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Mineralogical and Chemical Investigations of the Amguid Crater (Algeria): Is there Evidence on an Impact Origin?

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Abstract: Mineralogical and chemical investigations were carried out on intra-craterial bedrocks (Lower Devonian sandstone) and regolithic residual soil deposits present around the Amguid structure, to discuss the hypothesis of its formation through a relatively recent (about 0.1 Ma) impact event. Observations with an optical microscope on intra-craterial rocks do not unequivocally confirm the presence of impact correlated microscopic planar deformation features (PDFs) in quartz crystals. Field observations, and optical and instrumental analysis (Raman spectroscopy) on rocks and soils (including different granulometric fractions) do not provide any incontrovertible pieces of evidence of high energy impact effects or products of impact (e.g., high pressure—temperature phases, partially or totally melted materials, etc.) either in target rocks or in soils. A series of selected main and trace elements (Al, Fe, Mg, Ni, Co and Cu) were analysed on rocks and soils to evaluate the presence in these materials of extraterrestrial sources. Comparative chemical data on rocks and soils suggest that these last are significantly enriched in Fe-poor Mg-rich materials, and in Co, Ni and Cu, in the order. A large number of EDAX-SEM analyses on separated soil magnetic particles indicate an abnormally high presence of Al-free Mg-rich sub-spherical or drop-like silicate particles, showing very similar bulk chemistries compatible with forsterite olivine. Some particles were found associated with a Ni-rich iron metal phase, and this association suggests a specific extraterrestrial origin for them. Electron microscope analysis made on a large number of soil magnetic particles indicates that 98% of them are terrestrial phases (almandine garnet, tourmaline and Fe-oxides, in abundance order), whereas, only a few grains are of questionable origin. One of the Mg-rich silicate particles was found to be a forsterite (Mg = 0.86) Mn-rich (MnO: 0.23%) Cr-free olivine, almost surely of extraterrestrial sources. Electron microprobe analysis of three soil particles allowed identification of uncommon Cr-rich (Cr_2O_3 about 8%) spinels, poorly compatible with an origin from terrestrial sources, and in particular from local source rocks. We propose a specific extraterrestrial origin for sub-spherical olivine particles characterised by quite similar magnesian character. Excluding any derivation of these particles from interplanetary dust, two other possible extraterrestrial sources should be considered for them, i.e., either normal micrometeorite fluxes or strongly un-equilibrated, or the Vigarano type Carbonaceous (CV) chondrite meteorite material. In this case, further studies will confirm an impact origin for Amguid, as such magnesian olivine components found in soils might represent the only remnants of a vaporised projectile of ordinary non-equilibrated meteoritic composition.

Keywords: impact crater; chemical data; rocks; soil; instrumental analysis.

1. Introduction

Europeans discovered the circular structure known as the Amguid crater (26°05′17″ N, 04°23′49″ E, Figure 1) in 1948 and it was confirmed from an aircraft in 1954. Jean-Philippe le Franc made the first scientific description of it in 1969 [1]. One of the best-preserved impact craters on Earth—the Amguid crater in Algeria—is also one of the hardest to access (https://www.wondermondo.com/amguid-crater/):

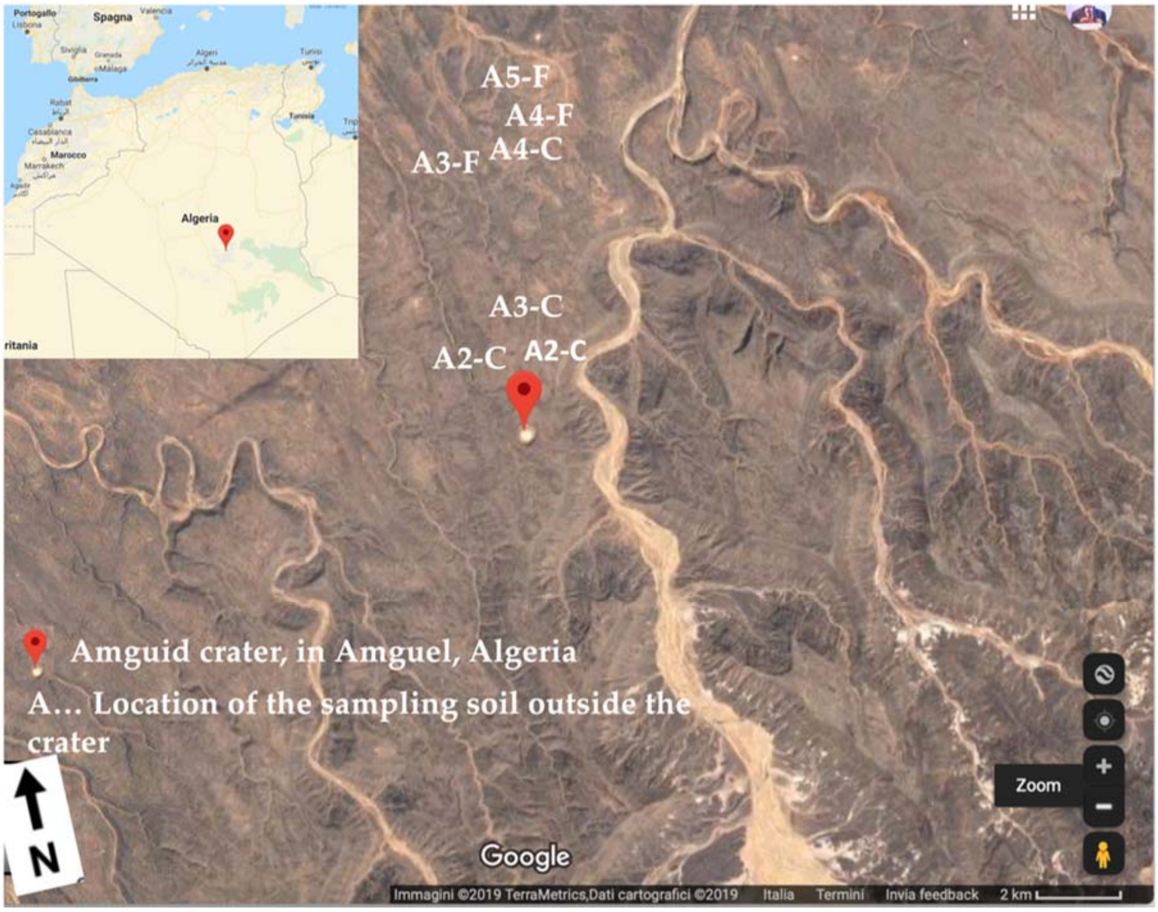

Figure 1. Amguid crater, Algeria.

Owing to the tough accessibility, relatively few visitors have reached the area so far. Hence, relatively few scientific studies were published after its discovery. The origin of the structure is correlated to an impact event proposed by Lambert et al. [1]. The theory of an impact event is assumed by some macroscopic structural and morphological features of the exposed crater rocks and evidence in them of microscopic planar deformation features (PDFs) in mineral phases (quartz) present in the possible target rocks, correlated to shock metamorphic effects [1].

During an Italian expedition made in February 2011, a series of "in situ" observations were dedicated to finding evidence of the possible impact event. To this aim, we also collected a set of materials, including substrate intra-crater rocks and soil samples from the surrounding area. This study aimed to ascertain the impact origin of the structure and, by the means of mineralogical and chemical data on the collected materials, shed light on the possible mode of impact and nature of the impactor [2].

2. General Information on the Amguid Structure

The morphological and structural features of the Amguid structure were described in detail by Lambert et al. [1]. The 550 m [3] crater is formed in Lower Devonian sandstones. It has an elevated rim of up to 65 m [3,4]. The bottom of the crater (observation on February 2011) is partially filled by very bright, and fine-grained eolian silts and sands (Figure 2), and in part, is covered by detrital materials composed of fall-back breccias, also containing a fine-grained component. The near-perfect preservation state of the crater led Lambert et al. [1] to estimate a presumed age of 0.1 Ma, although in reality, it is probably less.

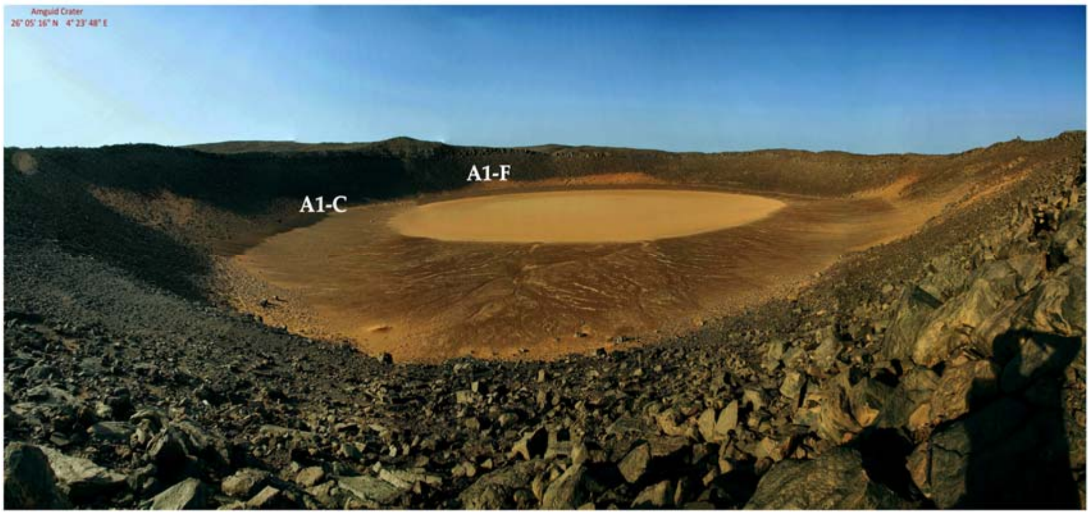

Figure 2. Image of the Amguid structure (intra-crater soils location).

There are a series of distinct sandstone bed outcrops on the internal walls of the crater, with a dip that becomes progressively steeper in the upper parts of the walls. According to Belhai and Sahoui [4], the upturned sandstones and overturned strata observed at the North-North-West-West (NNWW) and South-South-East (SSE) parts of the elevated rim are consistent with macroscopic impact deformation features. According to Lambert et al. [1], further evidence for an impact origin of Amguid is provided by up to three sets of PDF textures in quartz crystals from intra-crater rocks.

3. Foundations of the Present Investigations and Studied Materials

The complete absence within the Amguid structure, as well as in the surrounding area of materials compatible with the effects of a high-energy impact, is somewhat surprising, considering the diameter of the structure, the vast mass of the excavated crater materials and its presumed very young age. Therefore, we decided to focus our attention on alternative evidence for such an impact event by making field observations and collecting materials—not only inside or near the structure—but also at a considerable distance (about 6.5 km) from the crater.

Our field observations—made over a relatively wide area and focused on the recognition of impact macro products (e.g., fragments of the impactor, glassy or partially vitrified rock ejecta)—were entirely unsuccessful.

Thus, we decided to concentrate our attention on the search for impact evidence by considering the loose sedimentary materials (soil) that were based on geological grounds. Field morphological observations should be regarded as a more appropriate method for detecting evidences of impact events in terms of products (e.g., vitreous particles), or of remnants of the extraterrestrial projectile. Field observations on the Amguid area show that, where Devonian bedrock is not directly exposed, a regolith cover formed of a veneer of boulders, blocks and rock debris containing minor grain-sized components, is commonly present (Figures 2 and 3a,b).

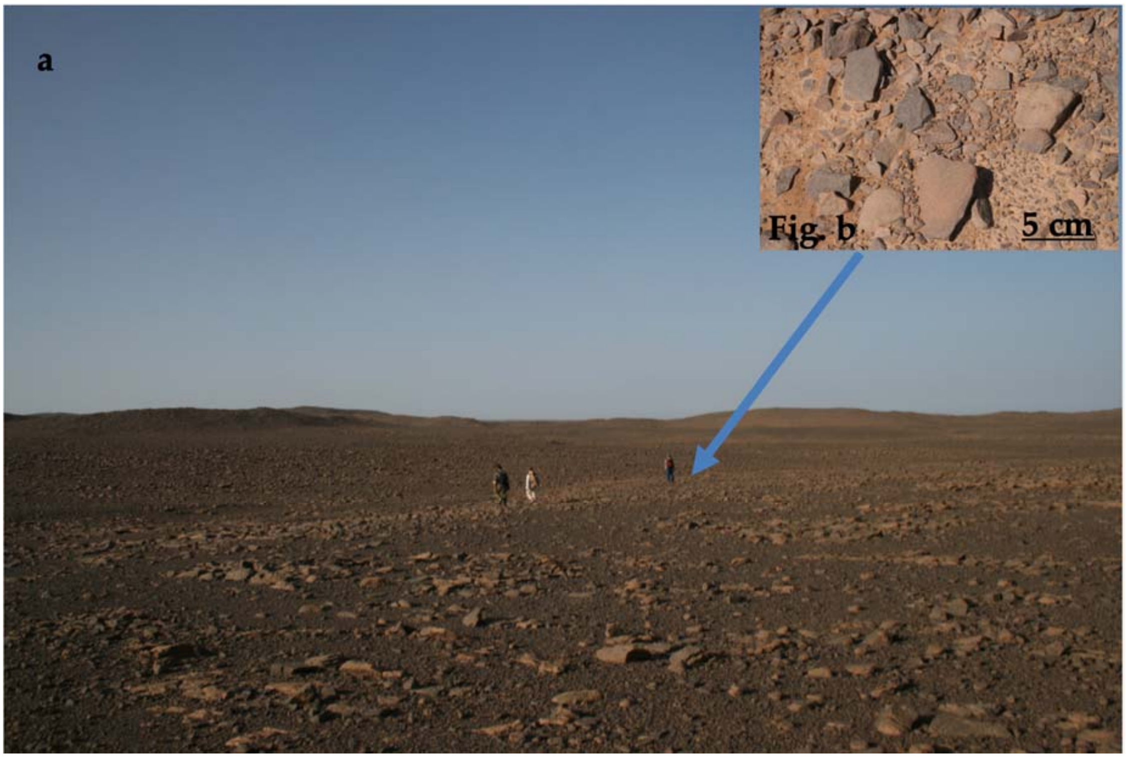

Figure 3. (**a**) Regolithic surfaces in areas proximal to the crater (up to 6.5 km distance) showing the presence of detrital soils formed by "in situ" alteration of substrate rocks; (**b**) particle of Figure 3a.

Such components are usually concentrated in minor deposits of variable, but usually limited thickness, which should be considered residual deposits and, because of their setting and physical properties (colour, granulometric heterogeneities, etc.), are easily distinguishable from the more recent fine-grained (silty) aeolian deposits, which are present at the bottom of the crater (Figure 1).

We postulate that, due to the presumed very young age of the Amguid structure (between 10,000 and 100,000 years [1]), and the Olocene significant climate change [5], there are no witness of parts of meteorite along the crater.

Thus, soil deposited sparsely within the regolith cover, as well as further from the crater, should represent the best candidates to search evidences of a high pressure (P) and temperature (T) impact metamorphic event.

In this scenario, we have to mention even the Hoggar volcanic activity. The Cenozoic alkaline volcanism of the Atakor massif (300 km far from the Amguid crater), has three main volcanic episodes [6].

The first, and the most voluminous magmatic episode occurred during the Miocene; the second episode (Miocene-Pliocene) began after the Tortonian period of quiescence. The final episode started after the Pliocene period of quiescence, from 1.95 ± 0.2 Ma to the present.

Eruption's products are exclusively basanites-tephrites that form scoria cones, necks and valley-filling lava flows, which constitute less than 3% of the total area of the Atakor massif [6].

Owing to the need to transport a limited amount of samples, we recovered from the Amguid crater and the surrounding area, only a < 500 µm fraction from the "in situ" sampling. Two distinct granulometric fractions (250–500 µm and <250 µm fractions) were analysed, excluding the <70 µm fractions to either avoid or limit contamination by very fine aeolian allochthonous materials.

Soil samples from four different small-sized deposits located at various distances from the crater were collected. The approximate distances from the Amguid structure and geographic coordinates of the collection points are reported in Table 1, and Figures 1 and 2.

Table 1. Location and macroscopic features of the studied materials.

Intra-Crater Rock Samples	Macroscopic Features	Location	Geographic Coordinates
	Rock Samples		
R-1	Light-grey medium grained sandstone	Upper E wall near the crater rim	26°05′17″ N 04°23′49″ E
R-2	Reddish coarse-grained sandstone	Upper E wall near the crater rim	26°05′17″ N 04°23′49″ E
R-3	Light-grey medium-grained sandstone	Lower E wall	26°05′17″ N 04°23′49″ E
R-4	Light-grey sandstone	Bottom E wall	26°05′17″ N 04°23′49″ E
	Soil Intra-Crater		
A1-C	Pinkish-coloured 250–500 µm	Bottom NW wall	26°05′17″ N 04°23′49″ E
A1-F	<250 µm	Bottom NW wall	26°05′17″ N 04°23′49″ E
	Soil Extra-Crater		
A2-C	Pinkish-coloured 250–500 µm	1 km N from the crater	26°05′30″ N 04°23′56″ E
A2-F	Pinkish-coloured <250 µm	1 km N from the crater	26°05′30″ N 04°23′56″ E
A3-C	Pinkish-coloured 250–500 µm	3 km N from the crater	26°04′54″ N 04°24′10″ E
A3-F	Pinkish-coloured <250 µm	6 km N from the crater	26°06′16″ N 04°23′48″ E
A4-C	Pinkish-coloured 250–500 µm	6 km N from the crater	26°06′16″ N 04°23′48″ E
A4-F	Pinkish-coloured <250 µm	6 km N from the crater	26°06′16″ N 04°23′48″ E
A5-C	Pinkish-coloured 250–500 µm	6.2 N km from the crater	26°07′40″ N 4°24′13″ E
A5-F	Pinkish-coloured <250 µm	6.2 N km from the crater	26°07′40″ N 4°24′13″ E

Using similar procedures, we also collected soil samples present in the incoherent breccia deposit exposed in the Amguid structure at the base of the NW wall in a zone not covered in February 2011 by aeolian deposits. Even for these samples, the two different granulometric fractions were analysed (Table 1).

For testing the presence of high pressure-temperature impact metamorphic effects on target materials, and for comparative geochemical studies, we collected sandstone bedrocks from distinct superimposed layers exposed towards the internal crater walls (from the bottom to the upper rim). Details on both the macroscopic features of the rocks and the exact location of intra-craterial materials are reported in Table 1 and Figures 1 and 2.

The Amguid crater, although smaller in size, could be briefly compared with the Meteor crater in Arizona [7]. Material characterised by highly shocked components at the Meteor crater is relatively rare and mainly restricted to the occurrence of Coconino sandstone-derived lechatelierite, and a relatively thin layer of fall-back breccia rich in melt particles. Inside the crater, the fall-back breccia occurs as a layer on top of the basal crater-filling breccia and underneath the overlying lake sediments [7], as well as in gullies along the lower inner crater walls and in patches outside the crater rim forming part of the upper ejecta blanket where it is preserved. That fall-back breccia is, moreover, known to contain a meteoritic component [7].

4. Methods

Optical microscopy was used to look for the presence of microscopic planar deformation features (PDFs) in both quartz crystals and vitreous substances in crater sandstones and soils, after embedding soil particles in epoxy resin and polishing them in thin sections. Similarly, we optically analysed concentrates of magnetic grains separated from soil samples.

A semi-quantitative chemical analysis of magnetic particles was made by Scanning Electron Microscope coupled with Energy Dispersive Spectrometric (EDS) analysis (SEM-EDS) techniques (Nova NanoSEM 450, ThermoFisher Scientific) at the Department of Physical Sciences, at the University of Bologna.

Mineralogical investigation on selected particles was obtained at the University of Florence, Department of Earth Sciences, by micro-Raman spectroscopy using a confocal microscope equipped with a Horiba/Jobin–Yvon spectrometer coupled with an 1800 g/mm single holographic grating. The laser beam (He-Ne source at 632.8 nm, 80 mW power), was focused on the samples using an ×50 objective lens and the Raman light was filtered by a double holographic Notch filter system (overall resolution 2 cm^{-1}) and collected by air-cooled CCD detectors.

Quantitative chemical analysis of single magnetic particles was made by the Cameca X-Five electron microprobe at the CAMPARIS micro-analyser centre (University of Paris VI) following procedures described in Seyler and Brunelli [8].

Bulk chemical analysis of rocks and soils relative to some selected main (Fe, Mg, Al) and trace (Ni, Co, Cu) elements were made using standard acid attack procedures (HCl-HF). The obtained solutions were analysed by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS, X Series II, ThermoFisher Scientific) solutions by using a Thermo Scientific X Series II at the Department of Earth Sciences, at the University of Rome.

5. Analytical Results

5.1. Observations Made with the Optical Microscope

As stated before, the main aim of optical microscope observation was the search for evidence of microscopic planar deformation features in quartz crystals of target rocks, as a consequence of a possible high pressure-temperature impact metamorphism [9–11], and for evidence of impact products (vitreous particles, remnants of the projectile) in soils from the Amguid area. In regards to microscopic planar deformation features, broad literature indicates that these are the most used parameters in the recognition of impact structures and terrestrial impact targets.

Optical observations were carried out on thin sections of six samples of intra-craterial sandstones collected in different points on the NW and NE walls and on two samples of soil particle englobes. Microscopic observations confirm the hypersilicic and sedimentologically ‘mature’ character of both materials constituted to more than 99% volume of quartz grains and, in the case of sandstones, of microcrystalline quartz cement.

The overabundance of detrital quartz grains, together with the recognised suite of accessory phases (mainly almandine garnet, tourmaline and zircon) indicates old granitoid and metagranitoid rocks as probable source materials.

Most of our attention was given to the search for the micro deformation textures as planar deformation features (PDFs), planar fracture (PF), and feather features (FF) in quartz crystals in intra-craterial bedrocks, previously found by Lambert et al. [1] and Sahoui & Belhai ([2], and taken as evidence of impact metamorphic effects [12,13]; thus, a probable impact origin for the Amguid structure. Our observations on such rocks have shown the significant presence of quartz crystals characterised by undulatory sub-planar metamorphic lamellae. Still, most of them are difficult to interpret. Besides, counting on a thin section of the number of these ‘deformed’ quartz grains, concerning the total number of the grains, indicates that grains with PDF-compatible textures are surely lower than 1%. In particular, our observations suggest that quartz grains with the three sets of PDF textures as found by Lambert et al. [1] are extremely rare (maximum 2–3 grains for each thin section). In addition, a similar abundance of ‘deformed’ quartz grains was also observed in soil particles (spherules) collected outside the Amguid structure, which surely cannot have been target material for the impact.

For this reason, we do not maintain that the micro deformation textures observed in the mineral phases of the Amguid proposed target rocks represent diagnostic parameters attesting a high pressure-temperature impact event.

Our preferred interpretation is that the observed deformation features in quartz crystals are indicative of a derivation from metamorphic terrains rather than correlated to a shock event Figure 4 [7,14,15].

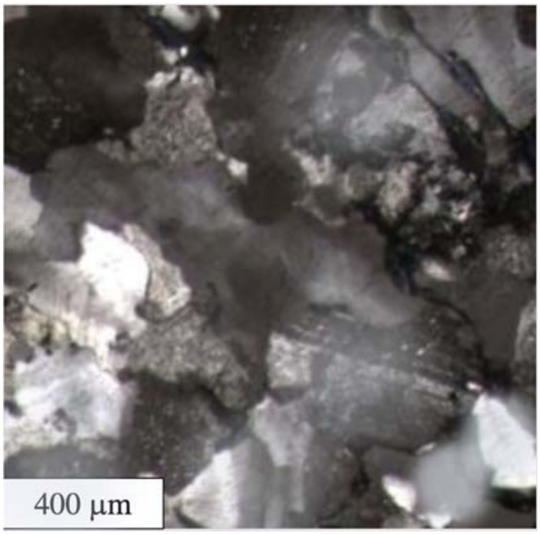

Figure 4. Optical observations of deformation features in quartz crystals.

The second purpose of our observations with the optical microscope was to ascertain the presence in the soil samples of vitreous particles and of other particles mineralogically compatible with extraterrestrial sources. We focused our attention on both magnetic and non-magnetic particles characterised by vitreous aspects (non-crystalline habit, globular and drop-like shape, absence of cleavage, etc.). Observations on thin sections of soil particles (spherules) did not allow identification of mineral phases of possible extraterrestrial origin (e.g., olivine, non-aluminiferous pyroxene).

5.2. Chemical Data on Crater Rocks and Soil

The chemical data reported in Table 2 refers only to some selected major and trace elements, which can furnish information as to the presence of mineral phases (Fe-Mg silicates, oxides, sulphides) whose potential extraterrestrial origin should be considered.

We consider, in the present study, only some selected geochemical parameters considered to be either terrestrial or extraterrestrial indicators.

In this context, for example, aluminium can be regarded as an exclusively ‘terrestrial’ element while other elements (Mg, Ni, Co), based on their well-known ‘extraterrestrial’ character [16–19], should be useful for detecting the presence of extraterrestrial input in soils. Data on a series of both lithophile and siderophile elements, plus Cu in intra-craterial bedrocks and soil/rock, are reported in Table 2. The comparison of average soil element contents in rocks and soils (see rock/soil enrichment factors, Table 2) show that these last are enriched in practically all elements but, in particular, besides the terrestrial Al, in Mg, Ni and Co.

Such element enrichments in soils should obviously be interpreted as a consequence of terrestrial rock weathering and pedogenic processes. For example, the enrichment of Al in such residual soils reflects its ‘immobile’ behaviour concerning most other elements. The appropriate interpretation of element abundance data in defining geochemical anomalies would, in priority, need knowledge of element background values, either in primary rocks or in derived soils. In our case, because of the limited amount of sampled materials for the Devonian bedrocks, reasonable element background values are given by element abundance data on intra-craterial rocks.

Table 2. Chemical data (ppm) on the Amguid rocks and soils.

Sample	Al ± 2.2	Mg ± 1.3	Fe ± 3.2	Mn ± 1.2	Co ± 0.01	Ni ± 1.2	Cu ± 1.3
				Rock (4 Samples)			
R-1	791	16.8	675	5.5	0.02	2.1	3.38
R-2	1253	30.1	1119	14.7	2.54	5.2	4.17
R-3	342	6.6	632	2.4	<0.01	3.2	2.66
R-4	705	15.5	553	2.4	<0.01	3.5	3.67
average	**773**	**17.2**	**744**	**6.25**	**0.65**	**3.5**	**3.47**
				Soil Intra-Crater			
A1-C	1170	24.2	819	6.5	n.d	13.08	7.39
A1-F	1940	55.1	1415	12.1	2.65	6.75	5.71
				Outside Crater (8 Samples)			
A2-C	1425	33.0	1040	12.4	2.07	23.09	8.65
A2-F	2298	66.1	1470	13.1	2.85	11.08	7.33
A3-C	3443	106.1	1862	18.6	5.02	14.64	11.00
A3-F	3144	101.1	1869	18.5	4.19	14.45	9.75
A4-C	1927	40.1	620	13.9	3.37	4.83	3.86
A4-F	2265	53.5	928	9.5	1.62	8.07	6.23
A5-C	1886	50.1	721	8.2	n.d.	18.54	13.66
A5-F	2543	73.8	1309	13.1	3.48	8.16	7.10
Average	**2204**	**60.3**	**1205**	**12.06**	**3.15**	**12.26**	**8.07**
soil average/rock average Enrichment factor, EF	**2.85**	**3.51**	**1.62**	**2.01**	**>4**	**3.42**	**1.75**
Al normalised (EF)		**1.23**	**0.57**	**0.70**	**>1.4**	**1.20**	**0.61**

There are, however, a series of arguments that suggest that the enrichment in soils of elements, such as Mg, Ni and Co, with respect to bedrocks (Lower Devonian sandstones), are not only due to the effects of pedogenic processes but indicate the presence in them of materials from foreign (non-terrestrial) sources.

It can be assumed that such a process occurred under quasi isochemical conditions; thus, positive element anomalies in soils will underline the presence in them of exotic materials. The Al-normalised element contents (see Table 2) confirm this hypothesis. Between the analysed elements in the soils, only Mg, Ni and Co prove to be more concentrated than Al. In our opinion, this is the best evidence of a significant presence in soils of a Fe-low Mg-rich component from external (extraterrestrial) sources.

Based on these assumptions, we stress that in soils intra and extra crater (up to 6.5 km distance), there are severe positive anomalies for Co and less critical (two–three times) Ni and Cu anomalies, which, at least in part, can be attributed to inputs from siderophile and chalcophile-rich sources, such as those represented by extraterrestrial materials.

We are conscious of the limits of such an assumption. It is well known that any terrestrial weathering process, even purely physical ones, may introduce minor chemical changes in the altered products. Once assumed that chemical anomalies in the Amguid soils should underline the presence of a non-terrestrial component, we treat to define the nature of such part by the analysis of single grain particles.

5.3. *Analysis of Individual Grain Particles*

After verifying the complete absence of vitreous particles in all analysed soil samples, we concentrated our attention on the study of other particles whose mineralogy and chemistry are theoretically compatible with extraterrestrial sources. Most mineral phases overabundant in extraterrestrial materials (e.g., olivine and other Fe-Mg silicates) possess a magnetic susceptibility that makes it easy to identify them in the magnetic fraction of the soils [16]. After identifying the mineralogy of single particles by optical methods, we decide to systematically analyse, by Electron Microprobe technique, a significant number of magnetic particles separated from the coarse-grained (250–500 µm) fraction of soils characterised by maximum Ni-Co-Cu anomalies (A2-C sample, Table 2). Particles were embedded in a resin matrix and polished as tick sections. A total of 192 particles were randomly selected and analysed for common major constituents, plus Cr and Ni. Quantitative chemical data by Electron Microprobe showed that almost all of the grains are terrestrial detrital phases (garnet >90, tourmaline >8%, low-Ni iron oxides <1%). It is worthy of note that all garnet grains are Fe-rich (almandine) indicating a possible derivation from metamorphic rocks rather than from volcanic ones. Only a microprobe analysis of four particles (about 2% of the grain components considered) deserves further comments. Their chemistry and attributed mineralogy are reported in Table 3. The main chemistry of particle AM 39 is compatible with a forsteritic olivine characterised by Mn content (0.23% MnO), which is high when compared to common terrestrial olivine (0.1%–0.2%, [20]. Observation at the optical microscope indicates that the particle consists of a relatively large (400 µm) almost transparent yellowish crystal, exhibiting a perfect crystalline habit, and no signs of surface weathering effects. This confirms the crystalline state (unmelted) of this particle. As olivine is by far the most reactive silicate phase during terrestrial weathering processes, the presence and habit of similar particles suggest very recent incorporation into detrital soils. The atomic Mg (Mg/Mg + Fe) value of this particle is 0.86, i.e., close to the upper limit of terrestrial olivine (0.87), [21] and well in the field of olivine from both micrometeorites and unequilibrated chondritic meteorites. The same parameter excludes any link with equilibrated chondrites ($0.16 < Mg > 0.33$ [21]). The Fe content and the total absence of Cr distinguish this olivine from those of the Antarctic micrometeorites and micrometeorites in general (FeO = 29–31%, Cr_2O_3 = 56%–57%) [22,23] whereas it matches olive composition from carbonaceous and unequilibrated ordinary chondrites (FeO = 25–31%, Cr_2O_3 = 0.08–0.4) [24,25].

Table 3. Chemistry and attributed mineralogy for some particles on the basis of electron microprobe analysis (%).

Sample	SiO_2	Al_2O_3	TiO_2	Cr_2O_3	FeO	MnO	MgO	NiO	Attributed Mineralogy
AM 39	40.35	0.05	0.01	0.02	13.71	0.23	46.67	0.13	Forsteritic olivine
AM-7	0.04	57.85	0.09	7.93	13.77	0.01	19.77	0.35	Cr-poor spinel
AM-8	0.06	58.95	0.08	8.05	11.91	0.02	20.89	0.36	Cr-poor spinel
AM-9	0.03	58.44	0.08	8.04	12.31	0.03	20.47	0.45	Cr-poor spinel

In addition to the identification by instrumental quantitative analysis of a crystalline olivine particle, optical observations at the microscope and SEM-EDS analysis made on a relatively high number, (about a hundred) of mineral grains, suggest that particles of possible olivine compositions are relatively abundant in soils collected in the areas proximal to the crater (up to 6.5 km distance). Based on the results of the microprobe analysis, we focused our attention on other magnetic particles whose morphology and optical properties suggested a possible exotic origin, in particular on grains of a spherical form somewhat diffused in Amguid soils and potentially compatible with the effects of melting processes. We submitted a series of such particles to a SEM-EDS chemical qualitative analysis at the University of Bologna and the results indicate a broad compatibility with a forsteritic olivine composition.

Figure 5 reports the results of such analysis on a sample from soils collected near the rim of the crater. It consists of a single transparent almost spherical particle associated with a minor grain of opaque phases. SEM-EDS analysis suggests a transparent component of an Al-low ferromagnesian silicate olivine-compatible composition and the blank fragment of an Ni-rich metallic iron.

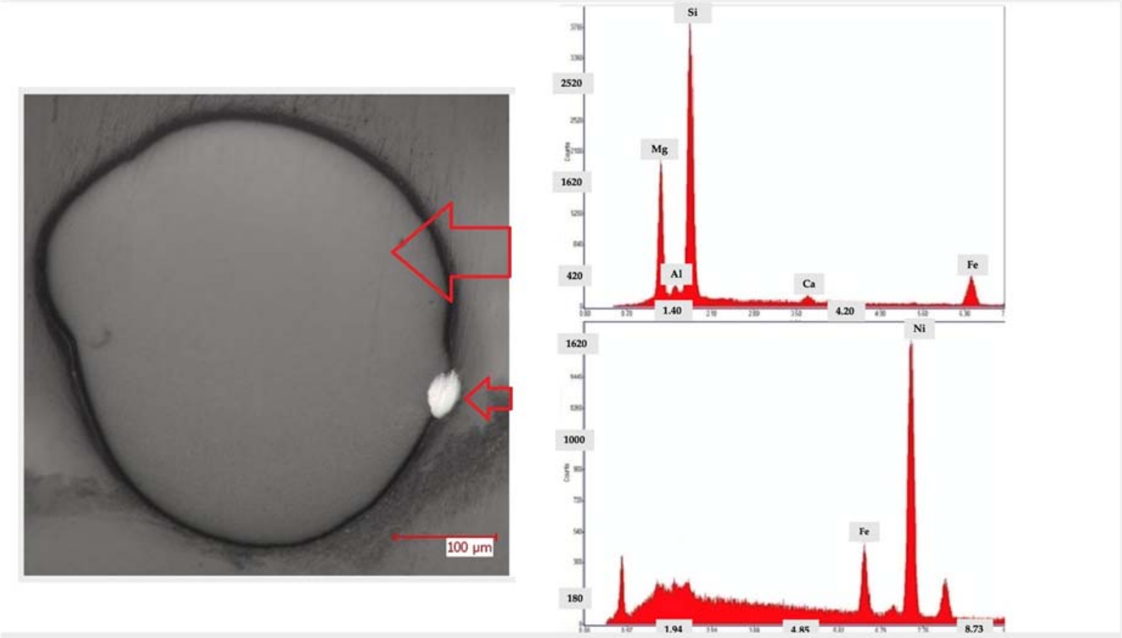

Figure 5. SEM- Energy Dispersive Spectrometric (EDS) analysis of a soil particle of a ferromagnesian silicate composition (olivine?) associated with a fragment of Ni-rich metal (Gasparotto, personal communication).

To get more in-depth mineralogical information about the nature of these particles, some of them were investigated by micro-Raman spectroscopy. The spectra (Figure 6, Caporali, personal communication) evidenced the presence of skeletal crystals of iron oxides (magnetite and possibly ilmenite) immersed in a ferromagnesian silicate component of probable forsteritic olivine composition. The morphology of the oxide crystals suggests that they are rapidly grown in an almost certain melted silicate matrix (Figures 5 and 6).

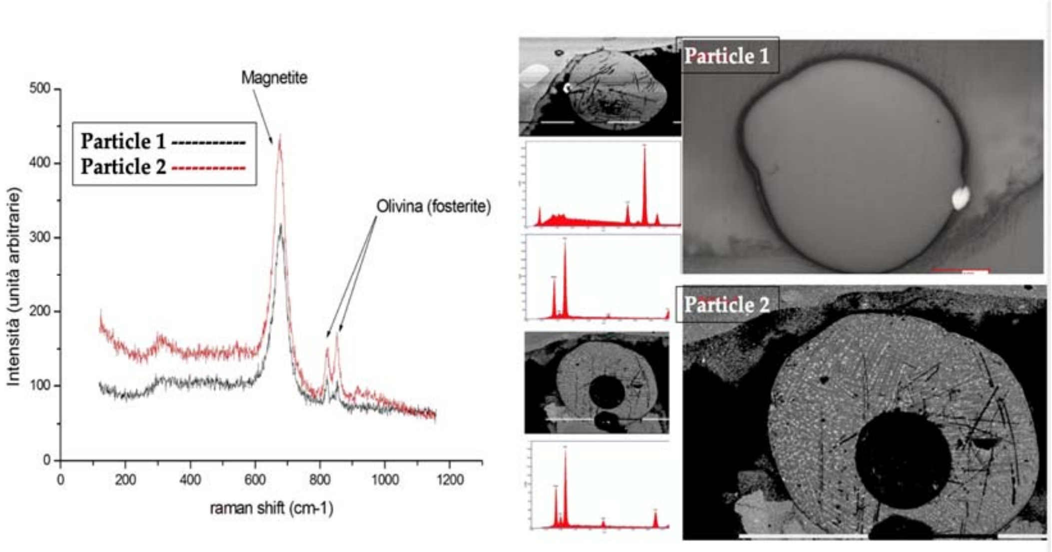

Figure 6. Raman spectral analysis of particles showing skeletal/dendroid crystals of oxides (magnetite, ilmenite?) immersed in a forsteritic olivine matrix (Caporali, personal communication).

As stated before, spherulitic particles very similar to that analysed by SEM-EDS and Raman techniques, and probably of extraterrestrial origin, are well represented in all soil deposits around the Amguid crater. The presence of both unmelted and melted forsteritic olivine particles and their possible relationship with a presumed impact event will be discussed in a forthcoming manuscript.

The major element chemistry of the three other particles of debatable (non-terrestrial) origin reported in Table 3 shows that they pertain to the family of Fe-Mg spinels characterised by a relatively high content of Cr (about 8% Cr_2O_3). Due to the solid solution series within the spinel group, the terminology is not always precise and tends to differ between authors, especially for the spinel group minerals containing considerable amounts of Cr. According to Wlotzka [26], spinels with a Cr/Cr + Al mole ratio <59 should be referred to as Cr-spinel, and this is the case of spinels from Amguid soils. Optical observations made under reflected light indicate quite similar morphological features for all spinel grains. They are brownish-coloured, and present in forms recalling chondrule aggregates instead of being single crystals.

Spinels are known to be very resistant phases during weathering processes so that their presence in Amguid detrital soils can be related to extraterrestrial Cr-spinels found in fossil meteorites [27].

Spinels are widely present in most igneous terrestrial rocks, but are concentrated almost exclusively in some mafic and ultramafic lithologies where their composition may change during progressive metamorphism and serpentinisation [28].

The graphs in Figure 7 report the composition (Al vs. Cr) of spinels from the Amguid soils compared to those of other terrestrial sources, including spinels from the Precambrian metamorphic basement of the Tuareg shield [29] and ultramafic xenoliths of the Hoggar volcanic field (300 km far from the crater).

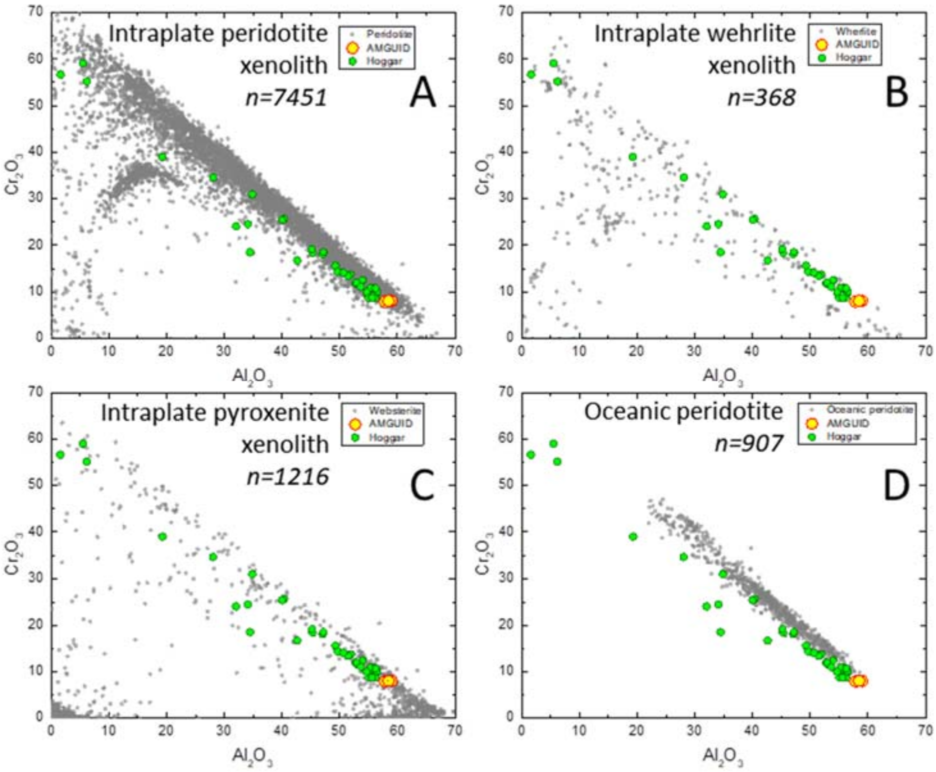

Figure 7. Chrome vs. aluminium variability of spinels from the Amguid area compared to other terrestrial sources. Amguid spinel composition is represented as yellow large circles (orange rim). The composition of ultramafics from the Hoggar volcanic field are plotted as green circles. Reference data fields are plotted as grey circles relative to: (**A**) Intraplate peridotite xenoliths; (**B**) Intraplate wherlite xenoliths; (**C**) Intraplate pyroxenite xenoliths and (**D**) Oceanic abyssal peridotites. Data for (**A**–**C**) are from the Geochemistry of Rocks of the Oceans and Continents (GEOROC) database (http://georoc.mpch-mainz.gwdg.de). Data for (**D**) are from the Petrological Database of the Ocean Floor (PetDB) (w.w.w.earthchem.org/petdb).

Data show that Amguid spinels are very close to the thick cloud of points (orange circle, Figure 7) with an own composition from spinels from most ultramafic rocks. They appear to be akin only to some spinels from websteritic, pyroxenitic and lherzolitic lithologies, characterised by a very fertile composition, i.e., strongly enriched in Al and incompatible elements. It is worth noting that these rocks represent an extremely rare occurrence in the Earth's record. Similar lithologies from the Hoggar volcanic field are represented by scattered, volumetrically insignificant, xenoliths with a composition very close to the bulk of the Hoggar ultramafics. Therefore, the related origin of the Amguid spinel may be related to Hoggar products, but it is very singular that anyone of the Amguid products have different composition like the Hoggar products (green circle, Figure 7).

In meteorites and other extraterrestrial materials, Al-Mg spinels are present as ubiquitous accessory mineral phases. They are present in the form of either individual crystals or chondrule-like aggregates similar to those found in the Amguid sediments. Cr spinels with a composition identical to that of Amguid spinels are present in some unequilibrated classes of ordinary chondrites [26], in Al-Ca rich refractory inclusions (CAI) in CV and CM chondrites [26,30,31] and in spinel-rich achondrite meteorites [32].

For this reason, we are led to exclude rocks of the Hoggar complex as sources for the Amguid detrital spinels, and other sources (terrestrial and extraterrestrial) should be considered.

Based on these overall considerations, it appears hard to attribute given sources to the Amguid spinel. The main argument speaking against extraterrestrial sources for them is that spinels are very poorly represented in common extraterrestrial materials; thus, the relative abundance of spinel grains in soils with respect to other possible extraterrestrial phases (Mg olivines) is hard to explain. On the other hand, a terrestrial origin for such spinels is plausible. In fact, the observed extreme chemical homogeneity between all spinel grains analysed suggests a unique and somewhat restricted source, this fact being more compatible with an extraterrestrial derivation rather than with terrestrial sources for which marked compositional variabilities should be considered.

6. Conclusions

Observations made in the field and analytical data reported in the present study pose intriguing questions about the hypothesis of an impact event, issues that will be briefly discussed here.

(a) Is there positive evidence for an impact origin for Amguid?

Differently from previous studies, apart from some impact-compatible macro-deformation present in the substrate crater rock, we did not find any certain physical pieces of evidence of impact metamorphic effects (i.e., PDF in quartz crystals in possible target rocks). Our search of products of impact (e.g., high pressure-temperature phases, vitreous materials, etc.) and of the debris of the projectile regarding both substrate rocks and soils have been entirely unsuccessful.

Comparative chemical data on crater rocks and soils indicate, in these last significant geochemical anomalies, that they are compatible with an extraterrestrial origin.

Instrumental analysis of individual grain particles suggests the presence of extraterrestrial components in the form of both unmelted and melted forsteric olivine microparticles (250–500 μm) and, possibly, of high-Cr spinels. Observations with the optical microscope indicate relatively high concentrations (abnormal?) of such microparticles in the soil samples collected up to a distance of 6.5 km from the crater.

(b) Does the non-terrestrial component in the Amguid soils correlate to either a normal flux of extraterrestrial microparticles or the fall of an important body?

The normal flux of extraterrestrial microparticles falling onto Earth mainly consists of interplanetary dust particles (IDPs) and micrometeorites from different sources. The relatively large size (>250 um) of the analysed particles and available qualitative and quantitative compositional data of olivine grains exclude IDPs as source materials.

On the other hand, the only available quantitative data concerning olivine (in particular the Ni content) speaks against a micrometeorite source [22] suggesting compatibility with ordinary chondrite meteorites and, thus, with a potential meteoritic body responsible for the Amguid event.

The ubiquitous presence of spinels in most extraterrestrial materials, including IDPs, micrometeorites and ordinary chondrite meteorites makes this mineral phase not discriminant in discussing their belonging to a given extraterrestrial source. They are known to be more represented in strongly unequilibrated ordinary and CV chondrites. Therefore, in the case, we accept the hypothesis that the relative abundance of spinel particles in Amguid soils correlates to an impact event, and so, we must suggest an unequilibrated and CV chondritic nature for the projectile.

To conclude, in our opinion, the most significant and probably unique indication that extraterrestrial materials recovered in the Amguid area correlate to an impact event is represented by the overabundance of particles of ferromagnesian silicate non-compatible with terrestrial sources.

(c) In the case of an impact origin for Amguid, what is the mass and nature of the projectile?

Previous observations and indications from our data, relative to mass and nature of the impactor and mode of the impact, appear contradictory and very hard to interpret. A relatively mass impactor should be considered on the base of the volume of the excavated rocks. Nevertheless, the liberated impact energy should have been quite limited to produce the typical shock metamorphic effects. This consideration excludes any hypothesis of hypervelocity, and of a hypervelocity impact of a metallic body, as in this case, remnants of the impactor and impact products should be present even when the projectile possesses a limited mass [33–36].

In our opinion, the most likely scenario would imply a low-velocity impact of a poorly compacted (strongly unequilibrated or carbonaceous chondritic?) asteroidal body. The presence of melted olivine particles would indicate that the reduced impact energy would have been still sufficient to cause complete desegregation, partial melting, and probably, partial volatilization of the projectile.

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