

# Libyan Desert Glass: geochemical composition and origin

Christian Koeberl<sup>1</sup>

## 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 zirconio). 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<sub>2</sub>, 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.*

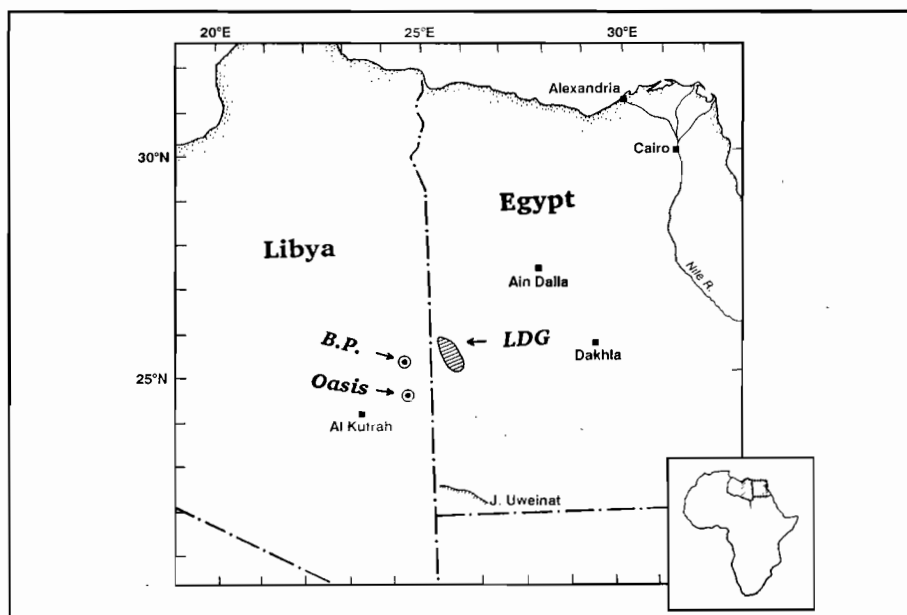
## Introduction

Libyan Desert Glass (LDG) is an enigmatic type of natural glass found in an area with an extension of about 6500 km<sup>2</sup>. 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

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

<sup>1</sup>Institute of Geochemistry  
University of Vienna  
Althanstrasse 14  
A-1090 Vienna (Austria)  
Fax: +43-1-31336-781  
e-mail: christian.koeberl@univie.ac.at



**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<sub>2</sub>, 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

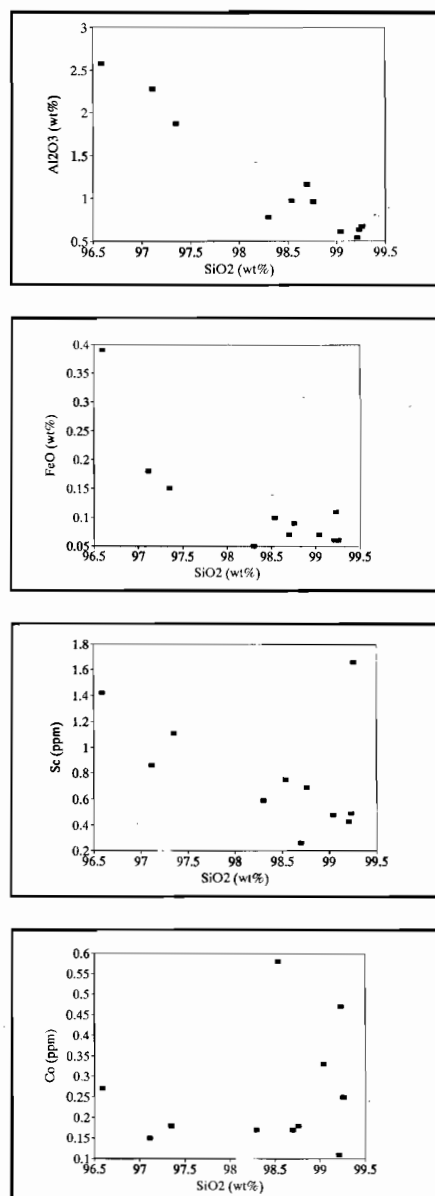
The geochemical studies on eleven LDG samples are discussed in detail by Koeberl *et al.* (1987); here, I present only some of the results. In short, major element compositions were determined by electron microprobe analyses, using an ARL SEMQ instrument at the University of Vienna, and with a Cameca 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).



	<i>Libyan Desert Glass</i>				<i>Surface Sand</i>		
	Average	Std.dev.	Min.	Max.	S-1	S-2	S-3
SiO <sub>2</sub>	98.37	0.89	96.59	99.26	86.81	98.25	65.59
TiO <sub>2</sub>	0.12	0.06	0.05	0.24	0.34	0.03	0.20
Al <sub>2</sub> O <sub>3</sub>	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
Na <sub>2</sub> O	0.005	0.001	0.003	0.007	0.10	0.05	0.02
K <sub>2</sub> O	0.009	0.003	0.006	0.014	0.40	0.23	0.21
P <sub>2</sub> O <sub>5</sub>	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 <sub>N</sub> /Yb <sub>N</sub>	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 Koerberl (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.

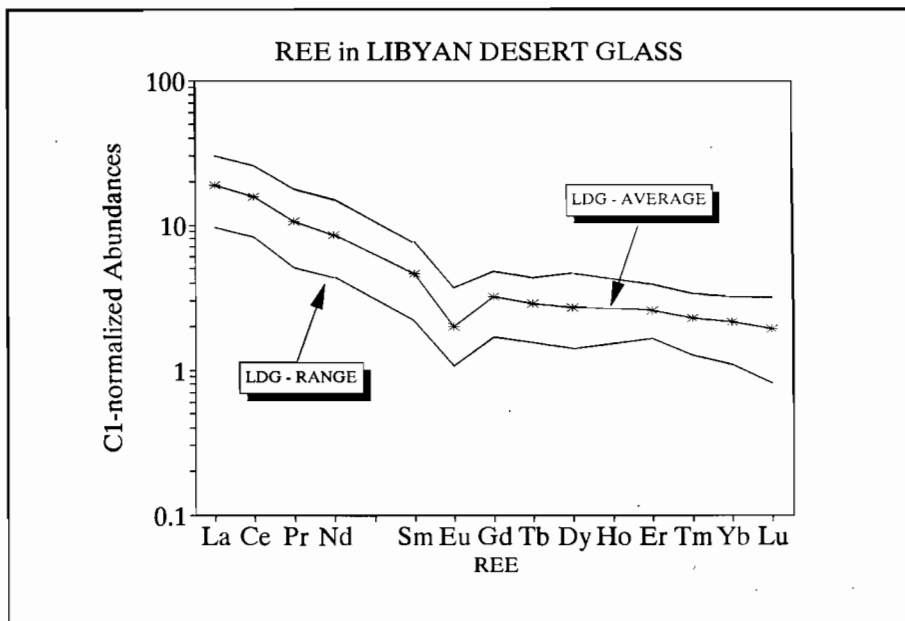


Fig. 3. Chondrite-normalized rare earth element (REE) abundance pattern for average LDG and its range. Normalization factors from Evensen *et al.* (1978), and Taylor and McLennan (1985).

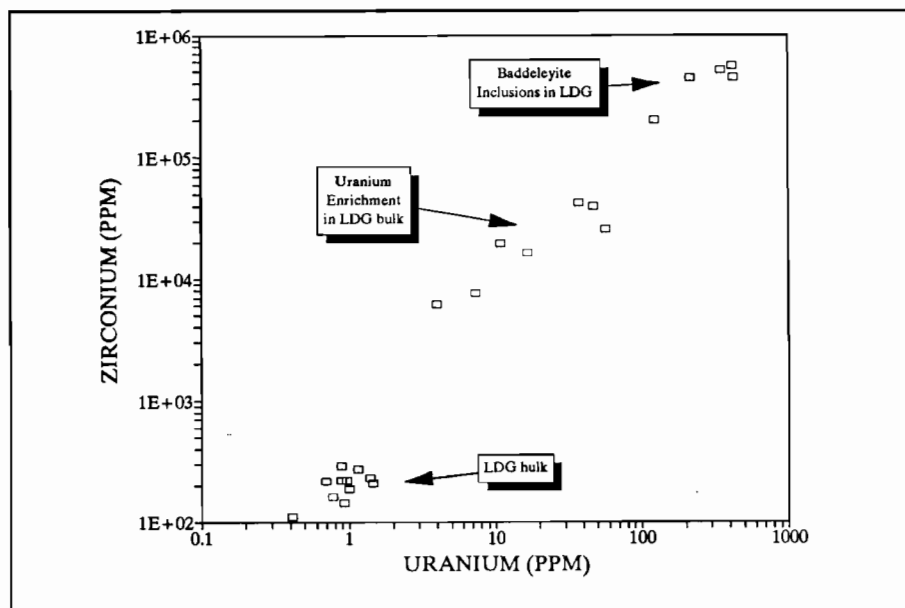


Fig. 4. Correlation of U and Zr in bulk LDG (data from Koerberl, 1985, 1997), baddeleyite inclusions (U=123-483 ppm), and U-rich zones (U=4.0-56.8 ppm); see Storzer and Koerberl (1991), and local sands and sandstone (from Murali *et al.*, 1988). It is evident that there is excess U in the bulk LDG that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

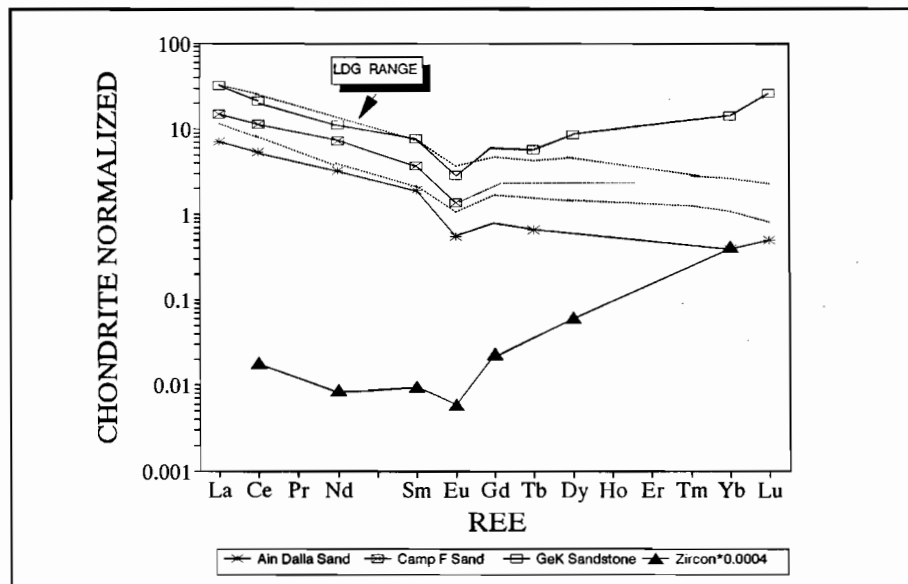


Fig. 5. Range of REE patterns in bulk LDGs (from Koeberl, 1985, and in prep.), and two local sands and one sandstone (from Murali *et al.*, 1988), compared with the pattern of zircon (Taylor and McLennan, 1985) recalculated to the level present if Zr in bulk LDG is solely derived from zircon.

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<sub>2</sub>O, 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  $0.116 \pm 0.042$  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 covariation 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 ( $\mu\text{m}$ )	0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0
SiO <sub>2</sub>	98.37	98.17	97.95	98.87	97.49	97.37	96.23	96.55	95.81	97.55	96.46
TiO <sub>2</sub>	0.12	0.13	0.19	0.09	0.12	0.12	0.18	0.13	0.18	0.12	0.15
Al <sub>2</sub> O <sub>3</sub>	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 <sub>2</sub> O	0.008	0.005	0.009	0.011	0.008	0.009	0.010	0.007	0.006	0.009	0.008
K <sub>2</sub> O	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

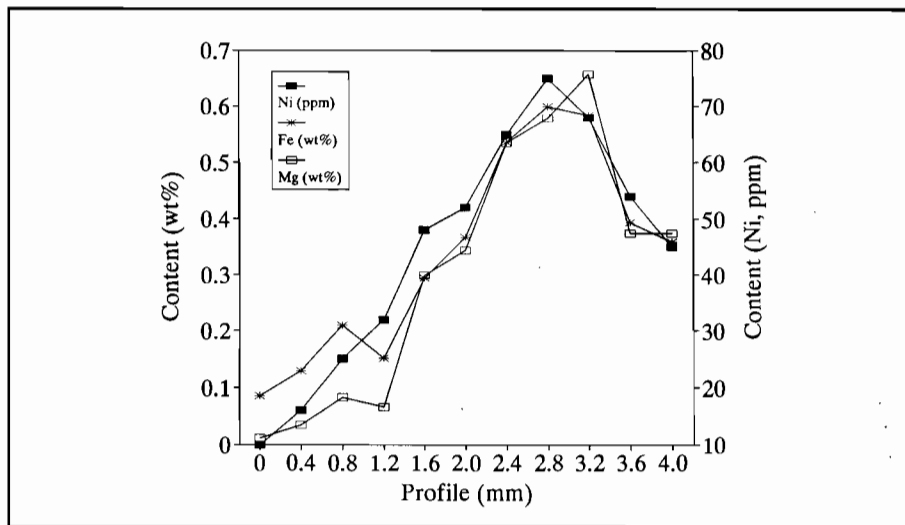


Fig. 6. Major element composition profile across the dark layer in LDG-8501, showing the covariation of Fe, Mg, and Ni, indicating a common source.

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.

## Acknowledgements

*Supported by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung (to C.K.). I am grateful to Prof. J. Underwood (Department of Geology, Kansas State University, USA) for samples of the BP and Oasis impact structures, to Prof. Th. Monod (Muséum d'Histoire Naturelle, Paris) and E. Diemer (Paris) for samples of Libyan Desert Glass and numerous discussions, and to D. Futrell (Los Angeles, USA) for some Libyan Desert Glass samples. Furthermore, I thank D. Jalufka (Vienna) for drafting a figure, and B. Abate (University of Vienna) for help with some measurements.*

## References

- ABATE B., KOEBERL C., UNDERWOOD J.R. JR., REIMOLD W.U., BUCHANAN P., FISK E.P. AND GIEGENGACK R.F., (1997, *in press*). BP and Oasis impact structures, Libya: Preliminary petrographic and geochemical studies, and relation to Libyan Desert Glass. *XXVIII Lunar Planet. Science Conf.*
- BAGNOLD R.A., 1933. A further journey through the Libyan Desert. *The Geographical Journal* (London), 82, 2: 103-129.
- BAGNOLD R.A., MYERS O.H., PEEL R.F. AND WINKLER H.A., 1939. An expedition to the Gilf Kebir and Uweinat, 1938. *The Geographical Journal* (London), 93, 4: 281-313.
- BARNES V.E., 1989. Origin of tektites. *Texas Jour. Sci.*, 41: 5-33.
- BARNES V.E., 1990. Tektite research 1936-1990. *Meteoritics*, 25: 149-159.
- BARNES V.E. AND UNDERWOOD J.R. JR., 1976. New investigations of the strewn field of Libyan Desert Glass and its petrography. *Earth Planetary Science Letters*, 30: 117-122.
- BERAN A. AND KOEBERL C., 1997 (*in press*). Water in tektites and impact glasses by fourier-transformed infrared spectrometry. *Meteoritics and Planetary Science*, 32.
- BIGAZZI G. AND MICHELE (DE) V., 1996. New fission-track age determinations on impact glasses. *Meteoritics and Planetary Science*, 31: 234-236.
- BODEN G. UND RICHTER E., 1984. Untersuchungen an Libyschem Wüstenglas mit Hilfe ionisierender Strahlung. *Chemie der Erde*, 43: 101-109.
- CLAYTON P.A. AND SPENCER L.J., 1934. Silica glass from the Libyan Desert. *Min. Mag.*, 23: 501-508.
- EVENSEN M.N., HAMILTON P.J. AND O'NIONS R.K., 1978. Rare-earth abundances in chondritic meteorites. *Geochim. Cosmochim. Acta*, 42: 1199-1212.
- FRENCH B.M., UNDERWOOD J.R. JR AND FISK E.P., 1972. Shock metamorphic effects in two new Libyan impact structures. *Geol. Soc. of America, Abstracts with Program*, 4: 510.
- FRENCH B.M., UNDERWOOD J.R. JR AND FISK E.P., 1974. Shock metamorphic effects in two meteorite impact structures, southeastern Libya. *Geol. Soc. of America Bull.*, 85: 1425-1428.
- FRESNEL F., 1850. Mémoire de M. Fulgence Fresnel sur le Waday - Suite (1). *Bull. Soc. Géogr.*, XIII: 82-116.
- FRIEDMAN I. AND PARKER C.J., 1969. Libyan Desert Glass: its viscosity and some comments on its origin. *Journ. Geophys. Res.*, 74: 6777-6779.
- FRISCHAT G.H., KLÖPPER C., BEIER W. UND WEEKS R.A., 1982. Glastechnologische Untersuchungen an Libyschem Wüstenglas. *Glastech. Ber.*, 55: 228-234.
- FRISCHAT G.H., KLÖPPER C., BEIER W. AND WEEKS R.A., 1984. Some properties of Libyan Desert Glass. *Journ. Non-Cryst. Solids*, 67: 621-628.
- FRISCHAT G.H., SCHWANDER R., BEIER W. AND WEEKS R.A., 1989. High-temperature thermal expansion of Libyan Desert Glass as compared to that of silica glasses and natural silicates. *Geochim. Cosmochim. Acta*, 53: 2731-2733.
- FUDALI R.F., 1981. The major element chemistry of Libyan Desert Glass and the mineralogy of its precursor. *Meteoritics*, 16: 247-259.
- GALEENER F.L., 1985. Raman and ESR studies of the thermal history of amorphous SiO<sub>2</sub>. *Journ. Non-Cryst. Solids*, 71: 373-386.
- GALEENER F.L., GEISSBERGER A.E. AND WEEKS R.A., 1984. On the thermal history of Libyan Desert Glass. *Journ. Non-Cryst. Solids*, 67: 629-636.
- GIEGENGACK R. AND ISSAWI B., 1975. Libyan Desert Silica Glass, a summary of the problem of its origin. *Annals Geol. Survey Egypt*, 5: 105-118.
- GILCHRIST J., THORPE A.N. AND SENFTLE F.E., 1969. Infrared analysis of water in tektites and other glasses. *Journ. Geophys. Res.*, 74: 1475-1483.
- JESSBERGER E. AND GENTNER W., 1972. Mass spectrometric analysis of gas inclusions in Muong Nong glass and Libyan Desert Glass. *Earth Planetary Science Letters*, 14: 221-225.
- JUX U., 1983. Zusammensetzung und Ursprung von Wüstengläsern aus der Großen Sandsee Ägyptens. *Zeit. dt. geol. Ges.*, 134: 521-553.
- KLEIN J., GIEGENGACK R., MIDDLETON R., SHARMA P., UNDERWOOD J.R. AND WEEKS R.A., 1986. Revealing histories of exposure using in situ produced <sup>26</sup>Al and <sup>10</sup>Be in Libyan Desert Glass. *Radiocarbon*, 28(2A): 547-555.
- KLEIN L.C., YINNON H. AND UHLMANN D.R., 1980. Viscous flow and crystallization behavior of tektite glass. *J. Geophys. Res.*, 85: 5485-5489.
- KLEINMANN B., 1969. The breakdown of zircon observed in the Libyan Glass as evidence of its impact origin. *Earth Planetary Science Letters*, 5: 497-501.
- KOEBERL C., 1985. Trace element chemistry of Libyan Desert Glass. *Meteoritics*, 20: 686.
- KOEBERL C., 1986. Geochemistry of tektites and impact glasses. *Ann. Rev. Earth Planetary Science*, 14: 323-350.
- KOEBERL C., 1990. The geochemistry of tektites: an overview. *Tectonophys.*, 171: 405-422.
- KOEBERL C., 1993. Instrumental neutron activation analysis of geochemical and cosmochemical samples. A fast and reliable method for small sample analysis. *J. Radioanalyt. Nucl. Chem.* 168: 47-60.
- KOEBERL C., 1994a. African meteorite impact craters. Characteristics and geological importance. *J. African Earth Sci.*, 18: 263-295.
- KOEBERL C., 1994b. Tektite origin by hypervelocity asteroidal or cometary impact: Target rocks, source craters, and mechanisms. In: B.O. Dressler, R.A.F. Grieve and V.L. Sharpton (Eds.), *Large Meteorite Impacts and Planetary Evolution*. GSA Special Paper, 293, 133-152.
- KOEBERL C., 1997 (*in preparation*). Geochemistry and origin of Libyan Desert Glass.
- KOEBERL C. AND BERAN A., 1988. Water content of tektites and impact glasses and related chemical studies. In: *Proc. XVIII Lunar Planet. Science Conf.*, Cambridge Univ. Press, pp. 403-408.
- KOEBERL C. AND SHIREY S.B., 1993. Detection of a meteoritic component in Ivory Coast tektites using rhenium-osmium systematics. *Science*, 261: 595-598.
- KOEBERL C., KLUGER F. AND KIESL W., 1987. Rare earth element determinations at ultratrace abundance levels in geologic materials. *J. Radioanalyt. Nucl. Chem.*, 112: 481-487.
- MATSUBARA K., MATSUDA J.-I. AND KOEBERL C., 1991. Noble gases and K-Ar ages in Aouelloul, Zhamanshin and Libyan Desert impact glasses. *Geochim. Cosmochim. Acta*, 55: 2951-2955.
- MCPHERSON D.M., 1984. *The thermal instability of Libyan Desert Glass*. MSc. Thesis, Alfred, New York: Alfred University, 49 p.
- MILLS A.A., 1968. Boron in tektites. In: L.H. Ahrens (Ed.), *Origin and distribution of the elements*,

- Pergamon Press, 521-531.
- MOORE C.B., CANEPA J.A. AND LEWIS C.F., 1984. Volatile nonmetallic elements in tektites. *Journ. Non-Cryst. Solids*, 67: 345-348.
- MORGAN J.W., HIGUCHI H., GANAPATHY R. AND ANDERS E., 1975. Meteoritic material in four terrestrial meteoritic craters. *Proc. VI Lunar Science Conf., Geochim. Cosmochim. Acta Suppl.* 6: 1609-1623.
- MÜLLER O. AND GENTNER W., 1973. Enrichment of volatile elements in Muong Nong-type tektites: Clues to their formation history? *Meteoritics*, 8: 414-415.
- MURALI A.V., ZOLENSKY M.E., CARR R., UNDERWOOD J.R. JR AND GIEGENGACK R.F., 1987. Libyan Desert Glass: Trace elements and gas inclusions. Geological Society of America, *Abstracts with Programs*, 19.
- MURALI A.V., ZOLENSKY M.E., UNDERWOOD J.R. JR AND GIEGENGACK R.F., 1988. Formation of Libyan Desert Glass. *Proc. XIX Lunar Planet. Science Conf.*: 817-818.
- MURALI A.V., LINSTROM E.J., ZOLENSKY M.E., UNDERWOOD J.R. JR AND GIEGENGACK R.F., 1989. Evidence of extraterrestrial components in the Libyan Desert Glass. *EOS Trans. Am. Geophys. Union* 70: 1178.
- NASRALLAH M.M. AND WEEKS R.A., 1984. Constraints on the fusion processes of some natural glasses. *Journ. Non-Cryst. Solids*, 67: 169-177.
- OAKLEY K.P., 1952. Dating the Libyan Desert Silica Glass. *Nature*, 170: 447-449.
- O'KEEFE J.A., 1976. *Tektites and their origin*. New York-Amsterdam: Elsevier, 254 p.
- OLSEN J.W. AND UNDERWOOD J.R. JR, 1979. Desert Glass: an enigma. *Aramco World Magazine*, 30, 5: 2-5.
- PAL D.K., TUNIZ C., MONIOT R.K., KRUSE T.H. AND HERZOG G.F., 1982. Beryllium-10 in Australasian tektites: Evidence for a sedimentary precursor. *Science*, 218: 787-789.
- ROCCHIA R., ROBIN E., FRÖHLICH F., MÉON H., FROGET L. ET DIEMER E., 1996. L'origine des verres du Désert Libyque: un impact météoritique. *C.-R. Académie des Sciences (Paris)*, 322, IIa: 839-845.
- ROE D.A., OLSEN J.W., UNDERWOOD J.R. JR AND GIEGENGACK R.F., 1982. A handaxe of Libyan Desert Glass. *Antiquity*, LVI: 88-92.
- SEEBEAUGH W.R. AND STRAUSS A.M., 1984. A cometary impact model for the source of Libyan Desert Glass. *Journ. Non-Cryst. Solids*, 67: 511-519.
- SEEBEAUGH W.R., KINSER D.L., HOFF R. AND WEEKS R.A., 1985. Cooling and crystallization rates of Libyan Desert Glass. *Journ. Non-Cryst. Solids*, 71: 387-395.
- SHAW H.F. AND WASSERBURG G.J., 1982. Age and provenance of the target materials for tektites and possible impactites as inferred from Sm-Nd and Rb-Sm systematic. *Earth Planetary Science Letters*, 60: 155-177.
- STORZER D. AND KOEBERL C., 1991. Uranium and zirconium enrichments in Libyan Desert Glass. Zircon, baddeleyite and high temperature history of the glass. *Proc. XXII Lunar Planet. Science Conf.*: 1345-1346.
- STORZER D. AND WAGNER G.A., 1977. Fission track dating of meteorite impacts. *Meteoritics*, 12: 368-369.
- STORZER D. AND WAGNER G.A., 1979. Fission track dating of Elgygytgyn, Popigai and Zhamanshin craters. No source for Australasian or North American tektites. *Meteoritics*, 14: 541-542.
- TAYLOR S.R., 1973. Tektites. A post-Apollo view. *Earth Sci. Rev.*, 9: 101-123.
- TAYLOR S.R., 1982. Planetary Science. *A Lunar Perspective*. Houston: Lunar and Planetary Inst., 481 p.
- TAYLOR S.R. AND MCLENNAN S.M., 1985. *The Continental Crust: its Composition and Evolution*. Oxford: Blackwell Scientific Publications, 312 p.
- UNDERWOOD J.R. JR, 1975. Reconnaissance geology of meteorite impact structures in SE Libya. *Geol. Soc. Am., Abstr. w. Programs* 7: 242.
- UNDERWOOD J.R. JR, 1976. Impact structures in the Libyan Sahara: some comparisons with Mars. *Proc. Intern. Coll. Planetary Geology, Geologica Romana*, 15: 337-340.
- UNDERWOOD J.R. JR, 1980. Meteorite from SW Egypt. No apparent connection with origin of Libyan Desert Glass. *Geol. Soc. Am., Abstr. w. Programs*, 12: 17.
- UNDERWOOD J.R. JR AND FISK E.P., 1980. Meteorite impact structures, Southeast Libya. In: M.J. Salem and M.T. Busrewil (eds.), *The Geology of Libya*, 3, 2. Symp. Geol. of Libya 1978 (London), p. 893-900.
- WEEKS R.A., NASRALLAH M., ARAFA S. AND BISHAY A., 1980. Studies of fusion processes of natural glasses by electron magnetic resonance spectroscopy. *Journ. Non-Cryst. Solids*, 38-39: 129-134.
- WEEKS R.A., UNDERWOOD J.R. JR AND GIEGENGACK R., 1984. Libyan Desert Glass: a review. *Journ. Non-Cryst. Solids*, 67: 593-619.
- YIOU F., RAISBACK G.M., KLEIN J. AND MIDDLETON R., 1984.  $^{26}\text{Al}/^{10}\text{Be}$  in terrestrial impact glasses. *Journ. Non-Cryst. Solids*, 67: 503-509.

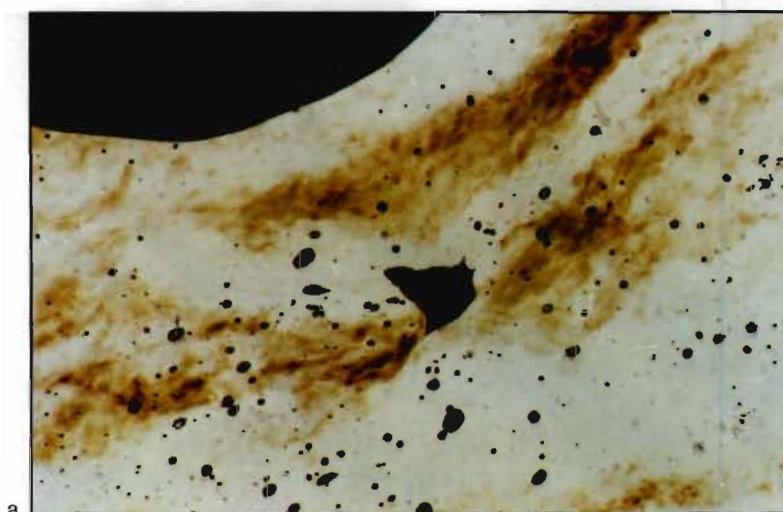
## Libyan Desert Glass: geochemical composition and origin

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

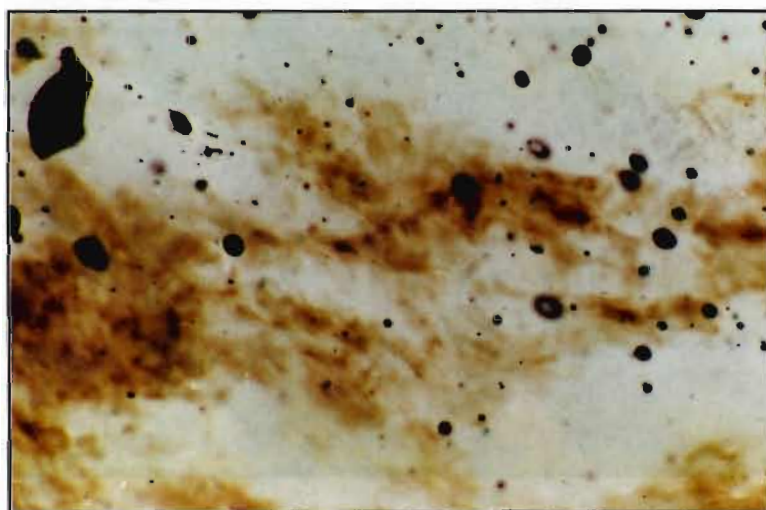
a) Dark bands occur as streaks in the glass; width of image: 2 mm.

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

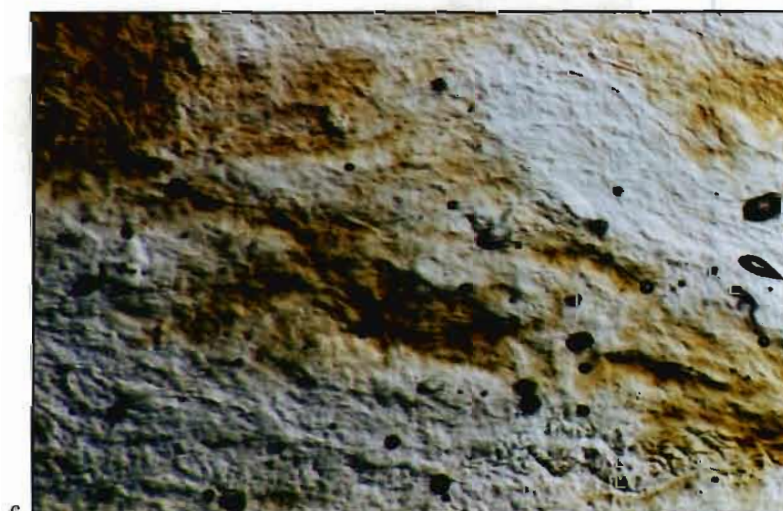
c) Side-illuminated photograph (field of view, 1 mm) indicating the stress within the glass.



a

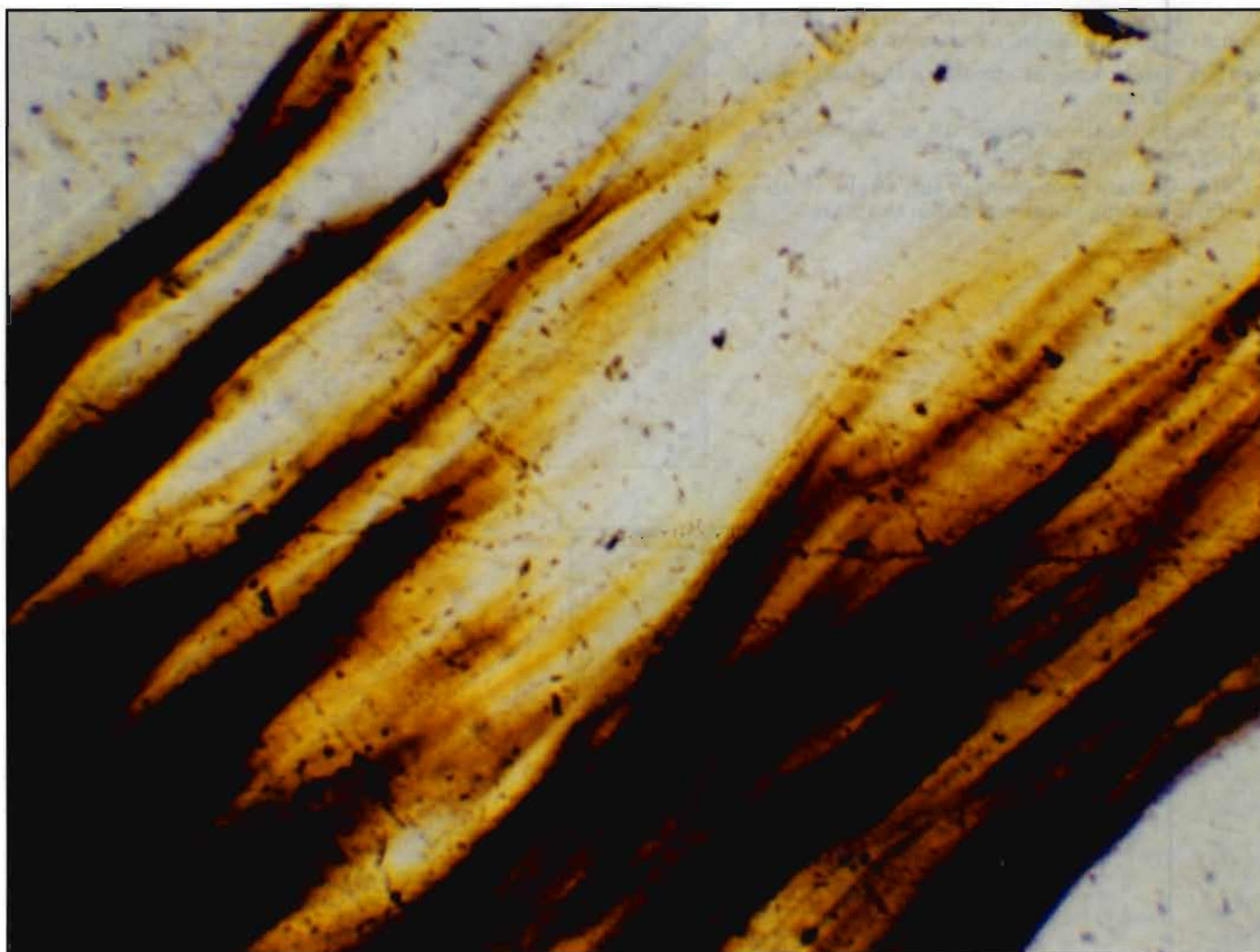


b



c

## 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).

---

SATARA

«**SILICA '96**»

Meeting on Libyan Desert Glass  
and related desert events

July 18, 1996  
Bologna University

Proceedings

Edited by  
Vincenzo de Michele



Centro Studi  
Luigi Negro



Pyramids  
Segrate (Milano) 1997

---