithology of the crater area. Locally on the crater rim, patchy exposure of Gariep marble (~500 Ma) and graphitic schist has been observed.

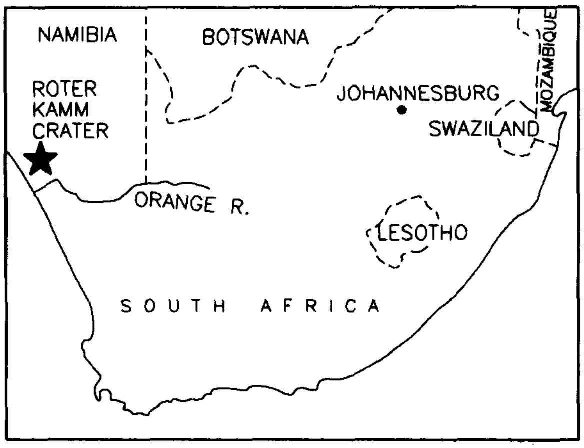

FIG. 1. Locality map of the Roter Kamm impact crater in the Namib Desert of southern Namibia.

Magnetic phases typical of the basement granites and granodiorites are hornblende, biotite, and minor amounts of magnetite (Reimold and Miller, 1989). According to these authors, the rim rocks are cut by extremely fine-grained, generally dark colored breccia veins and dykes that resemble pseudotachylitic breccias of the Vredefort and Sudbury impact structures. However, evidence of melting in such material from Roter Kamm is very limited (Reimold and Miller, 1989; Degenhardt *et al.*, 1994, 1996). Such breccia also occurs 1 km outside of the crater rim in an outlier of Gariep marble. At Roter Kamm, these breccias occur in a variety of types, ranging from dykes of tens of meters in thickness to submillimeter veinlets. For a more detailed account of the crater rim rocks, the reader is referred to Reimold and Miller (1989).

Several other investigations have been carried out at the crater during the last few years. These include detailed mineralogical and chemical studies on numerous breccia and country rock samples (Reimold and Miller, 1989; Reimold *et al.*, 1994; Degenhardt *et al.*, 1994, 1996), as well as geophysical (Reimold *et al.*, 1992; Brandt *et al.*, 1996), and ground penetrating radar investigations (Grant *et al.*, 1996, 1997). Owing to sparse outcrop, geophysical studies are a useful means to contribute to the understanding of the geology of the crater. Although geophysical signatures over terrestrial impact structures can not provide definite evidence for an impact origin, they may lead to the initial discovery of an impact crater and may complement the existing database for a known impact structure, providing a more definite assessment of the subsurface geology (Grieve and Pilkington, 1996). The two most commonly used geophysical surveys in the evaluation of possible impact craters are gravity and magnetic investigations (Grieve and Pilkington, 1996). Both of these methods were employed at the Roter Kamm crater.

First results of geophysical studies at Roter Kamm were reported by Fudali (1973) and included two gravity profiles and one magnetic profile across the crater interior (Fig. 3). The gravity data were modelled to fit a simple, bowl-shaped crater of ~700–800 m depth. Using information from the shapes of the gravity profiles, Fudali calculated a number of subsurface configurations for these

FIG. 2. (a) TM-5 LANDSAT image of the Roter Kamm impact structure and environs (courtesy Namdeb). North is up. (b) Aerial photograph of the Roter Kamm crater, showing the near circularity of the crater. The rim to rim diameter of the crater is ~2.3 km.

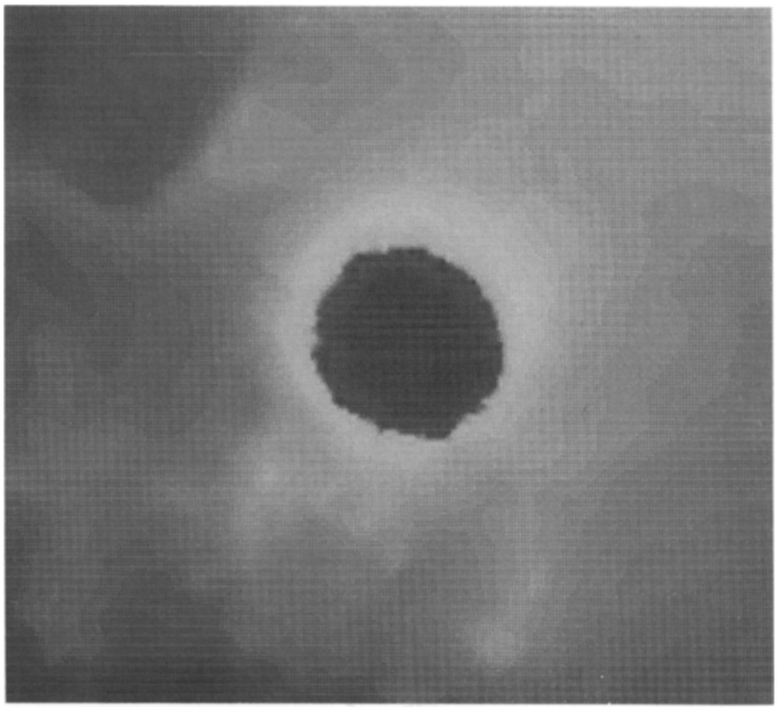

Fig. 2. *Continued.* (c) Digital elevation model of Roter Kamm and environs (courtesy Namdeb). Contours are shown in 10 m intervals. North is towards the top.

profiles and explained the observed profiles with a shallow body, whose lower boundary is bowl-shaped and unaffected by structural rebound effects. He modelled a two-layer crater fill: an open lens of sediments overlying a lower zone of brecciated country rock. For the crater fill, thicknesses of ~400 to 500 m for a breccia layer overlain by ~300 m of eolian sands were modelled by Fudali (1973). These values were obtained using density contrast estimates of 0.8 g/cm^3 for the sand fill (1.9 g/cm^3 for the sand *vs.* 2.7 g/cm^3 for the country rock) and 0.3 g/cm^3 for the brecciated zone. In addition, the lower boundary was arbitrarily fixed at a depth of 760 m and the crater sediment-breccia interface (or original crater floor) at a depth of 305 m. Based on these results and "other empirical observations and calculations," Fudali (1973) noted that his hypothetical crater floor is just what would have been predicted from scaling relationships using the crater diameter alone.

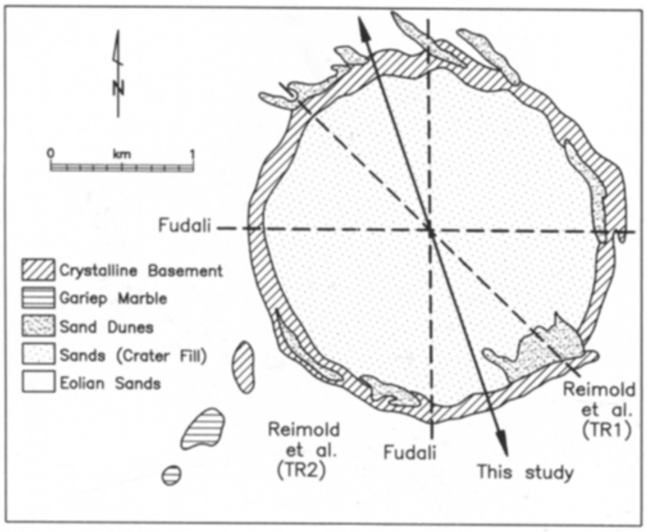

FIG. 3. Position of the geophysical profiles: previous work (Fudali, 1973; Reimold *et al.*, 1992) and this study (arrows indicate that the profile extended more than 1000 m beyond the crater rim).

Fudali's (1973) north-south magnetic profile was featureless, except for what he described as "appreciable noise" in the vicinity of the rim. He suggested that the magnetic signal over the crater interior was the result of the underlying crystalline basement being almost devoid of magnetite and that the "noise" in the vicinity of the rim was caused by brecciation and block rotation in the crater rim. A second geophysical survey was carried out by Reimold *et al.* (1992). Their study consisted of two magnetic traverses, which were oriented southeast-northwest and southwest-northeast (Fig. 3). They obtained results similar to those of Fudali (1973), except for "a higher noise level" over the interior of the crater, which they attributed to some magnetite and a variable moisture content of the upper sand fill.

Here we present the results of another gravity investigation, of new magnetic ground data obtained along traverses extending for the first time far beyond the crater rim, as well as a digital elevation model for the Roter Kamm crater.

GRAVITY RESULTS

The expected gravity anomaly for a simple bowl-shaped crater, such as Roter Kamm, is a negative and roughly circular gravity anomaly, which is due to the associated low density sedimentary and impact breccia crater fill, and the high porosity of these lithologies. After standard data reductions, which include corrections for instrument drift, elevation, latitude and severe topographic differences, as well as the removal of the first-order regional field, the typical gravity low is generally circular and extends to or slightly beyond the crater rim (Grieve and Pilkington, 1996). The amplitude and shape of the negative anomaly associated with simple impact structures depends on a number of factors, including crater size, level of erosion, nature and heterogeneity of the target materials, and the density contrasts between brecciated or fractured target rocks, sedimentary infill, and unaffected target material (Grieve and Pilkington, 1996).

For our investigation in 1995 June, 75 gravity stations, at 60 m intervals, were located along a single north-south traverse (Fig. 3), extending ~1000 m beyond the crater rim on both sides. The topographic profile measured along the gravity traverse and the gravity results are shown in Fig. 4a,b, respectively. Both the gravity and elevation profiles were measured relative to an arbitrary base station located on the southern upper crater rim. Station elevations were determined using a Kern level, and gravity readings were taken using a La Coste and Romberg gravimeter with a sensitivity of 0.01 mgal. Positions were also recorded for each of the gravity stations using a differential global positioning system (GPS). Standard gravity data reductions, including instrument drift, elevation, latitude effects, and terrain corrections were carried out and resulted in a centered, near-symmetrical anomaly of –8.8 mgal (Fig. 4b). The terrain effects amounted to ~1 mgal in areas of severe topography and <0.1 mgal in areas of subdued topography or flat ground.

The small positive perturbation on the outer southern rim (Fig. 4b) is most probably due to compositional differences in the basement rocks, which have been noted to be distinctly heterogeneous (Reimold and Miller, 1989; Reimold *et al.*, 1994). The low density crater

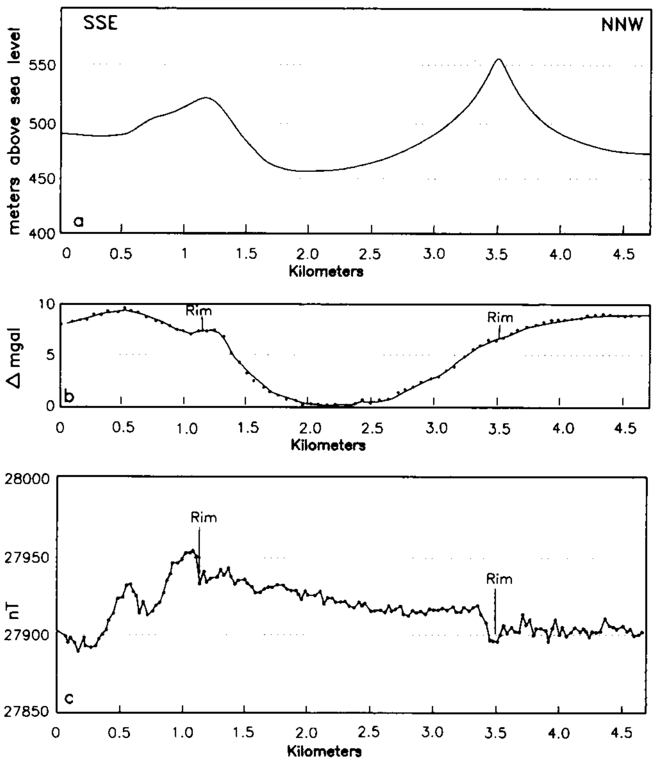

FIG. 4. (a) Elevation profile extending ~1000 m beyond the rim to the north and the south; (b) gravity profile showing a near-symmetrical anomaly of −8.8 mgal (the small positive perturbation on the southern rim is most probably due to compositional differences in the basement rocks or a local less brecciated volume of rock); and (c) magnetic profile across the crater showing a 30 nT anomaly indicative of an induced magnetized sill.

sediments and impact breccias that fill the crater are believed to be the primary cause of the observed negative anomaly over the crater interior. According to Grieve and Pilkington (1996), fracturing of the autochthonous rocks beneath the crater floor generally has little effect on the observed gravity anomaly in relatively small, simple bowl-shaped impact structures. However, these observations are not based on modelling results; and in the case of the Roter Kamm Crater, the observed anomaly (Fig. 4b) clearly indicates a source wider than the crater fill, that is, it most likely indicates a significant contribution from brecciation at and outside of the rim.

The density contrasts suggested by Fudali (1973) of 1.9 g/cm^3 and 2.7 g/cm^3 for the sand and the country rock, respectively, are typical values for these lithologies. As subsurface stratigraphic thicknesses are still unknown, more accurate gravity modelling than that carried out by Fudali is not possible. Also, because of the lack of statistical surface observations concerning the provenance of autochthonous breccia in the rim rocks, an estimate of the degree of brecciation or porosity of the surface breccias would not be representative of the subsurface breccias. Our results do, however, suggest that brecciation extends to at least 500 m beyond the rim and that brecciation is more significant than indicated by Fudali's (1973) estimates.

MAGNETIC RESULTS

The magnetic signatures of impact structures are generally far more complex than the gravity signatures (*e.g.*, Scott *et al.*, 1997). The typical magnetic effect observed at impact structures with crater diameters similar to that of Roter Kamm, is a magnetic low or a magnetically subdued or featureless zone (Dabizha and Fedynsky, 1975; Clark, 1983; Pilkington and Grieve, 1992). Consequently, the magnetic field over the crater differs from the regional magnetic field (Grieve and Pilkington, 1996). Ormö and Blomqvist (1996) consider this a typical feature in the magnetic expression of impact craters, as they noticed that these magnetic lows appear in craters of various sizes and with different target lithologies. Magnetic lows associated with impact craters may be related to oxidation of magnetite in the brecciated zone (Henkel and Pesonen, 1992), or to depth to the buried unaffected basement under the low magnetic sedimentary crater fill (Henkel, 1992). Disruption and disordering of magnetization vectors caused by brecciation may be another relevant factor (Beals *et al.*, 1963). According to Grieve and Pilkington (1996), the magnetic anomalies often do not show any relationship between the shape of the anomaly and the morphology of the impact structure. These authors further suggest that the form of the anomaly depends on the size of the structure and that some impact structures may not show any obvious magnetic anomaly at all.

According to Henkel (1992), crater fill and authigenic brecciation conceal or camouflage signals from the unaffected magnetic structures at depth. Henkel (1992) also noted that impact melt sheets and part of the brecciated basement are often remanently magnetized and produce thin sheet anomalies, with polarities of an anomaly related to the direction of the ambient geomagnetic field at the time of impact. The impact event may in some cases change the magnetization state of the target lithologies: target rocks may acquire shock remanent magnetization (SRM), thermoremanent magnetism (TRM), or chemical remanent magnetism (CRM), influenced by the direction of the Earth's magnetic field (see also Hart *et al.*, 1995; Gibson and Reimold, 1995; Henkel and Reimold, 1996, 1998). According to Cisowski and Fuller (1978), the strength of the SRM increases with ambient field intensity and decreases with distance from the point of impact. Grieve and Pilkington (1996) reported shock pressures of >1 GPa and temperatures less than the Curie points of magnetic phases as requirements for the occurrence of SRM. Fel'dman (1994) observed changes in magnetic properties due to shock induced mineralogical changes at shock pressures >30 GPa. These changes, particularly in mafic silicate minerals, include the production of magnetite from the thermal decomposition of amphibole and biotite.

At Roter Kamm, total magnetic field data were collected at 30 m intervals, along the same north-south traverse used for the gravity study (Fig. 3), using a proton magnetometer. The raw data were corrected for diurnal variations. The corrected profile is shown in Fig. 4c. The shape of this profile is somewhat different from the results obtained by Fudali (1973) and Reimold *et al.* (1992), which were generally featureless. Short-wavelength, high-amplitude anomalies, referred to as "noise" by previous workers (Fudali, 1973; Reimold *et al.*, 1992), were observed near the inner and outer crater rim sections slight (~30 nT) positive magnetic anomaly over the crater, which dies out abruptly outside of the crater rim (at ~700 m from the southern rim and 100 m from the northern rim), in an outward direction from the crater rim. It should be noted that the profiles of Fudali (1973) and Reimold *et al.* (1992) did not extend very far (<600 m) beyond the crater rim, which may be the reason why these authors did not observe the return to regional magnetic values outside the crater.

Available regional aeromagnetic data from an airborne survey (covering an area of 19 000 km^2 ~70 km to the northeast of the crater; supplied by the Department of Geophysics, University of the Witwatersrand), at a line interval spacing of 1 km, show no obvious magnetic anomalies in the area adjacent to the crater. Magnetic anomalies associated with dyke swarms and other linear features, trending northwest-southeast, and spaced at 5 km or more, were noted, however, to the northeast of the crater. These are the only obvious, large-scale, magnetic features in this region. The regional magnetic signature does not provide an obvious reason for the small perturbations seen on the magnetic profile (Fig. 4c). Airborne magnetic data for the crater itself and for the area to the south and west of the crater are not available.

Magnetic Modelling

As the +30 nT anomaly obtained over the crater is in contrast to the expected magnetic low, magnetic modelling was carried out in an attempt to explain the observed anomaly. A magnetic modelling program, Mag2dc (G. Cooper, Department of Geophysics, University of the Witwatersrand), was used in the modelling of the magnetic data. The program allows for manipulation of all parameters including magnetic susceptibility contrasts, shape, size, depth, and number of bodies. Constraints, such as the knowledge of the magnetic susceptibilities for all the rock types within and around the structure, are a prerequisite for an accurate magnetic model. These data, however, are not known for the Roter Kamm impact structure due to the lack of core samples, the typical lack of outcrop due to the eolian sand cover of most of the region, and the variability of the target lithologies. The only known magnetic parameters are magnetic inclination (–55°) and declination (20°W). Variations in the local geomagnetic field strengh (~27 950 nT) were used in the modelling. It should be noted that the magnetic susceptibility contrasts, used for the modelled bodies, in the modelling were all estimated and have very low values with respect to the country rocks. That is, the modelled bodies are only very slightly magnetised with respect to the target material. The modelling assumes that both source models are induced magnetized only, that is, no remanent magnetization was added.

By changing the variable parameters mentioned above for the bodies, a best-fit response curve was obtained (Fig. 5). The model obtained is an approximation and only one of many possible configurations. The actual bodies giving rise to the anomaly are most probably far more numerous and complex than those shown in the model (Fig. 5). The modelling was based on the assumption that the observed anomaly is almost entirely due to a magnetic sheet-like (melt) body occurring approximately at or a little above the crater floor at ~700 to 800 m depth (cf., Fudali, 1973).

According to Henkel (1992), the extension of impact melt sheets can be mapped fairly well by magnetic measurements. For example, this was shown for the Mien and Dellen impact craters, where Henkel estimated thicknesses of melt bodies entirely on the basis of magnetic model calculations, which considered a remagnetized upper part of the breccia layer below the melt sheet. From our model (Fig. 5), the simple melt sheet has a maximum volume of 0.4 km^3 (cf., Brent crater: 2×10^{-2} km^3, Grieve and Cintala, 1981), and a possible small variation in the magnetic susceptibility in the basement lithology on the northern rim is noted. It also appears that the central +30 nT magnetic anomaly is not only derived from within the dimensions of the impact structure, but also from the inhomogeneity or partial demagnetization of the surrounding rocks, particularly on the northern rim.

Digital Elevation Modelling

A digital elevation model (Fig. 2c) was constructed using contours from the 1:50 000 topographic map sheets. The model was further refined using drainage patterns captured from published topographic maps. Interpolation of these data allowed for a contour interval of 10 m. This model will be invaluable with regard to further detailed assessment of the geomorphology of the crater and environs as well as surface and subsurface geology. In addition, it is planned to compare digital elevation models of Roter Kamm obtained from various space borne platforms such as the European Remote Sensing Satellite (ERS) and the Shuttle Imagery Radar Experiments (SIR-C).

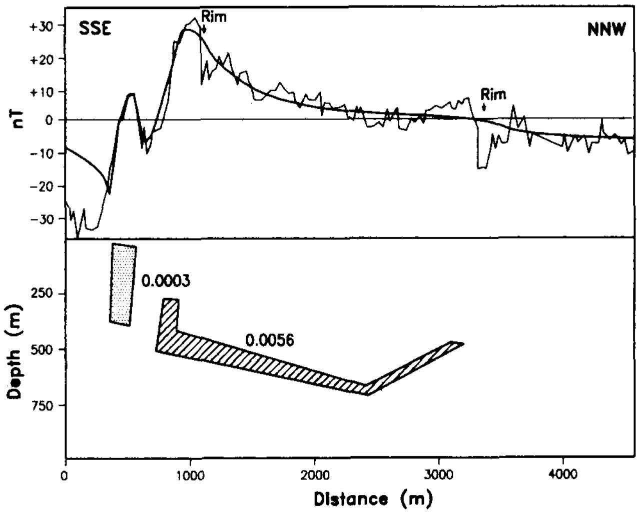

FIG. 5. Actual magnetic profile and best-fit modelled profile obtained using two simple bodies of a higher magnetic susceptibility, such as would be expected for a possible melt sheet occurring at the transient crater-breccia interface. The northern most body may be due to local susceptibility variations in the target material. Magnetic susceptibility is given in SI.

DISCUSSION

The negative gravity anomaly (–8.8 mgal) obtained over the interior of the Roter Kamm impact crater is within reasonable limits of that expected for an impact crater of these dimensions. The gravity anomaly clearly shows a strong basement brecciation effect, as the anomaly extends well beyond the crater rim. Thin sheet anomalies due to near-surface impact melt sheets and part of the brecciated zone are often remanently magnetized with the polarity being related to the direction of the ambient geomagnetic field at the time of the impact (Henkel, 1992). At the Roter Kamm crater, we observed a positive (+30 nT) magnetic anomaly in contrast to the expected magnetic anomaly. The magnetic anomaly (Fig. 4c) generally has a low noise level (on average <10 nT) and clearly indicates the occurrence of an induced and possible remanent magnetic source most probably in the shape of a thin, shallow (several hundred meters depth) layer inside the structure. Features such as this anomaly would become subdued if the feature occurred at considerable depth. Also, the variable proximity to crystalline rocks, exposed at the rim and below the fill inside the crater, will generate small local anomalies. These, however, would be expected to be symmetric with respect to the rim shape. In addition, one could expect overturned parts of the basement, creating a local repetition of magnetic layers. If these existed, small local anomalies would also be generated. An alternate explanation for the observed anomaly could be the formation of magnetic phases due to shock transformations.

In the 3.8 km wide Brent crater, several melt rock occurrences were reported (Grieve and Cintala, 1981) at a total volume of 2×10^{-2} km^3 of impact melt and an additional significant amount in melt fragments in suevitic breccia. Therefore, the 30 nT anomaly and larger contact anomalies at Roter Kamm (negative to the north and positive to the south) may well be due to the existence of a small magnetic melt body or lining at the crater floor-breccia interface in the interior of the crater. It should be noted that the variation of repeated measurements within a few meters of any given measurement site was found to be as high as 10 nT during a time interval of a few minutes, most probably due to the magnetisation of the observer. This value is approximately one-third of the value of the observed anomaly. In addition, the scarcity of impact melt and suevite (Reimold *et al.*, 1997) fragments found so far at the surface, despite a number of detailed geological rim traverses, could also be interpreted to indicate that only a limited amount of impact melt was produced in the Roter Kamm impact event. The short-wavelength, high-amplitude anomalies recorded at the crater rim are most probably caused by brecciation and block rotation (assuming significant remanent magnetization and block sizes larger than the measurement spacing) in the crater rim. This was previously suggested by Fudali (1973) and Reimold *et al.* (1992). Structural studies undertaken along the rim crest (Reimold and Miller, 1989; unpublished observations made by our group) have confirmed that block deformation and rotation, as well as faulting, are ubiquitous phenomena, characterizing the entire rim of this crater. The overall magnetic anomaly obtained, however, can be modelled as a sill-type structure with contact anomalies at the edges. The depths (700–800 m) of the modelled bodies, occurring at the base of the crater fill, are in agreement with the gravity results of this study as well as of Fudali's study (1973).

A seismic survey, which may provide better spatial resolution of subsurface geology, has not yet been undertaken. A seismic study would allow for a better understanding of the lithologies (thicknesses and densities) underlying the crater fill and sand cover. These results would allow, in turn, the calculation of a well-defined gravity model, which has not been possible to date. The Ground Penetrating Radar study carried out by Grant *et al.* (1997) only helped to define the gradation of the landforms associated with the crater, as radar penetration was limited to <5 m. These results were, therefore, of no use to our study in which subsurface information from much greater depths was required.

Our gravity results are similar to those obtained at the 1.13 km diameter Pretoria Saltpan (Tswaing) impact crater in South Africa (Brandt *et al.*, 1995), and at the 0.875 km diameter Wolf Creek crater in Australia (Fudali, 1979), where centered negative gravity anomalies were obtained over the crater interiors (cf., Pilkington and Grieve, 1992). The magnetic anomaly of the Pretoria Saltpan crater was generally featureless but also exhibited some short-wavelength, high-amplitude anomalies in the vicinity of the inner crater rim (Brandt *et al.*, 1995). In the case of the Pretoria Saltpan crater, however, several magnetic lamprophyre dykes were observed in outcrop, which could be associated with these anomalies.

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REFERENCES

Beals C. S., Innes M. J. S. and Rottenberg J. A. (1963) Fossil meteorite craters. In *The Moon, Meteorites and Comets* (eds. B. M. Middlehurst and G. P. Kuiper), pp. 235–284. Univ. Chicago Press, Chicago, Illinois, USA.

Brandt D., Reimold W. U. and Durrheim R. J. (1994) Geophysical signature of the Pretoria Saltpan impact structure and a possible satellite crater. *Meteoritics* **29**, 379–384.

Brandt D., Reimold W. U., Koeberl C. and Grant J. (1996) Geophysical signatures of the Roter Kamm impact crater, Namibia (abstract). *Lunar Planet. Sci.* **27**, 153–154.

Chao E. C. T. (1968) Pressure and temperature histories of impact metamorphosed rocks based on petrographic observations. In *Shock Metamorphism of Natural Minerals* (eds. B. M. French and N. M. Short), pp. 135–158. Mono Books, Baltimore, Maryland, USA.

Cisowski S. M. and Fuller M. (1978) The effect of shock on the magnetism of terrestrial rocks. *J. Geophys. Res.* **83**, 3441–3458.

Clark J. F. (1983) Magnetic survey data at meteoritic impact sites in North America. *Geomagnetic Service of Canada, Earth Physics Branch,* Open File **83–5**, 1–32.

Dabizha A. I. and Fedynsky V. V. (1975) The Earth's "star wounds" and their diagnosis by geophysical methods (in Russian). *Z. Vselennaya* **3**, 56–64.

Degenhardt J. J., Buchanan P. C., Reid A. M. and Miller R. M. (1994) Breccia veins and dykes associated with the Roter Kamm crater, Namibia. In *Large Meteorite Impacts and Planetary Evolution* (eds. B. O. Dressler, R. A. F. Grieve and V. L. Sharpton), pp. 197–208. Geol. Soc. Amer. Spec. Pap. **293**, Boulder, Colorado, USA.

Degenhardt J. J., Reid A. M., Miller R. M. and Reimold W. U. (1996) Breccias resembling melt bombs from the Roter Kamm Crater, Namibia. *Meteorit. Planet. Sci.* **31**, 413–415.

Fel'dman V. I. (1994) The conditions of shock metamorphism. In *Large Meteorite Impacts and Planetary Evolution* (eds. B. O. Dressler, R. A. F. Grieve and V. L. Sharpton), pp. 121–132. Geol. Soc. Amer. Spec. Pap. **293**, Boulder, Colorado, USA.

Fudali R. F. (1973) Roter Kamm: Evidence for an impact origin. *Meteoritics* **8**, 245–257.

Fudali R. F. (1979) Gravity investigation of Wolf Creek crater, Western Australia. *Journal of Geology* **87**, 55–67.

Gibson R. L. and Reimold W. U. (1995) Comment on 'Magnetic anomaly near the centre of the Vredefort structure: Implications for impact related magnetic signatures' by R. J. Hart *et al.* *Geology* **23**, 1149–1150.

Grant J. A., Koeberl C., Reimold W. U., Schultz P. H., Brandt D. and Franzsen A. J. (1996) The degradation history of the Roter Kamm impact crater, Namibia (abstract). *Lunar Planet. Sci.* 27, 447–448.

Grant J. A., Koeberl C., Reimold W. U. and Schultz P. H. (1997) Gradation of the Roter Kamm impact crater, Namibia. *J. Geophys. Res.* **102**, 16 327–16 338.

Grieve R. A. F. and Cintala M. J. (1981). A method for estimating the initial impact conditions of terrestrial cratering events, exemplified by its application to Brent crater, Ontario. *Proc. Lunar Planet. Sci. Conf.* **12th**, 1607–1621.

Grieve R. A. F. and Pilkington M. (1996) The signature of terrestrial impacts. *AGSO J. Austr. Geol. Geophys.* **16**, 399–420.

Hart R. J., Hargraves R. B., Andreoli M. A. G., Tredoux M. and Doucouré C. M. (1995) Magnetic anomaly near the centre of the Vredefort structure: Implications for impact related magnetic signatures. *Geology* **23**, 277–280.

Henkel H. (1992) Geophysical aspects of meteorite impact craters in eroded shield environment, with special emphasis on electric resistivity. *Tectonophysics* **216**, 63–89.

Henkel H. and Pesonen L. J. (1992) Impact craters and craterform structures in Fennoscandia. *Tectonophysics* **216**, 31–40.

Henkel H. and Reimold W. U. (1996) *Integrated gravity and magnetic modelling of the Vredefort impact structure—Reinterpretation of the Witwatersrand Basin as the erosional remnant of an impact basin.* Royal Institute of Technology Report, Stockholm, Sweden. 90 pp.

Henkel H. and Reimold W. U. (1998) Intergrated geophysical modelling of a giant, complex impact crater: Anatomy of the Vredefort Structure, South Africa. *Tectonophysics*, in press.

KOEBERL C., HARTUNG J. B., KUNK M. J., KLEIN J., MATSUDA J. I., NAGAO K., REIMOLD W. U. AND STORZER D. (1993) The age of the Roter Kamm impact crater, Namibia: Constraints from ^{40}Ar-^{39}Ar, K-Ar, Rb-Sr, fission track and ^{10}Be-^{26}Al studies. *Meteoritics* **28**, 204–212.

ORMÖ J. AND BLOMQVIST G. (1996) Magnetic modelling as a tool in the evaluation of impact structures, with special reference to the Tvären Bay impact crater, SE Sweden. *Tectonophysics* **262**, 291–300.

PILKINGTON M. AND GRIEVE R. A. F. (1992) The geophysical signature of terrestrial impact craters. *Rev. Geophys.* **30**, 161–181.

REIMOLD W. U. AND MILLER R. M. (1989) The Roter Kamm impact crater, SWA/Namibia. In *Proc. Lunar Planet. Sci. Conf.* **19th**, 711–732.

REIMOLD W. U., REID A. M., JAKES P. AND ZOLENSKY M. (1992). A magnetic survey across the Roter Kamm impact crater, Namibia (abstract). *Lunar Planet. Sci.* **23**, 1143–1144.

REIMOLD W. U., KOEBERL C. AND BISHOP J. (1994) Roter Kamm impact crater: Geochemistry of basement rocks and breccias. *Geochim. Cosmochim. Acta* **58**, 2689–2710.

REIMOLD W. U., KOEBERL C. AND BRANDT D. (1997) Suevite at Roter Kamm impact crater, Namibia. *Meteorit. Planet. Sci.* **32**, 431–437.

SCOTT R. G., PILKINGTON M. AND TANCZYK E. I. (1997) Magnetic investigations of the West Hawk, Deep Bay and Clearwater impact structures, Canada. *Meteorit. Planet. Sci.* **32**, 293–308.