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The Aouelloul crater, Mauritania: On the problem of confirming the impact origin of a small crater

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Abstract–The impact origin of small craters in sedimentary rocks is often difficult to confirm because of the lack of characteristic shock metamorphic features. A case in point is the 3.1 Ma Aouelloul crater (Mauritania), 390 m in diameter, which is exposed in an area of Ordovician Oujeft and Zli sandstone. We studied several fractured sandstone samples from the crater rim for the possible presence of shock metamorphic effects. In thin section, a large fraction of the quartz grains show abundant subplanar and planar fractures. Many of the fractures are healed and are evident only as fluid inclusion trails. A few grains showed sets of narrow and densely spaced fluid inclusions trails in one (rarely two) orientations per grain, which could be possible remnants of planar deformation features (PDFs), although such an interpretation is not unambiguous. In contrast, an impact origin of the crater is confirmed by Re-Os isotope studies of the target sandstone and glass found around the crater rim, which show the presence of a distinct extraterrestrial component in the glass.

INTRODUCTION

Aouelloul is one of only 18 currently known African impact structures (Koeberl, 1994; Reimold, 1996; Master *et al.*, 1996; Vincent and Beauvilain, 1996; Koeberl *et al.*, 1997). The crater is situated at 20°15'N and 12°41'W in the Adrar region, western Sahara Desert, Mauritania (Fig. 1). It was discovered from the air by A. Pourquié in 1938 and was first visited on the ground by Th. Monod in 1950 (Monod and Pourquié, 1951). The crater has a rim to rim diameter of ~390 m, although earlier reports gave an erroneous number of 250 m (Campbell Smith and Hey, 1952; repeated in, *e.g.*, Heybrock, 1961; Chao et al., 1966b; Cressy et al., 1972). The well-developed rim (Fig. 2) rises 15 to 25 m above the surroundings (53 m above the crater floor). The crater, which is situated in Ordovician Zli sandstone and Oujeft quartzite, is filled with a poorly sorted sandy silt, which is overlain by well-sorted windblown sand. Based on gravity data, Fudali and Cassidy (1972) suggested a maximum sedimentary fill thickness of ~23 m, underlain by a breccia lens extending to a maximum depth of 130 m. Grieve *et al.* (1989) calculated ~100 m for the depth of the breccia lens based on gravity data.

Glass fragments found at the crater were studied by Campbell Smith and Hey (1952), who found that they are Si-rich glass (similar to Darwin or Wabar glass), but interpreted the glass to be a mixture of a glassy meteorite with local sandstone. Some glasses contain microscopic Ni-rich Fe spherules, with 1.7–9.0 wt% Ni, which Chao *et al.* (1966a) interpreted as remnants from a meteoritic impactor. The glass is inhomogeneous with abundant schlieren of varied chemical composition, as well as partly digested quartz and feldspar grains (cf., Fig. 9 in Koeberl, 1994). The composition of the glass is similar to that of the Zli sandstone, with some enrichments in siderophile element contents (Chao *et al.*, 1966b; Koeberl and Auer, 1991). The glass contains lechatelierite and baddeleyite (El Goresy, 1965; El Goresy *et al.*, 1968) and has a low water content (Beran and Koeberl, 1997), which indicates a high-temperature history. Based on these observations and on the absence of any indication of volcanic rocks or activity, the glass was taken as key evidence for an origin by impact. Fission track and K-Ar dating of this impact glass yielded an age for the crater of 3.1 ± 0.3 Ma (Storzer and Wagner, 1977; Fudali and Cressy, 1976).

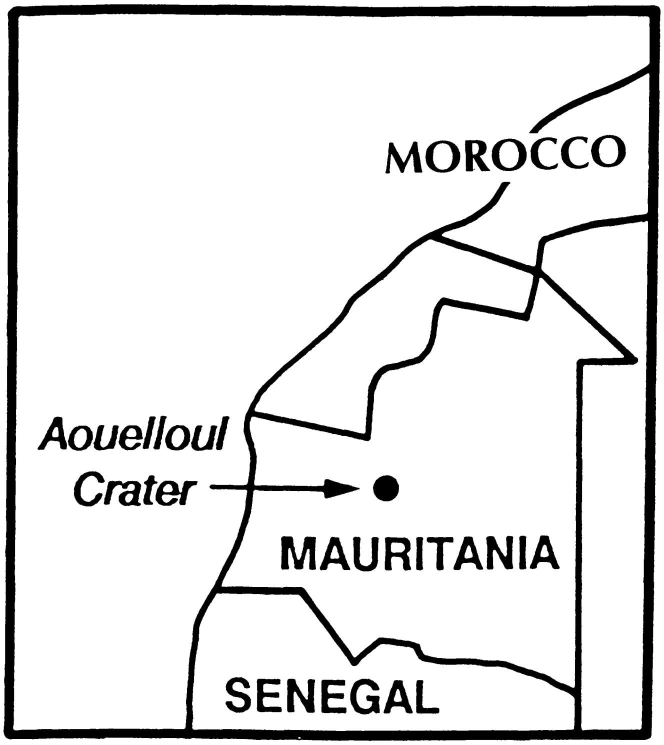

FIG. 1. Location map of Aouelloul crater in Mauritania, West Africa.

No petrographical studies of the sandstone and few geochemical studies on material from Aouelloul are available. Cressy *et al.* (1972) reported K, Rb, Sr, Th, and U contents, as well as the Sr isotopic ratio, in several samples of Aouelloul glass and sandstone and concluded that the glasses are derived from the local Zli sandstone. Some geochemical data of Aouelloul impact glasses and target rocks were reported by Koeberl and Auer (1991).

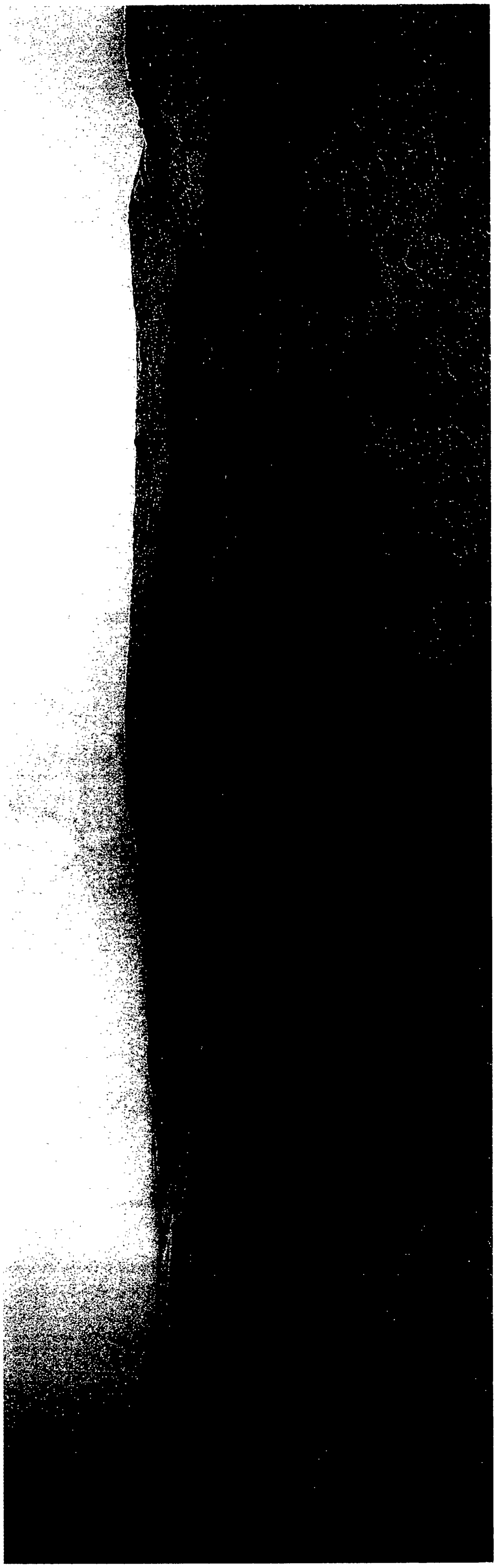

FIG. 2. Panoramic photomosaic of the Aouelloul crater, taken from the north-northwestern part of the crater rim, showing the limited outcrop at the crater rim.

No mineralogical evidence of shock metamorphism in crater rocks has yet been described (cf., Chao *et al.*, 1966b; Cressy *et al.*, 1972). The rarity or absence of shocked minerals in small craters that are formed in sedimentary target rocks is a common problem. Here, we provide some observations on the possible presence of shocked quartz in Aouelloul sandstones and seek to confirm the presence of a meteoritic component in the glasses by use of Re-Os isotope systematics.

FIELD OBSERVATIONS, SAMPLES AND METHODS

In 1989 October, the senior author participated in an expedition to the Aouelloul crater and collected ~200 glass and target rock samples. The crater rim is mostly covered by aeolian deposits (Fig. 2), which expose some loose blocks of sandstone. Solid outcrop is mostly restricted to the north and west parts of the rim. Where solid outcrop was encountered, rock sequences were upturned toward the crater center; strata were measured to dip, on average, 35° to 60°. In some rare cases along the western rim, overturned strata were observed; but because of limited outcrop, it is not clear if this represents only locally rotated blocks. Glass samples were found predominantly on the south, southeast, and north outer flank of the crater rim, with <10 pieces recovered from inside the rim on the southeast side. This represents a wider distribution than reported by Monod and Pourquié (1951). About 10% of the samples were found on the north side of the rim in a small 20 × 30 m patch. On the south and southeast side, near the bottom of the outer rim slope, samples were found scattered over an area of ~150 × 50 m.

Twelve petrographic thin sections were prepared of the seven target rock samples (from the north and west rim sections) for optical microscopy. For the Re-Os isotope analyses, ~30 g of the target rocks and 2 g of the impact glass were crushed and then pulverized in a corundum ball mill. Major and trace element contents were also measured in these samples. Due to low abundances of the siderophile elements in the target rocks, relatively large sample quantities (~10 g) were used for these studies. For analytical procedures, see Koeberl (1993) and Shirey and Walker (1995).

SEARCH FOR SHOCK METAMORPHIC EFFECTS

The presence of rocks and minerals exhibiting evidence for shock metamorphism is an unambiguous indication for the high pressures uniquely associated with impact cratering (see, *e.g.*, reviews by Stöffler and Langenhorst, 1994; Grieve *et al.*, 1996; Huffman and Reimold, 1996; and references therein). Planar deformation features (PDFs) in quartz are the most widely accepted evidence for shock metamorphism (e.g., Alexopoulos et al., 1988; Stöffler and Langenhorst, 1994). These effects are best developed in nonporous (crystalline) rocks. In porous rocks such as sandstones, the shock wave energy is largely dissipated for compression work. As a result, the pressure calibration and the progressive stages of shock metamorphism in porous rocks are distinctly different from those in crystalline rocks (*e.g.*, Kieffer, 1971; Kieffer *et al.*, 1976). Most common are fracturing and the formation of high-pressure modifications, as well as melting, while PDFs are rare.

In our petrographic study of the sandstones from the crater rim of the Aouelloul crater, we observed that, indeed, a large fraction (up to ~60 vol% per section) of the quartz grains are shattered or fractured, which are similar to observations in Coconino sandstone at Meteor Crater (Kieffer, 1971). Most of the fractured grains show subplanar as well as planar fractures; many of them outlined in the form of wide and irregularly spaced fluid inclusion trails, obviously representing healed (planar?) fractures (Fig. 3a). Some grains show single sets of

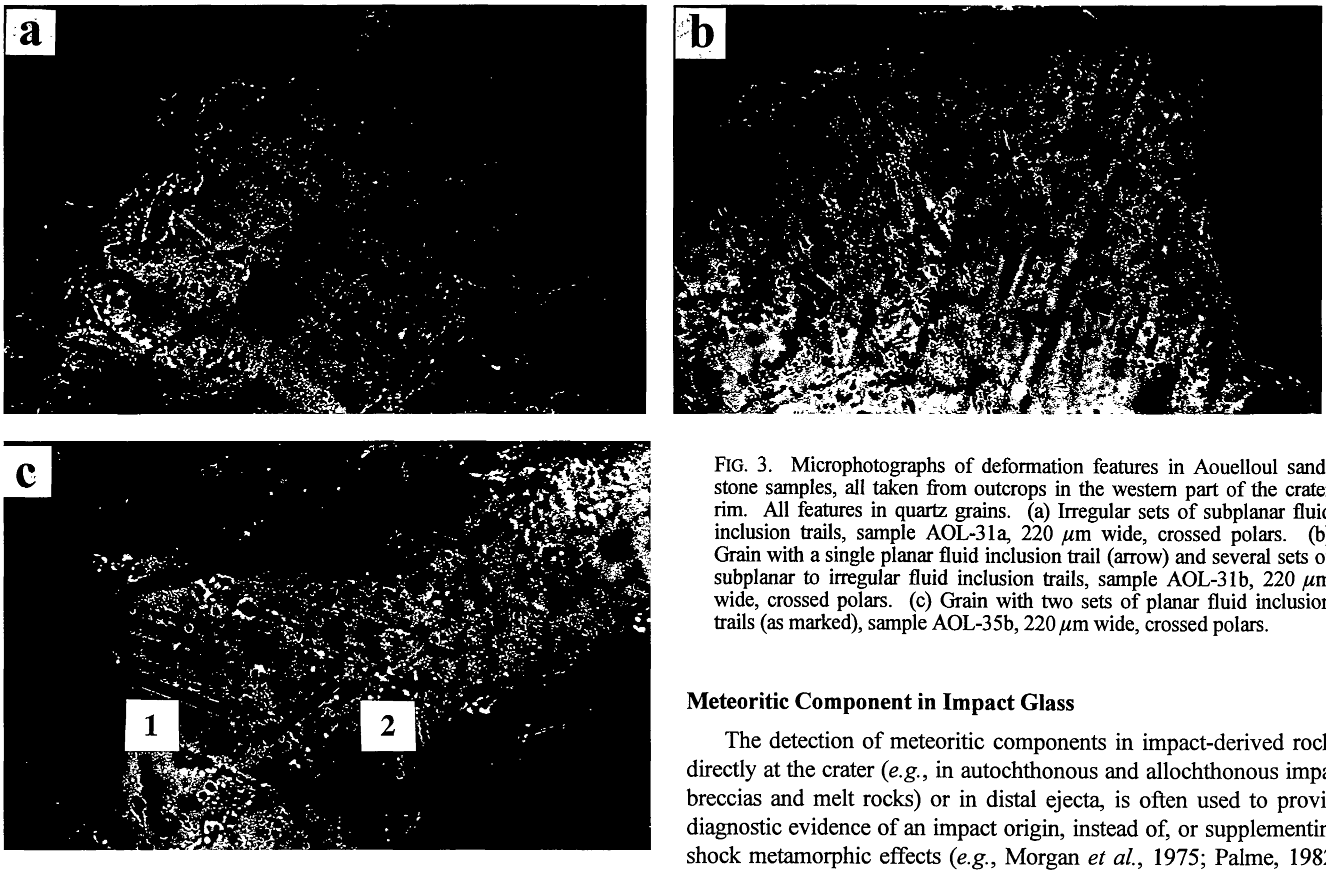

FIG. 3. Microphotographs of deformation features in Aouelloul sandstone samples, all taken from outcrops in the western part of the crater rim. All features in quartz grains. (a) Irregular sets of subplanar fluid inclusion trails, sample AOL-31a, 220 μm wide, crossed polars. (b) Grain with a single planar fluid inclusion trail (arrow) and several sets of subplanar to irregular fluid inclusion trails, sample AOL-31b, 220 μm wide, crossed polars. (c) Grain with two sets of planar fluid inclusion trails (as marked), sample AOL-35b, 220 μm wide, crossed polars.

optically unidentifiable planar lamellae, or coexisting subplanar and irregular fluid inclusion trails with more regularly spaced planar fluid inclusion trails (Fig. 3b). In a few rare cases, regularly spaced and narrow planar fluid inclusion trails, in form of two distinct and intersecting sets, were observed in quartz grains (Fig. 3c).

While fractures and healed fractures are common, only 2–4 grains per section were found to contain narrow and regular single sets of fluid inclusion trails (spaced ~4 to 12 μm), and even fewer contained two intersecting sets. The latter features could represent altered remnants of PDFs. Planar deformation features usually occur in planes corresponding to specific crystallographic orientations, with the (0001) or c (basal), $\{10\bar{1}3\}$ or ω, and $\{10\bar{1}2\}$ or π orientations being the most common (*e.g.*, Stöffler and Langenhorst, 1994). We determined the crystallographic orientations of the parallel and regular spaced fluid inclusions trails with a universal stage. Figure 4 shows a histogram with the orientations of the poles of the features relative to the c-axis of the quartz grains (after Engelhardt and Bertsch, 1969) and a fence diagram of the frequency of indexed PDFs *vs.* angle between c-axis and PDFs, including only indexed planes, following Grieve *et al.* (1996). Out of eight grains with two sets, only one could be measured with the U-stage, which indicates that only limited information can be obtained from the present measurements. Ten of the 16 measured sets could be assigned to angles corresponding to shock-characteristic planes, but it should be noted that for single sets no unequivocal indexing is possible. However, the shock-characteristic orientations $\{10\bar{1}3\}, \{10\bar{1}2\}, \{11\bar{2}2\}, \{11\bar{2}1\}$, and $\{10\bar{1}0\}$ (ω, π, ξ, s, and m, respectively) do occur in the present samples.

Meteoritic Component in Impact Glass

The detection of meteoritic components in impact-derived rocks, directly at the crater (*e.g.*, in autochthonous and allochthonous impact breccias and melt rocks) or in distal ejecta, is often used to provide diagnostic evidence of an impact origin, instead of, or supplementing, shock metamorphic effects (*e.g.*, Morgan *et al.*, 1975; Palme, 1982). Glass that is probably of impact origin, such as at Aouelloul, is ideal for the search for a meteoritic component. The major element composition of Aouelloul glass is in agreement with the composition of Zli sandstone (Chao *et al.*, 1966b; Koeberl and Auer, 1991). Chemical analyses (Koeberl and Auer, 1991; and in preparation) show enrichments in Fe, Co, Ni, and Ir, as has been noted before (Morgan *et al.*, 1975). From the interelement ratios, these authors concluded that there is evidence for a cosmic component, maybe a pallasite or an iron meteorite of groups IIIB or IIID (cf., Pernicka and Wasson, 1987), although this interpretation is not unequivocal, as the siderophile element contribution from the target rocks was not known.

One reason why Morgan *et al.* (1975) may have had trouble identifying the projectile type is that complex fractionation processes take place during the formation of impact glasses and melts. Studies of impact glasses from small craters, in which the meteorite has been partly preserved (*e.g.*, Meteor Crater, Wabar, and some Australian craters), showed that the siderophile elements are strongly fractionated in a nonsystematic way (*e.g.*, Mittlefehldt *et al.*, 1992). It has been demonstrated that the Re-Os isotopic system allows a much more straightforward confirmation of the presence of a cosmic component, although it does not permit to determine the meteorite type (cf., Koeberl and Shirey, 1993, 1997, and references therein). The use of Re-Os isotope systematics for the study of impact craters and ejecta is based on the admixture of very small amounts (<1%) of recondensed projectile material with low ^{187}Os/^{188}Os ratios to terrestrial target rocks with high ^{187}Os/^{188}Os ratios.

The four sandstones have low Os abundances and high ^{187}Os/^{188}Os ratios (Table 1), which are characteristic of relatively old crustal rocks, and in agreement with data for similar rocks at other impact structures (see Koeberl and Shirey, 1993, 1997, and references

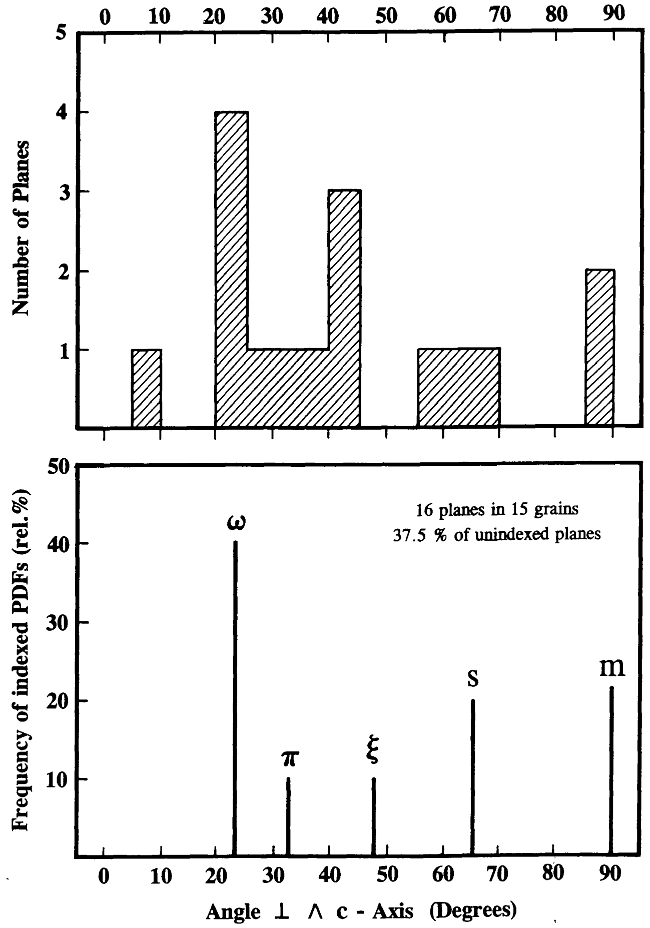

FIG. 4. Crystallographic orientation of planar fluid inclusion trails. (a) Histogram showing number of planes *vs.* angle between c-axis and planes, after Engelhardt and Bertsch (1969); the shock-characteristic orientations $\{10\bar{1}3\}$, $\{10\bar{1}2\}$, $\{11\bar{2}2\}$, $\{11\bar{2}1\}$, and $\{10\bar{1}0\}$ (ω, π, ξ, s, and m, respectively), are clearly present; (b) histogram showing only the frequency of orientations that follow rational crystallographic planes *vs.* angle between c-axis and planes, following the procedure recently proposed by Grieve *et al.* (1996), although here no unambiguous indexing was possible; only angle information is used.

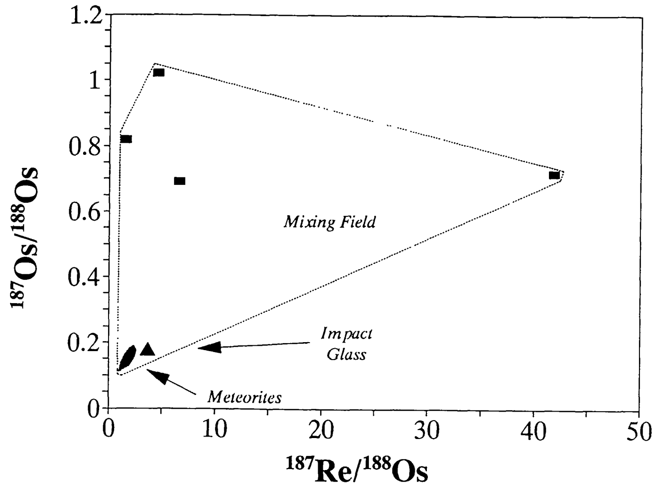

FIG. 5. Ratios of ^{187}Os/^{188}Os *vs.* ^{187}Re/^{188}Os for Aouelloul target rocks (sandstone) and impact glass (see Table 2). Plotted together with the data array for carbonaceous chondrites and iron meteorites (meteorite data after Walker and Morgan, 1989; Morgan *et al.*, 1992; and Horan *et al.*, 1992). The impact glass plots very close to the meteoritic values.

therein). In contrast, the ^{187}Os/^{188}Os ratio measured for the Aouelloul impact glass (Table 1) is very close to the data array defined by chondritic and iron meteorites (Fig. 5). However, the abundance of Os in the impact glass is not significantly higher than that in the sandstones, which is similar to what was observed for Bosumtwi crater target rocks and Ivory Coast tektites (Koeberl and Shirey, 1993). Thus, it confirms an extraterrestrial origin of the Os from elemental data alone; while the Os isotopic data clearly indicate that most of the Os in the glass is of meteoritic origin, as no chemical or petrological evidence exists to explain the low Os isotope ratio in terms of admixture of a major mantle component. In a ^{187}Os/^{188}Os *vs.* ^{187}Re/^{188}Os diagram, the impact glass plots into the mixing field defined by the target rock and meteorite compositions, as in several other impactite/target rock combinations (cf., Koeberl and Shirey, 1997). Our data confirm the presence of an extraterrestrial component in Aouelloul glass.

SUMMARY AND CONCLUSIONS

Aouelloul is a small crater, 390 m in diameter, which is exposed in sandstones in the Adrar region of Mauritania. Around the crater rim, abundant glass fragments (up to a few centimeters in size) were found, which on the basis of their composition and petrology were interpreted to be impact glass, thus, indicating an impact origin for the Aouelloul

TABLE 1. Rhenium-osmium isotopic data for Aouelloul impact glass and target rocks.

Sample	Re (ppb)	^{188}Os (10^{-15} moles/g)	Total Os (ppb)	^{187}Os (%)	^{187}Re/^{188}Os	^{187}Os/^{188}Os	(^{187}Os/^{188}Os)$_i$ (at 3.1 Ma)
Target Rock (Sandstone)							
AOL-31a	0.0942	7.58	0.012	8.7	41.82	0.7194	0.7173
AOL-31b	0.007	6.80	0.011	12.0	4.555	1.0191	1.0187
AOL-32	0.0064	13.6	0.0211	10.0	1.581	0.8190	0.8189
AOL-34	0.0097	4.96	0.0077	8.5	6.603	0.6917	0.6914
Impact Glass							
AOL-38	0.0117	10.72	0.0154	2.3	3.660	0.1731	0.1729

For details on the analyses, see text. Total Os includes radiogenic ^{187}Os, the percentage of which is given in the next column. Uncertainties quoted in the ^{187}Re/^{188}Os and ^{187}Os/^{188}Os ratios refer to the last digits. Total uncertainties in the ^{187}Os/^{188}Os ratio can be up to ±3 rel%, based mainly on the error propagation from the uncertainty in the spike calibrations; mass spectrometric uncertainties are usually <<1 rel%.

crater. However as no microscopic shock features have been found in rocks from the crater, this interpretation is not unequivocal. We have studied the petrography of sandstones exposed at the crater rim and found abundant fractured and shattered quartz grains. Only a few rare sets of planar fluid inclusion trails in up to two orientations were found, which could be healed remnants of PFs or PDFs. No unequivocal identification of PDFs in the sandstones was possible, confirming that these features are rare in small impact craters that formed in porous rocks. However, Re-Os isotope analyses of impact glasses and sandstones showed unambiguous evidence for the presence of a meteoritic component in the glass, which confirms the impact origin of this particularly small crater.

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