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Libyan Desert Glass: has the enigma of its origin been resolved?

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Abstract

Libyan Desert Glass is a silica-rich natural glass, found strewn over an area of ~ 6500 Km2, within the wide corridors between the sand dunes of the southwestern corner of the Great Sand Sea in western Egypt, near the Libyan border.
Since its discovery, allocation and mapping as early as 1932, the origin of the high silica Libyan Desert Glass still represents an unanswered enigma to all scientists and researchers. Different hypotheses have been proposed by many workers over the last seventy five years as to its origin and way of formation. It seems that modern, rather sophisticated science and technology means, including satellite imaging and supercomputer simulation have eventually been utilized to provide enough materialized support for the long suspected high temperature fusion process as being the responsible mechanism for the glass formation. Some of the recently obtained data on the subject is being elaborated herein.

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1. Introduction

The known Libyan Desert Glass (LDG) represents nowadays a rather peculiar, interesting and challenging type among natural glasses. This is because of its high purity and homogeneity on one hand, and its enigmatic origin and way of occurrence on the other hand.

LDG was first mentioned in 1850 [1] and became known, sited, investigated and scientifically documented only after its rediscovery by P. A. Clayton in 1932 [2]. Since its discovery, the mysterious glass has been and still the subject of many geological field studies and laboratory investigations and analyses. The results obtained from most of the studies and investigations led the majority of scientists to conclude that the glass was most likely originated through a high temperature impact of an extraterrestrial body into a sand or sandstone layer causing its fusion and subsequent solidification. But the absence of a nearby impact signature such as a crater, made some scientists believe that the melting process, could have occurred as a result of a low altitude explosion, of an extraterrestrial body generating a thermal pulse (airburst) causing the melting of surface and near-surface silica deposits.

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Up to date, nearly two hundred articles dealing with geological, chronological, chemical and physical data of the LDG have been published in scientific references including magazines, journals, proceedings and books. Among the most recent publications on the subject, supercomputer multiple simulations [3] and remote sensing [4] techniques have came up with scientific evidence supportive of the hypothesis of a high temperature fusion origin of the glass.

2. Appearance and chemistry

LDG is found strewn on the surface of the flat interdune corridors or streets of the southwestern corner of the Great Sand Sea, in the form of strongly wind-eroded, rounded to irregular fragments having broad ranges of sizes and masses. The glass fragments range in color from light yellow to light green to brownish green and from perfectly transparent to milky white. Occasionally, some glass pieces exhibit dark brown bands and streaks and / or white cristobalite spherulites, while others are clear, colorless and free from inclusions, if cut and polished, they make quite good gemstones [1, 2, 5, 6].

Excavation works indicated that the glass is found to a depth of ~ 2m [7]. The small-sized, rounded in shape fragments are found lying on the surface. Medium pieces are partially buried having their emerged faces being brilliantly wind-polished and soft, while their buried faces show finely-textured surfaces most likely due to solution etching. The larger pieces of block shape are usually buried and more angular [1]. Surface texture of LDG fragments show variations from the smooth, wind-polished surfaces characteristics of small-sized fragments to that exhibiting either one or any combination of surface textures such as facets, conical pits, complexly etched and finely-textured surfaces, solution-etched surfaces, grooves, impact fracture scars ……etc. [8].

Flow structure is quite evident in some glass pieces. Bubbles seem to adopt either elliptical form reflecting deformation of bubble during flow, or aligned, elongated and pointed form indicating deformation of pore space in material that barely melted. The fluidal structure is also characteristic of the layered dark brown bands and streaks [1, 2].

Chemically, LDG is uniquely characterized by its high silica content (~ 98 wt. %) as well as limited variations in major and minor elements concentrations. Results obtained by Fudali from bulk and microprobe analyses of four samples, selected from a large collection according to variations in color, were generally in good agreement with those obtained previously by Barnes and Underwood [5]. It was demonstrated that the glass is not entirely homogeneous on the microscale as bulk analyses would predict. While Al, Fe and Ti are uniformly distributed throughout the glass, and correlate well with one another in the Mg-free spots, Mg itself is confined within few locations and correlates only with Fe. The conclusion was that the parent material ought to be a sand or sandstone made of quartz grains coated with a mixture of kaolinite, hematite and anatase.

Weeks et al [8] in their review stressed the fact that the bulk chemical composition of LDG is almost the same as that of both the sandstone of the Nubia Formation underlying the Great Sand Sea and the quartz aggregates of the sand dunes. The homogeneity of LDG was again confirmed by Frischat et al [9], through the examination of four samples utilizing electron microscope and scanning electron microscopy. The OH concentration was determined to be between 1370 and 1800 ppm by the same authors utilizing infrared spectroscopy. When employing optical and electron optical techniques, on glass samples having dark brown bands, Frischat et al [10], observed relative inhomogeneity of the glass. The dark-brown streaks contained mainly Fe_2O_3, occasionally together with wollastonite ($CaSiO_3$) and cristobalite (SiO_2).

ICP-AES and ICP-MS were utilized by Barrat et al [11], to analyze the chemical composition of ten LDG samples, together with the Sr and Nd isotopic composition of another four samples. The results they obtained confirmed a close compositional similarity of LDG and mature sandstones. It was also concluded that the glasses are enriched with light rare earth elements, the contents of which correlate with the most abundant elements. This strongly indicates that the parent material was composed of quartz grains coated with a mixture of kaolinite and Fe-Ti oxides.

Cipriani et al [12] carried out micro-PIXE and ion beam ionoluminescence measurements on tow LDG samples containing brown streaks, and found that the clear portions contain considerable amounts of Si with Al, Zr, Sr, Ni, Fe and Mg as microconcentration elements. While the dark streaks are enriched with Fe and Mg, with an increment of Ni and depletion of Zr and Sr. They concluded that these features, together with rhenium-osmium isotopic data, and with the presence of iridium traces, indicate the fingerprint of a cosmic component.

Transmission electron microscopy coupled with energy dispersive spectrometer was used by Pratesi et al [13] to investigate the dark, brown or bluish streaks occasionally occurring in LDG. It was revealed that the amorphous spherules enriched in Al, Fe and Mg are homogeneously dispersed within the silica glass matrix. The dispersed spherules are also slightly enriched in Ca, Ti, Cr and Ni as compared to the matrix. The phases form an emulsion texture as a result of silicate-silicate liquid immiscibility.

Giuli et al [14] utilized Fe K-edge high resolution x-ray absorption near edge structure (XANES) spectroscopy, to conclude that the dark layers within some LDG samples contain higher Fe content in reduced state, suggesting that some or most of the Fe in these layers may be derived from an extraterrestrial origin (meteoritic projectile).

Backscattered electron images of LDG samples obtained by Gucsik et al [15] exhibited only weak brightness contrast indicating a homogeneous distribution of Al_2O_3 within the silica glass.

Koeberl [16] reported the enrichment of rare dark layers and streaks within LDG samples he investigated with siderophile elements mainly Ir, as well as rare earth elements. While the former is indicative of a chondritic component, the latter confirms a sedimentary parent rock.

Submicrometer-sized dust particles rich in siderophile (Fe, Co, Ni & Ir) elements have been reported by Murali et al [17] to dominate the dark streaks within some LDG fragments. Again, the enrichment of the LDG with meteoritic elements (Ni, Co, Fe, Cr, Ir, Ru, Rh, Pt and Pd) in chondritic ratios, together with the presence of rare earth and other lithophilic elements was also confirmed by Rocchaia et a [18].

3. Location and distribution

The area of occurrence of LDG was tentatively located and mapped for the first time by Clayton and Spencer since the early thirties of the last century [2]. More details about its location, the size and shape of the area over which the glass is scattered and the concentration of its surficial and subsurficial distribution, were collected, summarized and presented since then by many authors [1,8,13,16,19,20]. It is becoming clear that the glass is found strewn over an area of about 6500 km^2. It is mainly concentrated in a large ring-shaped area to the south of the Great Sand Sea, where the sandstones of the Cretaceous Nubia Formation cropout, and a smaller oval area to the north. For more details on the subject, information provided mainly in references [8, 13] would be of great value.

4. Geological age and stratigraphy

The formation age of LDG was estimated during the 1970′s and 1980′s by many researchers to be as early as 28.5 million years as an average. That was according to results obtained through fission-track analysis [8,11]. New experimental data, again through the fission-track dating technique obtained during the late 1990′s of the last century, confirmed the age estimated previously [13,14,21,22].

Geologically, and as a result of the remote location of the area of occurrence of LDG, together with logistic difficulties, and due to the harsh and subtle topography of its surroundings, and in spite of the many field expeditions to the area during the last few decades, some investigators [5], expressed caution regarding the lack of adequate details within issued reports about the general geology of the site where the glass is concentrated and its surroundings.

Weeks et al [8] reported the outcropping of scattered, highly polished Nubia Formation sandstone blocks within the interdune corridors. The latter are covered with alluvial-colluvial sediments deposited in what seem to be nowadays dry stream channels trending NE-SW. These deposits contain small- to medium-sized glass fragments, while larger glass pieces are notably concentrated in many places with the southern end of the area of glass occurrence. The glass transportation through fluvial action is also apparent. The authors concluded that the glass could have been formed at a surface which was stratigraphically higher than the present day ground level. In other words, the glass was not formed in the same place where it rests now.

Stratigraphically, both the sandstone and the silica-rich weathered debris of the Nubia Formation underlying and enclosing the LDG fragments, which are considered to be geochemically suitable source material for the glass, were most likely buried at about 400m underneath younger sediments of shale, siltstone and carbonate rocks, when the glass was formed 28.5 million years ago [8,23]. It was suggested that, the glass precursor material could have existed on or near a surface which was stratigraphically about 400m higher than the present ground surface [8], or alternatively, it is also possible that the glass was formed from another silica-rich rock formation within the whole of the Great Sand Sea area [23].

5. Thermal history and physical properties

Studying the role of melting history in microstructure of LDG, Merpherson et al [24], concluded that the glass was poorly annealed and exhibited high volume relaxation, as indicated by ~ 1% decrease in its linear thermal expansion between 1000 ad 1250ºC. They also observed that the glass undergoes high expansion and rapid crystallization when heated above about 1300ºC. Their conclusion was that LDG could not have stayed at elevated temperatures for long periods of time.

Seebaugh et al [25], used finite element analysis to calculate the thermal history of LDG, and based on the maximum obtained cristobalite grain spacing in different specimens, they got to the conclusion that glass sheets thicker than about 5m would completely devitrify during cooling. They estimated the melt-sheet thickness to be from 1.3 to 2.6m. The latter thickness would produce almost the same initial amount of glass estimated from field surveys of the glass distribution [8, 25].

Isothermal heat treatment and magnetic measurements carried out by Weeks et al [8], confirmed the oxidized state of iron within LDG fragments, which would indicate that the glass was fused and / or cooled in an oxidizing atmosphere similar to that of the earth and was cooled at a slow rate. The latter was also confirmed by thermal expansivity measurements.

Frischat et al [9], conducted dilatation properties determination and observed that the volume change over the temperature ranges covered (from – 180 to 1200ºC) varies from one sample to another. They came to the conclusion that a relatively open structure has been frozen in through cooling of the original melt at a rate higher than about 2k/min. The fictive temperature was estimated to be about 1200°C. The latter was deduced by Galeener and Geissberger [26] to be in the range of 1000 ±50ºC.

Annealing rates measurements results obtained by Galeener and Geissberger [26], revealed that the investigated glass samples, have not been chilled in seconds, nor they have cooled over long periods of time. High temperature dilatometery measurements conducted on different types of silica glasses proved that LDG behaves as does high temperature silica glass, and not in any way as low temperatures version of silica glasses.

Structurally, it is proved that LDG investigated samples exhibit virtually analogous Raman spectra to those obtained from almost pure silica synthetic glasses [26, 27]. IR spectroscopy also revealed that LDG is a typical anhydrous and amorphous silica glass [1]. It is quite obvious that the high silica content exhibited by LDG, would lead to highly viscous glass even at high temperatures. This could be the reason for the presence sometimes of excessive amounts of bubbles within the glass. The viscosity was estimated to be around 10^{13} poise at 1000ºC and 10^{10} poise at 1250ºC, which is lower than that of pure silica by two orders of magnitude [1]. The refractive index was found to range from 1.4600 to 1.4650, and the density from 2.20 to 2.206 g/cm^3 [1, 8].

6. Possible formation mechanisms

Since its discovery by the scientific community more than seventy years ago, and in spite of utilizing almost every possible and available theoretical, geological, experimental and simulatory piece of knowledge, scientists and researchers are not yet in full accord on the formative origin of LDG. Different formation hypotheses have been put forward by many scientists, including low and high temperature processes, as well as, terrestrial and extraterrestrial parent materials. But since the 1980′s, and after gathering enough experimental data, the majority of scientists started to believe that the glass has been originated through a high temperature fusion process, caused by an extraterrestrial body impacting a sand or sandstone medium in the Great Sand Sea area [1,5,7,10,11,13,14,16-21,28-34].

Defenders of the high temperature, hypervelocity shock event of an extraterrestrial body are supported by a huge wealth of visual and experimental findings including, the absence of aerodynamic molding of the glass fragments [28], results obtained through optical and electronoptical methods [10], presence of a meteoritic component in the glass, as revealed by ICP-AES and ICP-MS analyses, together with the Nd and Sr isotopic signatures of the LDG, which are consistent with the most likely target rock, the Nubia Group [11].

The high temperature impact origin of the glass is also supported by results obtained through fission-track analysis [21]. A high temperature fusion of a target sand or sandstone very rich in quartz is also confirmed by cathodoluminescence [29]. Mineral inclusions, mechanical deformations, fictive temperatures, thermal expansion and luminescence behaviors, together with iridium content and ratios of siderophile elements, are practical proofs for a high temperature formation mode [1,16,17,20].

The high temperature impact origin of the glass was once again confirmed through the absence of OH ions characteristic of amorphous silica produced at low temperatures, the absence of organic remains, the presence of lechatelierite (a pure silica inclusion), and the enrichment of the glass with meteoritic elements in chondritic proportions [14,18,33]. The same result is reached at through the use of NMR MAS analysis confirming the existence of all Si in fourfold coordination, and Al in four, five and sixfold coordination. Both findings indicate high temperatures and high pressures events [31]. Again, evidence indicating an impact origin for LDG is obtained through TEM investigations, which revealed that the colored streaks within the glass are the result of small glass spherules rich in Al, Fe and Mg forming an emulsion with the silica glass matrix resulting from silicate-silicate liquid immiscibility occurring on quenching from very high temperatures [13].

The less oxidized Fe in the dark layers within some glass samples, which are quite different from tektites, is believed to be of an extraterrestrial origin as do other meteoritic components within the glass, that is according to the results obtained using high-resolution x-ray absorption near edge structure (XANES) spectroscopy [14].

Lately, modern science and technology intervened in support of the hypervelocity, hyperenergetic impact or near impact event, which would have caused the fusion of the nearly pure quartz sand or sandstone terrestrial deposits. Originally, the intense, short-lived thermal pulse hypothesis was put forward because of the inability to identify at least the remains of the possible crater, which would have been created as a result of an extraterrestrial direct impact. The assumption that an atmospheric explosion could have created fireballs large and hot enough to produce the enigmatic glass was recently restressed by Boslough and Crawford [3], who carried out multiple simulations at high resolution utilizing Cray supercomputer at Sandia National Laboratories.

More recently, Landsat Enhanced Thermatic Mapper Plus (ETM+) images, Radarsat-1 data and Topographic information obtained by Shuttle Radar Topography Mission (SRTM), led to the conclusion that a meteorite impact could have created the crater named Kebira, and the shock of the highly energetic impact would have resulted in melting the quartz-rich sand or sandstone deposits at the impact site yielding the yet mysterious LDG [4].

7. Discussions

The proposed high temperature fusion mode of formation of LDG, caused by the impact of an extraterrestrial body, has been the most plausible mechanism among all others for a long time. Critics to such hypothesis raise many reservations including the absence of source crater, the type and composition of the precursor material exposed at the impact site surface when the glass was first formed 28.5 million years ago, the existence of blocks of clear, bubbles-free, homogeneous glass, which would have required very long times to be refined, and the obvious slowness of melting with depth, together the absence of breccias signatures in the glass due to dispersion of sand on impact.

The discovery most recently of the crater Kebira, Figs. 1 and 2, seem to have brought the long awaited answer to the formative clue of the glass. The crater size being the largest in the vicinity, its geographical location the nearest among others, and the topographical nature of the area which implies surficial fluvial drainage to the north or north-northeast within the southern part of the Great Sand Sea [35], are the possible answers for the site of occurrence and concentration of the glass in two different localities to the north-east of the crater site.

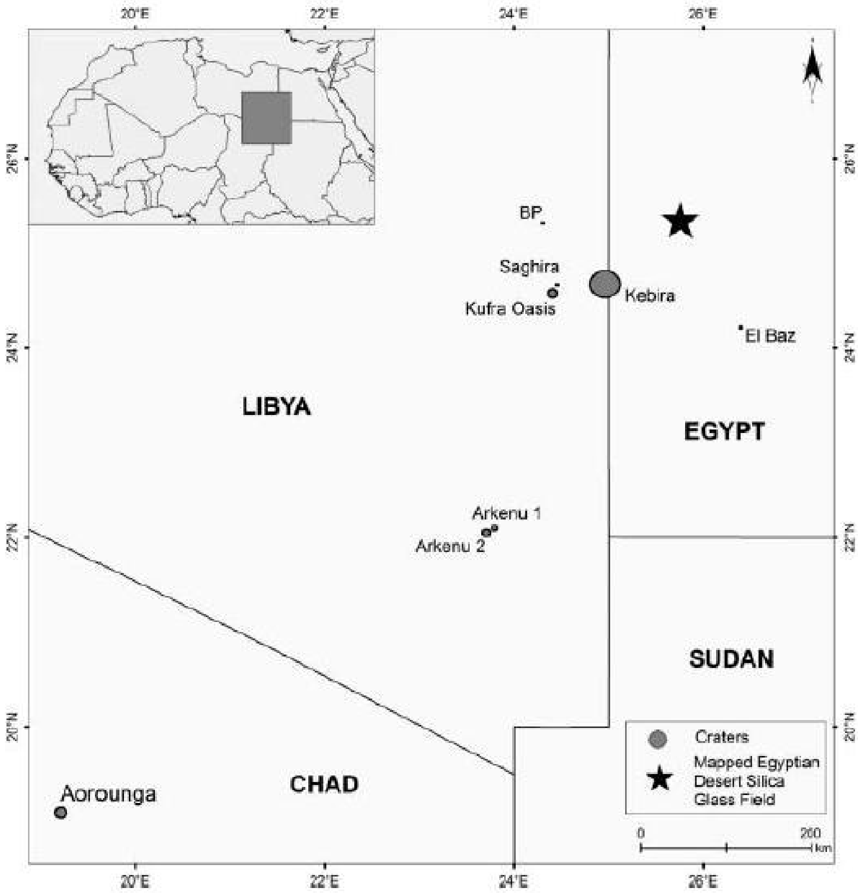

Fig.1. Location of the Kebira crater [Ref. 4]

8. Conclusions

Final confirmation that Kebira itself is truly an impact crater, and consequently it is the real and sole source of LDG should be established through field work and sampling from the proposed crater site, which no doubt requires that more effort and genuine work should be executed by earth and materials scientists among others within the scientific community. It is eventually left to the high temperature fusion hypothesis critics to examine, evaluate and make their final judgment in light of the available and forthcoming scientific evidence and knowledge.

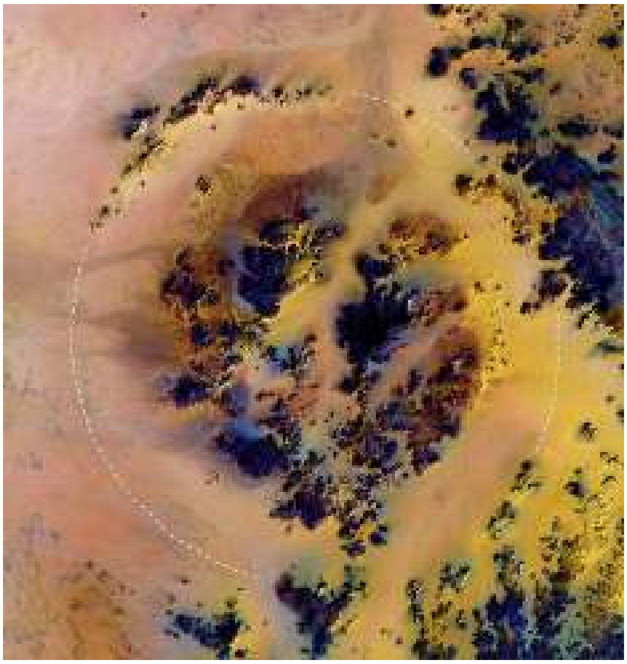

Fig.2. Landsat image of Kibera crater [Ref. 4]

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