

Magnetometer survey of the proposed Sirente meteorite crater field, central Italy: Evidence for uplifted crater rims and buried meteorites

Jens ORMÖ^{1*}, David GOMEZ-ORTIZ², Patrick C. McGUIRE^{1, 3}, Herbert HENKEL⁴,
Goro KOMATSU⁵, and Angelo Pio ROSSI⁶

¹Centro de Astrobiología, Instituto Nacional de Técnica Aeroespacial, Ctra de Torrejón a Ajalvir, km 4, 28850
Torrejón de Ardoz, Madrid, Spain

²Área de Geología, Departamento de CC. de la Naturaleza y Física Aplicada, ESCET, Universidad Rey Juan Carlos,
C/Tulipán s/n, 28933 Móstoles (Madrid), Spain

³McDonnell Center for the Space Sciences, Department of Earth & Planetary Sciences and Department of Physics,
Washington University, Saint Louis, Missouri 63130, USA

⁴Royal Institute of Technology, Department for Land and Water Resources, Teknikringen 76 10044 Stockholm, Sweden

⁵International Research School of Planetary Sciences, Università d'Annunzio, Viale Pindaro 42, 65127 Pescara, Italy

⁶ESA/ESTEC/RSSD/SCI-SM, Keplerlaan 1, 2200 AG Noordwijk, Netherlands

*Corresponding author. E-mail: ormo@inta.es

(Received 20 July 2006; revision accepted 24 November 2006)

Abstract—The Sirente crater field consists of a 120 m wide, rimmed main depression flanked to the northwest by about 30 smaller depressions. It has been dated to the first centuries A.D. An impact origin is suggested, but not confirmed. The small size combined with the properties of the target material (carbonate mud) would neither allow shock features diagnostic of impact, nor projectile vaporization. Consequently, a meteoritic component in the sediments would be very localized. At impacts of this size the projectile most likely is an iron meteorite. Any iron meteorites on the ground surface would, in Iron Age Europe, have been removed shortly after the event. However, if the depressions are of impact origin they should contain meteorites at great depth in analogy with known craters. The magnetic properties of iron meteorites differ distinctly from the very low magnetic sediments and sedimentary rocks of the Sirente area. We have used a proton precession magnetometer/gradiometer to produce magnetic anomaly maps over four of the smaller depressions (~8 m diameter), as well as two crossing profiles over a fifth depression (~22 m diameter). All show distinct magnetic anomalies of about 20 nT, the larger depression up to 100 nT. Magnetic modeling shows a best fit for structures with upturned strata below their rims, excluding a karstic origin but supporting an explosive formation. The 100 nT anomaly can only be explained by highly-magnetic objects at a few meters depth. All together, the magnetic data provides a strong indication for an impact origin of the crater field.

INTRODUCTION AND AIM OF STUDY

The Sirente crater field (42°10'N, 13°35'E) was recently discovered and proposed to be of meteoritic impact origin by Ormö et al. (2002a). Since then, the structure has been suggested to be merely an anthropogenic cattle-pond in a field of karstic sags (Speranza et al. 2004), or the result of a previously unknown type of mud-fountaining due to trapped gas (Stoppa 2006). The interest in the origin of the structure is enhanced by its young age (beginning of the first millennium A.D.) combined with its location in central Italy not far from Rome (Ormö et al. 2002a; Santilli et al. 2003). The crater field consists of a 120 m wide main crater

surrounded on its northern and western sides by about 30 smaller craters (satellite craters) with diameters varying from 2 to 20 m (Fig. 1). The deepest of the satellite craters has an apparent depth of 2 m. Machine excavation of two 10 m wide craters showed that they have a funnel shape, one of which was traceable to about 9 m depth (Ormö et al. 2002a, 2006). All the structures, including the main crater, are developed entirely in unconsolidated carbonate mud of mainly lacustrine origin. The uppermost meter of the carbonate mud (i.e., zone of rainwater percolation) as well as the infill of the smaller craters has a higher organic content (dark color) due to biogenic processes during pedogenesis. No meteoritic material is visible on the ground surface, nor have any

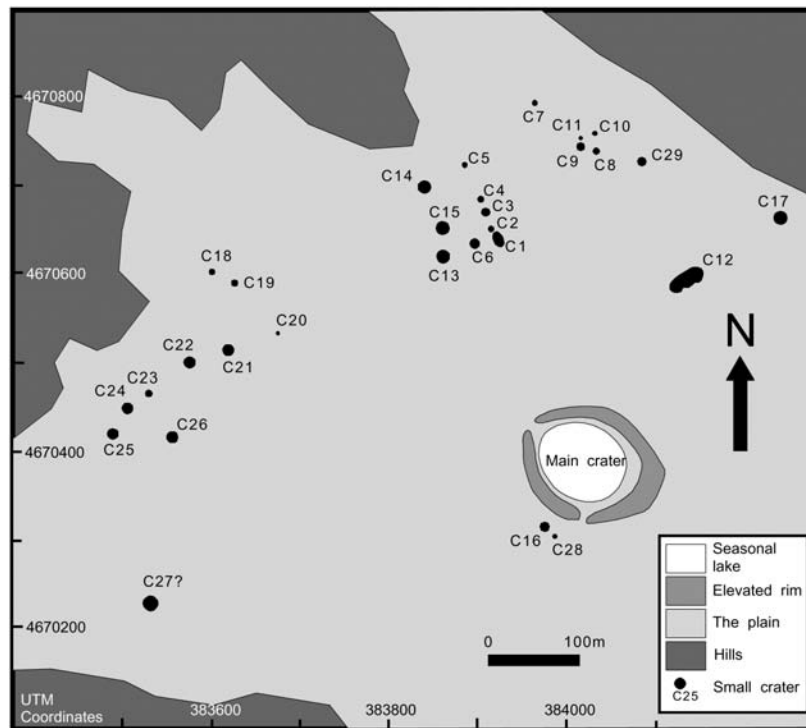


Fig. 1. The outline of the Sirente crater field (modified from Ormö et al. 2006).

geochemical traces of any meteorite been detected in material from the crater field (Ormö et al. 2006). No shock-metamorphic features from pressures diagnostic of hypervelocity impact have been detected. However, neither shock-metamorphic features nor strong geochemical anomalies are expected at craters of this size in carbonate mud (see discussion in Ormö et al. 2006). If the craters are of impact origin, the projectile causing the main crater would have had its velocity reduced during atmospheric entry to less than a few kilometers per second, and for the smallest craters the impactor's velocity would have been about 1 km/s (Bland and Artemieva 2006). Surface occurrences of meteoritic fragments around impact craters are rare in areas with a long history of iron-working (e.g., the crater fields in Estonia), but common at many of the known crater fields in Australia and the Americas to where iron-working spread in recent historical time (Ormö et al. 2006). Nevertheless, studies of both recent meteorite craters in Russia (e.g., Sterlitamak, Petaev 1992; Sikhote Alin, Svetsov 1998), and crater fields such as Campo del Cielo in Argentina that are thousands of years old (Cassidy and Renard 1996) have shown that the bulk volume of meteoritic fragments will be located at a depth of several meters below the ground surface, and that they can cause detectable magnetic anomalies (Cassidy and Renard 1996; Wright et al. 2005).

A preliminary magnetic survey of the Sirente crater field showed distinct magnetic anomalies connected with the smaller depressions (Ormö et al. 2002b). Speranza et al. (2004) measured the susceptibility of both the sediments

hosting the structures as well as the infill of one of the excavated funnel-shaped structures. They concluded that the susceptibility differences would be enough to explain the observed anomalies, however without supporting this statement with any modeling.

Due to the complications with proving an impact origin with geochemistry and shock features, the recovery of macroscopical meteorite fragments may be a viable option. If such fragments occur at Sirente, their most likely location is near the true crater floor (i.e., below the infill) of the larger craters (>15–20 m in diameter) or at the end of long penetration tunnels below the smaller craters. This is known from excavations of similarly sized craters (see review in Ormö et al. 2006). The assumed great depth to the true crater floor of the 120 m wide main crater (i.e., approximately 40 m; see review of depth/width ratios for simple craters given by Melosh 1989) and the lake that occupies its interior make it less suited for the search for meteoritic fragments. Therefore, we have made detailed magnetic anomaly maps and profiles over five of the small satellite craters in the crater field. Four of them were covered by the preliminary survey by Ormö et al. (2002b), which serves as a control of the new results. By using forward magnetic modeling, we can analyze potential causes for the anomalies. Magnetic modeling has successfully been used in the investigations of large impact craters (e.g., Ormö and Blomqvist 1996), but not, to our knowledge, for small craters in crater fields. Geophysical results alone cannot prove an impact origin, but they can disqualify other alternatives.

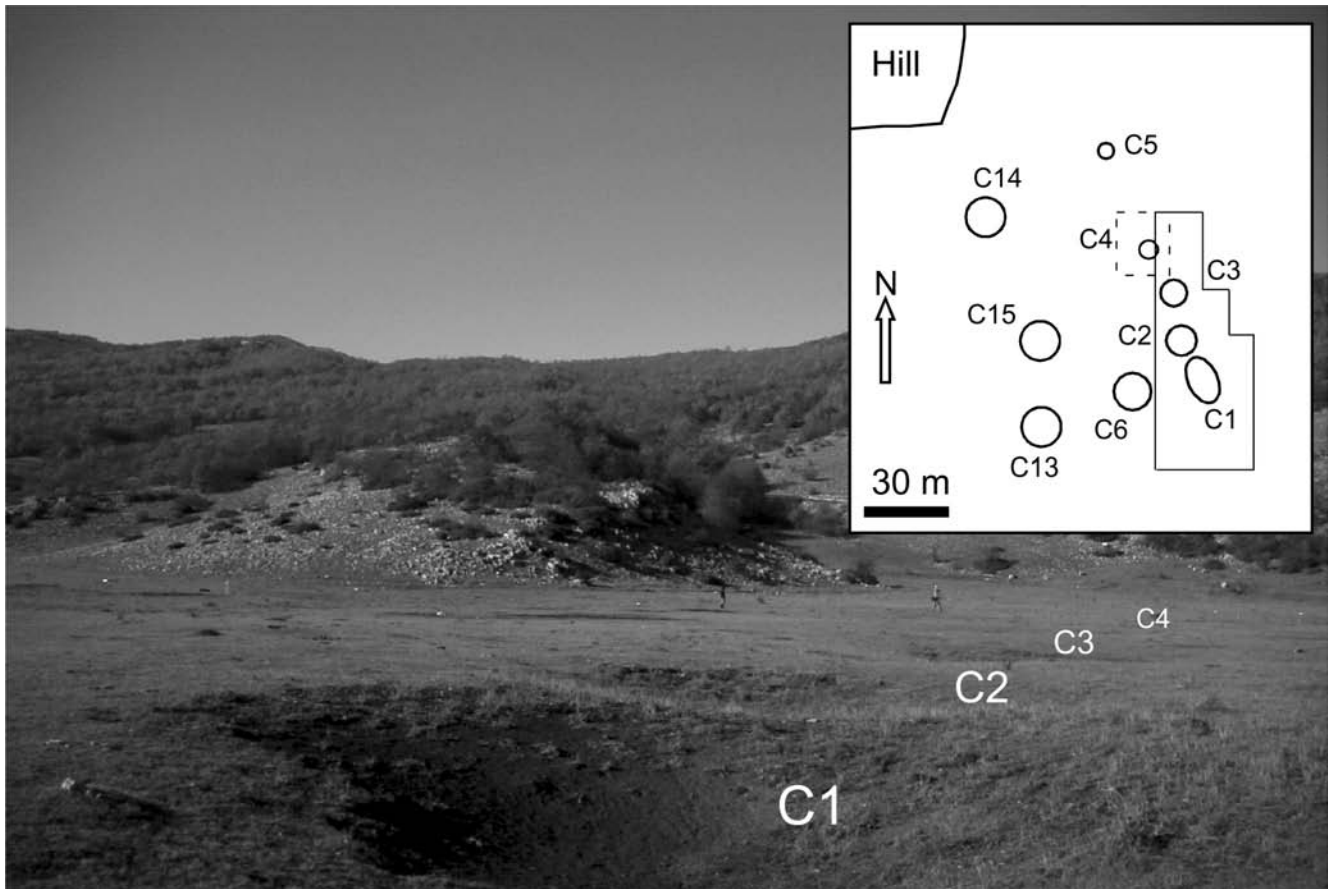


Fig. 2. The surface appearance and distribution of the investigated craters C1–4, and the outline of the areas covered by the magnetic survey over these craters (Fig. 4).

METHOD

Total Field and Gradiometer Mapping

The magnetic survey was done with a Geometrics G-856 Proton Precession Magnetometer configured as a gradiometer with two vertically separated sensors. This allows the measurement of the vertical gradient independent of diurnal variations. The gradiometer option provides increased detection and enhancement of anomalies due to objects at a distance of up to 5 times the separation of the sensors. The shallow anomalies of interest in this study (i.e., near-surface structure and/or magnetic objects) are better defined after removal of the regional magnetic gradient. In addition, the configuration with separated sensors is useful for calculations of the depth to buried objects. We used a sensor separation of 1.22 m on an aluminum staff. In addition, the use of open-source data, downloaded from the nearby L'Aquila Geomagnetic Observatory (42°23'N, 13°19'E), located about 32 km from Sirente field and consisting of the diurnal variations during the time of the survey, allowed us to use the data from both the bottom sensor (1.2 m above ground) and the top sensor (2.4 m above ground) to create maps of the total

field. The topography of each of the investigated structures was measured with a CST/Berger SAL series leveling instrument along N-S profiles crossing the center of the depression. It was decided that one profile through the crater center is sufficient as the apparent crater shapes are nearly symmetrically bowl-shaped.

The surveyed areas within the crater field were selected to cover parts of the preliminary survey of Ormö et al. (2002b) incorporating craters C1–4, and crater C17 (Fig. 1). Craters C1–4 are part of a row of craters and are among the most prominent in the crater field (Fig. 2). Crater C17 is one of the widest and deepest of the small craters. Due to time constraints, a complete magnetic map could not be constructed over C17. Instead, it was crossed by one N-S and one E-W survey line (Fig. 3). The distance between the measurement points in the C17 profiles was 1 m. The magnetic intensities for the profiles over C17 are given in Fig. 6.

The measurements covering craters C1, C2, C3, and C4 were done in grids outlined with the help of compass and measurement tape so that the lines were directed in straight N-S direction. The grid covering craters C1–C3 has a line spacing of 3 m and 3 m between each measurement point

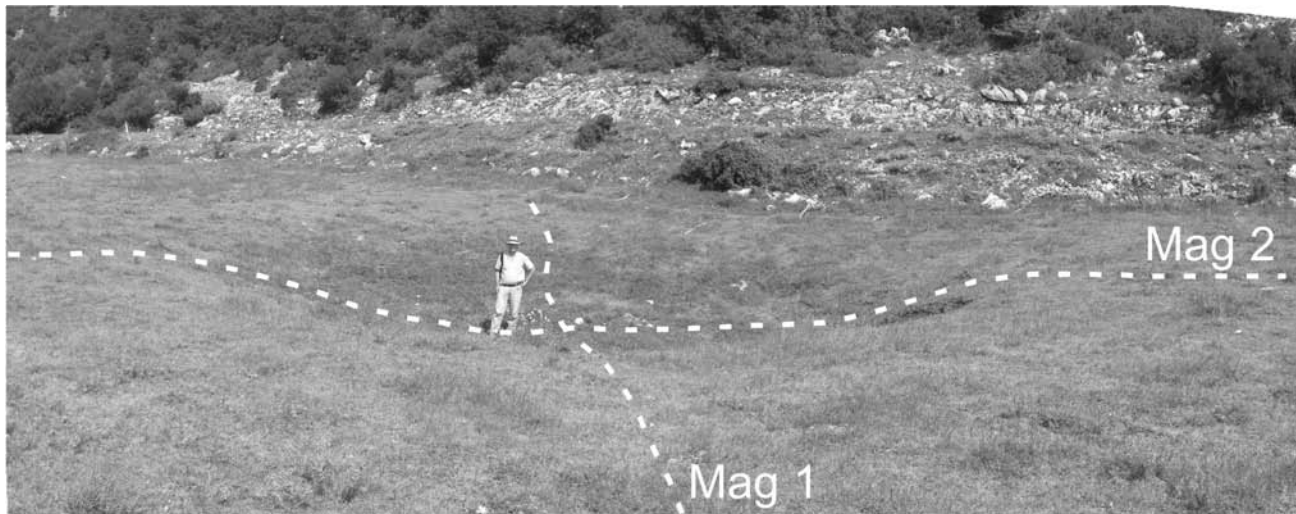


Fig. 3. The location of the magnetic profiles over crater C17. The photo is taken toward the north. The person for scale is 2 m tall.

(Fig. 4). The procedure was the same for the grid constructed over crater C4, but in this case the line spacing as well as measurement steps were 1 m (Fig. 4).

We used Geometrics MagMap 2000 and SSG-Surfer8 to generate the maps and profiles. The grid spacing during data treatment has been chosen to be equal to the measurement spacing (i.e., readings) in order to avoid over-gridding problems. Only the correction of diurnal variations has been applied to the original data, i.e., no filtering processing has been used in order to avoid artifacts that could arise due to an excessive processing procedure. We prefer to present the data as true to the original as possible, although this could result in a certain noisy appearance. Therefore, a very simple interpolation method has been used to ensure that observed anomalies are not caused by any smoothing or averaging procedure. The units for magnetic field strength used in the maps and models are nano-Teslas and susceptibility values used in the models are according to the International System of Units (SI).

Magnetic Modeling

The magnetic modeling was done with the 2.75-D software GM-SYS v. 4.9.41 from Northwest Geophysical Associates (NGA). The magnitude ($H = 46248.99$ nT), the declination (1.98°E), and the inclination (58.5°) of the geomagnetic field were taken from the International Geomagnetic Reference Field (<http://swdcd.db.kugi.kyoto-u.ac.jp/igrf>) for the location and altitude of the Sirente plain hosting the craters. We modeled the craters C4 and C17 for which we have the best resolution (1 m steps and line-spacing). For crater C4 we selected a N-S profile (M1) covering the maximum amplitude of the anomaly linked to the structure, as well as a WSW-ENE profile (M2) in the direction of the slope of the regional trend of the field (Fig. 4).

In order to take into account the height difference between reading stations into the modeling, information from the leveling profiles has been incorporated into the C4 and C17 models. Thus, the topography effects along each modeled profile are included in the models, but not the effect from the sides at right angles to the profiles. However, this effect is negligible due to the large distance.

The subsurface crater structure initially introduced in the modelings of the impact crater alternative for C4 is based on results from the excavation of the similarly sized, funnel-shaped craters C9 (Ormö et al. 2002a) and C8 (Ormö et al. 2006), thus the great depth relative to crater diameter (cf. Melosh 1989 on the depth/diameter relation for simple craters in rock). The subsurface structure of crater C17 (22 m in diameter) is assumed to be less funnel-shaped and instead more bowl-shaped in analogy with similarly sized craters at Sikhote Alin (Svetsov 1998). Karstic sag alternatives for C4 and C17 were also modeled, but only C17 is shown here, as the results for C4 were basically the same as for C17.

All bodies representing craters as well as karstic sags in the models are made up of several parts with finite x-, y-, and z-dimensions. Thus, using the 2.75D option implemented in GM-SYS, the volumes of the bodies have been extended laterally starting at the surface with the same length as the crater diameter and decreasing downward. In this way, both the funnel-shape (i.e., crater and karst) and the bowl-shape (i.e., crater) geometries can be taken into account.

By comparing the top-sensor and the bottom-sensor curves, it is possible to evaluate the depth of buried objects. Taking into account the indeterminability inherent to the geophysical modeling, it is very difficult to find a unique solution without using independent constraints during the modeling process. As it can only be assumed that the subsurface structure of C4 is similar to the excavated craters C8 and C9, there is no additional geological or geophysical

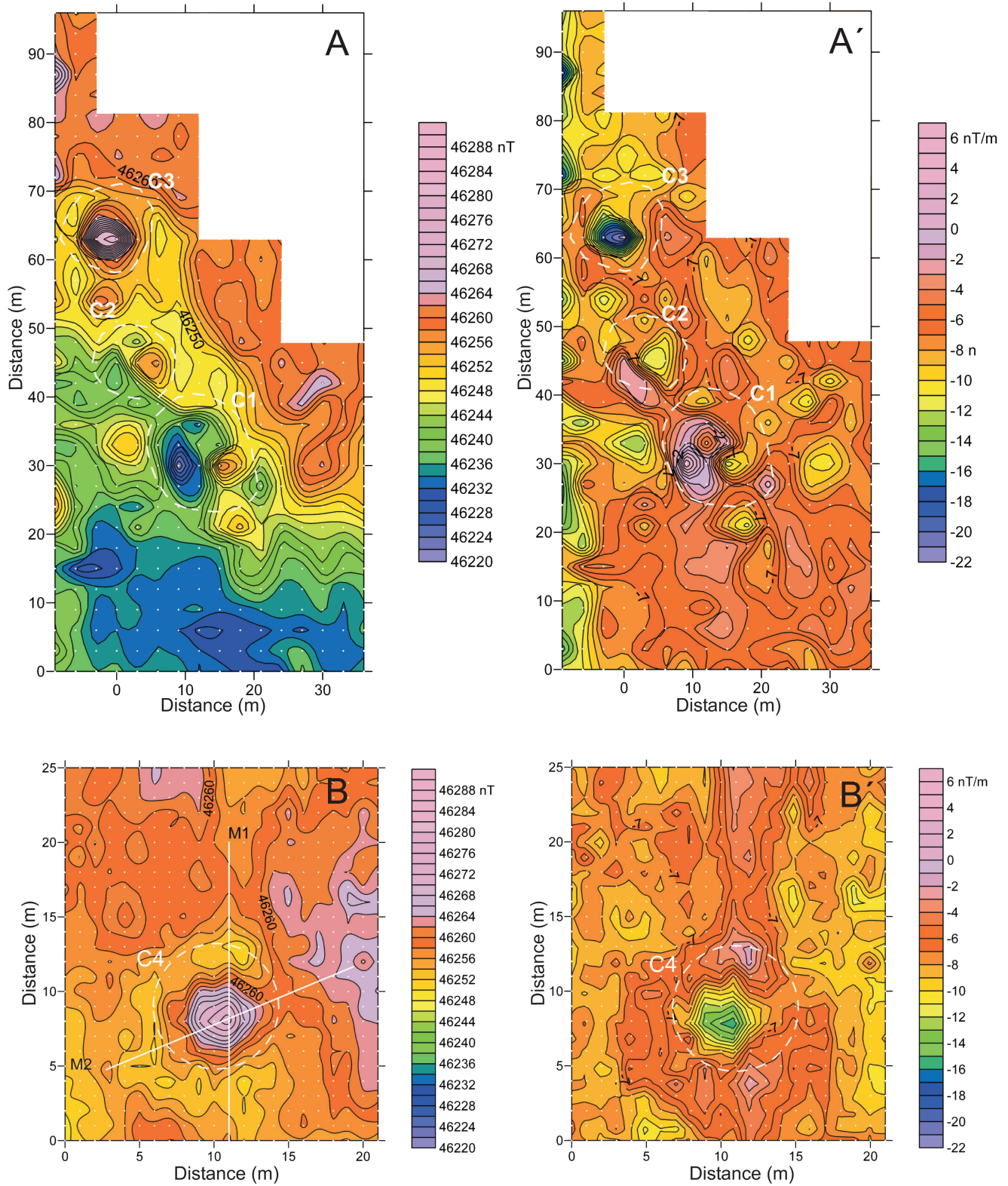


Fig. 4. Total magnetic field anomaly maps (a) and (b) and corresponding gradient maps (a') and (b') over the craters C1-3 (a) and (a') and C4 (b) and (b'). North is up. Modeled profiles M1 and M2 are indicated with white lines. The grid spacing is 3 m in the maps in (a) and (a'), and 1 m in the maps in (b) and (b'). White dots represent the locations of the station readings.

Table 1. RMS error for crater C4 (N-S profile, bottom sensor) obtained using a highly magnetic object (radius 0.3 m, susceptibility 3.2 SI) with and without remanence, located at different depths from 2 m down to 12 m. In all cases, the geometry of the apparent crater is the same (i.e., Figs. 5c and 5d) but without subsurface structure (i.e., all crater model bodies have the same susceptibility value). This test demonstrates that a magnetic object with properties that can be assumed for a meteorite in this size of crater needs to be located at a depth of 6–8 m to generate an anomaly of the same strength as the observed, but still with a poor fit. There is no important difference in the modeling results if remanence is present or not. Thus, a meteoritic object does not improve the fit (RMS error) of the model in Fig. 5, but cannot be excluded if existing at a depth greater than 12 m.

Remanence (<i>Q</i> value)	Depth to the object (m)	RMS error
0	12	7.042
0	10	6.414
0	8	5.762
0	6	5.703
0	4	7.540
0	2	25.329
0.8	12	7.058
0.8	10	6.446
0.8	8	5.779
0.8	6	5.743
0.8	4	7.527
0.8	2	23.118

data that help to constrain the magnetic modeling, and so we have decided to use the information obtained from both top and bottom sensors independently. At this point, we have two data sets at two different measurement levels. This can provide us with a better estimation of the relationship between depth and susceptibility of the objects to be modeled. In other words, using only information from one sensor would, at the best, give a good modeling fit. However, different combinations of susceptibility and depth could also provide the same fit. By instead using two data sets (bottom and top sensors) independently in the modeling process, the susceptibility and depth values for the modeled objects are changed until a good fit is obtained with both measurements.

Samples for susceptibility data of the sediments of the plain and the crater infill were collected by ourselves during our excavation of crater C9 (Ormö et al. 2002a), but were measured for their susceptibility and published by Speranza et al. (2004). From the anomaly maps in Fig. 4, it is clear that there is a slight regional NE-SW trend caused by the basement below the sediments. This basement is cropping out of the hills surrounding the plain. It consists of limestone, which has been the primary source for the carbonate mud deposited in the Sirente plain. For the basement, we used a susceptibility of 4×10^{-3} SI that is a mean value for carbonatic rocks given in the literature, ranging from $1 \times$

10^{-5} SI to 2.5×10^{-2} SI (Reynolds 1997). The dip of the basement surface in our models (up to 45°S-SW) seems quite steep and is probably a smaller topographic feature on the buried basement. A step-wise drop of the basement surface towards the south is expected for the tectonic half-graben hosting the plain (Ormö et al. 2002a), but most of this basement surface is outside of our measurement range.

We began the modeling of both crater C4 and crater C17 by using the mean susceptibility values for the pale sediments of the plain (9.29×10^{-4} SI) and the dark soil of the crater infill and uppermost meter of the plain (3.92×10^{-3} SI). The dark soil most likely gets its higher susceptibility from ferrimagnetic minerals formed by pedogenic processes (e.g., Maher and Thompson 1992). The very low magnetic susceptibility of the sediments results in a very small total magnetization even if remanent magnetization would be present. Thus, soil remanence is neglected in all models.

We generated a large number of models with as good a fit as possible between observed and generated anomaly curves for geologically likely (and unlikely) morphologies of both crater-like and sag-like features. The fit is expressed in the models as RMS error where the value closest to 0 represents the best fit.

The strong anomaly (100 nT) over C17 forced us to begin with a large volume karstic sag alternative with maximum susceptibility value for the structure infill, and the minimum susceptibility value for the pale sediments from the values given by Speranza et al. (2004). Still, it was not possible to generate the amplitude and shape of the observed anomaly (Fig. 6a). In the continued modeling of C17 we used the average susceptibility values for the sediments, but instead we introduced different configurations of highly magnetic material. The susceptibility of the high-magnetic bodies was selected based on data for iron meteorites given by Kukkonen and Pesonen (1983), Pesonen et al. (1993), and Terho et al. (1993, 1996). Remanence was neglected based on arguments given below.

From the experiences with the modelings of C17, we wanted to investigate the effect of meteoritic objects on the generated anomaly curve also in C4. Several models were created with a highly magnetic object, first at great depth and then in positions nearer to the surface (Table 1; Figs. 5c and 5d). To test the maximum possible consequence, we used a hypothetical meteorite with 0.3 m radius and a susceptibility of 3.2 SI (see discussion below). These simple models also demonstrate that such a small object could generate a magnetic anomaly that has a wavelength several meters in length (e.g., up to about 15 m for an object located at a depth of 4 m, and up to 20 m for the same object located at a depth of 5.5 m). This implies that, although the object is small, its associated anomaly can be completely defined using a reading spacing of 1 m or 3 m (i.e., with a Nyquist frequency of 2 m or 6 m). Thus, the sampling interval chosen in this study is appropriate enough to resolve the location of such highly magnetic small objects.

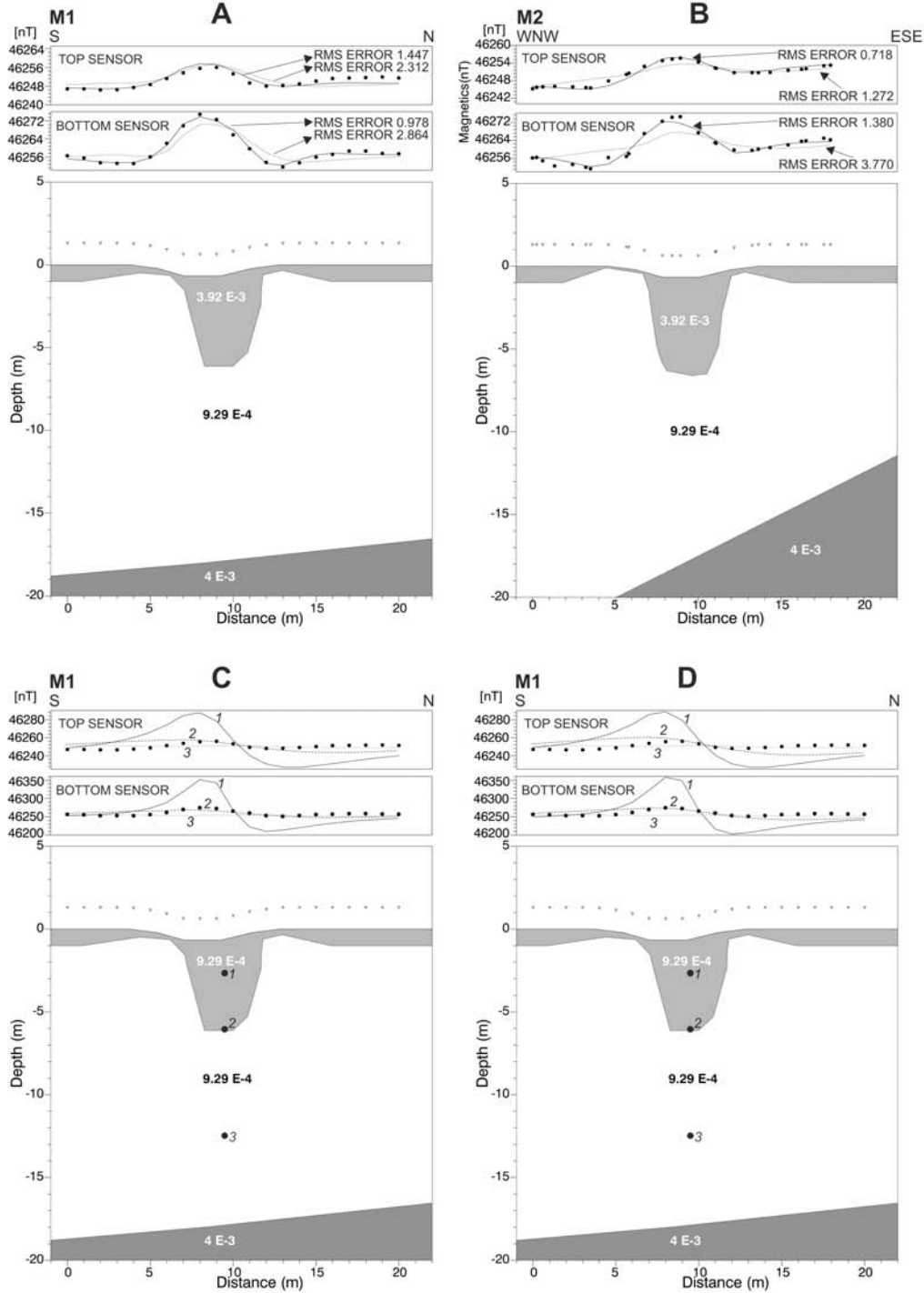


Fig. 5. Magnetic models of crater C4. (a) and (b) show the structure that generates the best fit of the model iterations (solid response curve) as well as the effects of removing the structural uplift at the rims (thin dotted response curve). (c) and (d) show the effect of a magnetic object at depths of 2 m (1), 6 m (2), and 12 m (3) without remanence (c) and with remanence $Q=0.8$ (d), profile M1 only. Observed magnetic intensity values are marked with dots. The generated model response curve is given as solid line (numbered line corresponds to each object location, respectively). Susceptibility is given with darker shades of gray corresponding to higher susceptibility values (the exception is in [c] and [d] where the subsurface crater structure is only indicated, but not introduced as body of different magnetization). The hypothetical location of the basement is visible at the bottom. RMS error is indicated for the models in (a) and (b). RMS error for models in (c) and (d) are given in Table 1. Dots above ground level represent the measurements location of the bottom sensor of the gradiometer (upper sensor would be 1.22 m above). Best fit is received for a crater structure without magnetic object, or with an object located deeper than 12 m (i.e., no influence on the curve in [c] and [d]). Eventual remanence of the object does not affect the result.

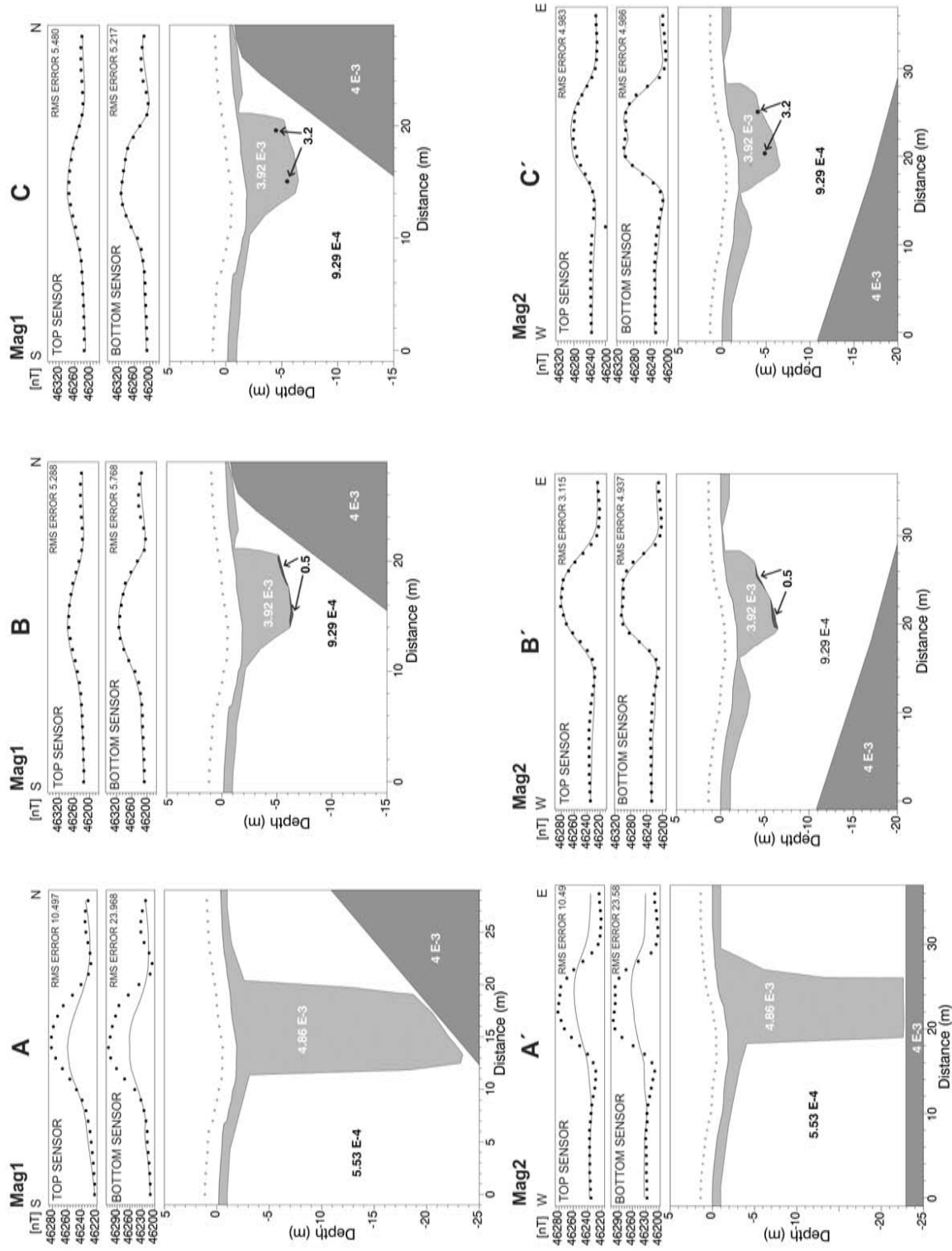


Fig. 6. Magnetic models for crater C17. (a) and (a') show a karstic doline alternative, (b) and (b') show the impact crater alternative with larger bodies of dispersed fragments highly magnetic objects (i.e., meteorites). (c) and (c') show the same impact crater alternative, but with localized occurrences (i.e., single fragments) of highly magnetic objects (i.e., meteorites). Observed magnetic intensity values are marked with dots. The generated model response curve is given as a solid line. Susceptibility values are given in the figure (darker shades of gray are higher values). The hypothetical location of the basement is visible at the bottom. RMS error is indicated for each model. Dots above ground level represent the measurements location of the bottom sensor of the gradiometer (upper sensor would be 1.22 m above).

We also tested the influence of remanence by introducing a Q value of 0.8 and with NRM directed parallel to the local geomagnetic field for maximum effect (Table 1; Fig. 5d). We choose to model iron meteorites, as it is known that 95% of all impacts of the magnitude required to generate the Sirente crater field would be by iron meteorites (Bland and Artemieva 2003, 2006). For C17, we did tests with many different volumes, susceptibility values and depths, since one option could be that the sources for the anomalies are larger volumes of dispersed highly magnetic objects rather than a small, single object. Magnetic modeling is an iterative process and not all of the tested model alternatives can be displayed here due to space constraints.

The best model fit for small, single objects is obtained with a susceptibility of 3.2 SI. This is a magnitude lower than the literature values for iron meteorites. However, the value is plausible, if we take into account the expected self-demagnetization effect of about a magnitude for a spherical iron object at the Earth's surface (Kukkonen and Pesonen 1983). An equally good fit is obtained for larger bodies with the lower susceptibility of 0.5 SI. This would be plausible for a larger volume of dispersed fragments with each fragment having a high susceptibility value. Iron is magnetically "soft," causing induced magnetization to be of greater importance than remanence. Some remanence is still expected for iron meteorites (Kukkonen and Pesonen 1983; Pesonen et al. 1993; Terho et al. 1993, 1996). When traveling through the Earth's atmosphere, the meteors are still space-cold and get heated above the Curie temperature only in a thin surface layer. This heated material can get a remanent magnetization on subsequent cooling in the Earth's magnetic field. It is unlikely, however, that it can accommodate to a consistent magnetic source structure within the penetration pit or along the ground surface where it may be deposited. To our knowledge, the only impact site where magnetic maps have been produced over buried meteorites is the Campo del Cielo crater field (Cassidy and Renard 1996). These maps show relations between positive anomalies and associated lows that indicate that induced magnetization dominates for the buried meteorites occurring at that site. It can, of course, only be assumed that a similar situation would occur at Sirente. Nevertheless, it can be seen as an indication that remanence may have little effect in our modeling. In any case, it would not influence the argumentation as it still implies highly magnetic objects within the ground.

RESULTS AND DISCUSSION

Magnetic Maps and Profiles

The magnetic survey shows distinct magnetic anomalies linked to all of the investigated small craters (Fig. 4). Most anomalies are in the magnitude of about 20 nT (Figs. 4 and 5), but crater C17 has an anomaly of up to 100 nT (Fig. 6). The

anomaly maps over craters C1–4 are consistent with the result of the preliminary survey by Ormö et al. (2002b) that was made with a similar instrument five years prior to this survey. The elongated crater C1 has a strong E-W trending positive anomaly and associated minimum near the center. The same situation occurs in crater C2, but here the minimum is less well developed. Crater C3 has a central positive anomaly with a rather circular associated minimum in analogy with the modeled crater C4. The gradient map in Fig. 4a' shows that it is not an effect of the regional trend. The most obvious ring-shaped minimum appears in the more detailed maps of crater C4 (Figs. 4b and 4b'). Similar associated lows occur on both sides of a central positive anomaly in crater C17 (Fig. 6). However, the central positive anomaly has two distinct peaks suggesting a combined source.

Modeling

The best fit between observed and generated anomalies over crater C4 was achieved by letting the pale-colored, low-magnetic sediment of the plain form an elevated rim around the crater depression, although it is not affecting the present topography of the crater (Fig. 5). By first impression it may look as if the crater structure was later covered by a dark soil. This is, however, not the case. The dark soil is due to a color change (i.e., organic content) during pedogenesis of the pale, carbonate mud. Assuming that the pedogenesis reached to approximately the same depth all over the structure, where there was an uplifted rim the lower boundary of the pedogenesis, consequently, followed the surface topography. Today, only a couple of craters in the crater field have uplifted rims still visible in the surface topography (see Ormö et al. 2006). It is known from the recent, similarly sized Sterlitamak crater that the surface expression of a crater rim in soft sediment is transient on a short time scale (Petaev 1992). Drilling of the Sirente main crater rim showed that pedogenesis mainly occurred since the structure was formed (Ormö et al. 2002a). When applied to C4, this would mean that the variation of the depth of the pedogenesis most likely represents the uplift of strata at depth below a once-existing topographic rim feature. In Fig. 5, we also show the effects of a model alternative that lacks this uplifted rim strata (i.e., similar to our tests with a karst sinkhole). This results in a poor curve fit, especially over the magnetic lows. The poorest fit is for the anomaly curves of the bottom sensor, which indicates that the reason for the magnetic lows must be located relatively near the ground surface (i.e., the rim structures). When compared with the analysis of the effects of magnetic objects at different depths (Table 1; Figs. 5c and 5d) it is clear that the differently developed lows around the craters C1–4 would be a consequence of variations in the subsurface expressions of their rims, and not from remanently magnetized objects as suggested by Ormö et al (2002b). The need for an uplift of rim strata for the best model fit between

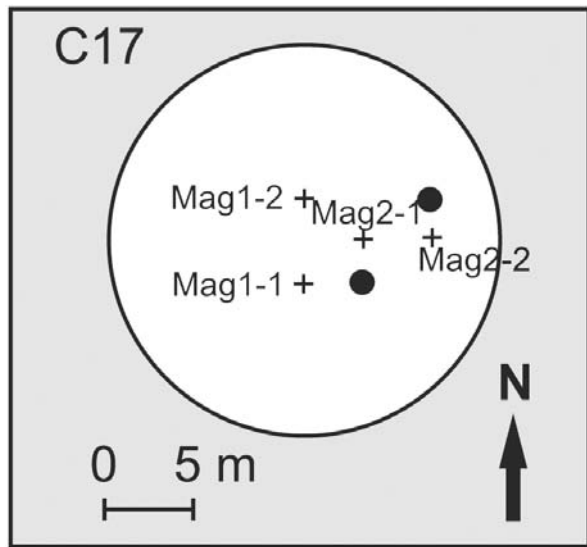


Fig. 7. Surface projection of the locations of the highly magnetic objects as given by the modeling of the impact crater alternative for crater C17. Crosses indicate relative positions of two highly magnetic objects in the profiles in Fig. 6. Solid circles indicate the positions of the objects after interpolating the results from the two modeled profiles.

observed and generated anomalies excludes the karstic sag alternative, which is a gravitational process with downward transport of material.

The modeling tests with a highly magnetic object at different depths in C4 suggest that the object needs to be at a depth shallower than 12 m to have any consequence on the shape of the generated anomaly curve in the model, independently of remanence (Figs. 5c and 5d). If the anomaly was only generated by an object at a certain depth, then the strength of the anomaly corresponds best with a depth of 6–8 m (relatively low RMS error in Table 1), although the shape of the generated curve does not fit to the observed curve (Figs. 5c and 5d).

From Fig. 5 and Table 1, it is clear that the best fit is received when the crater structure alone is generating the anomaly, not an object. A magnetic object alone is not capable of generating the ring-shaped magnetic low in C4. Therefore, it is most likely that the detected anomalies in C4, and possibly C1–3 with anomalies of similar shape and strength as C4, are due to the structure of the craters themselves and not from shallow magnetic objects. It would explain the differences in directions of the paired anomalies over the different craters. However, it can not be excluded that highly magnetic objects are located at greater depths than would influence the observed anomaly. A depth much deeper than 10 m is expected in a situation with a steeply inclined funnel crater in a material allowing great penetration depth (>10–15 m in analogy with the length of the penetration tunnels at the Campo del Cielo and Sterlitamak craters). In addition, it is known from numerical simulations that the more porous the target, the greater the penetration depth (Wünnemann and Collins 2006).

Also in the modeling of C17 it was clear that a sufficient fit between observed and generated anomaly curves could not be obtained for a karstic sag (Fig. 6a). A better fit was achieved for a bowl-shaped, rootless crater with upturned strata at depth below the rim (Figs. 6b and 6c). However, even when using the highest possible difference in the susceptibility values given by Speranza et al. (2004), we could not obtain the 100 nT anomaly measured above this structure. The models in Figs. 6b and 6c have a higher RMS error than the C4 crater models in Fig. 5. However, this must be seen in proportion with the five times stronger anomaly in C17.

The double-peaked anomalies in both profiles over C17 indicate separated objects (Figs. 6b and 6c). The best fit is obtained for objects 0.5 m in diameter with a susceptibility of 3.2 SI (Fig. 6c), or two locations with a larger volume (Fig. 6b), but with a slightly lower susceptibility value (5×10^{-1} SI). Still, this value is much higher than any rock available in the area (Servizio Geologico d'Italia-APAT 2005). As we do not have a complete anomaly map over C17, we must use the information from the crossing profiles to pinpoint the horizontal location of the objects with respect to the crater (i.e., they are most likely offset from the modeled profiles). In Fig. 7, we have plotted the locations of the objects as given by the profiles (Mag1-1 and Mag1-2, resp. Mag2-1 and Mag2-2). Profile Mag1 indicates that object 1 must be located south of the location given by profile Mag2, and that object 2 must be located north of the location given by profile Mag2. Profile Mag2 indicates that both objects must be offset to the east with respect to profile Mag1. This results in locations of the two objects as indicated by black filled circles in Fig. 7.

The objects seem to be about 4–5 m below the ground, the northeastern one slightly shallower than the one nearer to the center. Considering that the depth to the true crater floor in a small bowl-shaped crater is about one-third of the crater diameter (Melosh 1989), the objects in C17 would be located in the lowermost part of the crater infill. This is in analogy with occurrences of meteoritic fragments in small bowl-shaped craters (i.e., craters with explosive disruption of the projectile) such as the larger of those investigated by excavation at Sikhote Alin (Svetsov 1998) and the Odessa, Haviland, and Henbury craters, where fragments occur in a thin lining under the crater infill (Dence et al. 1977). The location of the objects toward the east of the crater center coincides with a NW-SE trajectory of the projectile as inferred from the outline of the crater field (cf. Ormö et al. 2006). The crater is symmetric in N-S direction, but asymmetric in E-W direction. The steeper and deeper western part could, in analogy with experimental craters (cf. Schultz and Anderson 1996), fit with an impact from the NW.

The existence of high-magnetic objects in crater C17 can only be confirmed by machine excavation or very exactly located drilling. Machine excavation to a depth of 5 m in carbonate mud requires, due to safety reasons, a very large

excavation pit (Ormö et al 2006). The site is located within a protected natural reserve. Two excavations for the evaluation of subsurface structure of two satellite craters have previously been performed (Ormö et al. 2006). A third excavation aiming only for the recovery of meteoritic material must be very well supported and have a high probability of success. Likewise, a successful drilling into a <0.5 m object at a depth of about 5 m needs a very exact positioning. This study is a first step toward the execution of any of the two alternatives.

CONCLUSIONS

It is shown that separate modelings of magnetic data from two vertically positioned sensors (i.e., gradiometer setup) is superior to a single-sensor modeling or a regular gradiometer measurement. For detection of magnetic matter in low magnetic surroundings, one profile is sufficient. With two profiles the source(s) can be more accurately located.

All of the investigated craters are associated with strong magnetic anomalies, at least one as high as 100 nT. The shape of the anomalies indicates upturned strata below the rims, excluding a karstic formation. The 100 nT anomaly can only be explained by highly magnetic point sources for which the depths can be calculated. Computer modeling suggests that the anomalies are caused by objects with magnetic susceptibilities much higher than any available rocks in the area. Their sizes and locations within the craters are consistent with the locations of meteorites in confirmed craters of similar size. The specific combination of crater field + crater shapes + magnetic source(s) at the crater floor of C17 is indeed a strong indicator of the meteoritic origin of the Sirente crater field.

Acknowledgments—The work by Jens Ormö was supported by the Spanish Ministry for Science and Technology (References AYA2003-01203 and CGL2004-03215/BTE). Both Ormö and Patrick McGuire were supported by separate fellowships from the Spanish Ramón y Cajal Program. The work by Goro Komatsu and Angelo Rossi was supported by funding from the Italian Space Agency. The authors wish to thank the Sirente-Velino Regional Park authorities for the permit (No. 114) to conduct scientific studies within the park. The authors are grateful for the constructive reviews by Mark Pilkington and Hernan Ugalde.

Editorial Handling—Dr. John Spray

REFERENCES

- Bland P. A. and Artemieva N. A. 2003. Efficient disruption of small asteroids by Earth's atmosphere. *Nature* 424:288–291.
- Bland P. A. and Artemieva N. A. 2006. The rate of small impacts on Earth. *Meteoritics & Planetary Science* 41:607–631.
- Cassidy W. A. and Renard M. L. 1996. Discovering research value in the Campo del Cielo, Argentina, meteorite craters. *Meteoritics & Planetary Science* 31:433–448.
- Dence M. R., Grieve R. A. F., and Robertson P. B. 1977. Terrestrial impact structures: Principal characteristics and energy considerations. In *Impact and explosion cratering*, edited by Roddy D. J. and Pepin R. O. New York: Pergamon Press. pp. 247–275.
- Kukkonen I. T. and Pesonen L. J. 1983. Classification of meteorites by petrophysical methods. *Bulletin of the Geological Society of Finland* 55:157–177.
- Maher B. A. and Thompson R. 1992. Paleoclimatic significance of the mineral magnetic record of the Chinese loess and paleosols. *Quaternary Research* 37:155–170.
- Melosh H. J. 1989. *Impact cratering: A geologic process*. New York: Oxford University Press. 245 p.
- 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.
- Ormö J., Rossi A. P., and Komatsu G. 2002a. The Sirente crater field, Italy. *Meteoritics & Planetary Science* 37:1507–1523.
- Ormö J., Rossi A., Komatsu G., Marchetti M., and De Santis A. 2002b. The discovery of a probable well-preserved impact crater field in central Italy (abstract #1075). 33rd Lunar and Planetary Science Conference. CD-ROM.
- Ormö J., Koeberl C., Rossi A. P., and Komatsu G. 2006. Geological and geochemical data from the proposed Sirente crater field: New age dating and evidence for heating of target. *Meteoritics & Planetary Science* 41:1331–1345.
- Pesonen L. J., Terho M., and Kukkonen I. 1993. Physical properties of 368 meteorites: Implications for meteorite magnetism and planetary geophysics. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 6:401–406.
- Petaev M. I. 1992. The Sterlitamak meteorite—A new crater-forming fall. *Solar System Research (Astronomicheskii Vestnik)* 26:82–99.
- Reynolds J. M. 1997. *An introduction to applied and environmental geophysics*. Chichester, New York: John Wiley and Sons. 796 p.
- Santilli R., Ormö J., Rossi A. P., and Komatsu G. 2003. A catastrophe remembered: A meteorite impact of the 5th century A.D. in the Abruzzo, central Italy. *Antiquity* 77:313–320.
- Schultz P. H. and Anderson R. R. 1996. Asymmetry of the Manson impact structure: Evidence for impact angle and direction. In *The Manson impact structure, Iowa: Anatomy of an impact crater*, edited by Koeberl C. and Anderson R. R. GSA Special Paper #302. Boulder, Colorado: Geological Society of America. pp. 397–417.
- Servizio Geologico d'Italia-APAT 2005. Foglio N. 368 “Avezzano” della Carta Geologica d'Italia a scala 1:50.000 e note illustrative (Geological map of Italy, sheet no. 368). Servizio Geologico d'Italia—Istituto Poligrafico e Zecca dello Stato (Italian Geological Survey), Rome.
- Speranza F., Sagnotti L., and Rochette P. 2004. An anthropogenic origin of the “Sirente crater,” Abruzzi, Italy. *Meteoritics & Planetary Science* 39:635–649.
- Stoppa F. 2006. The Sirente crater, Italy: Impact versus mud volcano origins. *Meteoritics & Planetary Science* 41:467–477.
- Svetsov V. V. 1998. Enigmas of the Sikhote Alin crater field. *Solar System Research* 32:67–78.
- Terho M., Pesonen L. J., Kukkonen I. T., and Bukovanska M. 1993. The petrophysical classification of meteorites. *Studies in Geophysics and Geodesy* 37:65–82.
- Terho M., Pesonen L. J., and Kukkonen I. T. 1996. Magnetic properties of asteroids from meteorite data—Implications for magnetic anomaly detections. In *Worlds in interaction: Small bodies and planets of the solar system*, edited by Rickman H. and Valtonen M. J. Dordrecht, The Netherlands: Kluwer. pp. 223–231.

- Wright S. P., Vesconi M. A., Gustin A., Williams K. K., Ocampo A. C., and Cassidy W. A. 2006. Revisiting the Campo del Cielo, Argentina crater field: A new data point from a natural laboratory of multiple low velocity, oblique impacts (abstract #1102). 37th Lunar and Planetary Science Conference. CD-ROM.
- Wünnemann K. and Collins G. S. 2006. The effect of porosity on meteorite impact processes (abstract #03991). Geophysical Research Abstracts, vol. 8. Vienna: European Geosciences Union.
-