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The Sirente crater, Italy: Impact versus mud volcano origins

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Abstract–The Sirente crater is a circular structure with a diameter of ~80 m. The rim deposit is an inverse-graded, matrix-supported breccia. Sedimentological features of the rim deposit suggest that the crater is not related to an explosion or violent mechanical displacement. The structure and texture of the deposit exhibit a primary sedimentary character. The rim deposits do not contain artifacts and do not show evidence of reworking. A multistage formation is reconstructed for the rim growth and associated deposits. The geometry and sedimentology of the deposits indicate that they were produced by the extrusion and accumulation of mudflow deposits. The dominant ejection mechanism was low mud fountains and the transport medium was water. Petrographic and geochemical evidence does not indicate any physical or cryptic trace of an extraterrestrial body.

The most realistic agent that explains the observed effects is a rapid local emission of mud and/or water. Geological processes capable of producing these features include piping sinkholes or, more probably, "caldera"-type mud volcanoes, which may result from underground water-table perturbation and/or decompression of deep CO_2/hydrocarbon gas reservoirs due to tectonic deformation or faulting activity during a seismic event. In both cases, the name "crater" for this geological form may be maintained, but there is no compelling evidence for an impact origin.

In this paper, the scientific literature on the Sirente crater is reconsidered in the light of new morphological, sedimentological, geochemical, and archaeological data. A new mechanism is proposed involving mud-fountaining.

INTRODUCTION

Ormö et al. (2001, 2002) have described a supposed meteorite impact structure from the Sirente area of Italy. In contrast, Speranza et al. (2004) argued for a human origin of the same structure. The impact origin has proven to be controversial. The Sirente debate provides an opportunity to review the features and origins of crater-form structures on the Earth's surface.

The Sirente crater is located in the Secinaro area (L'Aquila) in central Italy. Certain Italian myths and legends have been ascribed to the crater; these are outlined in Santilli et al. (2003). This generated much discussion and speculation that the meteorite impact produced the "vision" of Emperor Constantine with "XP," the symbol of Christ, shining above the Sun, causing his conversion to the Christian faith prior to the battle of Ponte Milvio in 312 A.D.

Previous Literature

Ormö et al. (2001, 2002) gave a preliminary description of the size and general shape of the crater rim. They also sampled organic material by drilling and dated the crater formation to around the 4th or early 5th century A.D. based on the ^{14}C date of ~1600 years (Ormö et al. 2002). They considered that the morphology of the crater rim was what should be expected for impact into a wet-clay sediment target, which would cause compaction of the substratum and formation of a depression. They reported that the possible impact explosion in the "Prati del Sirente" released energy equivalent to about 100 tons of TNT. Santilli et al. (2003) stated that an impact crater the size of Sirente should be surrounded by a field of smaller craters, and thus they attributed the numerous small pits in the area to secondary impacts of smaller bodies produced by the atmospheric disaggregation of the main meteorite mass. An interesting point of the paper is the discussion of impact into a "soft" target. Ormö et al. (2002) and Santilli et al. (2003) state that a sufficiently large meteorite striking the ground would essentially melt and vaporize, obviously producing a big explosion. However, the velocity of smaller bodies may be so reduced by atmospheric deceleration that they would

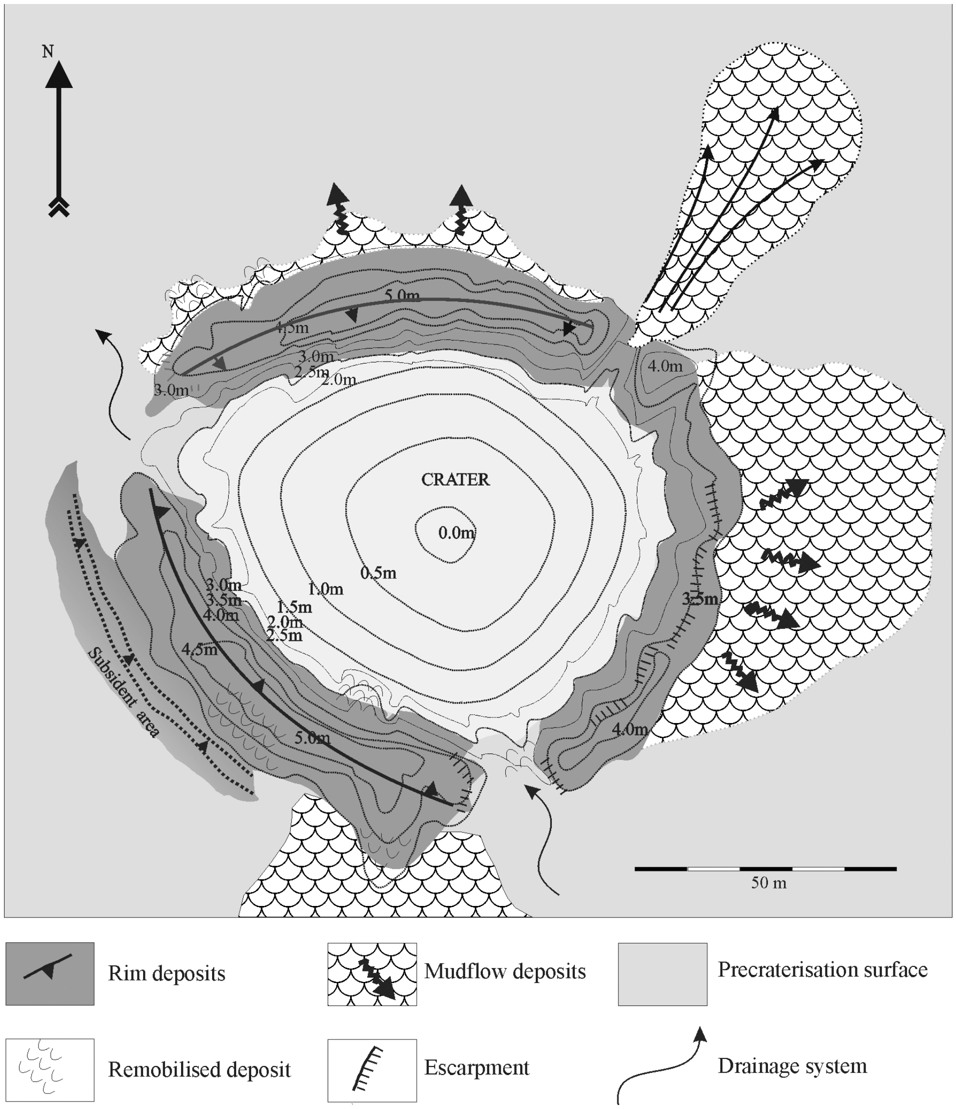

Fig. 1. A geological sketch map of the Sirente crater.

penetrate the ground without disintegrating or producing a significant explosion. Any meteorite fragments would have penetrated such a soft substratum sufficiently deeply not to be found at surface. Fragments might be detectable by geophysics at shallow depths, but no conclusive evidence has been found to date.

Speranza et al. (2004) disagreed with the interpretation of Ormö et al. (2002) and presented evidence that this kind of sag-pond is not unique to the Sirente site. Sub-circular ponds, with very similar morphological features and size to those exhibited by the main Sirente crater, are exposed in other neighboring mountain basins. In addition, they sampled soils from the Sirente crater area and various other Abruzzi soils with similar magnetic susceptibility values and geochemical compositions. These are significantly different from the values reported for soils contaminated by meteoritic impacts. Having disproved, in their opinion, the evidence for an impact origin, Speranza et al. (2004) suggested that the "Sirente crater," together with analogous ponds in the Abruzzi intermountain plains, were excavated to provide drinking water for the large numbers of sheep that in the past spent their summers in the Abruzzi highlands.

NEW FIELD EVIDENCE

The crater topography has been resurveyed in detail to a scale 1:500 resulting in the geological map shown as Fig. 1. In this work, all of the areas higher than the pre-crater ground level are referred to as the "rim" and the area below this the "crater." In addition, we have considered some previously neglected mudflow deposits as part of the crater structure. These flowed away from the rim, mostly to the southeast. Finally, newly discovered artifacts recovered from the crater are briefly described.

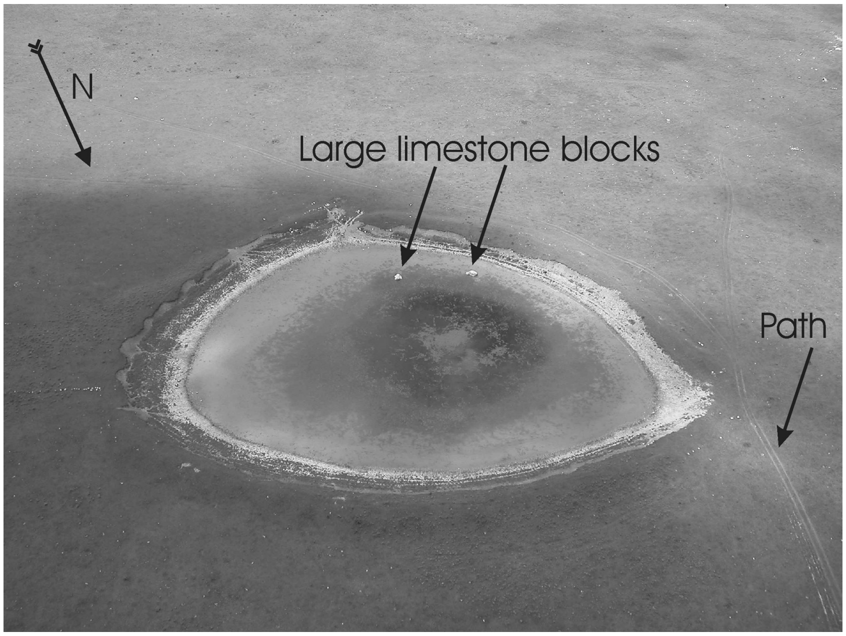

Fig. 2. An aerial photograph of the Sirente crater; the oblique diameter of the lake is about 80 m. White spots, indicated by arrows, are limestone blocks several meters across. The arrow to the right of the crater indicates a modern four-wheeled vehicle path.

Crater

The crater permanently contains water (Fig. 2). The maximum difference in average water levels between dry and wet seasons is ~1 m. There is no apparent outflow, but the lowest rim saddle constitutes a breach in the northwest. The deepest point is about 2.5 m below the plain and this is almost central to the external rim. The maximum diameter of the crater is 80 m. A cap of ice and snow covers the pond during the winter months and seasonal variation is clearly responsible for the production of varves in the crater sediments. Varved sediments, several meters thick, were encountered in drill cores recovered from inside the crater (Ormö et al. 2002). It is believed that these are part of the natural accumulation of sediments which, if accepted, indicates that the original crater was deeper.

Limestone blocks are scattered about the surrounding area (Speranza et al. 2004). They are homogenous in composition and identical to the limestones that outcrop in the Sirente plain (Speranza et al. 2004). Notably, the majority is rounded and show distinctive karstic surfaces.

A crucial feature of the crater is represented by two large limestone blocks, both several meters in diameter, which occur in the southern part of the crater. They are not rounded and do not show karstification. There is no evidence that these large blocks arrived in the crater after its formation.

Crater Rim

The rim and associated features are fresh and well preserved, being just partially modified along the inward part by creep and the movement of cattle. This testifies to a young age and is compatible with a general absence of notable erosion in the surrounding plain. The rim structure does not show internal erosion surfaces, paleosoils, or significant changes in grain size and composition.

The maximum diameter of the rim is 120 m. The morphometry indicates that the maximum elevation of the rim compared with the surrounding plain is about 2.5 m in the southwestern and northeastern sectors. The maximum difference in height between the rim crest and the pond bottom is 4.5 m. It has a steep external slope of ~30°, which is assumed to be primary. The external slope is modified at several points by a second accumulation emplaced at a lower angle of about 10°, which is mostly a remobilized deposit (see Fig. 1a). Additional visible surface failures, trenches, flow structures, and hummocky surfaces are seen at the meter scale; these are also assumed to be primary. This second deposit is seen in the southwestern sector and this appears to form a wider accumulation rim on top of the first one. The internal rim slope is more uniformly gently inclined and locally accommodated by creep and grain-flow phenomena. There are two main breaches in the rim to the northwest and the southwest, with a minor breach in the northeast. These breaches, which divide the rim into three main sectors (Fig. 1), may have been developed late in the rim evolution, but they are not related to any local or linear erosion features in the surrounding plain. They could have been slightly modified by anthropogenic means, as they afford natural access to the crater area. Inward drainage occasionally brings rain water from the plain into the crater through the breach in the southern sector, which is the only area exhibiting linear erosion and evidence of human reworking. Inside this breach, a small inward debris delta has formed in the crater (Fig. 1).

Deposits that are related to the rim are massive and matrix-supported, inverse-graded, or chaotic in all exposures along the inward rim. The rim matrix is formed by mud lumps of up to 1 cm in diameter, is strongly agglutinated and, in places, some intergranular voids have been preserved. These voids are interpreted to be deformed, intergranular spaces formed during the compaction of the soft mud lumps or slurry. Formation of these features is compatible with a fragmentation mechanism, ejection, and later accumulation of mud material. Included blocks are invariably limestone up to some tens of centimeters in diameter. They are rounded and preserve delicate karstic erosion features such as klints and grikes. This suggests that they were exposed to atmospheric agents for a significant time, but do not show any apparent mechanical shock in thin section. They are abundant and form about 10–15% of the rim by volume.

Sediment Analysis

The matrix of the rim deposit has been analyzed by optical microscopy and geochemical analysis. The matrix is silt-sized and has been tested using the cone method to determine the liquid and plastic limits, which define the water content boundaries between non-plastic, plastic, and viscous-fluid states (ASTM 1994). The plasticity index (PI) defines the plastic state. The plastic limit is 25 and plasticity index (liquid limit–plastic limit) is 14. At 39 vol% of water, the silt matrix is fluid (mud) with a density of 1.64 g/cm^3. These granulometric features indicate that this is well-sorted sediment subject to fluidization and depleted in clay components. Its most likely origin is by colluvial reworking of a previous slope detritus.

The limestone blocks have a density of 2.69 g/cm^3, which is very close to pure calcite. The blocks have an upper size limit of 50–60 cm. The larger blocks (several meters in size) have not been transported beyond the crater and may have been carried upward from beneath the crater by movement of dense, diapiric mud. It is notable that they do not show surface karst features, probably indicating that they were part of the underlying limestone substratum, and that there was not sufficient energy to incorporate them into the rim. In contrast, the smaller blocks may derive from more shallow level strata and these do show karstic erosion and reworking features. No shatter cones have been observed in any of the blocks.

In the deposit of the external rim, very few curved or planar contacts were observed, lamination is very rare, and limestone fragments are only a few centimeters across. This suggests an en masse transportation mechanism.

Structure and Mudflow Deposits Outside the Rim

An 80 m long depression surrounds the rim in the southwestern sector and terminates at the northwestern breach. This forms a 2 m wide and 50 cm deep area inclined towards the rim, which was not apparently filled by any material coming from the rim, even though major rim instability and gravity adjustments have been recorded in the southwestern sector. Mudflows did not cross the moat, so it is deduced that it was formed after the growth of the rim and the generation of mudflows.

Mudflow deposits are widespread around the northwestern, southeastern, and southwestern sectors of the crater rim. In most examples, they are only small accumulation lobes a few meters long, but some traveled several tens of meters away from the rim. Their true thickness cannot easily be evaluated, but it is less than 1 m. The top surface is flat, as expected from a fluid. Some form discrete tongues 30–40 m long and 5–6 m wide; others form aprons with a lobate external front. They are easily recognized, being distinctly vegetated. These mudflows escaped from the two main breaches and also overflowed the rim in the southeastern sector. They are absent in the northern and northwestern areas. The regional plain is slightly inclined toward the northwest, which contrasts with the flow direction of the mudflows. However, this discrepancy can be explained by the higher rim elevation in the northern and northwestern sectors, or by the inclined emission of a mud fountain. The northwestern breach seems younger than the other breaches and probably drained water from the crater when it was full. It opens towards the sinkholes, which actually drain the plain. It seems that the crater rim interrupted the previous drainage system and partially restricted it. In fact, during wet periods there is water accumulation against the crater rim and also against the main mud flows (Fig. 3).

Archaeological Findings

Human traces in the crater and surroundings, although limited, include several small ceramic and metal fragments and a Roman coin, recovered from the southeastern sector. This coin is of Julio-Claudian age, made during the first years of Tiberius (14–37 A.D.) and circulated for less than 50 years. The coin clearly points to the first half of the 1st century A.D. and suggests that the crater is older than the C-date (cf. Ormö et al. 2002).

The artifacts were found at the surface. However, the rim itself does not contain artifacts. The ceramics are mostly rough pottery as used for cooking from Roman times to the Middle Ages. Some small fragments could be slightly earlier and a few fragments have glaze or pigments, or simple decorations. The information inferred from the ceramics and other artifacts will be fully addressed in a separate paper.

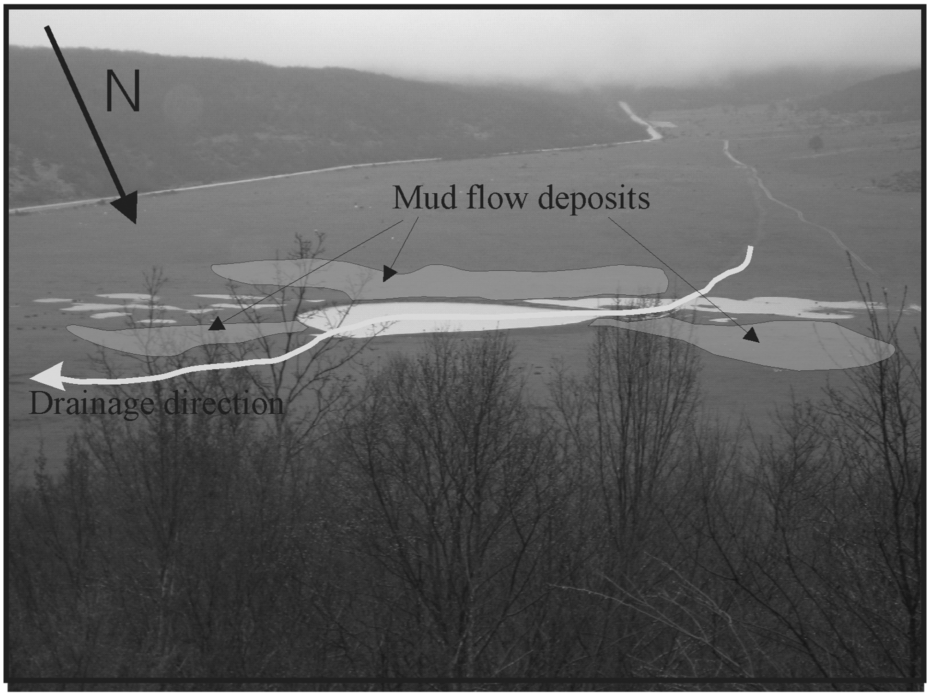

Fig. 3. The Sirente crater flooded during a wet period. The lake was about 95 m across at the time the picture was taken. Water accumulation outside the crater occurs because mudflows (outlined) and the crater rim have obstructed the previous drainage system. Photograph courtesy of F. Speranza.

Petrography and Geochemistry

The rim deposit is mainly calcareous silt with minor mafic volcanic components consisting of discrete grains of diopside, phlogopite, K feldspar and Ti magnetite (Fig. 4a). The Sirente soil examined at high magnification under transmitted polarized light lacks shocked quartz, zircon, and spherules. A sample of soil (SR01) was analyzed for both major and trace elements. The analysis, analytical methods, and detection limits are given in Table 1. Chemical analyses were obtained from the sediment forming the rim and the results compared with analyses of other soils from the Abruzzo area (Speranza et al. 2004). Our sample has an intermediate composition among those of the Sirente soil samples analyzed by Speranza et al. (2004) and its Cr/Ni value closely matches their sample C8 (Fig. 5f). Major element distributions indicate that soils from the Sirente plain and other intramountain basins from Abruzzo have an Si-Al-Fe- (plus other transition metals) rich component. This component is residual, being resistant to chemical weathering, i.e., carbonate dissolution, which affects the country rock limestone, and it is concentrated in the soil and mixed with fine-grained carbonate. Fe_2O_3t, TiO_2, Al_2O_3, Cr + Ni, and SiO_2 show a strong positive correlation, which indicates that these elements are concentrated in the silicate component (Figs. 5a–d). Relatively low TiO_2 and MnO indicate that there is no significant metal mineralization of the deposit.

Inductively coupled plasma mass spectrometry (ICPMS) of the silt matrix from the rim (Sample SR01) indicates that, while the lithophile and chalcophile trace metals (Pb, Sn, Wo, Mo, Bi, Ag, Sb, Zn, Cu, Au) are enriched by 2 to 200 relative to primordial mantle and chondrite, the siderophile trace metals, including V, Cr, Co, and Ni, are depleted by factors within 0.1–0.01 (Fig. 6a). The transition elements in SR01, normalized to primitive mantle, have similar distributions, but about one order of magnitude lower than the upper continental crust, except Pb and Zn, which have similar abundances (Fig. 6a). All the Cr and Ni values from Speranza et al. (2004) are intermediate between SR01 and the average upper crust values. There is no evidence of high concentrations of highly compatible transition metals in these samples (Gilmour and Koeberl 2004 and references therein). High LREE/HREE values compared with both CH1- and PM-normalized upper continental crust averages indicate a composition that is very much differentiated and enriched compared with any siderophile meteoritic composition (Figs. 6b and 6c).

The PGE concentration in impact meteorite craters may be up to 5 times chondrite. This, however, is not always the case (Reimold et al. 2000). In Fig. 6d, the PGE distribution in the crater rim sample SR01 is plotted and compared with C1 chondrite-normalized values (CH1N) for the primitive mantle and the upper continental crust (Naldrett and Duke 1980; Sun and McDonough 1989; Wänke et al. 1984; Taylor and McLennan 1985). The Ir group element concentrations (Os,

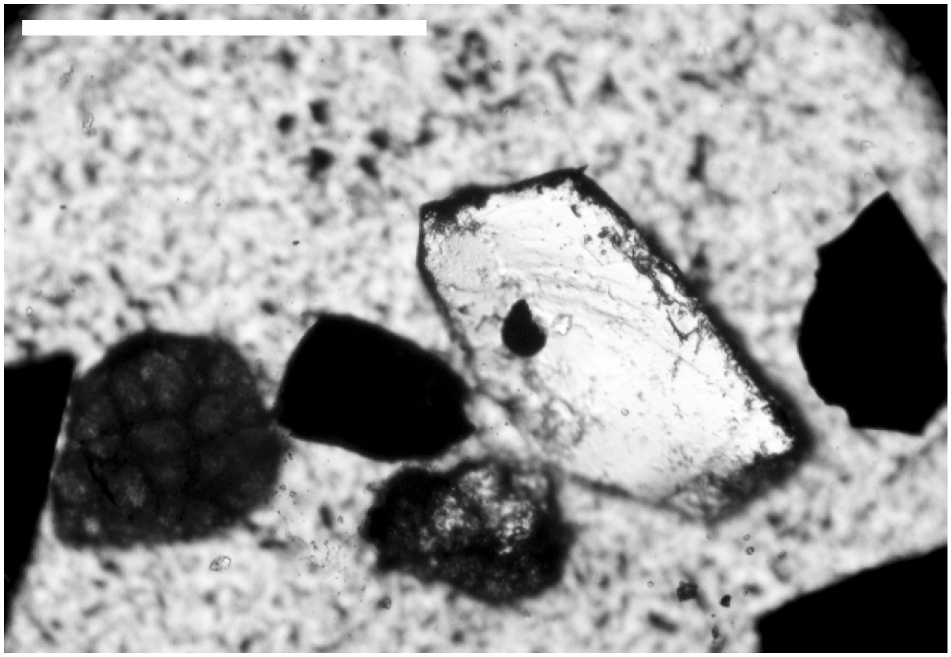

Fig. 4. A microphotograph of the discrete grains and minerals that form Sirente soil. They are K feldspar, magnetite, and microcrystalline quartz. The scale bar is 1 mm. The shape and internal structure do not show mechanical shock features.

Ir, Ru) are below the detection limits (<1.0 ppb) and cannot be directly evaluated. However, Pt group elements (Rh, Pt, Pd, Au) are between 0.002 and 0.007 CH1N. Therefore, the Ir group is lower than 0.001 CH1N, which is several orders of magnitude lower than expected for impact contaminated materials (Fig. 6d). Thus, there is no PGE signature to support an impact by a PGE-bearing projectile.

DISCUSSION AND CONCLUSIONS

Table 2 summarizes what are considered to be the essential criteria for proof of an impact structure (e.g., Gilmour and Koeberl 2000). These conditions are evaluated for the Sirente crater on the basis of new data presented in this paper and combined with data from previous literature.

Problems with an Impact Origin

The impact origin hypothesis requires: 1) the occurrence of shocked minerals, 2) siderophile-rich cryptic components at levels of one to two orders of magnitude higher than background, and 3) PGE anomalies showing enrichment in refractory Ir and Ru and depletion in the volatile Pd and Au (Gilmour and Koeberl 2000 and references therein). However, the apparent lack of direct evidence for meteorite impact, including the absence of typical shock structures and transition-noble metals, is inconclusive.

Concerning the lack of shocked mineral grains, Ormö et al. (2002) explain this by the soft nature of the target and relatively low impact velocity of the projectile. However, they present evidence that tentatively suggests heating of the target (Ormö et al. 2002). Vesiculation observed in their studied heated samples indicates near-atmospheric pressure and ignition at a temperature no higher than that of a wood fire. Such an increase of temperature in a soft and wet target is, however, a crucial point, as it would induce expansion due to the vaporization of water. According to Santilli et al. (2003), the hypothetical impact explosion in the case of a crater such as that at Sirente may have released energy equivalent to 1 kt of TNT, potentially devastating the surrounding area and producing a local earthquake. In this case, the explosion and cratering would have caused ground water vaporization, mechanical rock displacement, and a transient increase in air pressure. Without these effects, there is no explanation for crater formation. However, explosion features such as ejected blocks, surge deposits, and mechanical and thermal effects, which are well known from other impact craters or volcanic vents, are missing at Sirente. All such explosions occurring at ground level produce a base surge and a turbulent expansion of gases and/or vapor, which transport fine-grained fragments. The displaced material is deposited around the crater/vent forming a tuff ring apron marked by cross-lamination and dune beds (e.g., Nakada 2000). In some cases, flows are generated when the transport mechanism passes from a turbulent and low density current (i.e., surge), to laminated or high-density flow (i.e., a "pyroclastic" flow). In both cases, the transport medium is not condensed, as seen in mudflows. At the same time, coarse-grained ejecta from the crater would be expected to follow a ballistic trajectory falling outside the crater for a considerable

Table 1. Bulk rock analysis of sample SIR1.

Oxide	SIR01 wt%	Detection limit wt%	Element	SIR01 ppm	Detection limit ppm	Element	SIR01 ppm	Detection limit ppm	Element	SIR01 ppm	Detection limit ppm	Element	SIR01 ppm	Detection limit ppm
SiO_2	15.97	0.01	Au	1	1	V	54	2	Ga	7	1	Rb	87	2
Al_2O_3	8.28	0.01	Ru	<1	1	Zn	55.1	0.5	Gd	3.9	0.02	Sb	<0.2	0.2
CaO	36.2	0.01	Rh	<1	1	Zr	101	1	Ge	0.5	0.5	Sm	4.21	0.02
MgO	0.79	0.01	Pd	1	1	Ag	<0.2	0.2	Hf	2.4	0.1	Sn	2	1
Na_2O	0.13	0.01	Re	<1	1	As	<5	5	Ho	0.5	0.01	Ta	0.7	0.1
K_2O	0.96	0.01	Os	<3	3	Be	2	1	In	<0.1	0.1	Tb	0.52	0.01
Fe_2O_3	2.87	0.01	Ir	<0.1	0.1	Bi	0.3	0.06	La	30	0.05	Th	12.4	0.05
MnO	0.03	0.01	Pt	4	1	Cd	<1	1	Lu	0.208	0.002	Tl	0.81	0.05
P_2O_5	0.23	0.01	FeO	0.16	0.1	Ce	55.4	0.1	Mo	<2	2	Tm	0.209	0.005
TiO_2	0.41	0.01	Ba	181	3	Co	7.7	0.1	Nb	10.2	0.5	U	1.12	0.05
LOI	34.55	0.01	Cr	30	2	Cs	7.1	0.1	Nd	22.9	0.05	W	1.3	0.2
CO_2	26.83	0.01	Cu	18.8	0.5	Dy	2.82	0.02	Ni	26	1	Y	16.8	0.5
H_2O[a]	7.72	0.01	Sc	6	1	Er	1.63	0.01	Pb	23	2	Yb	1.39	0.01
Total	100.42		Sr	111	2	Eu	0.859	0.005	Pr	6.22	0.02			

[a]LOI (loss in ignition). $H_2O = LOI - CO_2$.

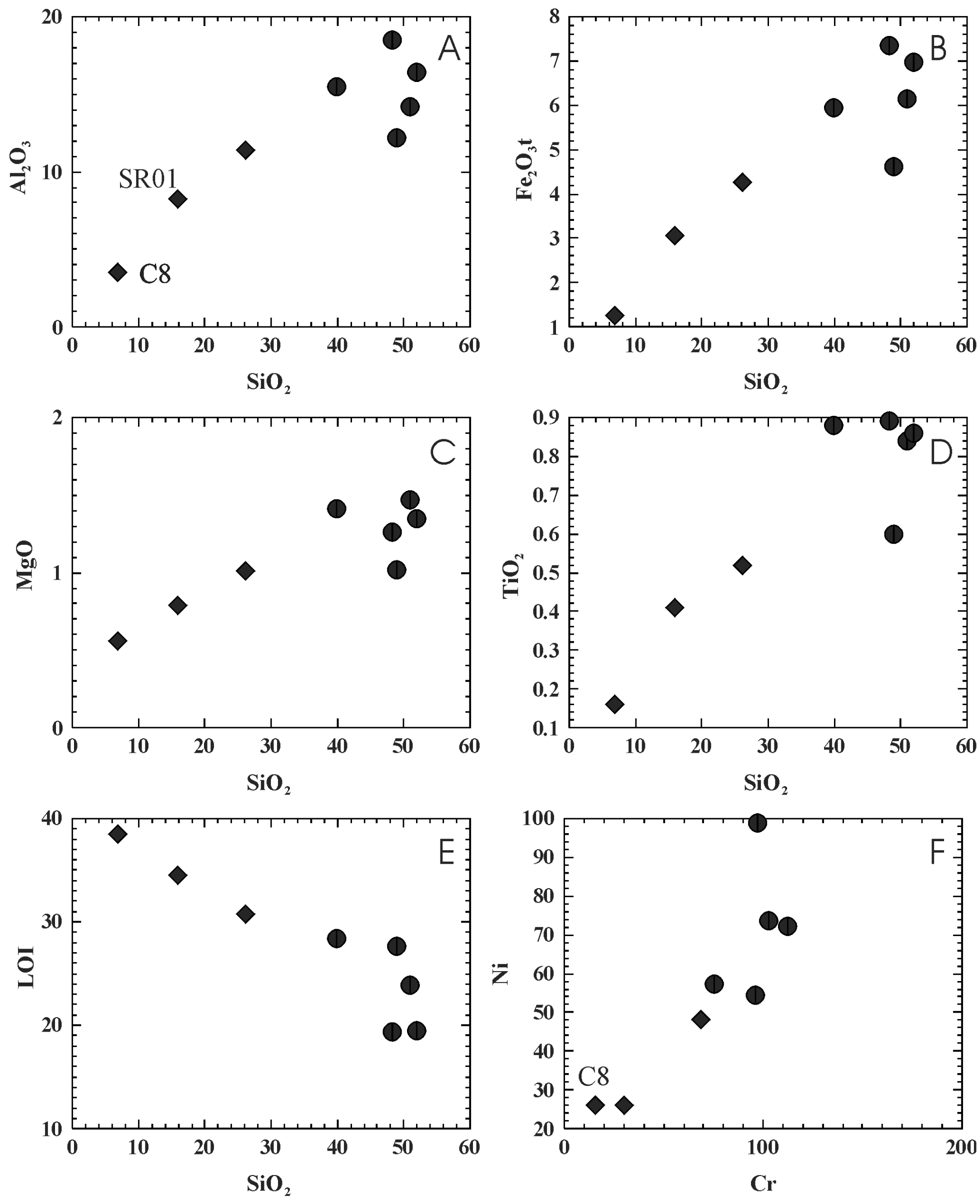

Fig. 5. Bivariant diagrams showing major and minor elemental composition of Sirente soil (SR01), three Sirente soil analyses (solid diamonds), and the composition of other soils from Abruzzi (Speranza et al. 2004). See text for discussion.

distance and preserving evidence of mechanical shock and heating. At the Sirente crater, the rim deposit and associated mudflows have chaotic textures and structures typical of an en masse depositional mechanism in a condensed medium such as water. In fact, water enables the formation of the abundant dense muddy matrix, which allows limestone block buoyancy and transportation. Mudflows are deposited by gravity-driven viscous flow in a condensed-water medium and cannot be confused with the wet surge lobate deposits observed around other impact or volcanic craters, because they have a different transport medium (vapor/gas) and depositional mechanism (turbulent). No surge deposits or high energy ejecta have been found inside or outside the rim. What is seen is a deposit with very limited flow forming the rim and typical mud flow deposits of low profile in the surrounding plane outside the rim.

The main criterion indicative of meteoritic contamination is the presence of anomalously high concentrations of platinoid group metals and other trace elements, the origins of which are not linked to mantle-derived products such as ultramafic igneous rocks (Shukolyukov et al. 2000; Koeberl et al. 2000; Reimold et al. 2000). According to Ormö et al. (2002), the siderophile-rich cryptic component and PGE anomalies at the Sirente crater are consistent with the presence of Ti-rich precipitates, which may represent meteorite contamination. However, Ti-rich grains recognized

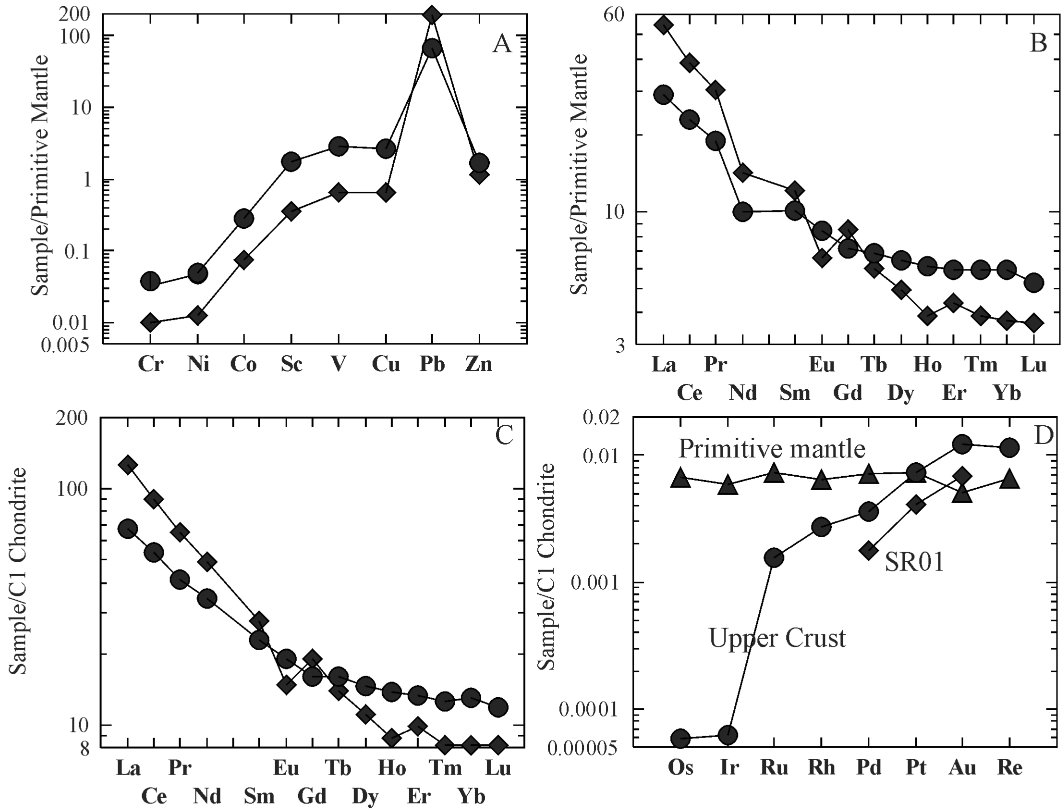

Fig. 6. a) Transition metal abundances normalized to primitive mantle, acr. PM, (Sun and McDonough 1989), for SR01 sample (solid diamonds) and average Earth continental crust composition, acr. AECC, (solid circles). b) Rare earth element abundances, normalized to PM, for SR01 sample (solid diamonds) and V (solid circles). c) Rare earth element abundances, normalized to chondrite (Nakamura 1974), for SR01 sample (solid diamonds) and AECC (solid circles). d) Platinoid metal abundances, normalized to chondrite, for SR01 sample (solid diamonds), AECC (Taylor and McLennan 1981) (solid circles), and PM (solid triangles).

Table 2. A list of questions concerning the main constraints for an impact origin of a crater structure, answered for the Sirente crater.

Findings	Sufficient condition	Necessary condition	Sirente crater
Meteorite fragments	Yes	No	No
Spherulae	Yes	No	No
VHP mineral phases	Yes	No	No
Iridium and platinoid	Yes	No	No
Blast evidence	No	Yes	No
Ballistic ejecta	No	Yes	No
Mechanical shock	Yes	No	No
Melted sediments	Yes	No	No
Rim presence	No	Yes	Yes
Ejection of older material	No	Yes	Yes
Transition metals	No	No	No
Chronicles and legends	No	No	No

in the crater deposits are different from Ti-rich spherules, but similar to those that occur in Apennine soils contaminated by mafic volcanism (Speranza et al. 2004). Other insoluble elements may be enriched by carbonate alteration phenomena and concentrated in the remaining Si-rich component (silt) of the Sirente rim deposit. Alternatively, a possible mixing of cryptic meteorite-contaminated components through volatile condensation and subsequent chemical diffusion of siderophile elements at concentrations higher than reasonable terrestrial materials and with high Ir-group/Pd-group ratios could be good evidence of an impact (e.g., Koeberl et al. 2000). This is not observed and all trace element data, having a typical upper-crust terrestrial abundance and distribution, point to a lack of contamination.

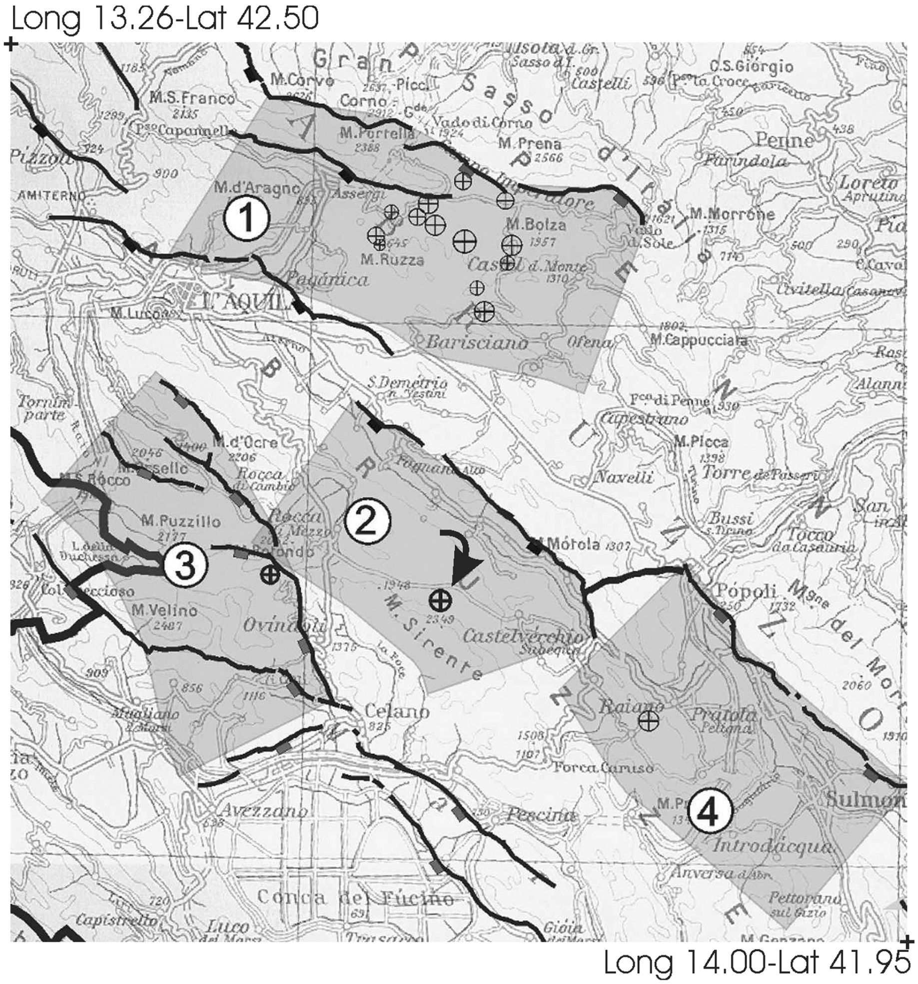

Fig. 7. A sketch map of the seismic areas (in gray) and active faults associated with the "crater" in Abruzzo. Map simplified after Boncio et al. (2004). Crater locations are indicated by a crossed circle after Speranza et al. (2004). The Sirente crater is indicated by an arrow. 1 = Gran Sasso, 2 = Sirente plain, 3 = Campo Felice e Ovindoli, and 4 = Sulmona.

Human Origin

The presence of some human artifacts indicates that the site was used by humans for at least two thousand years. However, there are no recognizable buildings or structures remaining, and no historical documents referring to the site have been discovered. The crater rim appears to be neither an artifact nor a reworked sedimentary structure. The original massive or inverse-graded material is preserved, as are some typical sedimentary structures. No evidence of human transport of the larger limestone blocks, nor signs of digging have been observed. Several large blocks are present, but they are not in contact with each other and are unlikely to have been used to reinforce the rim structures. A human origin does not explain the presence of a subsiding sector around the rim. Also, it does not explain the presence of mudflows and breaches in the rim. It seems unlikely that the excavation was made as a water reservoir as fresh water, since more suitable sites for watering livestock occur in the area.

PREFERRED HYPOTHESIS

Considering all the data available, and particularly the new geological observations presented in support of sedimentation by mudflows, the following hypothesis is proposed: the Sirente crater structure developed by mud-fountaining that generated the rim and mudflows while also mobilizing underlying karstic limestone blocks. The formation of mud-fountains implies the sudden generation of over-pressure conditions in the substratum. Well-sorted silt materials are prone to liquefaction by strong perturbations such as seismic shocks or sudden gas/water over-pressure. The presence of large blocks of limestone from the crater substratum is consistent with diapiric movement. Finally, subsidence of the southwestern sector of the rim is possibly linked to mass compensation after diapirism and ejection. Water-mud fountains, excluding phreatic/hydrothermal eruptions, have been observed associated with piping sinkholes (Beck 1984) and mud volcanoes (Murton and Biggs 2003). Both are geologically neglected forms and can be regarded as variants of the more common karstic and secondary volcanic phenomena. The Sirente area has a relatively impermeable silty layer overlying a limestone karstic substratum, which is favorable to the formation of a piping sinkhole. However, at present, it seems that the karst system works by driving water from the surface underground and not vice-versa, as is required for a piping sinkhole. In addition, piping sinkholes usually have modest rims and show little ejection of dense materials (i.e., rocks). Mud volcanoes are a much more complex phenomenon, occurring in areas including Taiwan, Indonesia, Malaysia, Iran, Mexico, Colombia, Trinidad, Azerbaijan, and Italy. They can be a few meters to a few hundreds of meters wide and form small pools or hills up to a few tens of meters high. They commonly occur in areas of earthquake activity, associated with Cenozoic fold belts. They usually erupt along active faults and originate from clay beds resting on fracturated rock substrata at depths of up to several kilometers (e.g., Murton and Biggs 2003). Mud volcanoes can be ephemeral or persistent and are generated by the slow, violent, or even catastrophic release of gas, water, and mud. The gas release can be linked to hydrocarbon gas accumulation or volcanic or non-volcanic gases and vapor. Release can be triggered by earthquakes or tectonic deformation. The Sirente crater is in a high seismicity area and is close to an active fault (Boncio et al. 2004). The presence of similar craters in Abruzzo has been described by Speranza et al. (2004) and all these craters are closely associated with high seismicity zones and active faults (Fig. 7). The stratigraphy, i.e., silt overlying a rock basement, is favorable to the formation of both piping sinkholes and mud volcanoes. Hydrocarbon-sustained mud volcanoes are known in other areas of Abruzzo, but there is no evidence for hydrocarbon or oil emissions at Sirente (Centamore et al. 2003). However, high-pressure CO_2 reservoirs in the Apennines of central Italy are well known and CO_2 reservoir decompression triggered by earthquakes is geologically feasible and consistent with the observed features of the Sirente crater (Chiodini et al. 1999). In the Rieti province of Abruzzi, mud/gas explosions producing craters were eyewitnessed from the San Vittorino Plain in 1704. These were probably triggered by two high magnitude (6.8 and 6.6) earthquakes occurring in the Aquila-Rieti area (Bersani and Castellano 2002).

The presence of ephemeral, earthquake-triggered mud volcanos at Sirente and in other areas of Abruzzo could be an important paleoseismological feature.

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