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An anthropogenic origin of the "Sirente crater," Abruzzi, Italy

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Abstract–In this paper, we review the recent hypothesis, based mostly on geomorphological features, that a ~130 m-wide sag pond, surrounded by a saddle-shaped rim from the Sirente plain (Abruzzi, Italy), is the first-discovered meteoritic crater of Italy. Sub-circular depressions (hosting ponds), with geomorphological features and size very similar to those exhibited by the main Sirente sag, are exposed in other neighboring intermountain karstic plains from Abruzzi. We have sampled present-day soils from these sag ponds and from the Sirente sags (both the main "crater" and some smaller ones, recently interpreted as a crater field) and various Abruzzi paleosols from excavated trenches with an age range encompassing the estimated age of the "Sirente crater." For all samples, we measured the magnetic susceptibility and determined the Ni and Cr contents of selected specimens. The results show that the magnetic susceptibility values and the geochemical composition are similar for all samples (from Sirente and other Abruzzi sags) and are both significantly different from the values reported for soils contaminated by meteoritic dust. No solid evidence pointing at an impact origin exists, besides the circular shape and rim of the main sag. The available observations and data suggest that the "Sirente crater," together with analogous large sags in the Abruzzi intermountain plains, have to be attributed to the historical phenomenon of "transumanza" (seasonal migration of sheep and shepherds), a custom that for centuries characterized the basic social-economical system of the Abruzzi region. Such sags were excavated to provide water for millions of sheep, which spent summers in the Abruzzi karstic high pasture lands, on carbonatic massifs deprived of natural superficial fresh water. Conversely, the distribution of the smaller sags from the Sirente plain correlates with the local pattern of the calcareous bedrock and, together with the characteristics of their internal structure, are best interpreted as natural dolines. In fact, reported radiocarbon ages for the formation of the main sag pond and of the smaller sags differ (significantly) by more than two millennia, thus excluding that they were all contemporaneously formed by a meteoritic impact.

INTRODUCTION

Circular shapes have always stimulated man's imagination. Recently, Ormö et al. (2002a) proposed that a ~130 m-wide sub-circular depression (or sag) located in a karstic plane at the toe of Mt. Sirente in the Abruzzi Apennines (Italy; Fig. 1) represents the first discovered meteorite impact crater of Italy. This interpretation relies on the shape of the sag (hosting a permanent pond), which is surrounded by a saddle-shaped rim rising up to 2.2 m above the surrounding plain (Fig. 2a). Moreover, some 17 smaller depressions (without any raised rim) located about 300–400 m west and northwest of the main depression (e.g., Figs. 1 and 2d) are interpreted by Ormö et al. (2002a) as the "crater field" produced by the shower of fragments of the same meteoritic impact. During the survey, drilling, and excavations, Ormö et al. (2002a) did not find any meteorite fragment nor evidence of shocked or fused materials, which are typical for impacts. As geochemical argument to support the meteoritic nature, Ormö et al. (2002a) state that the rim material and the upper 4 m of the main crater infill are impregnated with ferric oxides and that rusty crusts with high Fe and Mn content occur in the rim material. Furthermore, in one rusty crust fragment, they observed two very small (micron-sized) granules composed of Ni (no picture provided).

Radiocarbon dating of a paleosol, recovered from a drill core below the sag pond rim in the Sirente plain, yielded an age of 1650 ± 40 yr BP (Ormö et al. 2002a), interpreted as being emplaced over the surrounding soil after 412 AD.

Many small sub-circular depressions surrounded by a

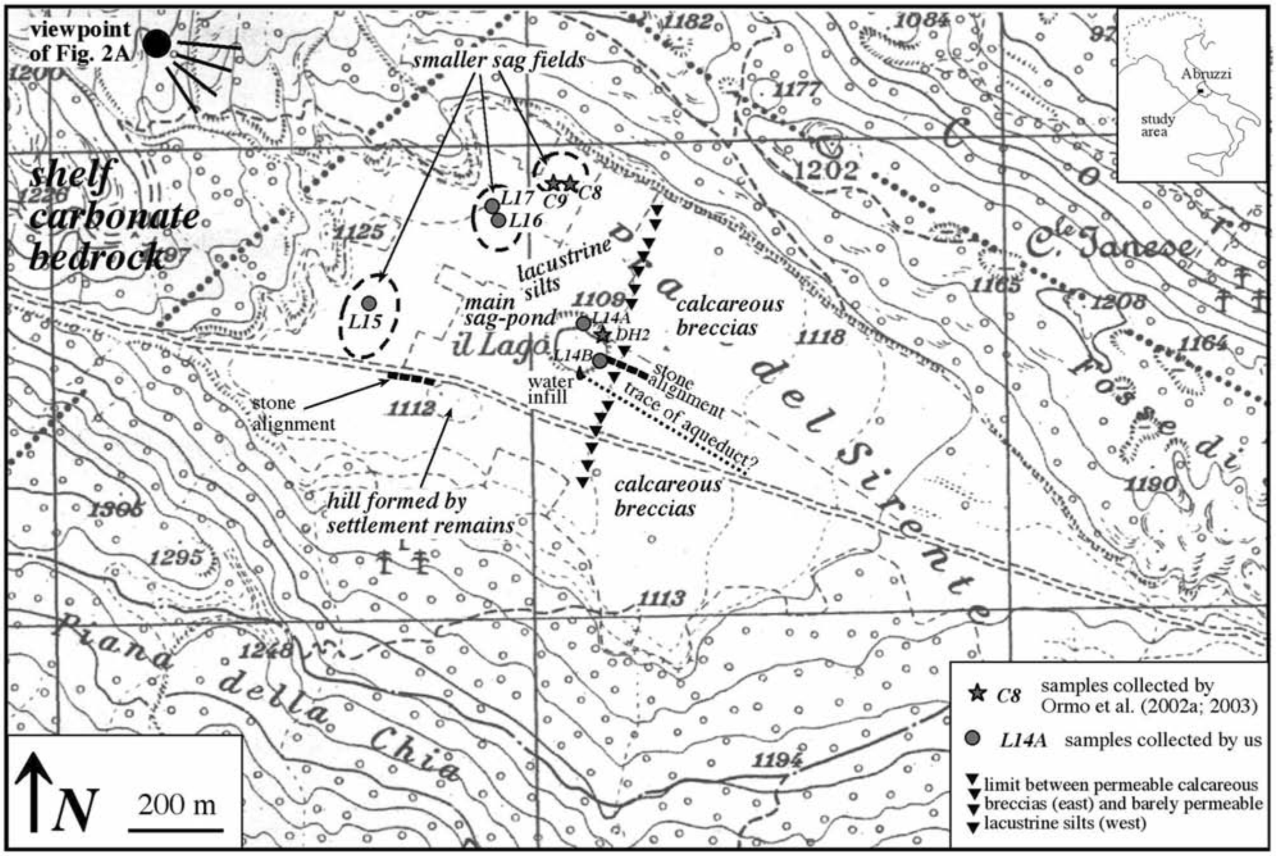

Fig. 1. Map of the Sirente plain (copy of an Istituto Geografico Militare (Italy) 1:25,000 topographic map) and sampling sites. Continuous and dashed altitude lines are drawn every 25 and 5 m, respectively. In the entire map area (except the plain), the shelf carbonate bedrock is exposed. The open circles represent trees. The double dashed line marks a dirt road trace.

(more or less pronounced) saddle-shaped rim can be observed in several intermountain plains from the Abruzzi highlands. The most spectacular examples of these depressions (almost always hosting ponds) are exposed within the Gran Sasso Range, some 30 km north of Mt. Sirente (Fig. 3 and Table 1; sag pond L18 is from the Velino Massif, 10 km west of the Sirente plain). These depressions are very similar (in both size and shape) to the sag pond in the Sirente plain. In some cases, the height of the saddle-shaped rim is comparable (if not higher) to the one from the Sirente plain (Fig. 3e). These sags are exposed at an altitude similar to (or slightly higher than) that of the Sirente plain, mostly within narrow tectonic valleys bounded by shelf carbonate horsts. These depressions are believed to have been dug by man centuries ago (though the precise period of excavation is unknown) to create reservoirs to collect drinking water for livestock.

Nearly all the sags are located in correspondence (or very close) to local small springs so that they can virtually contain water the whole year through. This correspondence suggests that the localities of sag digging were conditioned by the availability and distribution of small-spring waters. The case of sag pond L18 (from Piani di Pezza, Velino Massif; Table 1) exemplifies the typical geological-hydrological context, though this sag has poorly pronounced (likely eroded) saddle-shaped rims with respect to most of the Gran Sasso sags. This 100 m-wide sag (located close to the "Deramo" hut) was dug within virtually impermeable calcareous-silt lacustrine sediments very similar to those surrounding the Sirente sag pond and is adjacent to the contact with a glacial moraine made by permeable coarse breccias. A small (but perpetual) spring at the lacustrine deposits-moraine contact is dammed within a (Renaissance-age) fountain and, in turn, feeds the adjacent sag pond.

In this paper, we review the Ormö et al. (2002a; 2003) interpretation of the Sirente plain morphology and geological features. Relying on the observation of similar shapes in several other sags from nearby Abruzzi karstic plains and on new geochemical/geophysical data from soils and sediments sampled both in the Sirente and in other Abruzzi depressions, we show that the "Sirente crater" is most likely the result of human activity.

THE SIRENTE PLAIN AND ITS SAGS

The karstic plain located at the northeastern toe of Mt. Sirente, which hosts the sub-circular sags, has a mean altitude of about 1100 m (Fig. 1). The main sag pond is located in the

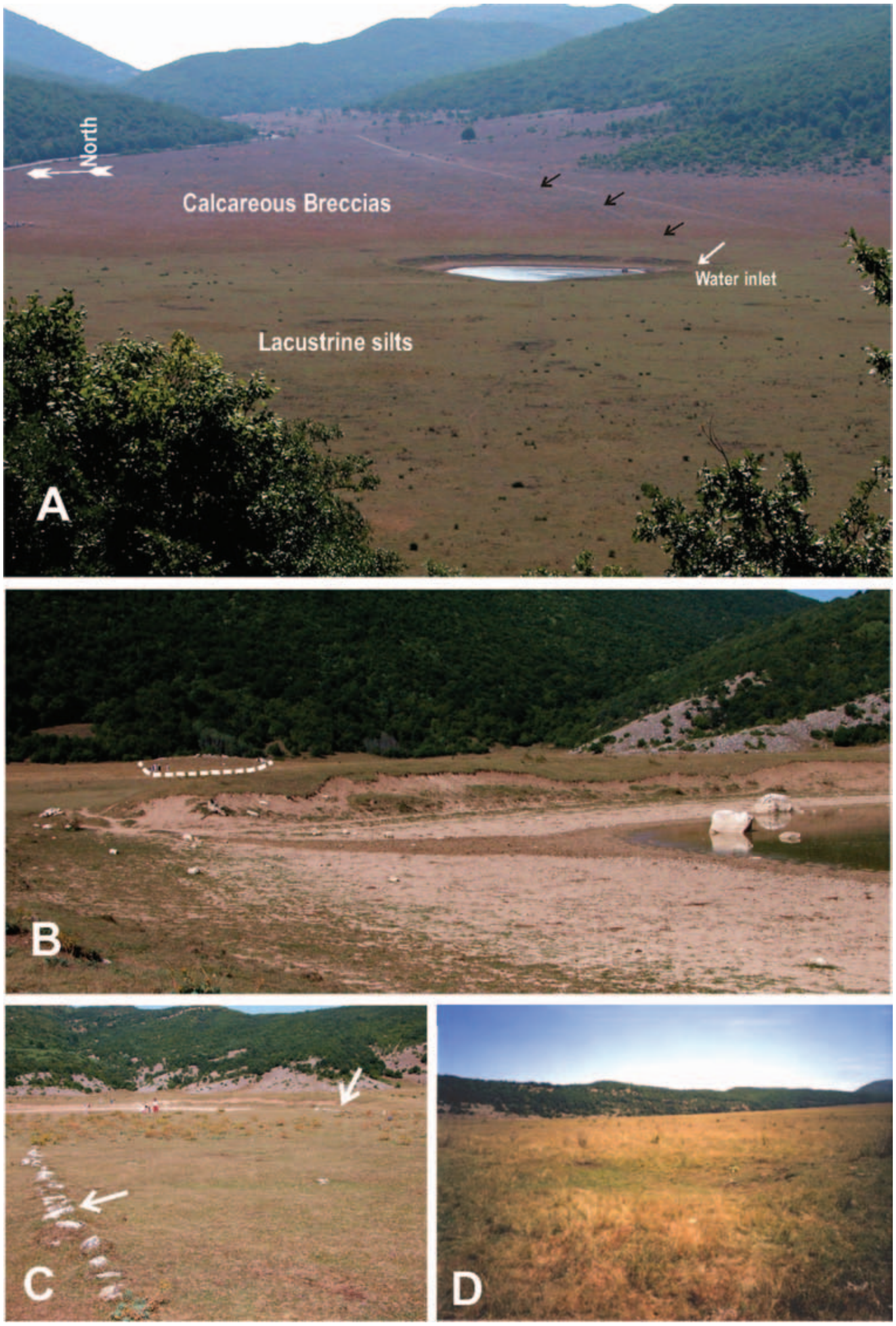

Fig. 2. Photographs from the Sirente plain: a) the main sag (“crater” according to Ormö et al. [2002a, 2002b, 2003]). Note that the sag is located in the lowermost part of the plain, where low-permeability lacustrine silts are exposed. Conversely, in the eastern part of the plain, highly permeable calcareous breccias crop out (see the sharp change of vegetation color behind the lake). Also, note a rectilinear trace in the soil (black arrows) likely running over a small buried aqueduct (or draining trench), which starts from the southern interruption of the rim (water inlet point); b) a close-up of the inlet of water observed in the southern interruption of the rim (the picture was taken at the end of August 2003). The dashed white line marks the mound of stacked limestone blocks exposed southwest of the sag pond, likely the remnant of an ancient human building. Also, note the two large (not metamorphosed, not shocked) limestone boulders exposed within the sag, which should not have survived a meteoritic impact; c) one of the two rows of aligned stones (foreground, the other is indicated by a white arrow) well-exposed to the east of the main sag (Fig. 1); and d) one of the smaller sags exposed to the north-northwest of the main sag. The yellow and green grass correspond to the areas external and internal to the sag, respectively.

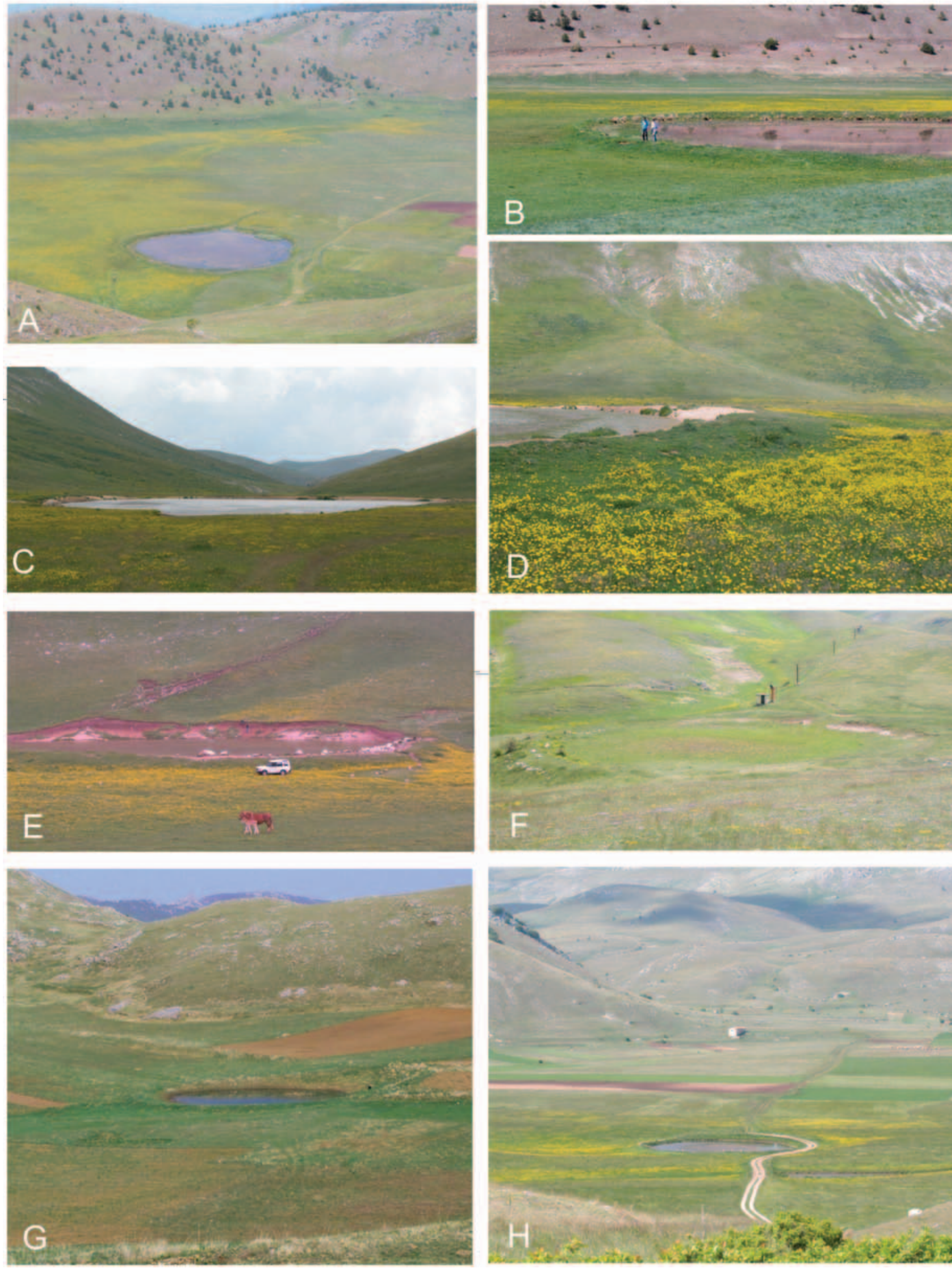

Fig. 3. Photographs of sag ponds from the Gran Sasso Range highlands (see Table 1 for precise locations and diameters) with typical circular shape, saddle-shaped rims, and dimensions similar to the main sag pond in the Sirente plain: a and b) Lago di Filetto (L02, diameter 91 m); c and d) Lago di Barisciano (L11, diameter 124 m); e) an unnamed sag pond in the locality "Fossa di Paganica" (L09, diameter 113 m). Note that the rim is higher than the Land Rover; f) Laghetto di Assergi (L07, diameter 52 m), which is presently dry and filled by sediments; g) an unnamed sag pond in the locality "Il Prato" (L04, diameter 49 m); and h) an unnamed sag pond in the locality "Le Locce" (L13, diameter 51 m).

Table 1. Location, elevation, and diameters of sub-circular sags from the Gran Sasso Range (except sag L18, from the Velino Massif) and the (mean) low-frequency (0.92 kHz), low-field (0.38 mT) magnetic susceptibility (χ) of present-day soils and superficial sediments sampled in some of them.[a]

Code	Sag name	Latitude N	Longitude E	Elev. (m)	Diam. (m)	χ (10^{-6} m^3/kg)
L01	Fonte Pantani	42°23′12.4″	13°33′20.4″	1382	29	–
L02	Lago di Filetto	42°23′33.2″	13°33′10.3″	1371	91	0.55 (n = 6; sd = 0.18)*
L03	(Close to S. Stefano)	42°20′47.1″	13°38′38.8″	1220	118	–
L04	(Loc. Il Prato)	42°22′36.3″	13°39′46.4″	1553	49	1.84 (n = 3; sd = 0.09)
L05	Lago Racollo	42°24′56.2″	13°39′37.1″	1568	88	1.43 (n = 6; sd = 0.78)
L06	Lago S. Pietro	42°23′16.3″	13°39′58.9″	1591	120	–
L07	Laghetto di Assergi	42°24′26.6″	13°33′54.8″	1578	52	–
L08	Lago Pietranzoni	42°25′38.1″	13°37′29.9″	1614	86	–
L09	(Loc. Fossa di Paganica)	42°24′46.4″	13°35′44.9″	1680	113	1.36 (n = 3; sd = 0.03)
L10	(Loc. La Fossetta)	42°24′16.6″	13°35′13.2″	1650	90	2.29 (n = 3; sd = 0.14)
L11	Lago di Barisciano	42°23′58.4″	13°36′07.5″	1604	124	1.33 (n = 3; sd = 0.09)
L12	Lago di Passaneta	42°23′23.5″	13°37′36.5″	1560	171	1.60 (n = 3; sd = 0.13)
L13	(Loc. Le Locce)	42°21′39.0″	13°38′15.4″	1220	51	1.24 (n = 3; sd = 0.11)
L18	(Piani di Pezza)	42°10′50.6″	13°28′08.2″	1450	100	–

[a]Elevation (Elev.) is given in meter above sea level. Diameter (Diam.) is measured rim-to-rim. The number of measured samples (n) and the standard deviation (sd) values are in parenthesis. The asterisk indicates an anomalously small χ value.

lowermost part of the Sirente plain (Figs. 1 and 2a) and is characterized by low-permeability lacustrine calcareous silts. Conversely, just east of the sag pond, only permeable calcareous breccias are exposed (see the variation of vegetation color in Fig. 2a).

The excavation of one of the smaller sags (“crater C9”) by Ormö et al. (2002a) revealed that the depression overlies a vertical funnel-shaped dark soil body, while the host rock is formed by pale lacustrine calcareous silts. This vertical funnel-shaped soil body below sag C9 is in contrast with the oblique impact suggested by Ormö et al. (2002a), which obviously would not create a sub-vertical hole. The shape and the structure of the soil infilling actually resemble that found by trenching of a doline (or sinkhole) in another Abruzzi intermountain basin (the Aremogna plain; see D’Addezio et al. 2001) (Fig. 4). The small depressions of the Sirente plain would appear to be, in fact, dolines formed within the calcareous silts. Karstic fields containing several dolines are very common in the Abruzzi highlands and are formed in extremely permeable shelf limestones (many large dolines are spectacularly exposed all over the Sirente range).

Ormö et al. (2002a) state (page 1511) that radiocarbon dating of “crater” C9 gave a radiocarbon age of 3810 ± 90 yr BP, which is interpreted as a calibrated age of ~2229 BC. This age is completely incompatible (~2600 yr older) with the age reported by the same authors for the Sirente sag pond formation (AD 412 ± 40). Then, radiocarbon data from Ormö et al. (2002a) clearly prove that the formation of the main sag pond and the smaller sags are not synchronous, thus excluding the possibility that they were formed during a meteoritic impact. Age data from “crater” C9 were omitted in the subsequent paper by Ormö et al. (2003), who state that, “the age data suggest a contemporaneous formation of the main and small craters although with large error bars.”

In any case, there are also other bits of evidence further supporting our karstic interpretation of the smaller sags from the Sirente plain: 1) none (from a total of 17, according to Ormö et al. [2002a]) shows an “in relief” rim (as craters should do); and 2) all the depressions cluster in areas where the carbonate substratum is closer to the plain (Fig. 1), implying that their occurrence is limited to places where the carbonate substratum is shallower and the thickness of the (barely permeable) lacustrine silts is smaller.

In subsequent excavation and investigation of sag C8, Ormö et al. (2003) found a structure similar to C9 and obtained dates on charcoal and heated clay that are slightly older (reported ages AD 125 ± 174 and AD 238 ± 100, respectively) than the main depression excavation age (AD 412 ± 40) but more than 2300 yr younger than the age indicated for the adjacent sag C9. The age discrepancy between sags C8 and C9 and the main sag pond would instead fit with a karstic origin for these structures, i.e., natural dissolution occurred over a time period. The ages of the samples recovered from the main sag and from sags C8 and C9 are between 2229 BC and 412 AD (Ormö et al. 2002a; 2003), i.e., from the Bronze Age to the late Roman times. Therefore, human activity in the Sirente plain would turn out to be well-correlated with the formation of these structures. Thus, another explanation for the age discrepancy would be that these structures were dug by man and/or are natural dolines filled by man over a time interval protracted for almost three millennia. The sags could have been used for waste disposal, pottery firing, etc.

Suggestions of “brecciated” material (Ormö et al. 2003) and “horizons strongly compressed by impact” showing “dislocation” below the sag pond (Fig. 8 of Ormö et al. [2002a]) are compatible with other structures we currently observe in the trenches of similar material in other Abruzzi

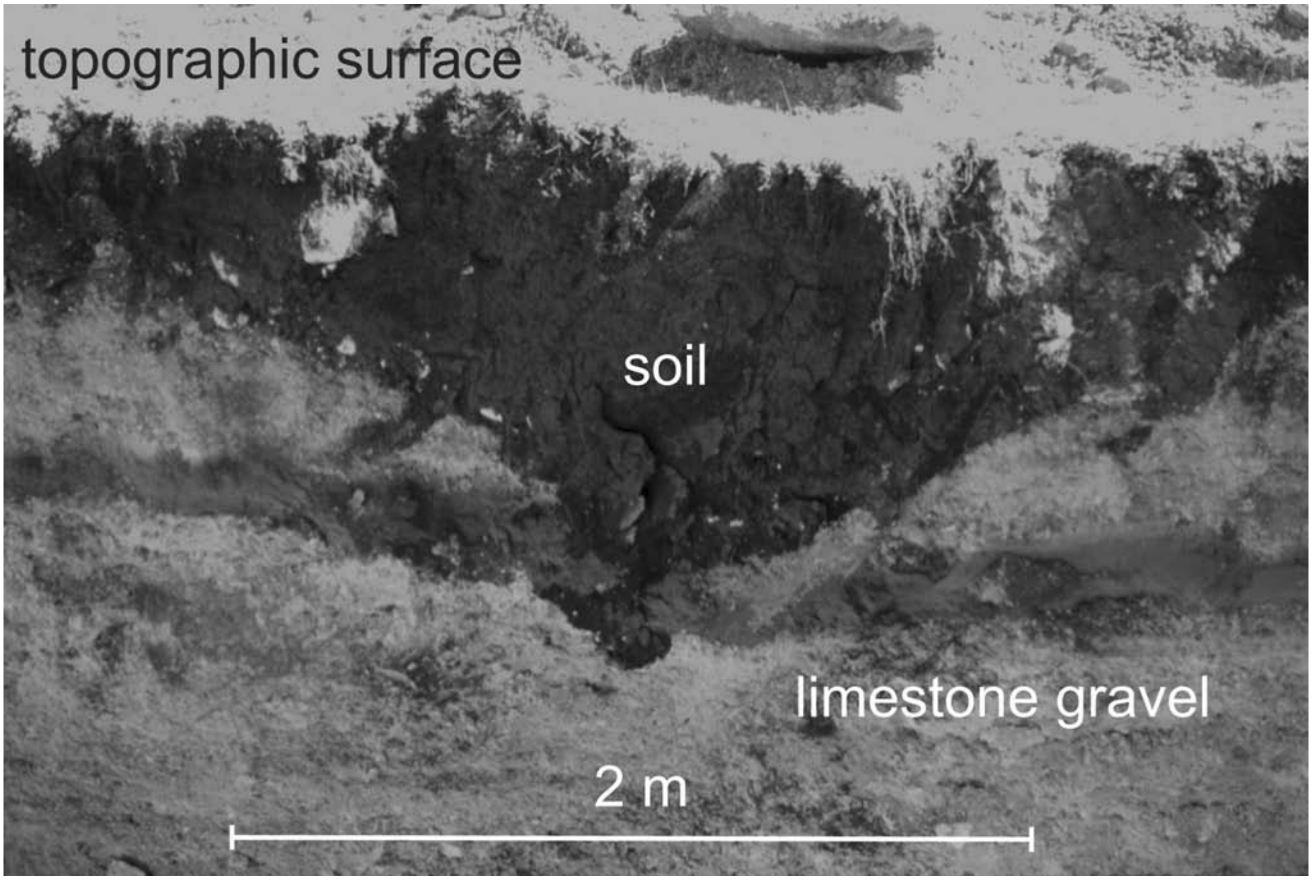

Fig. 4. Cross section of a doline exposed in a trench excavated for paleoseismological study in the Aremogna plain, Abruzzi (D'Addezio et al. 2001). The overall shape and structure resemble that described by Ormö et al. (2002a, their Fig. 4; 2003, their Fig. 2) for the excavated C9 and C8 depressions in the Sirente plain. Photo courtesy of Giuliana D'Addezio.

sags. Laminated sediments are common in those paleolakes. The apparent compaction and slight deformation may be easily accounted for by drying and flooding cycles, and the small dislocation observed may be due to coring (as also suggested by Ormö et al. [2002a]). In fact, it is noteworthy that in pit DH1, excavated by Ormö et al. (2002a) in the interior of the "main crater," the same horizons found compacted in the close core DH2 (drilled in the rim) do not show any evidence of compression.

SEARCH FOR EXTRATERRESTRIAL (ET) MATERIAL

In a positively identified impact crater in Campo del Cielo (Argentina), with dimensions smaller than the Sirente main sag pond, detailed excavation allowed the recovery of ~5200 kg of meteorite and iron-shale fragments (Cassidy 1971). In the 110 m-diameter Kaali crater, dated at about 2600 ± 200 yr BP, about 2.5 kg of meteoritic iron was recovered, as well as disseminated magnetic spherules (Veski et al. 2001). Despite a similar bedrock lithology (carbonates) and an older age, the topography of the Kaali crater is much more pronounced—the rim rises about 5–10 m above the surrounding plain with a 16 m-deep depression (compared to the 1–2 m-deep Sirente pond). Ormö et al. (2002a) admit that their search for extraterrestrial matter was unsuccessful. However, they suggest that "the occurrence of rusty crust in the rim" (page 1513) and the energy dispersive X-ray (EDX) observation of two spongy Ni-bearing micron-size particles could indicate a possible extraterrestrial origin (no picture provided). Iron concentration, by oxydo-reduction in the vadose zone of soils, is ubiquitous in such environments. In order to confirm or negate the presence of extraterrestrial material in the soils of the Sirente sags, we performed magnetic and geochemical measurements.

Sampling in the Abruzzi Sags

We sampled present-day soils and sediments exposed in the internal parts of the sags from the Gran Sasso Range and the Sirente plain and collected samples of paleosols from former trench excavations (aimed at paleoseismology purposes) across Abruzzi (Pantosti et al. 1996; D'Addezio et al. 2001). The location of each sampled site is detailed in Tables 1 to 3.

Soils from 8 sags (Fig. 3 and Table 1) were sampled along the Gran Sasso Range. In the Sirente plain, we sampled the main depression in two points (L14A and L14B, showing pale, unaltered, and pedogenized calcareous sediments, respectively; Fig. 1). We also sampled the brown soil cropping out within two smaller sags (L15 and L17; Fig. 1) and the slightly altered silty lacustrine sediment exposed within another sag L16 (Fig. 1).

Samples of paleosol were recovered from paleoseismological trenches previously excavated in two intermountain basins located in between the Sirente and Velino massifs (Piani di Pezza and Campo Porcaro, ~10 km west of the Sirente plain) and in another intermountain basin (Aremogna plain, located in the Massif of Mt. Greco, ~50 km southeast of the Sirente plain) in southwest Abruzzi (Table 3). These paleosols were dated and described in detail by Pantosti et al. (1996) and D'Addezio et al. (2001), respectively. All these paleosols developed on a similar geologic substratum (Meso-Cenozoic marine shelf carbonates) and in analogous climatic conditions (i.e., in the same region and at a similar elevation). The ages of the paleosols range between ~5000 BC and 1400 AD (Table 3). Two silty lacustrine sediment samples (one from sag C8 and one [DH2] drilled in the rim of the main sag) and a paleosol sample from a trench dug in sag C9 (Ormö et al. 2002a, 2003) were given to the INGV paleomagnetic laboratory in January 2002, and their magnetic susceptibility was measured for magnetic modeling purposes.

Magnetic Properties

The low-frequency (0.92 kHz), low-field (0.38 mT) magnetic susceptibility (χ) of all samples was measured using an AGICO Kappabridge KLY-2 instrument at the paleomagnetic laboratory of the INGV, Rome. The measurements are listed in Tables 1–3 and shown in Fig. 5.

The low-field (mean) magnetic susceptibilities of the two soil samples from the Sirente plain ($1.38–1.75 \times 10^{-6}$ m^3/kg; Table 2) are in the same range of variability defined by the present-day soil samples from the Gran Sasso Range sags ($0.55–2.29 \times 10^{-6}$ m^3/kg; Table 1) and are significantly higher than those exhibited by the underlying lacustrine sediments in the Sirente plain ($0.25–0.64 \times 10^{-6}$ m^3/kg; Table 2). For comparison, we measured the low-field magnetic susceptibility of similar, unweathered, silty pale lacustrine sediments cropping out in the nearby Piani di Pezza plain, which provided a mean value of $\sim 0.11 \times 10^{-6}$ m^3/kg.

Moreover, the (mean) magnetic susceptibility value obtained for the paleosol recovered from the C9 excavation in the Sirente plain (2.21×10^{-6} m^3/kg; Table 3) is consistent with the range of variability ($0.74–8.57 \times 10^{-6}$ m^3/kg; Table 3) of paleosols developed during different historical ages from the Abruzzi region. Values 0.55 and 0.74 ($\times 10^{-6}$ m^3/kg) from a Gran Sasso soil and an Abruzzi paleosol, respectively (marked with an asterisk in Tables 1 and 3), are anomalously small compared to the remaining soil-paleosol values. A likely

Table 2. Mean low-frequency (0.92 kHz), low-field (0.38 mT) magnetic susceptibility (χ) of various samples from the Sirente plain (see text).

Code	Sample type	χ (10^{-6} m^3/kg)
L15	Soil	1.75 (n = 3; sd = 0.04)[a]
L17	Soil	1.38 (n = 3; sd = 0.22)
L16	Brown altered silty lacustrine sediments	0.64 (n = 3; sd = 0.05)
L14B	Brown altered silty lacustrine sediments	0.60 (n = 3; sd = 0.04)
L14A	Light colored silty lacustrine sediments	0.32 (n = 3; sd = 0.04)
DH2	Light colored silty lacustrine sediments	0.29 (n = 3; sd = 0.01)
C8	Light colored silty lacustrine sediments	0.25 (n = 3; sd = 0.01)

[a]The number of measured samples (n) and standard deviation (sd) values are in parentheses.

explanation for such behavior is that these two samples contain a significant amount of small fragments of the calcareous bedrock and/or the calcareous lacustrine sediments, which are expected to significantly lower the whole-sample susceptibility value. Paleosols developed in mid-latitudes of Europe, Central Asia, and China during the interglacial periods of the last million years typically show similar (mean) magnetic susceptibility values ($1–3 \times 10^{-6}$ m^3/kg; e.g., Evans and Heller 2003).

The contrast in (mean) magnetic susceptibility between the soil filling dolines with a structure similar to that illustrated in Fig. 4 and the pale calcareous-silt lacustrine sediments underneath is sufficient to explain the magnetic anomalies of 20–30 nT preliminarily reported by Ormö et al. (2002b) for many of the smaller sags from the Sirente plain. Ormö et al. (2002b) state that the magnetic anomalies can be ascribed to objects characterized by a remanent magnetization with different direction with respect to the present geomagnetic field. They then conclude that these buried objects are most likely meteorite fragments. However, pedogenic processes in temperate soils are widely known to produce in situ nucleation and growth of very fine-grained magnetite and/or maghemite particles that cause a typical "magnetic enhancement" (e.g., Maher 1986; Maher and Taylor 1988; Evans and Heller 1994; Maher 1998; Florindo et al. 1999; Maher and Thompson 1999). A bulk magnetic susceptibility value of about 2×10^{-6} m^3/kg corresponds to 3 per mil of magnetite equivalent (specific χ of 0.6×10^{-3} m^3/kg). Therefore, the observed magnetic susceptibility can be entirely due to common pedogenesis processes. An eventual meteoritic contribution to the magnetic susceptibility of soils in the Sirente plain would have to be extremely small, and in any case, it is not necessary to justify the measured magnetic susceptibilities.

To reach a higher sensitivity on the content of ferrimagnetic particles, we performed hysteresis measurements on seven of the samples selected for magnetic

Table 3. Mean low-frequency (0.92 kHz), low-field (0.38 mT) magnetic susceptibility (χ) of Abruzzi Holocene paleosols (from trench excavations).

Sample (unit)	Locality	Massif	Latitude N	Longitude E	Elev. (m)[a]	Calibrated age (yr)	χ (10^{-6} m^3/kg)[b]
P1W-05 (5a1)[c]	Piani di Pezza	Velino	42°11′20″	13°28′05″	1475	2210 BC–990 BC	8.57 (n = 3; sd = 0.35)
P1E-11 (3a1)[c]	Piani di Pezza	Velino	42°11′20″	13°28′05″	1475	1230 BC–1400 AD	3.49 (n = 3; sd = 0.23)
P2W-S1 (5a2)[c]	Piani di Pezza	Velino	42°11′20″	13°28′05″	1475	2410 BC–2030 BC	7.04 (n = 6; sd = 0.12)
P3E-S1 (5b3)[c]	Piani di Pezza	Velino	42°11′05″	13°28′48″	1475	5210 BC–4890 BC	5.43 (n = 3; sd = 0.22)
P3W-50 (3a3)[c]	Piani di Pezza	Velino	42°11′05″	13°28′48″	1475	127 BC–401 AD	4.43 (n = 3; sd = 0.03)
PH4S-S2 (4b4)[c]	Park Hotel	Velino	42°09′08″	13°30′12″	1400	560 BC–790 AD	4.31 (n = 3; sd = 0.17)
PH4S-S4 (4b4)[c]	Park Hotel	Velino	42°09′08″	13°30′12″	1400	430 BC–660 AD	1.87 (n = 3; sd = 0.04)
PH4S-S21 (4d4)[c]	Park Hotel	Velino	42°09′08″	13°30′12″	1400	600 BC–770 AD	0.74 (n = 3; sd = 0.20)*
TR2-S1 (3b)[d]	Aremogna	Greco	41°48′44″	14°02′35″	1415	3350 BC–2940 BC	2.84 (n = 1)
TR2-S2 (3a)[d]	Aremogna	Greco	41°48′44″	14°02′35″	1415	3320 BC–2920 BC	2.81 (n = 1)
TR2-S3 (3a)[d]	Aremogna	Greco	41°48′44″	14°02′35″	1415	3320 BC–1030 AD	2.72 (n = 3; sd = 0.06)
C9[e]	Sirente plain	Sirente	42°10′41″	13°35′25″	1109	–	2.21 (n = 3; sd = 0.23)

[a]Elevation (Elev.) is given in meters above sea level.
[b]The number of measured samples (n) and standard deviation (sd) values are given in parentheses. The asterisk indicates an anomalously small χ value.
[c]Pantosti et al. (1996).
[d]D'Addezio et al. (2001).
[e]Ormö et al. (2002a).

susceptibility measurements (Table 4) using a Micromag vibrating sample magnetometer at Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE), Aix en Provence. The hysteresis cycle shape and coercivity/magnetization parameters indicate soft (i.e., low-coercivity) magnetite-like grains. Saturation magnetization (Ms) varies from 140 to 251 mAm^2/kg in soil of the Gran Sasso Range and Velino massif. The Sirente samples exhibit lower values (21 and 121 mAm^2/kg for C8 and C9, respectively). Thus, they have a smaller magnetite content.

If supporting the meteoritic origin of the Sirente sags, one might argue that metallic grains residing in these soils for 1600 yr would have been nearly totally "rusted." However, rusting would have induced extensive formation of Fe^{3+}-bearing paramagnetic and ferrimagnetic oxy-hydroxides (such as akaganéite, lepidocrocite, ferrihydrite, goethite, maghemite, and magnetite, with magnetically ordered phases favored under mid-latitude climatic conditions; see Bland et al. 1998). Moreover, magnetic particles from the impactor are more likely made of magnetite as the metal grains are oxidized at high temperature during the impact and atmospheric trajectory. Magnetite stability in temperate soils is quite high (Maher and Thompson 1999). In any case, the magnetic susceptibility of a soil contaminated by meteoritic particles should be significantly higher than the values shown by the other Abruzzi soils.

Ormö et al. (2002a) document (page 1513) that the rusty crust fragments from the rims of the Sirente sag pond contain silicates, clay material, and rare granules of quartz, K-feldspar, one zircon, iron-rich granules, and sometimes, Mn-rich zones. Such mineral assemblage indicates a significant contribution of tephra from volcanoes located along the Tyrrhenian margin of Italy, ~100 km west of Sirente, which were strongly active between 700 and few tens of Kyr ago (Serri et al. 1993). In fact, a section exposing some meters of tephra may be observed close to the Anatella Spring, a few km west of the Sirente plain. Therefore, we conclude that the Fe and Mn abundance of the rim material of the Sirente sag pond (as well as the significant Fe content of the other soils and paleosols from Abruzzi), is likely to be predominantly due to volcanic contribution.

Chemical Tracers

Seven of the soil samples described in the above section have been subjected to geochemical analysis at CEREGE (Table 5) using an ICP-AES spectrometer and the following protocol. About 0.3 g of material is finely ground in an agate mortar and heated at 900 °C in a graphite crucible to obtain the loss on ignition (LOI). The remaining material is fused in $LiBO_2$ and then dissolved in HCl for injection in the spectrometer line. As PGE are not detectable using this technique, we chose to look for Ni and Cr contents as ET matter tracers. To account for variable dilution (e.g., by carbonates and organic matter) and concentration processes, we also performed a normalization to Fe or Ti content (Fig. 6). Normalization to Fe is common in the meteoritics literature, while Ti has the advantage of being rather immobile in weathering processes and concentrated in the Earth's crust relative to meteorites. For the reference ratios of various types of meteorites and terrestrial surface materials, we used the average values reported by Jarosewich (1990) and Taylor et al. (1983), respectively.

The Sirente samples exhibit lower values of Ni (26 to 48 ppm) and Cr (15 to 69 ppm) than samples from the other sags (Ni = 50 to 100 ppm; Cr = 75 to 115 ppm), correlated to larger LOI and lower SiO_2 (Table 5). Figure 6 demonstrates that no clear ET signature differentiates the Sirente samples from the Abruzzi sag samples. The C8 Sirente carbonate-rich lacustrine sediment sample (maximum LOI of 38%) shows a

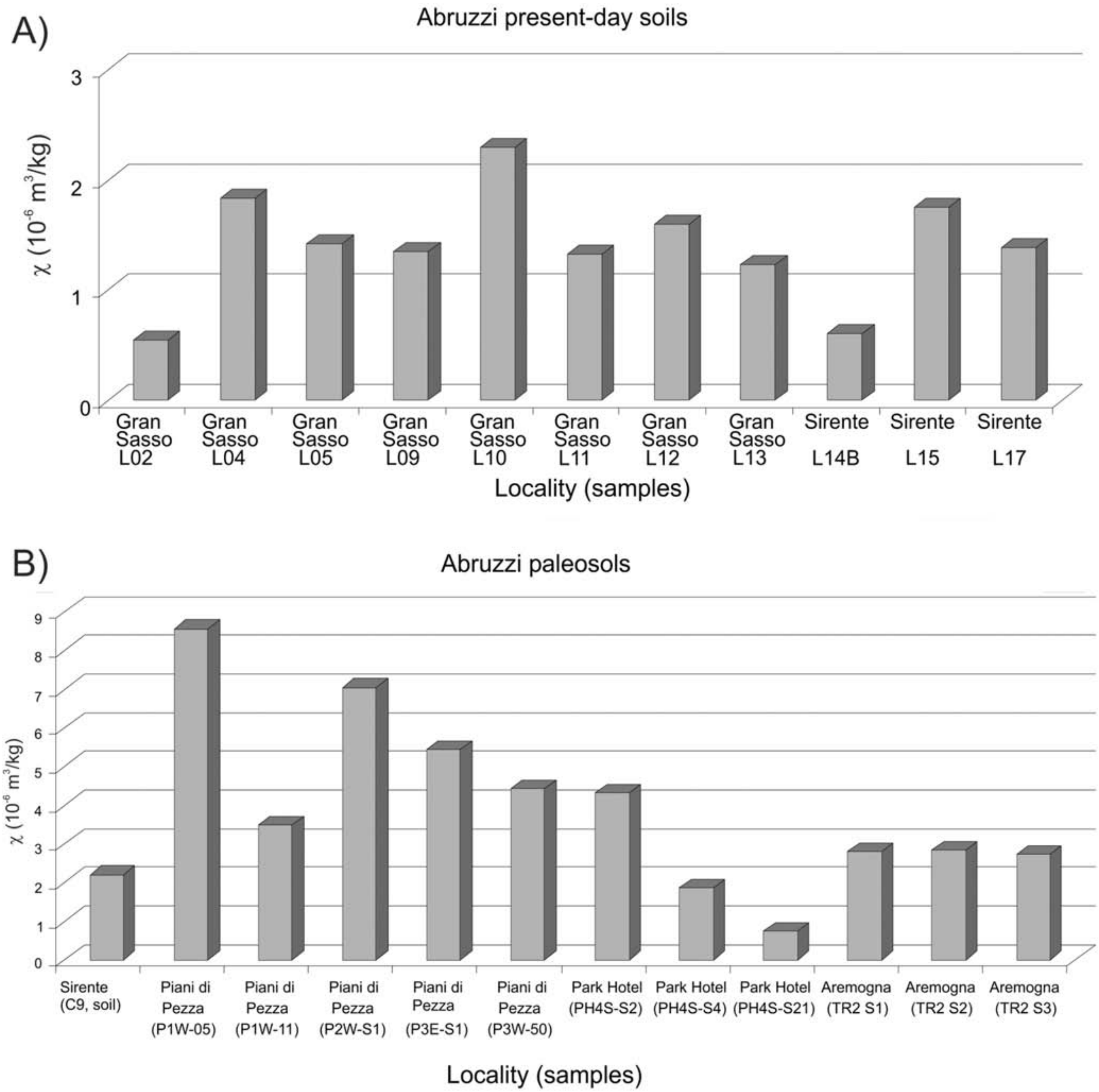

Fig. 5. Comparison of low-field magnetic susceptibility values for: a) present day soils from sag ponds from the Gran Sasso Range and the Sirente plain (Tables 1 and 2); and b) holocene paleosols from different trenches from Abruzzi (Table 3).

somewhat higher Ni/Fe ratio than the other sample but a lower Cr/Fe ratio. Though the Ni/Fe ratio of the Sirente sample C8 is higher than the other samples from Abruzzi, ET contamination is unlikely to account for this outlier because: 1) sample C8 has a Cr/Fe ratio smaller than other Abruzzi samples, and 2) its Ni/Fe ratio value is much smaller (by three to four orders of magnitude) than meteorite and contaminated soils values (Fig. 6). The Ni/Fe versus Cr/Fe ratios of several samples from the soil contaminated by the Tunguska explosion (Hou et al. 1998) are roughly aligned along a line connecting meteorites with a group formed by continental crust, loess, and the Abruzzi sags (including Sirente; Fig. 6a). Moreover, the Ni/Fe values from Tunguska and other contaminated soils from well-established craters (Hodge and Wright 1970, 1971; Fig. 6a) are similar to meteorite values and 10^3–10^4 higher than the Sirente sample values (including sample C8). Therefore, we conclude that the Ni source in sample C8 is likely to be the volcanic tephra and/or the surrounding carbonates.

In fact, sample C8 is a lacustrine silt sample and was

Table 4. Hysteresis properties of selected soil samples from different Abruzzi massifs (see Tables 1 to 3 for location).[a]

	Gran Sasso L04	Gran Sasso L09B	Gran Sasso L10	Gran Sasso L11	Velino P3W-50	Sirente C8	Sirente C9
Mass (g)	0.20	0.29	0.28	0.22	0.18	0.39	0.27
Hc (mT)	4.2	5.1	3.6	4.2	7.0	9.2	7.5
Ms (mAm^2 kg^{-1})	177.3	144.3	233.0	140.8	251	21.1	121.9
Mr/Ms	0.06	0.08	0.05	0.07	0.15	0.16	0.15
χ_{HF} (nm^3 kg^{-1})	112.4	72.7	84.0	57.5	105.1	10.0	77.8

[a]Hc is the coercivity; Ms is the saturation magnetization; Mr is the saturation remanent magnetization; χ_{HF} is the magnetic susceptibility measured in high fields, reflecting the paramagnetic contribution to the bulk low-field magnetic susceptibility.

formed by a mixture of silty calcareous fragments and residual oxides arising from carbonate dissolution. The shelf carbonates exposed in the Sirente and other Abruzzi massifs contain (mostly Fe and Al) oxides at few percentages. Still, during sub-aerial alteration (and dissolution of the Ca carbonate), such insoluble oxides may concentrate, as can be observed in the metric-scale bauxite pockets frequently exposed along mid-Cretaceous strata in outcrops located a few km from the Sirente plain (Accordi and Carbone 1988), which were exploited until some decades ago for Al extraction.

Therefore, the poorly documented SEM observation by Ormö et al. (2002a) of two Ni-bearing micron-sized spongy grains in these crusts could easily be interpreted as a volcanic/carbonate origin. The Ormö et al. (2002a) quote of "two spongy granules composed of Ni" is, in fact, quite problematic. Grain composed of Ni as the sole or main element cannot be of meteoritic origin, as Ni is practically always intimately associated with a larger amount of iron in extraterrestrial matter.

The geochemical observations of Ormö et al. (2002a) are very limited and only qualitative. In fact, they are not in contradiction with our quantitative analyses. We propose to interpret their Fe-Mn crusts as redox mobilization in the soil profile and their "two micron-sized spongy granules composed of Ni" as volcanic or carbonate contamination (or even laboratory contamination; the report of only two micron-sized grains without any picture and reliability criteria, including a description of sampling and preparation procedures, is, in our opinion, nearly meaningless). At this level of concentration, there is obviously no chance that the presence of such granules will show up in the total Ni or magnetic contents. Finally, geochemical investigations including Ir amount determination conducted independently at the University of Vienna failed to reveal unambiguously an impact signature (C. Koeberl, personal communication; Ormö et al. Forthcoming).

HUMAN ORIGIN OF THE "SIRENTE CRATER"

The "Transumanza" Custom

Historically, the rugged Abruzzi region has been a land of sheep herding. Its economy, society, and culture have been deeply inter-related to sheep breeding. Such activity has conditioned or profoundly influenced the distribution of the population, the morphology of the landscape, the location and architectonic style of villages and towns, and the pattern of roads and paths. For almost four millennia, tens of thousands (millions in periods of economic peak) of sheep (and their shepherds) spent winters in the mild Apulia plains (southern Italy) and summers in the fresh Abruzzi highlands (Fig. 7). Such migration was motivated by the hardness of snowy winters in Abruzzi and the aridity of the torrid Apulia pastures during summer.

The seasonal two-fold migration of the shepherds, their families, and the herds was called "transumanza." The transumanza is a very old social custom, known since pre-Roman times (Varrone and Plinius widely reported about it in the 1st century BC and 1st century AD, respectively). It was common all over central-southern Europe, though it reached its maximum development in the Abruzzi region. People and herd moved from Apulia to Abruzzi (and back) once a year along well-established tracks, about 100 m-wide, called "tratturi" (Fig. 7). Most of these tracks began between Celano and L'Aquila (Fig. 7), i.e., in the areas of the fresh pasture of the Mt. Sirente and Gran Sasso Range highlands. According to Arpea (2003, personal communication), one the starting points of the Celano-Foggia tratturo (Fig. 7) was exactly within the Sirente plain. The tratturo officially started at Celano (at an altitude of 800 m above sea level), but was connected with the surrounding highlands (where sheep spent summers) through second-order (and smaller) paths, called "bracci." One of these bracci ran from the Sirente plain to Celano.

The transumanza prospered in Roman times then obviously declined during the Middle Age before reaching a new "renaissance" between the 12th and 16th century, when Abruzzi became one of the main producers of wool in Europe (Regione Abruzzo 2000). Up to the 19th century, the transumanza has represented the main economic resource of Abruzzi. L'Aquila, the regional capital of Abruzzi, was founded in the 13th century, likely owing to the very favorable economic conditions and welfare induced by the revival of the transumanza.

Due to the great permeability of fractured shelf carbonates, there are neither rivers nor big springs in the highlands exposed on top of the Abruzzi massifs. Still, these

Table 5. Chemical composition of selected soil and sediment samples from different Abruzzi massifs (see Tables 1 to 3 for location).

	Gran Sasso L04	Gran Sasso L09B	Gran Sasso L10	Gran Sasso L11	Velino P3W-50	Sirente C8	Sirente C9
SiO_2 (%)	48.3	50.9	51.9	48.9	39.9	6.90	26.1
Fe_2O_3 (%)	7.34	6.15	6.98	4.62	5.95	1.25	4.27
Al_2O_3 (%)	18.5	14.2	16.4	12.2	15.5	3.52	11.4
MgO (%)	1.26	1.47	1.35	1.02	1.41	0.56	1.01
TiO_2 (%)	0.89	0.84	0.86	0.60	0.88	0.16	0.52
LOI (%)	19.4	23.9	19.5	27.6	28.4	38.5	30.8
Total	95.69	97.46	96.99	94.94	92.04	50.89	74.10
Ni (ppm)	98.9	54.5	73.7	57.4	72.1	26.0	48.1
Cr (ppm)	96.9	95.8	102.8	75.3	112.2	15.5	68.9

highlands are very suitable for the pasture of livestock (mostly sheep) during summer times, since they are predominantly tree-free and covered by fresh green grazing-land. Given the economic importance of transumanza for Abruzzi, the lack of surface waters and the presence of millions of sheep grazing grass during the summer (Ivone 2002), the excavation of small depressions at the bottom of small karstic-tectonic valleys, where water is more prone to accumulate, is a logical consequence of the efforts to overcome the environmental problems induced by the paucity of superficial waters and, possibly, is the simplest solution. Nearly all the larger sags observed are located in correspondence (or very close) to local small springs, so that they can virtually contain water the whole year through. This correspondence suggests that the localities of sag digging were conditioned by the availability and distribution of small-spring waters.

Ormö et al. (2002a) state (page 1520) that "water for cattle is customary supplied by creating wells with water from the surrounding mountains or by damming a creek." The first statement does not correspond to reality (water nappes below these karstic massifs were never reached by wells, as the tops of aquifers are 800–1500 m below the surface), while the second is incorrect. Obviously, there are no proper creeks on the Abruzzi karstic highlands but only small (and often ephemeral) springs showing no outcomes. Springs exceptionally feed small streams, which are soon swallowed by the karstic limestone. Then, the excavation of the sub-circular sags, when allowed by the nature of the substratum, seems to be better suited for maximizing the use of the little water provided by the small springs from the Abruzzi highlands and creating quite large water reservoirs.

Lacking historical sources defining the digging ages, these relatively large sags may, in principle, have been produced at any time since at least the 2nd millennium BC (it is estimated that the transumanza could have prospered during the Bronze Age; Regione Abruzzo 2000).

Evidence of Human Activity in the Sirente Plain

Adjacent to the main sag from the Sirente plain (toward the east-southeast) and about 300 m toward the southwest, some rows of aligned stones are exposed for a length of a few tens of meters (Figs. 1 and 2c). Such stones are believed to indicate ancient paths, which are inferred to have run through the Sirente plain since Roman and pre-Roman times (Arpea 1999). Another evident sign of human presence is observed in the small hill or mound located ~200 m southwest of the main sag (Figs. 1 and 2b). This mound is entirely formed by a stack of limestone blocks and possibly indicates an ancient building or some other man-made structure. Unfortunately, no archaeological work has been carried out so far to document the nature of the boulder stack and its age.

The main sag containing a pond (Fig. 2a) is accurately described by Ormö et al. (2002a). However, contrary to Ormö et al. (2002a), who state (page 1511) that there is no inlet or outlet for running water in this main pond, we found a plastic tube bringing water along the southern interruption of the saddle-shaped rim encircling the depression (Figs. 1, 2a, and 2b). The rim-interruption also drains into the pond surface waters from the area south and southeast of the sag. Conversely, the northwestern interruption of the rim could represent the outlet of water during periods of strong rain and springtime fusion of snow. The water supply allows the pond to persist nearly all year (the picture of Fig. 2b was taken at the end of summer 2003, which was the hottest summer in at least five centuries; Luterbacher et al. 2004). We do not know where the water supplied from the tube comes from. We speculate that it may originate from a hypothetical distal spring through a small aqueduct, which could be buried beneath a nearly east to west oriented ~1 m-wide rectilinear trench starting from the water inlet point (Figs. 1 and 2a; top-right of Fig. 5a of Ormö et al. 2002a). The trench is partly filled by limestone blocks (see Fig. 5a of Ormö et al. 2002a) and is mainly evident from the change in vegetation color (this may also indicate that water is collected through a draining trench instead of a proper aqueduct). Clearly, the plastic tube was introduced during recent decades, and indicates that some work was made recently to restore the hydraulic efficiency of the sag pond. In fact, though the "transumanza" has progressively declined during the 20th century and has completely ceased today, the pond from the Sirente plain is still used to provide drinking water during the

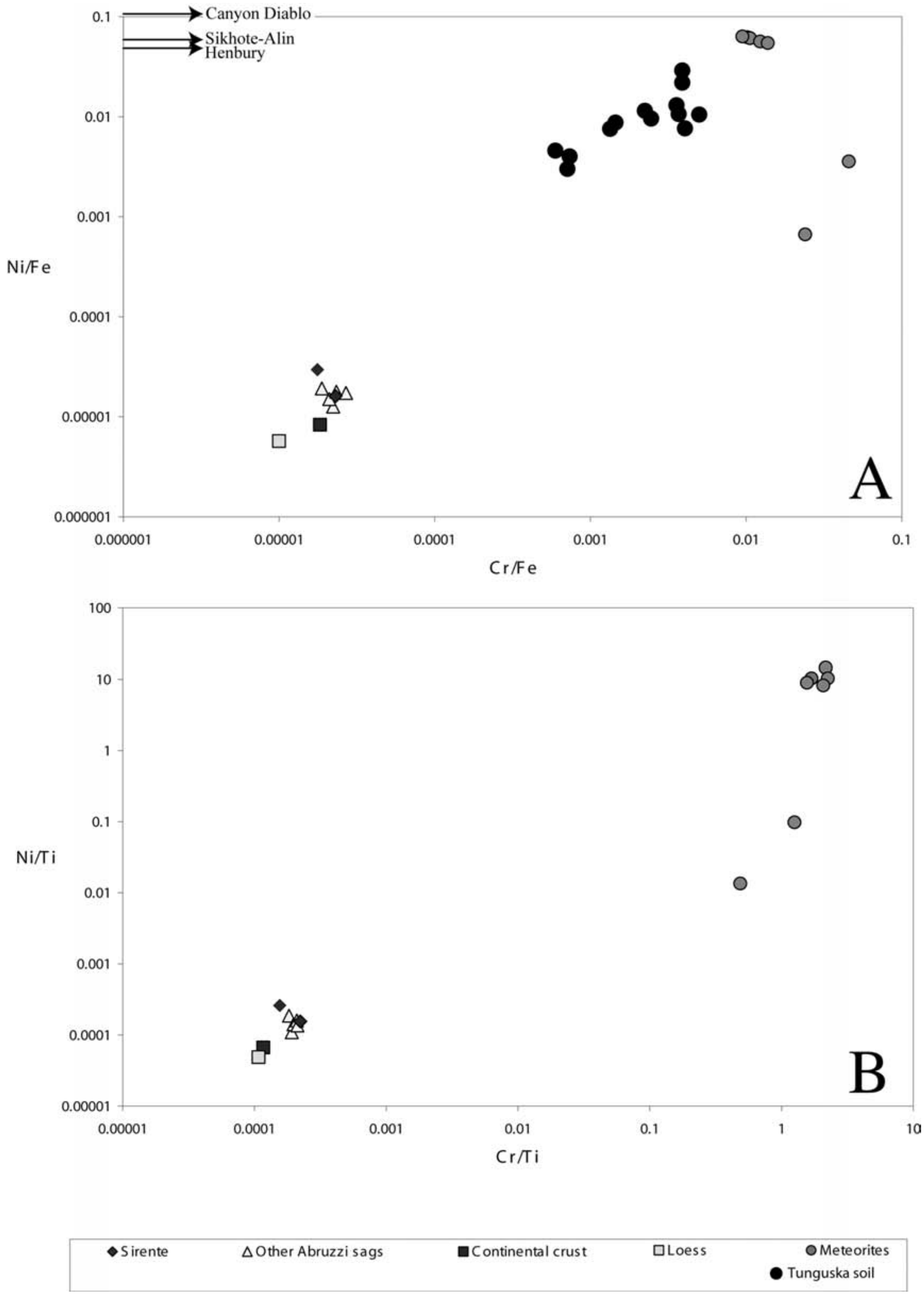

Fig. 6. Ni and Cr content normalized to Fe (a) or Ti (b) content for the studied Abruzzi samples (Table 5) compared to referenced mean values for continental crust and loess (Taylor et al. 1983) and for soils contaminated by meteoritic dust and various meteorite groups. Data from the Tunguska site are from Hou et al. (1998); data from the Henbury craters (no Cr value available) are from Hodge and Wright (1971); data from the Canyon Diablo and Sikhote-Alin craters (no Cr value available) are from Hodge and Wright (1970); data relative to meteorites are from Jarosewich (1990). In the top right corner of the diagram, the cluster corresponds to various chondrites, and the two points with lower Ni values correspond to eucrite and howardite analysis.

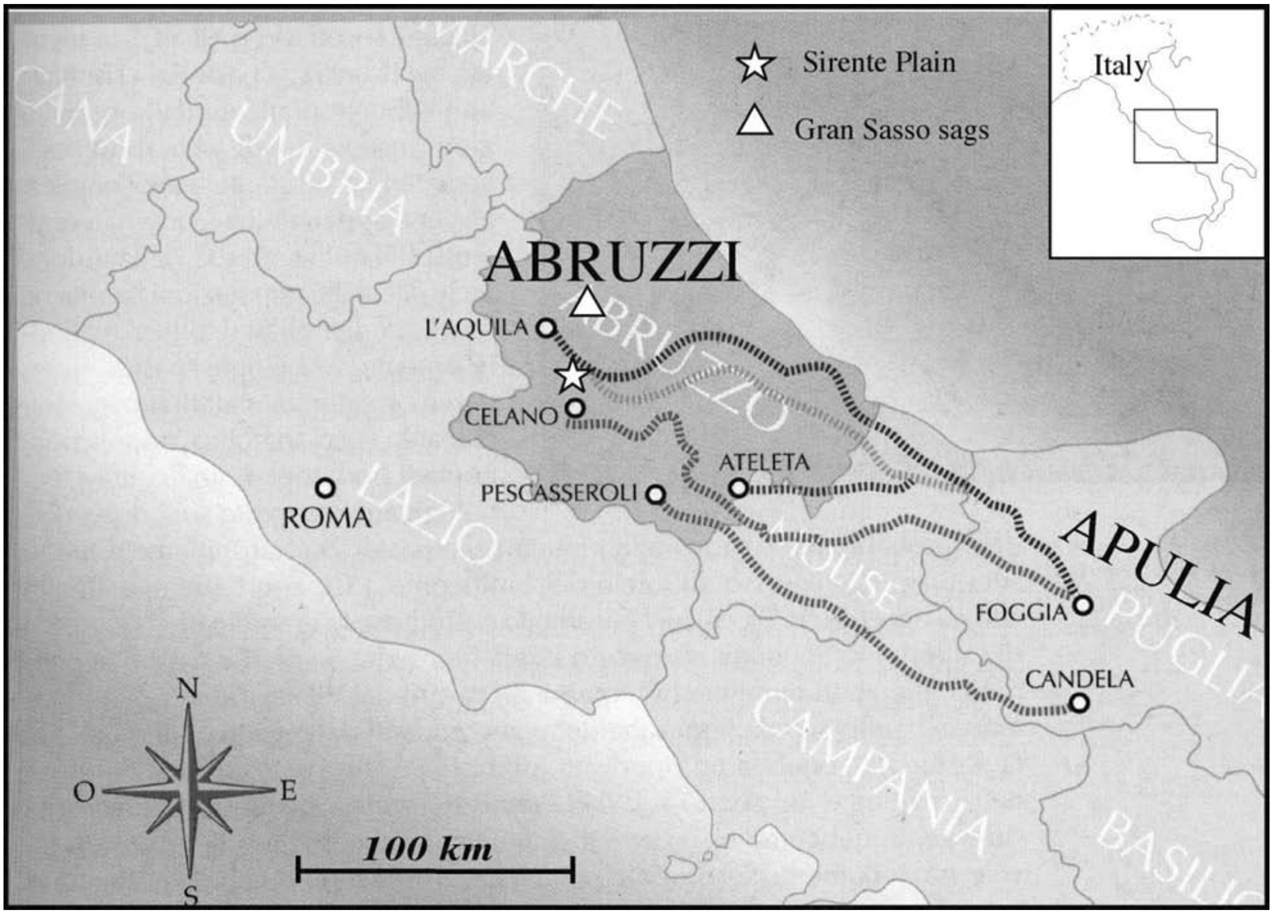

Fig. 7. Map showing the location of the Gran Sasso sags and Sirente plain and the principal paths ("tratturi"; dashed-lines) of the two-fold seasonal migration of herds from Abruzzi to Apulia (from Regione Abruzzo 2000).

summer for a limited number (tens) of cows, sheep, and horses.

The direction of the aqueduct (or draining trench) indicates that the small spring feeding the pond is located further east. Such a peculiar sag pond location suggests that the sag was indeed dug within the plain formed by low-permeability lacustrine silts to retain water but as close as possible to the spring water likely located near the breccia-silt contact. This situation minimizes the length of the aqueduct, still avoids reservoir leakage, and is very similar to the geological-hydrological context described in the Introduction for sag pond L18 from the Velino Massif.

DISCUSSION

Based on our observations and analyses, the charcoal and burned clay material found in the C8 and C9 sags and the morphological characteristics of the main sag are more suggestive of human activity than impact. To dismiss an anthropogenic origin of the main Sirente structure, Ormö et al. (2002a) state that the size and shape of the structure is "special" and "unique" and at odds with other man-made structures, which should be, according to them, devoted to crop irrigation. This claim is obviously discarded by our report of numerous similar structures in Abruzzi that were/are actually devoted to sheep drinking. The circular shape, besides being a traditional shape for antique human settlements and buildings, is, obviously, the most efficient one in terms of volume ratio of dug and transported material over stored water.

Ormö et al. (2002a) also doubt that 1600 years ago human groups would have had the manpower and technology required to dig such a structure. Again, this is obviously in total contradiction with innumerable archaeological evidences all over central Italy and our present observations. When the wealth of a community critically depends on the availability of herd drinking water, there is no need of further technology than intelligence, patience, and muscles. The displaced volume can be estimated at $\sim 1.1 \times 10^4$ m^3 for a 1 m-thick layer all over the main sag (diameter ~120 m, excluding the rim). We can estimate a (conservative) value of 1 m^3 per day for a worker using a shovel and baskets carried by donkeys. Therefore, the whole job could be achieved in one year by a group of 30 people. It could be, in fact, spread over several years according to the balance with other activities of the group. Continued maintenance, as well as eventual clay extraction for building and pottery manufacturing purposes, could help keep the structure functional throughout centuries.

The volume of the rim of the Sirente main sag is ~3.1 × 10^3 m^3 (by considering mean values of 1.5, 10, and 130 m for height, width, and diameter, respectively), i.e., one-third to one-fourth of the sediment volume dug from the main sag itself. This implies that the soil and sediment recovered during the excavation must have been spread over the surrounding plain and/or used for building and pottery manufacturing purposes. Such "mass deficit" of the rim with respect to the inner sag is also common for the other depressions we have observed in the Gran Sasso Range (Fig. 3 and Table 1), indicating that the modes of excavation and use of extracted sediment was similar for the Gran Sasso and Sirente sags.

Finally, we note that two large (some m^3) limestone blocks occur inside the main sag pond (Fig. 2b). Their presence and their lack of significant deformation or metamorphism is not compatible with the hypothesis that they survived a meteoritic impact. Otherwise, it should be assumed that they fell inside the "crater" and jumped over its southern rim sometime after the impact, which appears highly unlikely.

CONCLUSIONS

The measurement of the low-field magnetic susceptibility of soil and sediment samples from the Sirente sags, from other similar sags from neighboring karstic highlands, and from paleoseismological trenches elsewhere in Abruzzi provided similar magnetic susceptibility values, which is typical for limestone-derived debris and soils. The values obtained for parameters sensible to an eventual ET contamination in all the magnetic and geochemical analyses performed on samples collected from the sags of the Sirente plain are fully compatible with the natural sedimentary and pedogenetic processes of the Abruzzi region.

Taking into account that no meteorite fragment nor high-pressure impact mineral was recovered during drillings and excavations, the meteorite impact hypothesis formulated by Ormö et al. (2002a) is only supported by the shape and distribution of the Sirente plain sags. Many sub-circular sags (mostly containing ponds) exposed in the karstic Abruzzi highlands have a shape and size very similar to the so called "Sirente crater." Such depressions were excavated by man, to provide drinking water for millions of sheep that spent summers in the Abruzzi massifs (and winters in Apulia), in the framework of a seasonal herd's (and shepherds') migration process called "transumanza." The transumanza supported the economy of Abruzzi since about two millennia BC before a final decline occurring in the last century. One of the second-order starting points of a well-established path traced for herd migration (the Celano-Foggia "tratturo") was within the Sirente plain, implying the presence there of tens (hundreds?) of thousands of sheep during the summer. Moreover, the "Sirente crater" itself is located in the lowermost part of the Sirente plain, which is covered by barely permeable lacustrine silts, suggesting that it was dug by man in the part more favorable for water accumulation.

The smaller depressions of the Sirente plain cannot be interpreted as a "crater field" (Ormö et al. 2002a) as, according to radiocarbon dates provided by Ormö et al. (2002a, 2003), the formation ages of sag C9 and of the main sag pond differ (significantly) by more than two millennia, thus excluding that they all formed at the same time during a meteoritic impact.

Consequently, we interpret these smaller sags of the Sirente plain as dolines since: 1) none has a saddle-shaped rim; 2) they are located in a karstic environment; and 3) excavations by Ormö et al. (2002a, 2003) in two of these depressions have revealed funnel-shaped dark soil bodies placed within pale silty lacustrine sediments. We believe that the interpretation of the sub-vertical funnel-shape of the soil below the trenched sags as a product of oblique meteoritic impact (as suggested by Ormö et al. [2002a]) is untenable. This geometry is, in fact, typical of dolines and has been observed elsewhere in Abruzzi.

Our field survey of the Sirente plain highlights that this zone is a karstic plain that has been clearly inhabited by (permanent or seasonal?) settlements for a long time. In a similar natural environment, it is reasonable to imagine that the main depression was dug to gather drinking water for the livestock. In fact, neither superficial running waters nor large springs are available in the area (as in the other Abruzzi highlands).

We cannot warrant a meteoritic impact origin for the Sirente sags as suggested by Ormö et al. (2002a, 2003), and we believe that the evidence best supports the interpretation that the smaller sags are natural dolines used by man and that the main sag was, in fact, dug by man for livestock drinking water purposes.

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Editorial Handling—Dr. Richard Grieve

REFERENCES

Accordi G. and Carbone F., editors. 1988. *Progetto finalizzato geodinamica, carta delle litofacies del Lazio-Abruzzo ed aree limitrofe e Note illustrative*. Roma: Consiglio Nazionale delle Ricerche. 223 p.

Arpea M. 1999. *Roccadimezzo e l'altipiano*. L'Aquila: Japadre Editore. 270 p.

Bland P. A., Sexton A. S., Jull A. J. T., Bevan A. W. R., Berry F. J., Thornley D. M., Astin T. R., Britt D. T., and Pillinger C. T. 1998. Climate and rock weathering: A study of terrestrial age dated ordinary chondritic meteorites from hot desert regions. *Geochimica et Cosmochimica Acta* 18:3169–3184.

Cassidy W. A. 1971. A small meteorite crater: Structural details. *Journal of Geophysical Research* 76:3896–3912.

D'Addezio G., Masana E., and Pantosti D. 2001. The holocene paleoseismicity of the Aremogna-Cinque Miglia fault (central Italy). *Journal of Seismology* 5:181–205.

Evans M. E. and Heller F. 1994. Magnetic enhancement and palaeoclimate: Study of a loess/palaeosol couplet across the loess plateau of China. *Geophysical Journal International* 117:257–264.

Evans M. E. and Heller F. 2003. *Environmental magnetism. Principles and applications of enviromagnetics*. San Diego: Academic Press. 299 p.

Florindo F., Zhu R., Guo B., Yue L., Pan Y., and Speranza F. 1999. Magnetic proxy climate results from the Duanjiapo loess section, southernmost extremity of the Chinese loess plateau. *Journal of Geophysical Research* 104:645–659.

Hodge P. W. and Wright F. W. 1970. Meteoritic spherules in the soil surrounding terrestrial impact craters. *Nature* 225:717–718.

Hodge P. W. and Wright F. W. 1971. Meteoritic spherules in the soil surrounding the Henbury meteorite craters. *Journal of Geophysical Research* 76:3881–3895.

Hou Q. L., Ma P. X., and Kolesnikov E. M. 1998. Discovery of iridium and other element anomalies near the 1908 Tunguska explosion site. *Planetary and Space Science* 46:179–188.

Ivone D. 2002. *La transumanza. Pastori greggi tratturi*. Torino: Giappichelli Editore. 198 p.

Jarosewich E. 1990. Chemical analysis of meteorites: Compilation of stony and iron meteorite analyses. *Meteoritics* 25:323–337.

Luterbacker J., Dietrich D., Xoplaki E., Grosjean M., and Wanner H. 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. *Science* 303:1499–1503.

Maher B. A. 1986. Characterization of soils by mineral magnetic measurements. *Physics of the Earth and Planetary Interiors* 42: 76–92.

Maher B. A. 1998. Magnetic properties of modern soils and loessic paleosols: Implication for paleoclimate. *Palaeogeography, Palaeoclimatology, Palaeoecology* 137:25–54.

Maher B. A. and Taylor R. M. 1988. Formation of ultrafine-grained magnetite in soils. *Nature* 336:368–371.

Maher B. A. and Thompson R. 1999. *Quaternary climates, environments, and magnetism*. Cambridge: Cambridge University Press. 390 p.

Ormö J., Rossi A. P., and Komatsu G. 2002a. The Sirente crater field, Italy. *Meteoritics & Planetary Science* 37:1507–1521.

Ormö J., Rossi A. P., 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., Rossi A. P., and Komatsu G. 2003. The Sirente crater field: Outline, age, and evidence for heating of the target (abstract). 3rd International Conference on Large Meteorite Impacts.

Pantosti D., D'Addezio G., and Cinti F. R. 1996. Paleoseismicity of the Ovindoli-Pezza fault, central Apennines, Italy: A history including a large, previously unrecorded earthquake in the Middle Ages (860–1300 AD). *Journal of Geophysical Research* 101:5937–5959.

Regione Abruzzo 2000. *Abruzzo: Le vie della transumanza*. Pescara: Carsa Edizioni. 143 p.

Serri G., Innocenti F., and Manetti P. 1993. Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of central Italy. *Tectonophysics* 223:117–147.

Taylor S. R., McLennan S. M., and McCulloch M. T. 1983. Geochemistry of loess, continental crustal composition, and crustal model ages. *Geochimica et Cosmochimica Acta* 47:1897–1905.

Veski S., Heinsalu A., Kirsimäe K., Poska A., and Saarse L. 2001. Ecological catastrophe in connection with the impact of the Kaali meteorite about 800–400 BC on the island of Saaremaa, Estonia. *Meteoritics & Planetary Science* 36:1367–1375.