IMPACT GLASS AT THE DAKHLEH OASIS, EGYPT: EVIDENCE FOR A CRATERING EVENT OR LARGE AERIAL BURST?

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Introduction: Impact cratering is an important geological process that affects all planetary objects with a solid surface. *Hypervelocity impact craters* (or meteorite impact craters) are the most visible product of hypervelocity impact. They form when a projectile is large and coherent (~20 m for an iron object and ~50 m for a stony body) enough "to penetrate the Earth's atmosphere with little or no deceleration and to strike the ground at virtually its original cosmic velocity (>11 km/s)" [1]. At smaller diameters, the projectile is slowed down by passage through the Earth's atmosphere and *penetration craters* are formed (e.g., the Sikhote-Alin crater field in Russia, formed from a meteorite shower in 1947). *Large aerial bursts,* or airbursts, are not well understood, but they represent an important class of impact event that either do not form craters, or which form very shallow structures that are easily erased [2].

In this study, we report on the discovery of unusual silicate glasses – the Dakhleh Glass (DG) – from the Dakhleh Oasis, Western Desert, Egypt. Recent work indicates that the Dakhleh Glass formed from an impact event ~150 ka during Middle Stone Age occupations [3]. However, no source crater has been recognized to date. Importantly, the glasses are not tektites, which leaves two possible explanations: (1) the glasses represent the proximal ejecta from an unknown source crater somewhere in the Dakhleh Oasis region, or (2) the glasses formed from a large aerial burst.

Dakhleh Oasis: The Dakhleh Oasis is a ~1200 km^2 wind-ablated depression in the central Western Desert of Egypt. The region comprises a series of Cretaceous to Eocene sedimentary rocks, predominantly sandstones, limestones, and shales, with minor siltstones and phosphatic horizons. These lithologies are unconformably overlain by a series of Pleistocene lacustrine sediments, predominantly calcareous silty sediments (CSS) [4]. The Dakhleh Oasis region has been the focus of geoarchaeological investigations by the Dakhleh Oasis Project (DOP) for over 25 years [5].

Dakhleh Glass: DG has been discovered at 6 locations in the Dakhleh Oasis region, separated by >40 km, in 2 main settings: as a lag deposit on the deflated surfaces of Pleistocene lacustrine sediments (Fig. 1a), and in situ within the same sediments (Fig. 1b). The geochemistry and micro-textures of the DG indicate that it formed during an impact event [3]: This evidence includes:

(1) *Geochemistry* – CaO and Al_2O_3 contents reach ~25 and ~18 wt%, respectively, which is unlike any known volcanic glass. Furthermore, there are no documented volcanic features within several hundred km of the Dakhleh Oasis.

(2) *Lechatelierite* – Glasses with SiO_2 contents of >90 wt% (i.e., lechatelierite) are found as enclaves and schlieren with the DG. The presence of lechatelierite, which forms at temperatures >1700 ^{o}C [6], rules out a formation of DG via the burning of vegetation or organic-rich sediments. Lechatelierite is restricted to impact melt-bearing materials.

(3) *Shattered quartz* – Intensely fractured quartz grains are ubiquitous in the DG. While not representing unequivocal shock metamorphic indicators, these shattered quartz grains similar to those observed in the target rocks of the Libyan Desert Glass, which formed via meteorite impact [7]. Similar shattered quartz is also common at the BP and Oasis impact structures, Libya [8]. Importantly, at Dakhleh, fractured quartz grains are only found in the Pleistocene lacustrine sediments, within which DG occurs [9].

(4) *Spherules* – The presence of isolated spheroids of pyrrhotite and calcite provide additional evidence for an impact melt origin of DG. Spherules of these phases have been documented at many terrestrial impact structures and are interpreted as immiscible globules [10, 11].

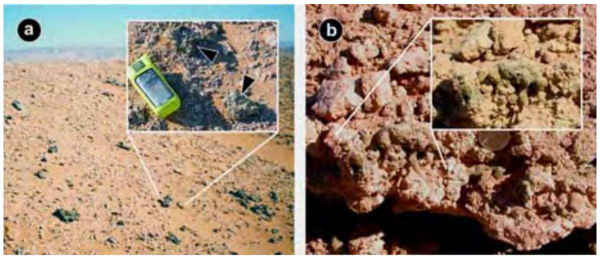

Figure 1. (a) DG up to ~15 cm across, occurring as a lag deposit on fine silts beneath a veneer of calcrete fragments. 15 cm long GPS for scale. (b) DG in-situ within Pleistocene lacustrine sediments. 2.5 cm diameter coin for scale.

Impact cratering event or large aerial burst? The impact origin of the DG has now been established [3]; however, no source crater has been discovered. Several possible features have been highlighted by remote sensing studies [12], and further fieldwork is planned. An impact cratering event is considered likely for several reasons. DG is very like impact glass found in the *proximal* ejecta deposits of many terrestrial impact structures: DG contains abundant clinopyroxene crystallites, lechatelierite, clasts of target rock, and globules of immiscible melt. In addition, the DG chemistry is most compatible with the melting of a wide range of different target rocks [3].

An airburst origin for the DG is supported by the (current) lack of a source crater and it may also account for the lack of unequivocal shock metamorphic indicators, which require relatively high shock pressures. Could an airburst the size of Tunguska have formed the DG? The Tunguska event occurred in 1908 when a comet or asteroid ~50–100 m in diameter, released its energy of ~15 MT (TNT equivalent; ~10^{16} J), at an altitude of ~5–10 km [13]. It is estimated that ~200 km^2 of forest was ignited by this event, but no melting of soils or rocks occurred [13]. Thus, a Tunguska-size event could not have formed the DG. Recent, numerical modeling of slightly larger airbursts (comet diameters 40–200 m), suggests that soil is only melted to a depth of 0.5 cm [14]. The lack of melting in Tunguska-size events led Wasson [2] to propose a "new" class of impact event; namely *large aerial bursts* (i.e., events in the energy range up to ~10^{19}–10^{20} J). While there remains no unequivocal evidence for a large aerial burst in the geological record, Wasson [2] has presented a convincing case that such events should occur, and that layered tektites may be the product.

Critical to this discussion of airbursts is projectile strength, which is directly related to the projectile type: stony bodies are typically weaker than iron meteoroids. Comets are most likely substantially weaker than asteroids [15]. Furthermore, observations of the asteroid Itokawa suggest that it is a rubble-pile body with a bulk density of 1.9 ± 0.13 g cm^{-3} [16]. Bland and Artemieva [15] investigated the rate of small impacts on Earth and found that stony projectiles <10^8 kg will deposit most of their energy in the Earth's atmosphere. This is considered to be the case for the Tunguska event. These authors also noted that cometary bodies with masses of 10^{10}–10^{12} kg do not reach the Earth's surface, but deposit their energy in the upper atmosphere. It is not clear if the surface effects from such an impact, or that of a rubble-pile asteroid, would be sufficient to melt significant amounts of target rock(s).

A further analogy for large aerial bursts may be nuclear weapons tests of the 1940's to 1960's, in which the device was detonated at altitudes ranging from a few 100 m to several km (Fig. 2). It is estimated that energy released from all the *underground* Nevada tests produced ~7 x 10^5 kg of high-silica melt glass per kiloton of yield [17] (e.g., "trinitite" from the 1945 Trinity Test). However, it is not clear how much melt is produced in *airbursts*, relative to underground events.

Figure 2. Photgraph of the Stokes Test at the Nevada Test Site, August 1957; test height ~500 m; yield 19 kt. Image: http://nuclearweaponarchive.org/index.html

Future directions: Further work is required to fully understand the effects at the Earth's surface of large aerial bursts. Further fieldwork is planned at Dakhleh to investigate whether this impact glass formed from such an event – in which case a rubble-pile asteroid or comet may have been responsible – or if a source crater lies undiscovered somewhere in the Dakhleh Oasis region. We also note that there are interesting similarities (e.g., lack of "typical" shock metamosphic indicators) to other impact glasses that lack confirmed source craters and that likely formed from volatile-rich target rocks (e.g., [7, 18])

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