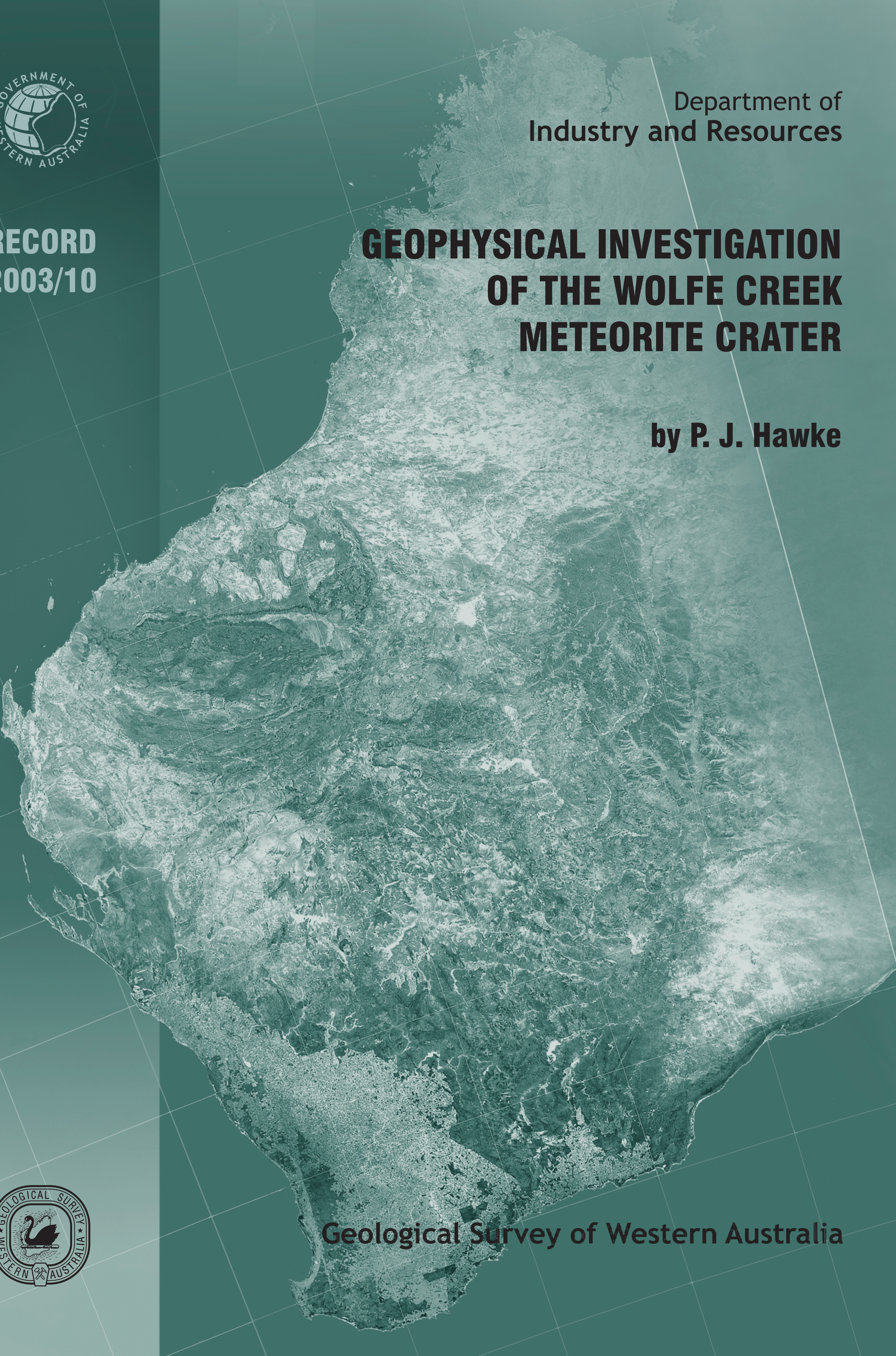

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GEOPHYSICAL INVESTIGATION OF THE WOLFE CREEK METEORITE CRATER

by P. J. Hawke

Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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Geophysical investigation of the Wolfe Creek Meteorite Crater

by

P. J. Hawke[1]

Abstract

The Wolfe Creek Meteorite Crater is 880 m in diameter and is centred at latitude 19°10'S, longitude 127°48'E. The crater was formed in ?Devonian sandstones of the eastern Canning Basin, where they overlie Mesoproterozoic sedimentary rocks of the Birrindudu Basin in the southeast Kimberley region, Western Australia. A recent high-resolution airborne geophysical survey identified subtle magnetic anomalies, less than 4 nT in amplitude, coincident with the crater rim, the base of the inner crater wall, and the centre of the structure. Other products from the airborne survey include radiometric data and a digital elevation model. A negative gravity anomaly of 20 $\mu m/s^2$, due to impact breccia and post-impact sedimentary fill, is also coincident with the crater.

Forward modelling of gravity data using constraints on the density of the impact breccia and crater fill suggest apparent and true crater depths of 150 and 320 m respectively, which are about 30% greater than expected for a simple impact crater the size of Wolfe Creek. The sources of the magnetic anomalies are interpreted to be maghemite within the regolith and post-impact crater fill.

KEYWORDS: impact structures, meteorite craters, geophysics, aerial magnetic surveys, radiometric surveys, gravity, geophysical models, Wolfe Creek, Kimberley region.

Introduction

The Wolfe Creek Meteorite Crater is located at latitude 19°10'S, longitude 127°48'E, about 100 km south of Halls Creek, in the southeast Kimberley region of Western Australia (Fig. 1). The structure is the world's second-largest impact crater on land from which meteorite fragments have been recovered, the largest being Meteor Crater (Arizona U.S.A.). The crater is the main attraction of the Wolfe Creek National Park and is a popular tourist destination. It may be accessed by an unsealed track that joins the Tanami Road 145 km south of Halls Creek.

Wolfe Creek Crater is one of the best preserved examples of a large simple impact crater. The outer wall of the crater slopes up at an angle of about 15º to form a raised crater rim 35 m above the surrounding plain (Fig. 2). The inner walls are steep, facing inward at angles of up to 40º (Bevan and McNamara, 1993). The crater floor is presently about 55 m below the rim and 20–25 m below the surrounding plain. The crater was probably about 150 m deep at the time of impact, but this has been reduced by erosion of the rim and partial filling by eolian sand and evaporite (gypsum and calcite) deposits. The crater is slightly elliptical in plan view, with major and minor axes of 935 and 825 m, and an average diameter of about 880 m. This geometry probably reflects an oblique impact, with the meteorite incident on a trajectory from the northwest or southeast. The present-day crater floor has an average diameter of about 700 m.

A high-resolution airborne magnetic and radiometric survey over the Wolfe Creek Crater was commissioned by the Geological Survey of Western Australia (GSWA) as part of a more regional survey of the west Tanami region. These data are compiled and interpreted as part of an ongoing PhD project, at the University of Western Australia, to catalogue the geophysical signatures associated with meteorite impacts in Australia.

Previous investigations

The Wolfe Creek Crater was first recognized in 1947 by geologists of the Vacuum Oil Company during airborne reconnaissance of the Canning Basin (Reeves and Chalmers, 1948). Originally named 'Wolf Creek' after a local waterway, historical research has revealed that the surname of the person after it was named was in fact 'Wolfe' (Bevan, 1996). While the crater and nearby creek have been renamed, the earlier name is still used for the meteorite fragments recovered from the site. The structure

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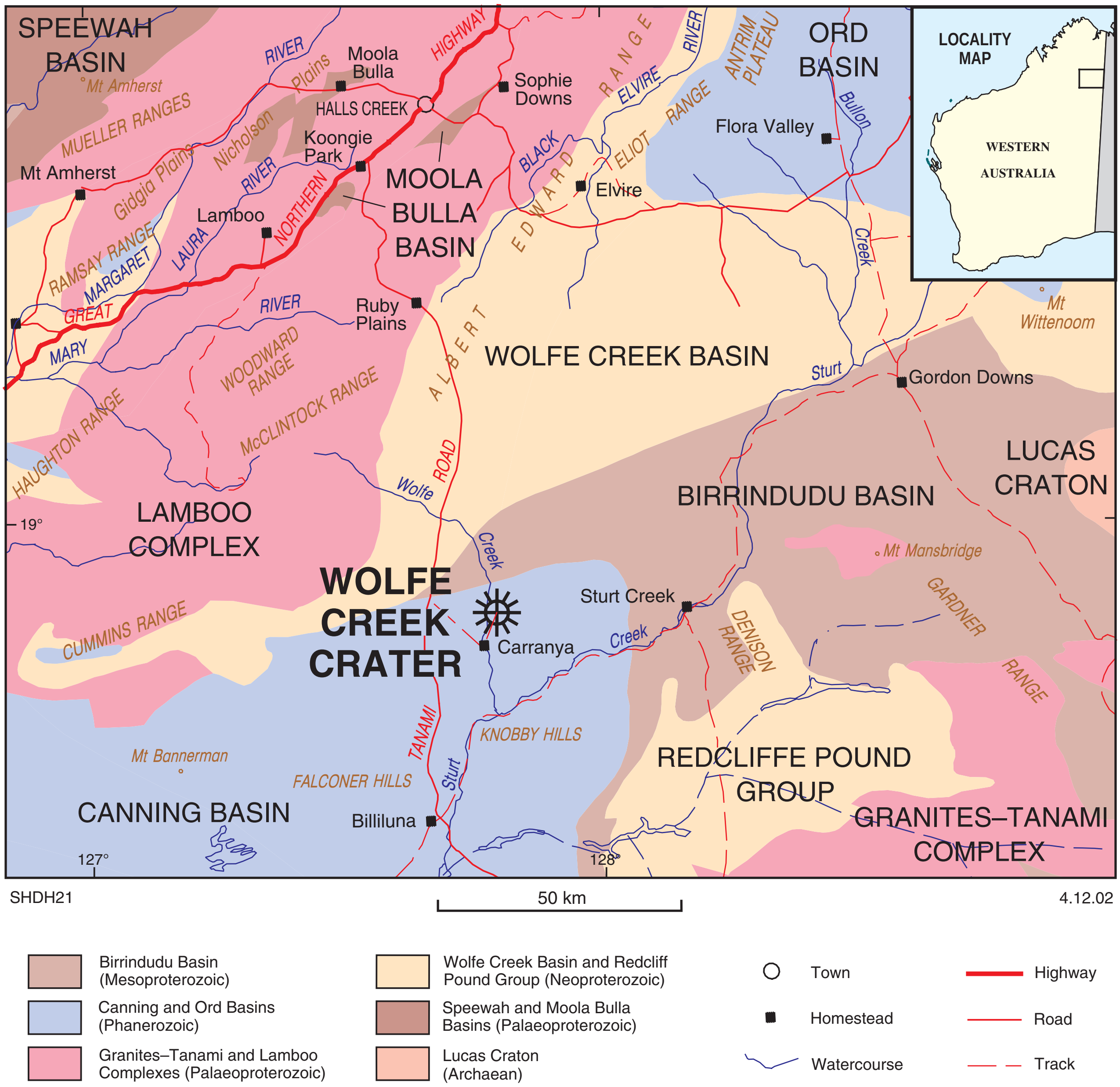

Figure 1. Regional basement geology map showing the location of the Wolfe Creek Meteorite Crater (adapted from Myers and Hocking, 1998)

was initially thought to be of explosive volcanic origin, but was later reinterpreted as an impact crater after comparison to photographs of Meteor Crater (Arizona, U.S.A.). An impact origin of the crater was confirmed in 1948 by a field party from the Bureau of Mineral Resources (now Geoscience Australia), who recovered samples of highly weathered meteorite material (Guppy and Matheson, 1950).

Fresh meteorite fragments are rare, with only 1.3 kg of unoxidized material collected from the site (Bevan, 1996). Several small samples weighing up to tens of grams were recovered 4 km southeast of the crater (Taylor, 1965). However, there is some controversy as to whether these fragments are related to the Wolfe Creek Crater or represent a separate meteorite fall. More common are iron-shale 'balls' of heavily weathered meteorite (Cassidy, 1954; McCall, 1965; Bevan and McNamara, 1993), which can be up to several decimetres in diameter. Similar iron-shale balls have been reported at Meteor Crater. The iron shale balls contain a small amount of fresh metal, which is often microscopic in size (LaPaz, 1954; Knox, 1967). Several tonnes of weathered meteorite have been collected, and indicate that the crater was formed by an iron–nickel meteorite. To produce a crater the size of Wolfe Creek, the meteorite was probably around 50 m in diameter. Analyses of fresh material yielded a chemical composition including 9.22% Ni, 18.4 ppm Ga, 37.3 ppm Ge, and 0.036 ppm Ir, placing the meteorite into chemical group IIIAB (Scott et al., 1973).

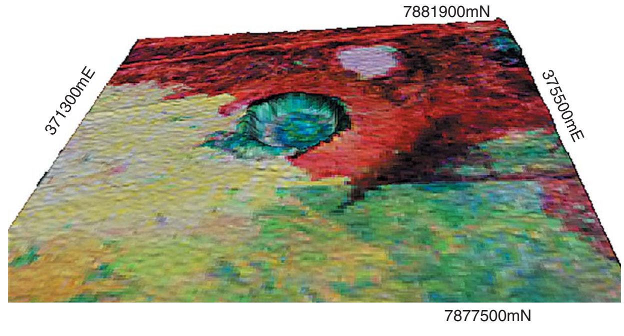

Figure 2. Landsat 741 image draped over the topographic model of the Wolfe Creek Crater (viewed from the south). Width of view is about 3.5 km

Miura (1995) claimed to have found an anomalously dense quartz grain, exhibiting shock lamellae, at the crater rim, although this claim has not been substantiated in literature. From trace concentrations of Fe, Ni, and Ti, Miura (1995) suggested that the grain was recrystallized in the vapour plume resulting from the impact.

A quartz grain exhibiting planar fractures (PFs), shown in Figure 3, was identified by Franco Pirajno of GSWA in a sample taken from several hundred metres north of the crater rim by Robert Cross (Western Australian Department of Industry and Resources). Planar fractures are spaced at irregular intervals of between 50 and 300 µm. Such features are indicative of low levels of shock in the range of 5 to 8 GPa (French, 1998). These grains may represent shocked ejecta material; however, it is also possible that the planar features are not related to the Wolfe Creek impact event.

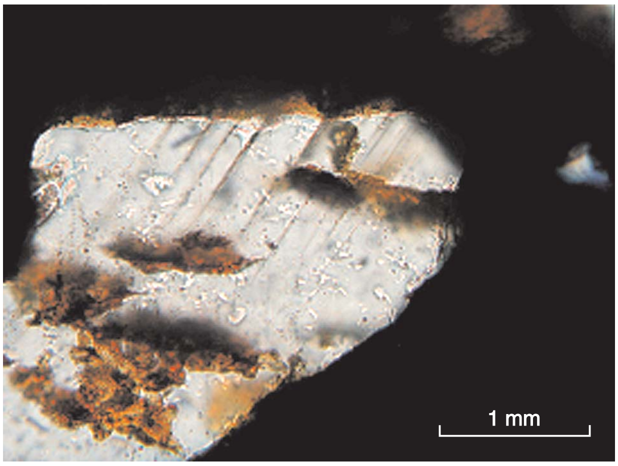

Figure 3. Quartz grain bearing planar features (PFs), possibly representing weakly shocked ejecta material. Fractures are spaced at 50–300 µm intervals. Dark-red material is iron oxide (photo courtesy of Franco Pirajno)

Geology

The geology of the Wolfe Creek Crater is summarized in Figure 4. The crater was formed in gently folded sandstone, described by Blake et al. (1977) as medium- to coarse-grained quartz arenite with interbeds of flaggy micaceous arenite. They mapped this unit as the 'Ima Ima Beds' of the Mesoproterozoic Birrindudu Basin; however, Myers and Hocking (1998) showed this sandstone as part of the Devonian sequence of the eastern Canning Basin.

A laterite surface was probably developed during the Miocene. The plains surrounding the crater are covered with a thin veneer of eolian sand, which commonly forms longitudinal dunes tens of kilometres in length.

There is strong asymmetry to the crater, with sand banked high on the east-northeastern part of the rim and a greater exposure of bedrock to the southwest. A comet-like tail of dune sand lies to the west of the crater. This is most likely an effect of the prevailing wind, depositing sand on the windward side of the raised crater rim, while sweeping clear the leeward side, rather than being directional disposition of ejecta resulting from an oblique impact.

The crater has been largely filled with eolian sand, producing an almost perfectly flat crater floor. The centre of the floor is occupied by dark-grey deposits containing a mixture of gypsum and calcite with quartz sand. These evaporite deposits contain linear chains of 'sinkholes', possibly reflecting increased water flow along fractures within the sandstone basement.

The extent of the deformation of the sandstone beds in the crater wall varies around the rim, from gentle doming in places, to complete outward overturning (McCall, 1965) so that the stratigraphy is locally inverted, with basement sandstone overlying the Miocene laterite (White et al., 1967). These features are consistent with an impact origin of the structure.

Oxidized iron-shale fragments of the Wolf Creek meteorite have been found on the flanks of the crater, up to several hundred metres out from the crater rim. McCall (1965) reported that a number of shale balls are welded into the laterite to the southwest of the crater (Fig. 4). The iron-shale balls are composed primarily of goethite or limonite, with a lesser amount of maghemite (McCall, 1965; White et al., 1967). The iron oxides contain a relic amount of nickel and cobalt, typically less than 1.3% Ni and 0.3% Co, but as high as 8.7% Ni and 0.6% Co (White et al., 1967), although most was lost during weathering. Two exotic nickel-bearing minerals, named reevesite and cassidyite, were discovered in the Wolf Creek shale balls, providing additional evidence of their extra-terrestrial origin.

There are conflicting records of the amount of ejecta present on the flanks of the crater. Guppy and Matheson (1950) suggested that the raised rim contains up to 90 ft (30 m) of broken rock 'thrown up by the explosion of the meteor'. In contrast, McCall (1965) described the rim as essentially in situ outcrop with little evidence of ejecta.

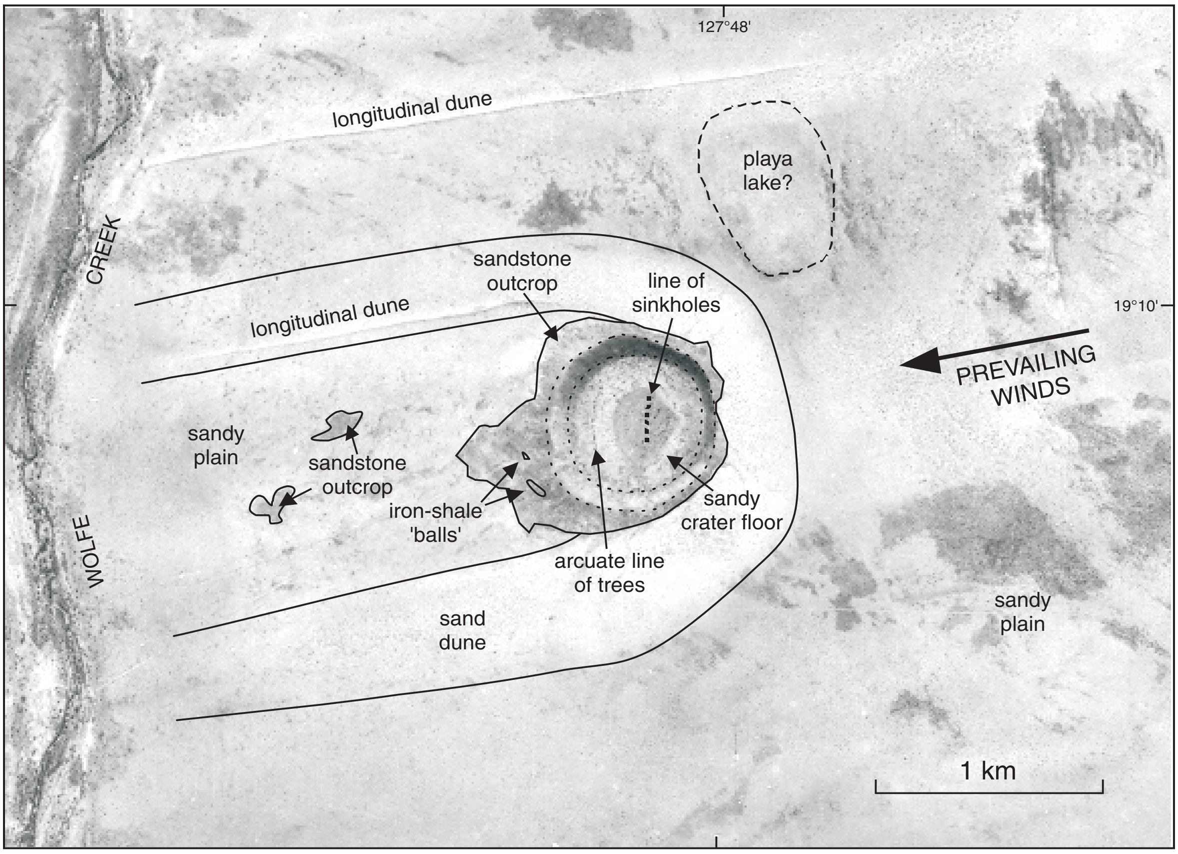

Figure 4. Aerial photograph of the Wolfe Creek Crater with a simplified geological interpretation (adapted from McCall, 1965; Bevan and McNamara, 1993)

Fudali (1979) offered a moderate viewpoint, noting local patches of laterite and bedded quartzite defining the pre-impact surface, but suggested that the rocks near the rim do not appear to be 'solid outcrop'. He also used geophysical evidence to support the interpretation of a 'substantial thickness of rubble under…the rim'.

The laterite surface that covers the target sandstone is assumed to have developed in the Miocene. Disruption of this surface by the weathered meteorite iron-shale balls suggests that the Miocene is the maximum age of the impact (Guppy and Matheson, 1950). An absolute age of impact of 300 000 years was obtained by Shoemaker et al. (1990) from $^{36}Cl/^{10}Be$ and $^{41}Ca/^{36}Cl$ ratios of a fresh meteorite fragment.

Geophysical surveys

Magnetic and radiometric data

Detailed airborne magnetic and radiometric data were collected over a 4 × 4 km area centred on the Wolfe Creek Crater on north–south lines spaced 50 m apart. A nominal terrain clearance of 40 m was specified for the survey, although the actual flying height varied between 30 and 60 m, particularly near the crater. Magnetic data were collected using a cesium vapour magnetometer, and radiometric data were acquired using a 32-litre crystal scintillator. The data were processed using standard routines that are detailed in the survey logistics report on the attached CD-ROM. Images of the magnetic data are shown in Figures 5a and 5b. The digital elevation model derived from the airborne survey and a ternary colour composite of radiometric data are shown as Figures 5e and 5f.

Variations in the magnetic field over the crater are very subtle, reflecting the non-magnetic nature of the sandstone target. The dynamic range of total magnetic intensity over the survey area is 12 nT (Fig. 5a), which includes a linear magnetic regional field of 2.5 nT/km increasing towards the southwest. Individual anomalies due to near-surface features are generally less than 4 nT in amplitude.

Two circular magnetic anomalies, concentric around a single peak, are coincident with the position of the Wolfe Creek Crater. The circular anomalies correlate with the position of the crater rim and the base of the present-day inner walls of the crater. In the total field data the high magnetic response of the crater is slightly offset to the north, due to the dipolar nature of the magnetic field (Wolfe Creek Crater is at a magnetic latitude of 50°S). Reducing the data to the pole (RTP) effectively removes this offset (Fig. 5b).

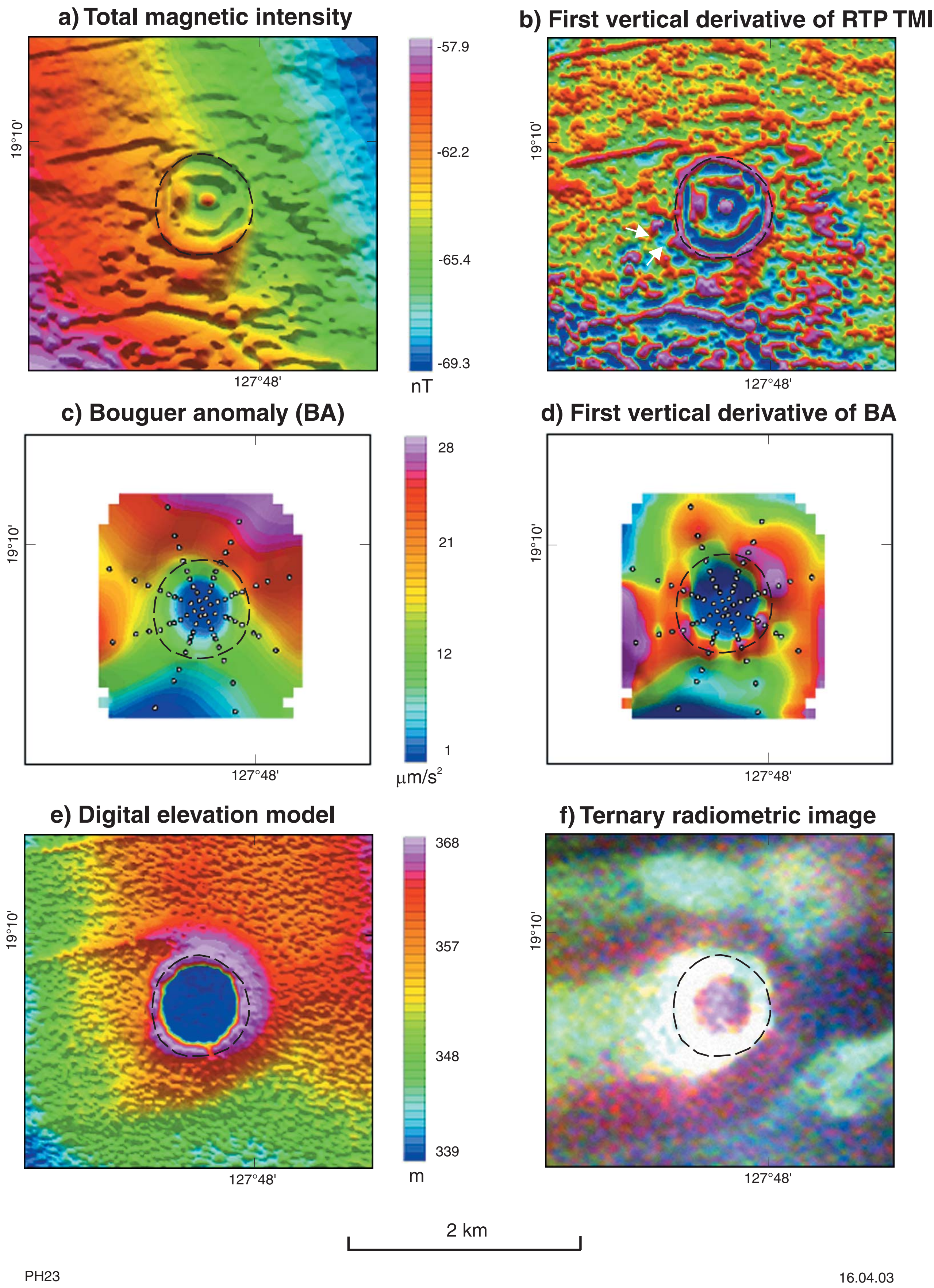

Figure 5. Geophysical images of the Wolfe Creek Crater. The dashed line shows the crater rim

Linear magnetic anomalies trending west-southwesterly coincide with longitudinal sand dunes. A small concentration of heavy minerals or maghemite within the dunes would be sufficient to produce these anomalies. The magnetic relief increases slightly towards the southern margin of the survey area. This is interpreted to reflect a marginally more-magnetic bedded unit within the target sandstone.

Small, discrete magnetic anomalies on the flanks of the crater (shown by white arrows in Figure 5b) may be due to accumulations of weathered meteorite material. The iron-shale balls are reported to be highly magnetic due to a high content of secondary maghemite (Knox, 1967). As the individual balls are small, it would not be expected that they would produce a detectable magnetic anomaly unless they were locally concentrated during deposition.

Surface lithologies are reflected in the radiometric signature (Fig. 5f) of the crater. Sandstone basement, outcropping on the rim and flanks of the crater, gives a strong radiometric response in all three channels (white). The wind-formed dunes have a low-count potassium response (dark red), perhaps due to a feldspar component in the sand. A similar response is observed from the sandy floor of the crater. The evaporite deposits within the centre of the crater do not appear to have a distinct radiometric response.

Gravity data

A detailed gravity survey over the Wolfe Creek Crater was conducted during 1976 by Fudali (1979). Data were collected on four lines with an average station spacing of about 90 m to form a radial pattern centred on the middle of the structure. Gravity measurements were made with a Worden gravity meter and station elevations were optically surveyed. Topography and gravity measurements were made relative to an arbitrary base station in the centre of the crater. Instrument drift, latitude, free-air, and terrain corrections were applied to the data. Several Bouguer densities between 1.8 and 2.2 g/cm^3 were calculated during processing, with a density of 2.0 g/cm^3 considered the most appropriate.

Bouguer anomaly values (for a density of 2.0 g/cm^3) were digitized from profiles and located by comparing the survey plan in Fudali (1979) with the elevation model created from the airborne survey. Additional measurements by Fudali (1987) identified two bad stations in the original survey, but do not other otherwise change the observed response and are not included here. No attempt has been made to merge the data with the national gravity database. Gravity data are presented in Figures 5c and 5d.

After removing the regional gradient from the gravity field, a negative anomaly of 20 μm/s^2 is coincident with the Wolfe Creek Crater. This response is expected for a simple impact crater, with the negative anomaly due to impact breccia and fractured rock in the floor of the crater, and post-impact crater fill. A local central gravity high of about 2 μm/s^2 (Fig. 6) is correlated with the evaporite deposits in the centre of the crater floor. An apparent gravity high around the rim of the crater, best observed in the vertical derivative image (Fig. 5d), is interpreted to reflect outcropping basement. The lower gravity response outside the crater is interpreted to reflect a surface layer of eolian sand, soil, and rubble, estimated by Fudali (1979) to be up to 25 m thick.

The negative gravity response of the crater was forward modelled by Fudali (1979) assuming a density contrast of 0.5 g/cm^3 between sand and the target sandstone, and 0.25 g/cm^3 between fractured and undisturbed rock. These contrasts were selected to represent the differences in dry bulk-densities of undisturbed sandstone, breccia, and quartz sand fill, measured by Fudali (1979) to be 2.25, 2.0, and 1.75 g/cm^3 respectively. A post-impact fill thickness of 95 m and a total thickness of 275 m of disturbed rock are interpreted from the model. When the current topographic relief of the crater is included, apparent and true crater depths of 150 and 330 m are implied. This is about 30% greater than the depths of 114 and 245 m predicted for an 880-m diameter crater by the morphometric relationships given in Grieve and Pilkington (1996).

Forward modelling

A simple 2D forward model of a single magnetic and gravity traverse through the crater was constructed using Encom's potential field modelling software, ModelVision. Data from magnetic survey flight line 100430, which bisects the crater, and the gravity profile collected on a bearing of 24° were modelled. An interpretation of the crater structure based on the forward models is shown in Figure 6.

The variable height of the stinger-mounted magnetic sensor was included in the magnetic model using radar altimeter data. The magnetic response of the Wolfe Creek Crater may be broken down into three components: (1) a circular magnetic high of 1.5 nT amplitude, coincident with the crater rim; (2) a 1.5 nT high at the base of the inner crater wall; and (3) a central peak of roughly 4 nT.

Much of the outer-rim anomaly can be accounted for by modelling the effects of the uneven drape of the aircraft over the steep crater walls, where the sensor is closer to surficial magnetic sources at the top of the rim than when over the crater floor. These surficial sources may be due to a weak uniform magnetization of the target sandstones, as inferred in Figure 5, or they may represent a true near-surface layer of maghemite within the regolith. Although a good fit is achieved on the northern rim of the crater, an additional near-surface source seems necessary on the southern rim to properly fit the data. This could indicate the presence of thick laterite or an accumulation of weathered meteorite 'iron-shale'.

The inner circular anomaly can be adequately modelled by tabular magnetic sources 25 m below the present-day crater floor. The sources are located near the base of the sandy post-impact crater fill that overlies the original crater floor. It is likely that this feature is due to maghemite or heavy minerals within the sand, perhaps

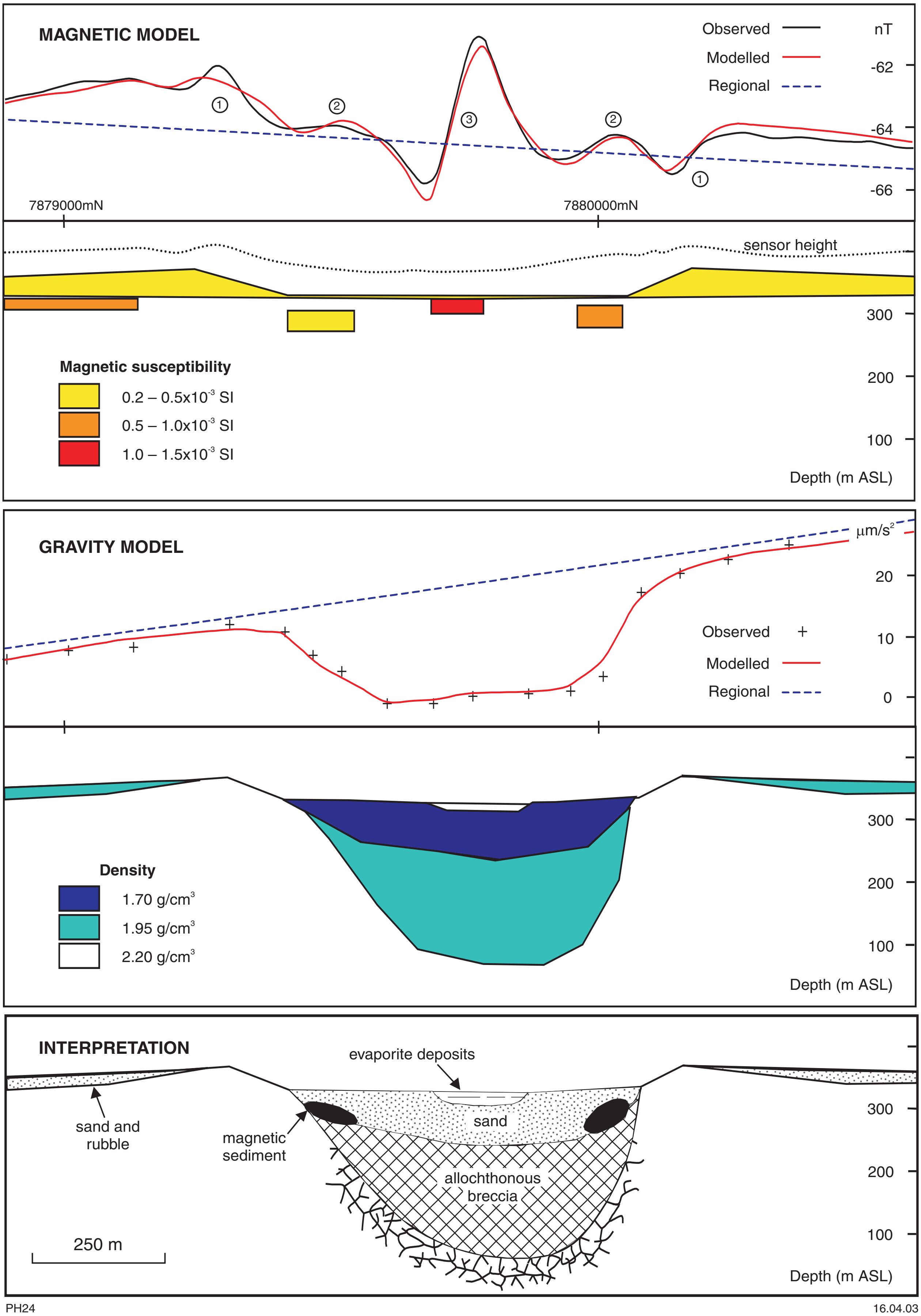

Figure 6. Interpretation of the structure of the Wolfe Creek Crater based on forward modelling of magnetic and gravity data

concentrated by the action of wind swirling around the crater floor. Mineralogical sources are assumed to be similar to those that produce the linear magnetic anomalies associated with longitudinal sand dunes to the north and west of the crater. A weakly magnetic melt sheet may be interpreted as an alternative source of the anomaly. However, it would be expected that an impact melt should accumulate near the centre of the breccia lens, and not at the margin.

The forward modelling indicates that the central magnetic anomaly is due to a magnetic source near the top of the present-day crater floor. This anomaly is spatially associated with the evaporite deposits that have formed in the centre of the crater, possibly reflecting a greater accumulation of maghemite within these deposits.

The gravity forward model was aimed to reconstruct the earlier model created by Fudali (1979). Based on Fudali's (1979) bulk-density measurements, a target density of 2.20 g/cm^3 was assumed, with density contrasts of 0.5 g/cm^3 between target rock and crater fill, and 0.25 g/cm^3 between target rock and breccia.

This model agrees with the results of the earlier study — a thickness of 95 m of low-density crater fill, overlying 170 m of autochthonous breccia, giving interpreted apparent and true crater depths of 150 m and 320 m respectively. The small positive Bouguer anomaly of the centre of the crater is interpreted as a near-surface density source that correlates with the evaporite claypan.

While this gravity model is constrained by reasonable density contrasts, it should be noted that it is possible to achieve equally good results by adjusting the density and thickness of the breccia and crater-fill bodies. In order to fit the model to the morphometric constraints of Grieve and Pilkington (1996), density contrasts of 0.35 and 0.6 g/cm^3 must be used for the difference between the target rock and the impact breccia and crater-fill respectively; but these values are not consistent with the petrophysical measurements made by Fudali (1979).

Conclusions

The Wolfe Creek Crater is the world's second-largest land meteorite crater of confirmed status, where meteorite material has been recovered from the site. The crater is slightly elliptical, with an average diameter of 880 m, suggesting that it was formed by an oblique impact with the meteorite incident from the southwest or northeast. Analyses of recovered meteorite material suggest that the crater was formed by a iron–nickel meteorite of chemical group IIIAB. The size of the crater indicates that the meteorite was probably around 50 m in diameter.

The geophysical characteristics of the Wolfe Creek crater include:

- weak, circular magnetic anomalies of 1.5 nT amplitude, correlating with the crater rim and the base of the inner crater wall;
- a discrete magnetic anomaly of 4 nT coincident with the centre of the crater;
- a broad negative gravity anomaly of 20 µm/s^2 over the crater;
- an annular gravity high, best seen in the image of first vertical derivative, coincident with the crater rim;
- a 2 µm/s^2 gravity peak in the centre of the crater due to denser evaporitic sediment at the top of the present-day crater floor;
- a circular pattern in radiometric and Landsat data reflecting outcrop of the target sandstone on the raised crater rim.

A comet-like tail to the west of the structure is observed in several geophysical and remote-sensing images. This reflects the deposition of sand around the crater rim by the prevailing winds, which blow from the east-northeast, and is not the result of an oblique impact.

Forward modelling of the gravity data using constraints from limited density measurements suggests apparent and true crater depths are 150 and 320 m respectively. These depths are about 30% greater than predicted by the currently accepted morphometric relationships for simple impact craters. An equally good model may be created to fit the morphologic constraints by varying the density contrasts. The annular magnetic anomaly coinciding with the crater rim is largely an artefact of the variable flying height of the survey. Maghemite within the regolith and post-impact crater fill is interpreted to be the source of other magnetic anomalies within and around the Wolfe Creek Crater.

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