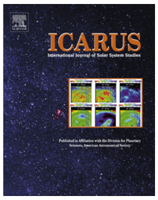
Icarus 257 (2015) 221–229

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Maskelynite in asteroidal, lunar and planetary basaltic meteorites: An indicator of shock pressure during impact ejection from their parent bodies

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ARTICLE INFO

Article history:
Received 15 December 2014
Revised 15 April 2015
Accepted 10 May 2015
Available online 16 May 2015

Keywords:
Moon
Mars
Asteroid Vesta
Impact processes
Collisional physics
Meteorites

ABSTRACT

Maskelynite is a diaplectic glass that forms from plagioclase at shock pressures of ∼20–30 GPa, depending on the Ca concentration. The proportion of maskelynite-rich samples in a basaltic meteorite group correlates with the parent-body escape velocity and serves as a shock indicator of launching conditions. For eucrites (basalts widely presumed to be from Vesta; $v_{esc} = 0.36\ \mathrm{km\ s^{-1}}$), ∼5% of the samples are maskelynite rich. For the Moon ($v_{esc} = 2.38\ \mathrm{km\ s^{-1}}$), ∼30% of basaltic meteorites are maskelynite rich. For Mars ($v_{esc} = 5.03\ \mathrm{km\ s^{-1}}$), ∼93% of basaltic meteorites are maskelynite rich. In contrast, literature data show that maskelynite is rare (∼1%) among mare basalts and basaltic fragments in Apollo 11, 12, 15 and 17 soils (which were never ejected from the Moon). Angrites are unbrecciated basaltic meteorites that are maskelynite free; they were ejected at low-to-moderate shock pressures from an asteroid smaller than Vesta.

Because most impacts that eject materials from a large (⩾100 km) parent body are barely energetic enough to do that, a collision that has little more than the threshold energy required to eject a sample from Vesta will not be able to eject identical samples from the Moon or Mars. There must have been relatively few impacts, if any, that launched eucrites off their parent body that also imparted shock pressures of ∼20–30 GPa in the ejected rocks. More-energetic impacts were required to launch basalts off the Moon and Mars. On average, Vesta ejecta were subjected to lower shock pressures than lunar ejecta, and lunar ejecta were subjected to lower shock pressures than martian ejecta.

H and LL ordinary chondrites have low percentages of shock-stage S5 maskelynite-bearing samples (∼1% and ∼4%, respectively), probably reflecting shock processes experienced by these rocks on their parent asteroids. In contrast, L chondrites have a relatively high proportion of samples containing maskelynite (∼11%), most likely a result of catastrophic parent-body disruption 470 Ma ago.

1. Introduction

Basalts are fine-grained igneous rocks composed mainly of Ca-rich plagioclase and Ca pyroxene. They have been observed as extrusive flows on large differentiated, planetary and sub-planetary rocky bodies including Mercury (Head et al., 2011), Venus (Jull and Arkani-Hamed, 1995), Earth (BVSP, 1981), the Moon (Heiken et al., 1991), Mars (Carr, 1973) and Vesta (McCord et al., 1970; Ammannito et al., 2013). Basaltic rocks available for laboratory study include samples from the Earth, Moon, Mars, and perhaps as many as seven asteroids – the eucrite parent body (probably 4 Vesta; e.g., Consolmagno and Drake, 1977; Binzel and Xu, 1993), the unidentified angrite parent body (e.g., Mittlefehldt et al., 2002), the unidentified mesosiderite parent body (Rubin and Mittlefehldt, 1992, 1993), and the plausibly separate parent bodies of the ungrouped meteoritic basalts NWA 011 (Yamaguchi et al., 2002), Ibitira and NWA 2824 (Mittlefehldt, 2005; Bunch et al., 2009), Asuka 881394 (Wimpenny et al., 2013), NWA 5721 (Bunch et al., 2011), and possibly others.

Shock effects in extraterrestrial basalts include brecciation, deformation of mineral crystal lattices, creation of high-pressure polymorphs of common minerals, the transformation of plagioclase grains into diaplectic glass (maskelynite) that retains the original grain shape, production of shock veins, and whole-rock impact melting (e.g., Bischoff and Stöffler, 1992). Although many shock effects in basaltic rocks were produced on their parent bodies by

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http://dx.doi.org/10.1016/j.icarus.2015.05.010
0019-1035/

hypervelocity impacts (e.g., Chao et al., 1970), some must have been produced during launch off their parent bodies (e.g., Stöffler et al., 1986; Artemieva and Ivanov, 2004). In this paper I argue that the proportion of samples containing maskelynite (Fig. 1) in a basaltic meteorite group is a unique indicator of the shock pressures engendered during launch of near-surface rocks to velocities exceeding those necessary to escape their parent body.

Plagioclase of An_{49} composition transforms into maskelynite at shock pressures $\geqslant$29 GPa (Stöffler et al., 1986); An_{94} plagioclase transforms at $\geqslant$20 GPa (Fritz et al., 2011). The higher the calcic content of plagioclase, the lower the shock pressure required to transform the plagioclase into maskelynite (Fig. 11 of Stöffler et al., 1986; Fig. 3 of Fritz et al., 2011). As pointed out by Fritz et al. (2011), this is due to the fact that more-anorthitic plagioclase contains more Al–O bonds (which are weaker than Si–O bonds) and can endure less confining pressure; thus, lower shock pressures are required for maskelynitization. Plagioclase in martian basalts ($An_{\sim 50}$; Meyer, 1996) would be maskelynitized at ~29 GPa; plagioclase in lunar basalts (generally An_{75-95}; Papike et al., 1991) at ~20–24 GPa; plagioclase in eucrites ($An_{\sim 90}$; Duke and Silver, 1967) at ~20 GPa; and plagioclase in angrites ($An_{\sim 100}$; Mittlefehldt et al., 2002) at ~20 GPa.

2. Results

2.1. Shock effects in unlaunched planetary basalts

Basaltic rocks that were never launched off their parent bodies are available from two sources: the Earth and Moon. The shock effects (or lack thereof) in these rocks form a baseline for comparisons to basaltic rocks that were ejected from their parent bodies by energetic impact events.

2.1.1. Earth

Terrestrial basalts occur as flood basalts on continents, in rift zones, ocean floors, island arcs and back-arc basins. They form massive shield volcanoes over stationary mantle hot spots; the prime example is Mauna Loa, the largest volcano on Earth, with an estimated volume of 7.5×10^4 km^3. Basalts also compose cinder cones – conical hills of pyroclastic debris that can form on the flanks of shield volcanoes.

The proportion of terrestrial basaltic rocks that exhibit shock effects is miniscule. The principal exception is basalt from the 1.8-km-diameter Lonar Crater in India. The crater lies within the Deccan Traps, an enormous province of flood basalt covering an area of ~500,000 km^2 in west-central India (Mahoney, 1988). Lonar basalts include such diverse shock products as microbreccias, suevite-like rocks, small impact-melt spherules, maskelynite, vesiculated plagioclase glass, and extensively fractured augite grains with shock-induced, closely spaced, twin lamellae (Fredriksson et al., 1973a,b; Fudali et al., 1980; Wright, 2008; Wright et al., 2011).

2.1.2. Moon

Apollo astronauts hauled back a total of 382 kg of lunar rocks and soil; the three Luna spacecraft brought back 0.32 kg. All of the shock effects exhibited by these samples were produced directly or indirectly by impacts on the Moon. Most Apollo mare basalts are weakly shocked or unshocked (e.g., Chao et al., 1970). Engelhardt et al. (1971) found that only ~4% (3 out of 79) of basaltic fragments >0.25 mm in size in Apollo 11 soil contain maskelynite. No maskelynite was found among 58 basalt fragments >0.25 mm in size in Apollo 12 soil (Engelhardt et al., 1971). Less than 1% of the grains with plagioclase compositions in Apollo 12 soil are maskelynite (Engelhardt et al., 1971). Steele et al. (1972) studied 26 Apollo 15 basaltic rake samples and reported "little evidence of shock" and no maskelynite. Neal and Taylor (1993) described 38 Apollo 17 rake samples of high-Ti mare basalts and reported no maskelynite. (Apollo 15, 16 and 17 rake samples have an average weight of 15.9 g and were collected from the soil with a rake having a 1-cm tine spacing; Allton and Bevill, 2003.) It appears that, volumetrically, very few small lunar mare basalts (3/201) were shocked on the surface of the Moon to pressures sufficiently high to form maskelynite (i.e., 20–24 GPa; Fritz et al., 2011).

The paucity of maskelynite is not confined to small lunar samples. Neal and Taylor (1993) described 54 high-Ti mare basalts (ranging in mass from 0.6 g to 8.1 kg and averaging 364 g) from Apollo 17 samples and did not report any maskelynite. In their overview of lunar rocks, Taylor et al. (1991) did not report maskelynite in any mare basalt. It appears that the proportion of maskelynite-bearing lunar basalts among Apollo samples is ~1%.

There is also a paucity of maskelynite in lunar anorthosites. For example, Fernandes et al. (2013) found no maskelynite among 12 feldspathic Apollo 16 rake samples that they examined.

2.2. Shock effects in basaltic meteorites

2.2.1. Lunar basaltic meteorites

As of this writing, there are 209 well-characterized lunar meteorites listed in the on-line Meteoritical Bulletin Database (MBD). Many of these specimens are actually different pieces of the same meteorite that broke apart in the atmosphere or after landing on Earth; these samples are "fall paired." I estimate the number of

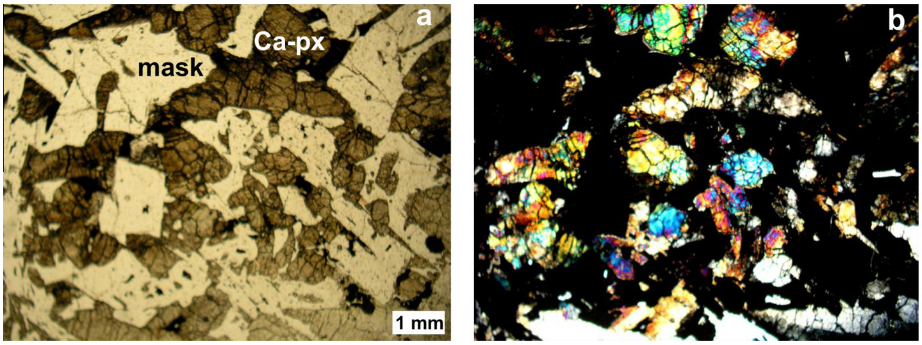

Fig. 1. Maskelynite (mask) and Ca-pyroxene (Ca-px) in the Los Angeles shergottite (stone 1). (a) Maskelynite appears clear and Ca-pyroxene appears yellowish brown to gray in microscopic images made in transmitted light. (b) The same region viewed in crossed polarizers (x-nicols). Maskelynite is isotropic and appears black as do all glasses when viewed using x-nicols. Ca-pyroxene is birefringent and appears yellow, green and blue in colored images. Both images are to the same scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)