Libyan Desert Glass: geochemical composition and origin

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Riassunto

Il vetro del Deserto Libico (LDG) è molto ricco in silice (circa 96,5-99% in peso) e mostra modeste variazioni nella quantità degli altri elementi chimici, compresi quelli in tracce. La sua origine è ancora controversa, anche se l'ipotesi dell'impatto resta la più probabile. Si riscontrano tuttavia alcune caratteristiche leggermente diverse da quelle dei classici corpi vetrosi presenti talora dentro o intorno al cratere d'impatto. L'origine da impatto è dimostrata dalla presenza di strie e strutture fluidali, di minerali parzialmente digeriti, di lechatelierite (quarzo fuso ad alta temperatura) e di baddeleyite (derivata dalla decomposizione ad alta temperatura dello zircone). Inoltre, è probabile la presenza di costituenti meteoritici. In questo lavoro vengono studiati i livelli scuri del LDG, nei quali sono state rinvenute quantità superiori alla media di elementi siderofili, incluso l'iridio. Ciò dimostra che vi è materiale condritico in quantità superiore allo 0,5%. I grafici relativi all'abbondanza delle terre rare indicano che la roccia soggetta all'impatto era di natura sedimentaria. Nonostante una certa affinità tra gli elementi in tracce del LDG e delle arenarie Nubiane, sussiste una leggera differenza chimica tra LDG e sabbie raccolte *in situ*. Vengono anche effettuati confronti preliminari tra la composizione del LDG e quella delle strutture da impatto «BP» e «Oasi» presenti nella vicina Libia.

Abstract

Libyan Desert Glass (LDG) is very rich in silica at about 96.5-99 wt.% SiO$_2$, and shows a limited variation in major and trace element abundances. Although the origin of LDG is still debated by some researchers, an origin by impact seems most likely. There are, however, some differences from «classical» impact glasses, which occur in most cases directly at or within an impact crater. Evidence for an impact origin includes the presence of schlieren and partly digested mineral phases, lechatelierite (a high-temperature mineral melt of quartz), and baddeleyite (a high temperature breakdown product of zircon). In addition, the existence of a meteoritic component is very likely. Rare dark layers and streaks within LDG samples were studied in the course of this work, and enrichments in the siderophile elements, including Ir, were found. These enrichments indicate the admixture of up to about 0.5 % of a chondritic component. The rare earth element abundance patterns are indicative of a sedimentary precursor rock. Although there is a similarity of LDG trace element composition with Nubian sandstone in general, there are some chemical differences between LDG and surface sands collected in the area of the LDG occurrences. Some preliminary comparisons of LDG compositions have also been made with material from either the BP or Oasis impact structures.

Introduction

(Pl. L a, b and c in colour section.)

Libyan Desert Glass (LDG) is an enigmatic type of natural glass found in an area with an extension of about 6500 km^2. This area, or strewn field, is located between sand dunes in the southwestern corner of the Great Sand Sea in western Egypt, near the border of Libya. Therefore, the name «Libyan» Desert Glass is not entirely correct, given today's geographical boundaries, but refers to the traditional name of the desert (Fig. 1). Although the first report of LDG is usually ascribed to Clayton and Spencer (1934), the first account of its existence seems to be a note by Fresnel (1850), who travelled in the area in 1846 and reported about the occurrence of glass in the desert. However, Clayton and Spencer (1934) were the first to provide a detailed scientific description of the glass and its occurrence, following some initial descriptions by P.A. Clayton in 1932. In addition, R.A. Bagnold visited the LDG area in the 1930s (e.g., Bagnold, 1933; Bagnold *et al.*, 1939).

The inaccessibility of the LDG area was the reason for a relative paucity of visits to the location. In the 1970s visits by, for

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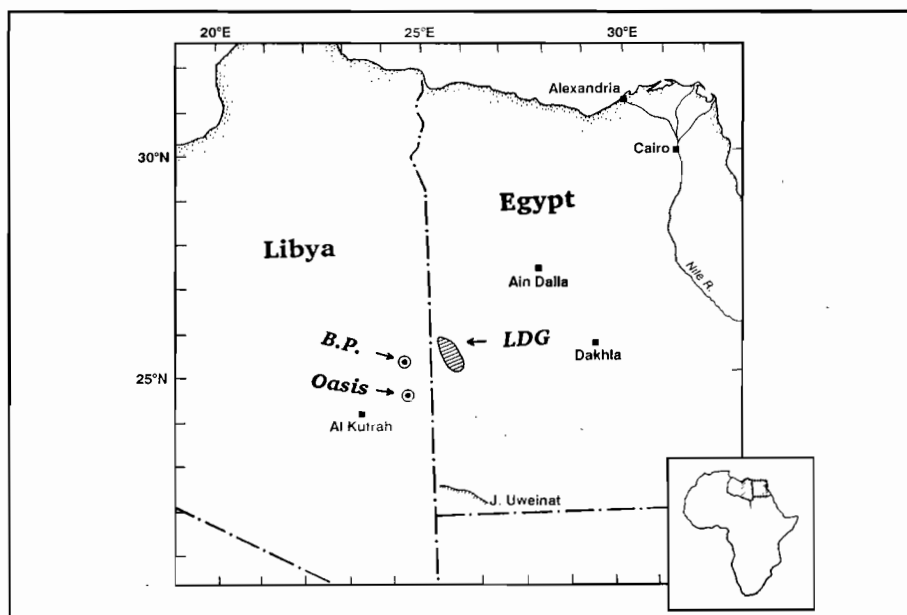*e-mail: christian.koeberl@univie.ac.at*

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Fig. 1. Location map, showing parts of Egypt and Libya. The position of the LDG field (in western Egypt) is shown in relation to the BP and Oasis impact structures in neighboring Libya. In general, no LDG is found in Libya. The name derives from the classical name for the NE part of the Sahara, known since the time of Herodotus as the Libyan Desert.

example, J.R. Underwood, E.P. Fisk and V.E. Barnes led to the collection of a large number of LDG samples and some petrographical work (e.g., Barnes and Underwood, 1976). In addition, two impact structures were discovered just west of the LDG strewn field, already in Libya: the BP and the Oasis impact structures (e.g., French et al., 1972, 1974; compare Koeberl, 1994a), which are of interest because of a possible connection with the origin of the LDG; see below for a more detailed discussion.

In macroscopic examination, the glass shows irregular shapes with signs of sand abrasion and other erosion features. The fission track age of LDG has been determined to be about 29 Ma (Storzer and Wagner, 1977, 1979), an age recently confirmed by Bigazzi and de Michele (1996). LDG is a natural glass very rich in silica with about 96.5-99 wt.% SiO_2, and shows a limited variation in major and trace element abundances (e.g., Barnes and Underwood, 1976; Fudali, 1981; Weeks et al., 1984; Koeberl, 1985). The chemical composition falls into a narrow range, as demonstrated by previous studies mainly of the major elements, with only relatively few trace element data available so far (see, e.g., Fudali, 1981; Barnes and Underwood, 1976; Weeks et al., 1984; and Koeberl, 1985). However, the available trace element data (for example, those for the rare earth elements) indicate abundances and interelement ratios that are typical of upper crustal rocks (e.g., Weeks et al., 1984; Koeberl, 1985; Storzer and Koeberl, 1991).

Since its discovery, Libyan Desert Glass has been the subject of a number of studies, ranging from glass technological aspects to petrographical and geochemical works. Various aspects have been studied, for example, by the following authors: Barnes (1990), Boden and Richter (1984), Friedman and Parker (1969), Frischat et al. (1982, 1984, 1989), Galeener (1985), Galeener et al. (1984), Jessberger and Gentner (1972), Klein et al. (1986), Kleinmann (1969), Matsubara et al. (1991), McPherson (1984), Mills (1968), Moore et al. (1984), Murali et al. (1987, 1988, 1989), Nasrallah and Weeks (1984), Oakley (1952), Olsen and Underwood (1979), Roe et al. (1982), Seebaugh et al. (1985), Underwood (1980), and Weeks et al. (1980). The above list does not claim to be complete.

The origin of LDG has been the subject of a controversy (see, e.g., Giegengack and Issawi, 1975; Weeks et al., 1984), which - in the view of some researchers - is not yet settled. However, the

majority of workers favour an origin by impact (e.g., **Barnes and Underwood, 1976;** Seebaugh and Strauss, 1984; Storzer and Koeberl, 1991; Rocchia *et al.*, 1996). It should be noted, though, that there are some differences between LDG and «classical» impact glasses (compare, e.g., Koeberl, 1986, 1990, 1994a, b; Taylor 1973; Barnes, 1989). Moreover, no impact crater has yet been conclusively identified to be associated with the glass occurrence. A relatively high water content (about 0.15-0.2 wt.%) was reported by Frischat *et al.* (1982, 1984), which is rather on the high side for typical impact glasses (Gilchrist *et al.*, 1969; Koeberl and Beran, 1988). Furthermore, Jux (1983) claimed to have found neogene microfossils in the glass (!) and argued vividly for some kind of a sol-gel origin of LDG. His conclusion has been refuted, however, by, e.g., Rocchia *et al.* (1996). The present study aims at reviewing the evidence for an impact origin of LDG.

Methods

The geochemical studies on eleven LDG samples are discussed in detail by Koeberl *et al.* (1987); here, I present only some of the results. In short, major element compositions were determined by electron microprobe analyses, using an **ARL SEMQ** instrument at the University of Vienna, and with a Cameca Camebax instrument at the NASA Johnson Space Center, Houston. Analytical conditions were 15 kV acceleration voltage and 10 nA beam currents. Standard ZAF correction procedures were used. Very long counting periods (20 minutes) and careful background evaluation procedures were used for trace element analyses of Ni, Mn, and P by microprobe. Trace element abundances were analyzed by instrumental neutron activation analysis (INAA) following procedures described by Koeberl *et al.* (1987) and Koeberl (1993), as well as by atomic absorption spectrometry (see Koeberl *et al.*, 1987, for further analytical details).

Geochemical composition

The average major and trace element composition of LDG, calculated from eleven individual samples (see Koeberl, 1997) is given in Table 1, together with the standard deviation and range. This table provides the most complete trace element information available so far for LDG and confirms that the compositional range of LDG is very limited. Fig. 2 shows some examples of variations of various major and trace element contents with the silica content. It is evident that there is an inverse correlation between the silica content and the content of most lithophile major and trace elements. However, no correlation between the Co content and the silica content is observed. This holds also for other volatile and siderophile elements, which show an irregular distribution. The composition of three surface sands collected at the LDG strewn field is also given in Table 1 for comparison.

Fig. 3 shows the chondrite-normalized rare earth element (REE) abundance pattern for the average and range of the LDG abundances. This pattern, with a distinct negative Eu anomaly and high light REEs and lower and flat heavy REE patterns, is typical for upper continental crustal rocks (e.g., Taylor and McLennan, 1985), similar to the patterns shown by tektites (e.g., Koeberl, 1986, 1994b). These patterns do not show any indications of the influence of hydrothermal processes or other low-temperature fluidal interactions, and are also unlike the patterns exhibited by any volcanic glasses.

Fig. 2. Harker correlation diagrams for the silica content versus the contents of Al, Fe, Sc, and Co in the eleven analyzed LGD samples (compare Koeberl, 1997).

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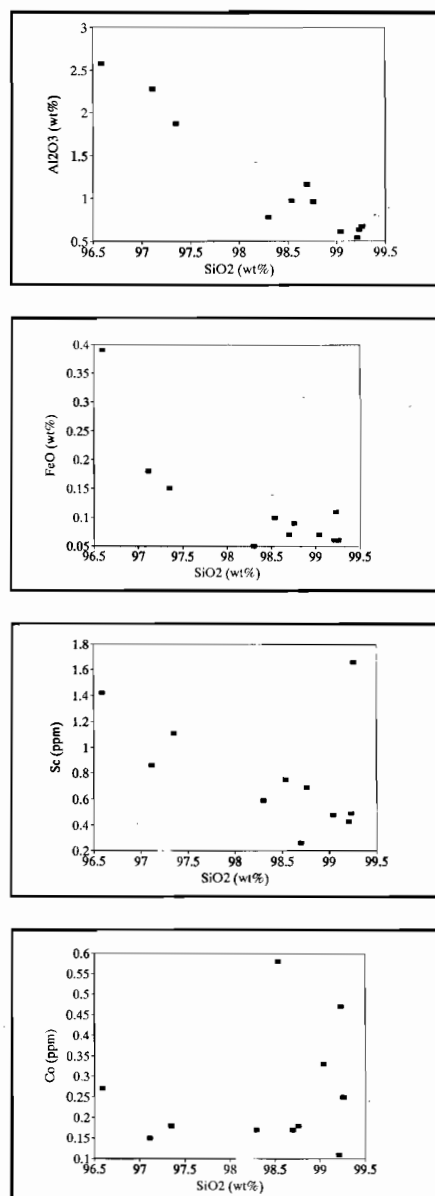
	Libyan Desert Glass				Surface Sand		
	Average	Std.dev.	Min.	Max.	S-1	S-2	S-3
SiO₂	98.37	0.89	96.59	99.26	86.81	98.25	65.59
TiO₂	0.12	0.06	0.05	0.24	0.34	0.03	0.20
Al₂O₃	1.19	0.69	0.54	2.58	3.29	0.09	3.03
FeO	0.12	0.09	0.05	0.39	1.43	0.10	23.58
MgO	0.011	0.002	0.008	0.015	0.22	0.02	0.15
CaO	0.01	0.00	0.01	0.02	1.95	0.07	1.35
Na₂O	0.005	0.001	0.003	0.007	0.10	0.05	0.02
K₂O	0.009	0.003	0.006	0.014	0.40	0.23	0.21
P₂O₅	0.01	0.005	0.005	0.012	0.05	0.02	0.010
L.O.I.	n.a.	n.a.	n.a.	n.a.	3.85	0.19	5.24
Total	99.85				98.44	99.04	99.46
Li	10.4	2.79	7.13	16.6	n.d.	n.d.	n.d.
Be	0.64	0.83	0.053	2.5	n.d.	n.d.	n.d.
Na	37	13	23	60	770	390	160
Cl	18	6	10	29	n.d.	n.d.	n.d.
K	74	22	45	115	3200	1300	900
Sc	0.79	0.42	0.26	1.66	4.28	0.41	6.26
Cr	5.74	2.64	1.8	10.4	30.5	3.62	33.7
Mn	13.2	3.62	7.6	19.1	139	10	200
Fe	929	417	305	1720	12100	908	159000
Co	0.26	0.14	0.11	0.58	3.87	0.48	14.1
Ni	2.5	2.0	1	8	9	0.6	11
Cu	3.45	1.77	1.58	7.76	n.d.	n.d.	n.d.
Zn	8.01	4.72	3.34	20.4	15	1	34.7
Ga	1.1	0.5	0.4	2.5	6.1	0.93	13.8
As	0.17	0.06	0.08	0.028	1.87	0.22	8.91
Se	0.02	0.01	0.01	0.04	0.88	0.05	0.06
Br	0.06	0.02	0.02	0.09	0.11	0.02	0.08
Rb	0.46	0.12	0.28	0.68	17.1	5.49	28
Sr	24	7	17	37	40	10	10
Zr	196	47	105	270	470	40	100
Ag	0.02	0.01	0.01	0.05	0.06	0.01	0.01
Sb	0.09	0.03	0.042	0.16	0.35	0.062	0.71
Cs	0.09	0.06	0.039	0.28	0.61	0.12	0.29
Ba	37.09	12.87	21	55	65	35	30
La	6.91	1.99	3.52	11.1	19.7	4.93	13.3
Ce	15.11	4.26	7.8	24.7	40.2	9.14	24.2
Pr	1.48	0.48	0.7	2.45	n.d.	n.d.	n.d.
Nd	6.01	2.07	3.06	10.6	17.9	4.39	11.5
Sm	1.06	0.35	0.5	1.76	3.62	0.82	2.92
Eu	0.17	0.07	0.093	0.32	0.68	0.17	0.49
Gd	0.97	0.27	0.52	1.46	2.9	0.7	2.8
Tb	0.17	0.05	0.09	0.25	0.52	0.12	0.48
Dy	1.03	0.34	0.54	1.78	3.1	0.7	2.8
Er	0.64	0.17	0.41	0.97	n.d.	n.d.	n.d.
Tm	0.08	0.02	0.045	0.12	0.25	0.05	0.16
Yb	0.53	0.16	0.27	0.79	1.51	0.28	0.84
Lu	0.07	0.02	0.031	0.12	0.23	0.039	0.11
Hf	4.30	1.10	2.45	6.63	16.9	1.19	2.53
Ta	0.28	0.13	0.08	0.49	0.77	0.067	0.38
W	0.16	0.10	0.05	0.41	0.8	0.05	1.3
Ir (ppb)	0.04	0.08	0	0.2	<0.2	<0.1	<0.2
Au (ppb)	0.66	0.17	0.4	0.9	2.5	0.1	0.4
Hg	0.01	0.01	0	0.018	<0.04	<0.02	0.06
Pb	24.51	6.54	18.7	41.6	n.d.	n.d.	n.d.
Th	2.59	0.83	1	3.84	5.39	1.05	2.64
U	0.96	0.28	0.41	1.45	1.38	0.35	5.05
K/U	89.00	50.23	41.74	219.51	2319	3719	178
Zr/Hf	46.17	7.26	37.82	60.47	27.81	33.61	39.53
Zr/U	215.6	54.3	137.9	304.3	340.58	114.29	19.80
La/Sc	9.87	2.45	5.94	13.54	4.60	12.02	2.12
La/Th	2.73	0.35	2.23	3.52	3.65	4.70	5.04
Th/U	2.72	0.45	2.21	3.86	3.91	3.00	0.52
La_N/Yb_N	8.92	1.46	6.50	10.87	8.89	13.12	12.55
Eu/Eu*	0.51	0.06	0.43	0.65	0.64	0.69	0.52

Table 1
Chemical Composition of Libyan Desert Glass and Associated Surface Sands.

Data for Libyan Desert Glass averaged from analyses by Koeberl (1997). See text for details. Major element data in wt%, trace element data in ppm, except as noted. n.a. = not applicable; n.d. = not determined.
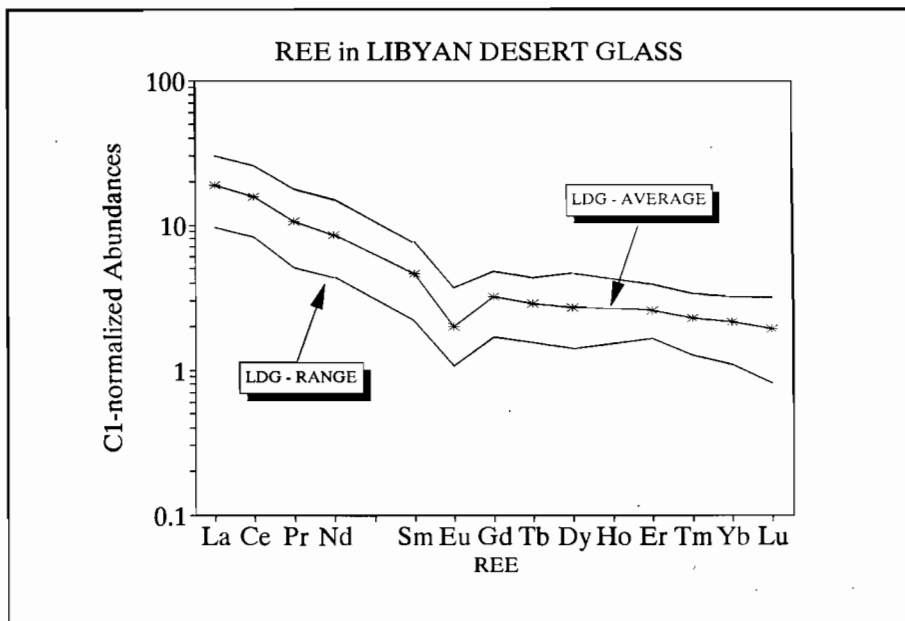
Fig. 3. Chondrite-normalized rare earth element (REE) abundance pattern for average LDG and its range. Normalization factors from Evensen *et al.* (1978), and Taylor and McLennan (1985).
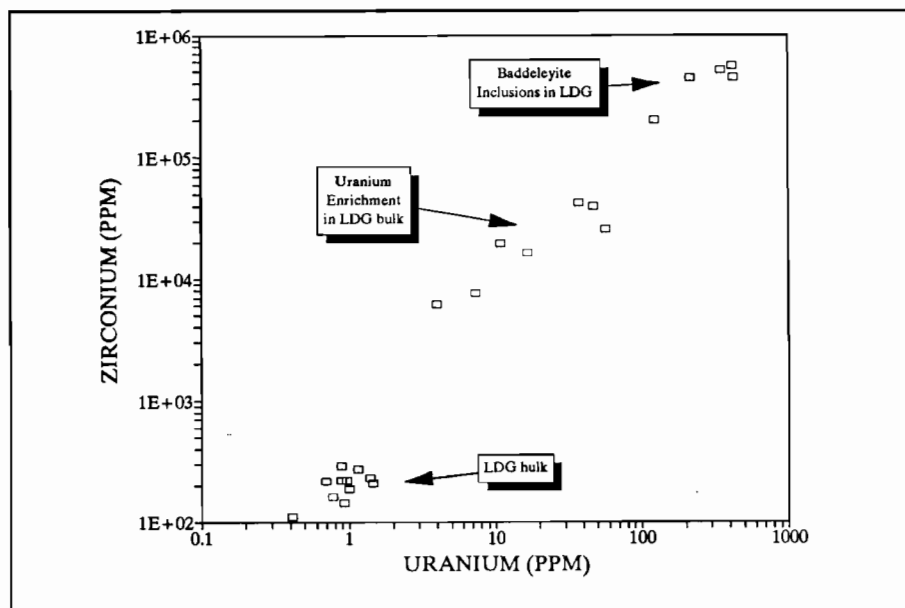

Fig. 4. Correlation of U and Zr in bulk LDG (data from Koeberl, 1985, 1997), baddeleyite inclusions (U=123-483 ppm), and U-rich zones (U=4.0-56.8 ppm); see Storzer and Koeberl (1991), and local sands and sandstone (from Murali *et al.*, 1988). It is evident that there is excess U in the bulk LDG that cannot be explained by a contribution from zircon alone. Modified after Storzer and Koeberl (1991).

Fig. 4 shows the results of the study of the uranium contents in the bulk LDG in comparison with uranium-rich zones, which has been reported by Storzer and Koeberl (1991). There is a clear positive correlation between the concentrations of U and Zr. Two main groups of Zr/U rich zones were found by Storzer and Koeberl (1991), with one type being high in Zr and U and coinciding with baddeleyite inclusions. Baddeleyite (ZrO$_2$) is a breakdown product of zircon and was described in LDG by Kleinman (1969), who also found some remnant zircon crystals that were only partly transformed into baddeleyite. The other group was not evident from optical microscopy, but was only found from the uranium enrichments in the glass, where Zr was found at the same locations that showed U enrichments. In both cases, the distribution of U (as determined from the fission tracks) and Zr follows flow structures and schlieren-like structures. This clearly indicates glass flow. In the case of the second group of Zr/U rich zones, the baddeleyite was already diluted in the flowing glass, and the structures of that flow are preserved. The mere fact of baddeleyite occurrence (which requires temperatures of 1500-2000 °C) and the unambiguous evidence for glass
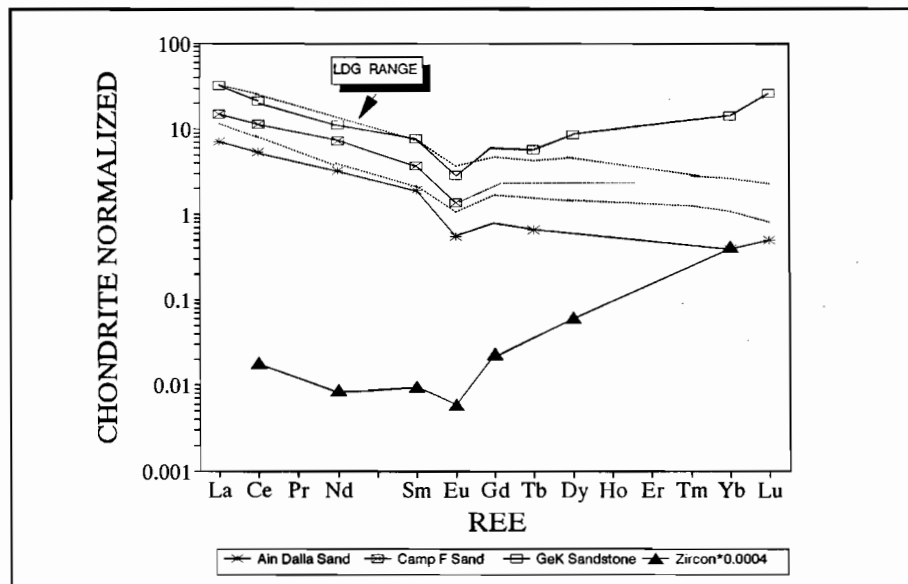
Fig. 5. Range of REE patterns in bulk LDGs (from Koeberl, 1985, and in prep.), and two local sands and one sandstone (from Murali *et al.*, 1988), compared with the pattern of zircon (Taylor and McLennan, 1985) recalculated to the level present if Zr in bulk LDG is solely derived from zircon.

flow are in clear contradiction to any low temperature origin.

The bulk U content of the LDG is about 10 times higher than what would be expected if all U would be supplied by zircon (cf. Taylor and McLennan, 1985). Fig. 5 shows the REE patterns of LDG (from Koeberl, 1985, 1997) in comparison with local sand and sandstone (from Weeks *et al.*, 1984), and the pattern of zircon (Taylor and McLennan, 1985). The zircon pattern has been recalculated to show the contribution to the REE pattern if all Zr in the LDG is supplied by zircon, indicating that zircon will only contribute about 5-20% to the REE abundances for the heaviest REE. The Camp F sand LREE pattern fits the LDG well; however, this sand cannot be the sole precursor, as evident from the Zr/U correlation. This is in line with Murali *et al.*'s (1988) conclusion, who suggested desert sand (e.g., similar to Ain Dalla sand) and surficial Fe-cemented alluvial or some Nubia sandstone as precursors.

Storzer and Koeberl (1991) suggested from their Zr/U and REE data that none of the sands or sandstones from various sources are good candidates to be the sole precursors of LDG. This is in agreement with the surface sand data shown in Table 1, which is not identical to the average LDG composition. Some admixture of monazite and/or apatite (e.g., from some type of sediment) seems likely to explain both the excess U and the REE patterns, although a better correlation is found with rocks from the BP and Oasis impact structures (see below).

Impact origin of Libyan Desert Glass

There is abundant evidence for an impact origin of LDG, and little or no evidence for a low-temperature origin. The evidence for an impact origin includes the presence of schlieren and partly digested mineral phases, lechatelierite (a high-temperature mineral melt of quartz), baddeleyite, a high temperature breakdown product of zircon (Kleinmann, 1969; Storzer and Koeberl, 1991). The REE abundance pattern does not show evidence for a low temperature process. The formation of blocks of clean homogeneous glass of the size of LDG is obviously a problem for an impact origin, but is not inconsistent with such an origin, as shown in a study by Klein *et al.* (1980).

The water content of LDG has recently been studied by Beran and Koeberl (1997). Their data for Libyan Desert Glass (0.055 to 0.155 wt% H_2O, 8 samples) are similar to those of

Gilchrist et al. (1969) and Frischat et al. (1982), who found values of 0.069 wt% (1 sample) and 0.137 to 0.180 wt% (4 samples), respectively, but the average of data of Beran and Koeberl (1997) at 0.116±0.042 wt% is lower than that determined by Frischat et al. (1982) at 0.164 wt%, which is in better agreement with an impact origin.

More important, though, is the existence of a meteoritic component in LDG (Murali et al., 1989; Rocchia et al., 1996; Koeberl, 1997). These authors have found that the contents of siderophile elements, such as Co, Ni, and Ir, are significantly enriched in some rare dark bands that occur in some LDG samples. To study such dark bands in more detail, detailed electron microprobe analyses were done across a dark zone, as shown in Pl. L a-b-c. This figure illustrates the cloudy and irregular nature of the dark bands in LDG, and shows flow and stress texture of the glass.

The results of the microprobe analyses are given in Table 2. The analyses were designated to determine Ni at the ppm level by very long counting times (20 minutes per spot) as well as monitoring the background (also by long counts on both sides of the peak). Fig. 6 shows the results: the contents of Fe, Mg, and Ni are high in the dark zone and low in the «normal» LDG. This co-variation can only be explained by a common source for those elements. Together with the observations of Murali et al. (1989), Rocchia et al. (1996), and Koeberl (1997) of high Ir contents in the dark zones, these data are only consistent with the presence of a meteoritic component. This is also in agreement with Re-Os isotopic data of dark bands in LDG (Koeberl, 1997); this method provides an unambiguous fingerprint of a cosmic component (compare Koeberl and Shirey, 1993).

Comparison with rocks from BP and Oasis structures

The BP impact structure is located in Libya at 25° 19' N and 24°20' E. It is named after the BP Exploration Company. The structure consists of two eroded and discontinuous rings of hills surrounding a central block, the S half of which is deeply eroded.

Table 2
Chemical Composition Across a Dark Band in Sample LYD 8501.

Major element data in wt%. Data for P, Mn, and Ni in ppm.

Distance (µm)	0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0
SiO_2	98.37	98.17	97.95	98.87	97.49	97.37	96.23	96.55	95.81	97.55	96.46
TiO_2	0.12	0.13	0.19	0.09	0.12	0.12	0.18	0.13	0.18	0.12	0.15
Al_2O_3	1.25	1.35	1.71	0.71	1.33	1.48	1.39	1.47	1.59	1.18	1.42
FeO	0.109	0.167	0.27	0.195	0.378	0.472	0.69	0.77	0.75	0.507	0.461
MgO	0.019	0.058	0.137	0.109	0.496	0.57	0.888	0.96	1.09	0.62	0.62
CaO	0.040	0.032	0.028	0.029	0.036	0.044	0.059	0.065	0.070	0.050	0.034
Na_2O	0.008	0.005	0.009	0.011	0.008	0.009	0.010	0.007	0.006	0.009	0.008
K_2O	0.010	0.010	0.009	0.011	0.012	0.011	0.015	0.011	0.009	0.012	0.011
Total	99.926	99.922	100.303	100.025	99.87	100.076	99.462	99.963	99.505	100.048	99.164
P	41	49	51	42	46	40	45	51	58	43	49
Mn	38	43	48	56	85	46	100	81	55	58	32
Ni	10	16	25	32	48	52	65	75	68	54	45
Fe	0.085	0.130	0.210	0.152	0.294	0.367	0.536	0.599	0.583	0.394	0.358
Mg	0.011	0.035	0.083	0.066	0.299	0.344	0.535	0.579	0.657	0.374	0.374
Fe/Mg	7.395	3.711	2.540	2.306	0.982	1.067	1.002	1.034	0.887	1.054	0.958
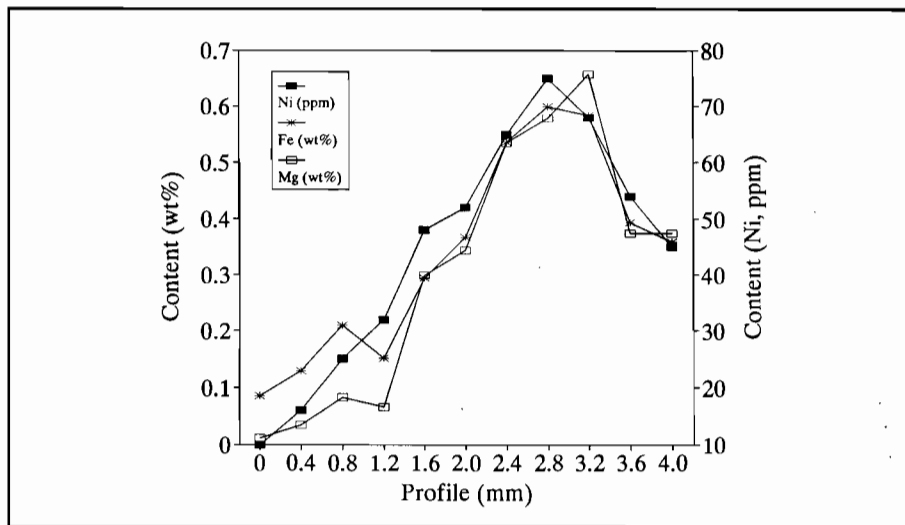
The inner ring is about 2 km in diameter with an average relief of 30 m, while the outer ring has a diameter of about 2.8 km and a maximum relief of about 20 m. Recent space-shuttle-radar studies show that the structure probably is 3.2 km in diameter, the outermost disturbed beds being covered by a thin veneer of sand (Underwood, 1975, 1976, French *et al.*, 1974, Underwood and Fisk, 1980). The rocks at the center of the structure show intense jointing. Rocks exposed are the Cretaceous (?) Nubia Group and include quartz sandstone, siltstone, and conglomerate. Medium- to coarse-grained quartz sandstone yielded shocked quartz grains with multiple sets of planar deformation features (PDFs) (French *et al.*, 1974). The geology of the structure has been studied in some detail (see, e.g., Underwood and Fisk, 1980).

The Oasis impact structure, also in Libya, is centered at 24°35' N and 24° 24' E. This eroded structure, named after the Oasis Oil company, has a diameter originally determined to be about 11.5 km, but the most prominent part is a central ring of hills, about 5.1 km in diameter and 100 m high. The diameter of Oasis, determined from radar images, is now estimated to be approximately 18 km (e.g., McHone *et al.*, 1995). Similar to the situation at the BP structure, a thin cover of sand obscures the outermost disturbed beds. The structure exposes the same rocks as the BP structure (ca. 85 km NNW of Oasis). As at BP, multiple sets of planar elements were detected in quartz grains (French *et al.*, 1974). As with the BP structure, the age of the Oasis structure is only constrained as younger than the target rocks, which are sandstones of the Nubia Group.

Abate *et al.* (1997) report on preliminary results of a study of the petrographical characteristics and geochemical composition of 29 samples from the BP and Oasis sites. Such a study is particularly desirable because of a possible association of the structures with the occurrence of Libyan Desert Glass (see below). Most of the samples (from both structures) were mostly submature, moderately to poorly sorted, medium to fine-grained quartzite sandstone, or quartzitic breccia. Most of the samples studied by Abate *et al.* (1997) did not show evidence of shock, but in a few sections some quartz grains with up to 3 sets of shock-characteristic planar deformation features were found, in agreement with earlier findings by French *et al.* (1974). The results available so far for the major and trace element composition of the BP and Oasis rocks indicate a limited range in composition of all analyzed samples (Abate *et al.*, 1997).

The geographic proximity of the BP and Oasis structures to

the LDG strewn field has previously led to speculation that one of them might be the LDG source crater. The geochemical studies of Abate et al. (1997) provide some background for such a comparison. These authors found a distinct similarity between the average compositions of LDG and rocks from both structures - BP and Oasis. For example, all have low alkali element contents, and quite similar interelement ratios. The chondrite-normalized rare earth element (REE) diagrams also show this similarity. However, the data available so far do not allow a firm conclusion regarding a connection between either the BP or the Oasis structures and LDG, because of the general similarity of all rock types in this area of Egypt and Libya. However, it is possible to conclude from the data of Abate et al. (1997) that LDG most likely formed from rocks that had compositions very similar to those found at both of these impact structures. Further chemical and isotopic work on the rocks from the BP and Oasis impact structures and should help to provide additional information regarding such a connection.

Conclusions

The origin of Libyan Desert Glass, a high-silica natural glass that occurs in the desert in western Egypt, has been enigmatic for some time. Various theories, ranging from production in a low-temperature (long-time) sol-gel process to an origin in a high-temperature (short-time) impact process have been proposed. Evidence for an impact origin includes the presence of schlieren and partly digested mineral phases, lechatelierite (a high-temperature mineral melt of quartz), baddeleyite, a high-temperature breakdown product of zircon. In addition, chemical studies show the existence of a meteoritic component in the glass.

In this study, data for the major and trace element composition of rare dark layers and streaks within LDG samples clearly indicate enrichments in the siderophile elements, including Ir. These enrichments, and enrichments of Mg, indicate the admixture of up to about 0.5 % of a chondritic component. The rare earth element abundance patterns are indicative of a sedimentary precursor rock. Although there is a similarity of LDG trace element composition with Nubian sandstone in general, there are some chemical differences between LDG and surface sands that were collected in the area of the LDG occurrences. Some preliminary comparisons of LDG compositions with rocks from the BP and Oasis (Libya) impact structures indicate a close similarity in composition between rocks from impact structures and the average LDG composition. In conclusion, an impact origin of LDG is consistent with all available data, although the question of the source crater is still not resolved.

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Libyan Desert Glass: geochemical composition and origin

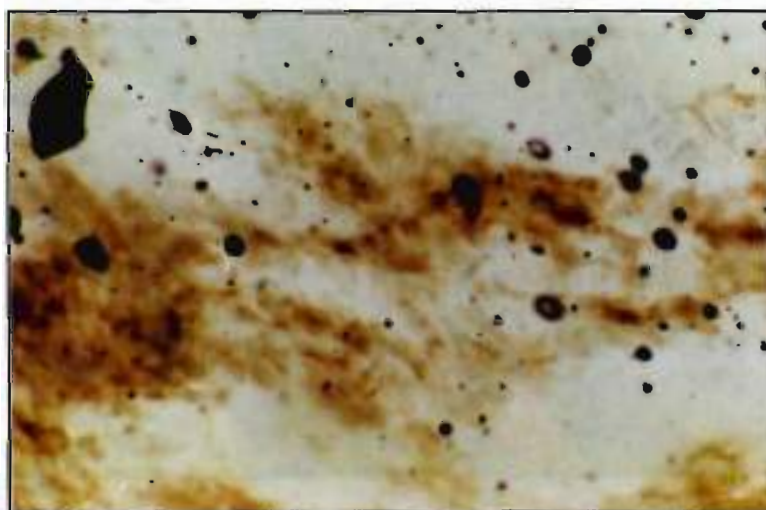*Pl.* L. Microphotographs of dark streaks across a sample of LDG (LDG-DG), transmitted light.

a) Dark bands occur as streaks in the glass; width of image: 2 mm.

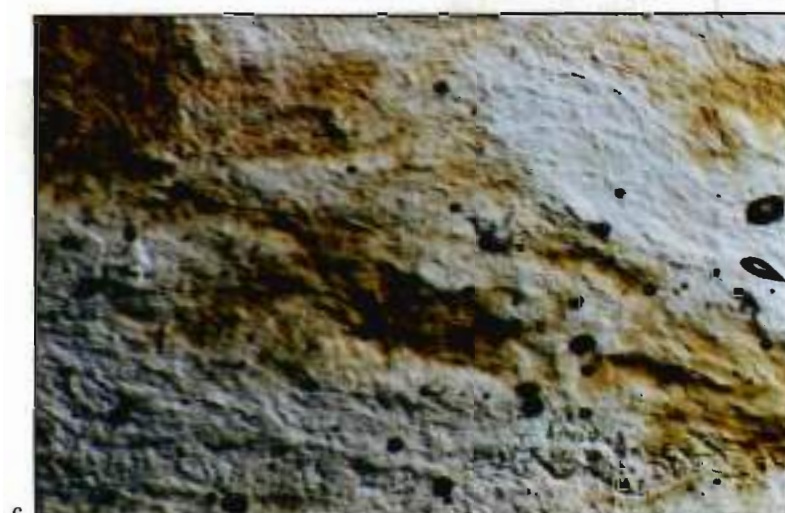b) Close-up (width of image, 0.8 mm) showing the cloudy nature of the dark bands.

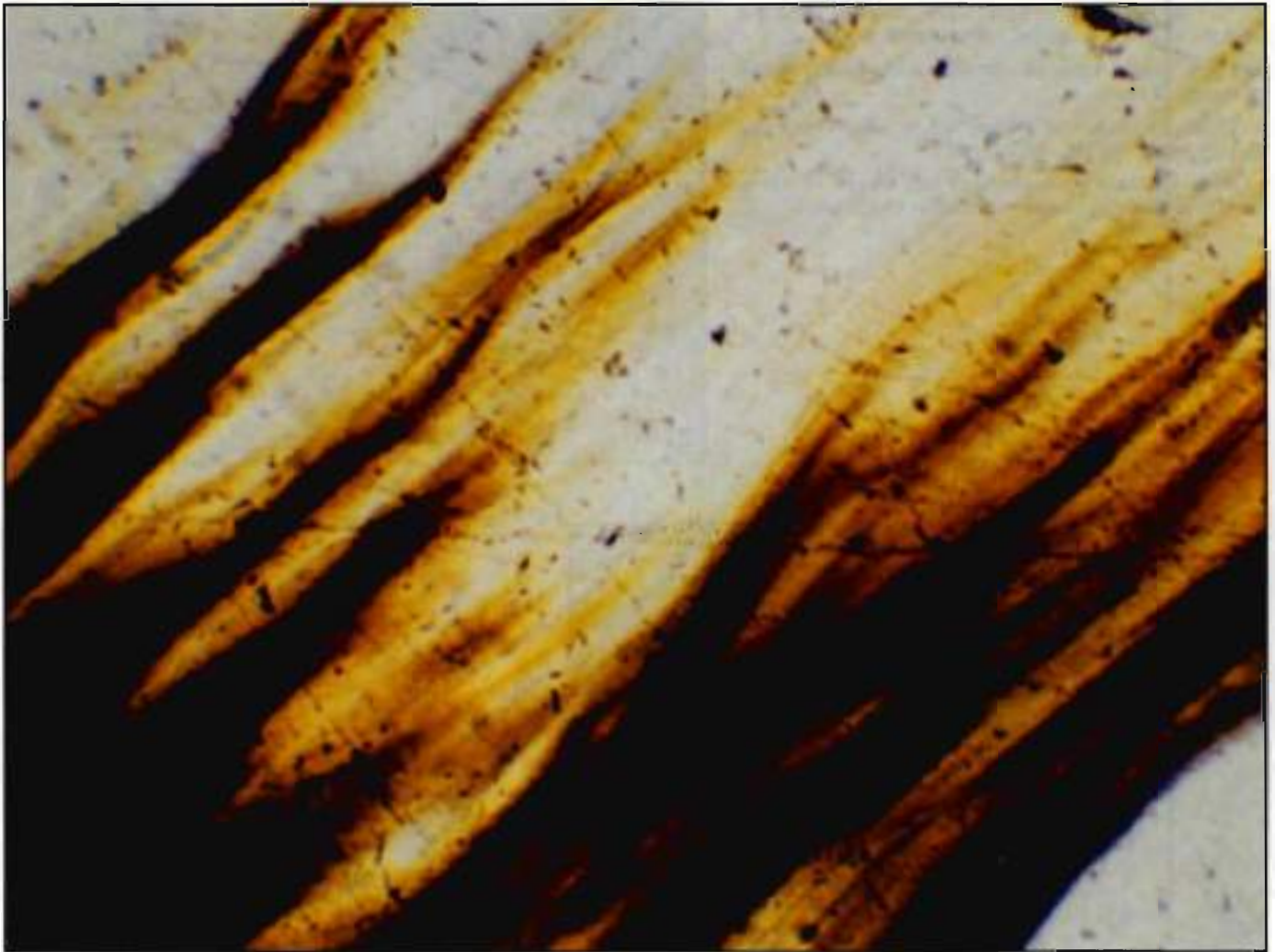c) Side-illuminated photograph (field of view, 1 mm) indicating the stress within the glass.
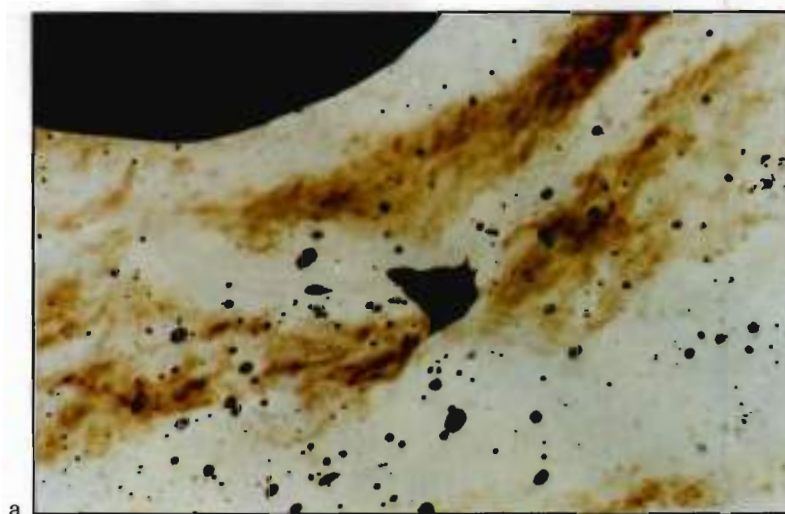
Chondritic debris in Libyan Desert Glass

Pl. M. Photomicrograph of dark streaks in LDG
(DSLDG-4; Type II variety in our classification; field of view measures 2 mm).

SAHARA

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