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Report

Olivine–phyric martian basalts: A new type of shergottite

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Eighteen of the 26 meteorites believed to be martian rocks are classified as shergottites (Table 1). Shergottites are commonly divided into two types. Basaltic shergottites are pyroxene–plagioclase basalts, and lherzolitic shergottites are olivine–pyroxene cumulates derived from basaltic magmas (McSween and Treiman, 1998). However, five martian meteorites recently discovered in African deserts (Dar al Gani (DaG) 476, Sayh al Uhaymir (SaU) 005, Dhofar 019, Northwest Africa (NWA) 1068 and 1195) are olivine–phyric basalts. This martian rock type was previously known only in the form of lithology A of Elephant Moraine (EET)A79001 (classified as a basaltic shergottite), but is now emerging as a distinct, third

TABLE 1. Shergottites.*

Full name and probable pairings	Short name	Reference
Basaltic shergottites		
Shergotty	Shergotty	1
Zagami	Zagami	1
Elephant Moraine A79001 (lithology B)	EETA79001 (EET-B)	1
Queen Alexandra Range 94201	QUE 94201	1
Los Angeles	Los Angeles	2
North West Africa 480	NWA 480	3
North West Africa 856	NWA 856	4
Dhofar 378	Dhofar 378	5
Lherzolitic shergottites		
Allan Hills A77005	ALHA77005	1
Lewis Cliffs 88516	LEW 88516	1
Yamato 793605	Y-793605	1
Grove Mountains 99027	GRV 99027	6
YA 1075	YA 1075	7
Olivine–phyric shergottites†		
Elephant Moraine A79001 (lithology A)	EETA79001 (EET-A)	1
Dar al Gani 476/489/734/670/876	DaG 476	8–10
Sayh al Uhaymir 005/008/051/094/060/090	SaU 005	11–13
Dhofar 019	Dhofar 019	14–17
North West Africa 1068/1110	NWA 1068	18
North West Africa 1195	NWA 1195	19

*Compilation as of *Meteoritical Bulletin 85* (Russell *et al.*, 2002) and the 65th Meteoritical Society meeting abstract volume (*Meteorit. Planet. Sci.* **37 Suppl.**).
†Type name suggested in this report.
References: (1) McSween and Treiman (1998). (2) Rubin *et al.* (2000). (3) Barrat *et al.* (2002b). (4) Jambon *et al.* (2001). (5) Ikeda *et al.* (2002). (6) Lin *et al.* (2002). (7) Yanai (2002). (8) Zipfel *et al.* (2000). (9) Folco *et al.* (2000). (10) Mikouchi *et al.* (2001b). (11) Zipfel (2000). (12) Gnos *et al.* (2002). (13) Goodrich, unpubl. data (2002). (14) Taylor *et al.* (2000). (15) Mikouchi and Miyamoto (2001). (16) Lentz and McSween (2001). (17) Taylor *et al.* (2000). (18) Barrat *et al.* (2002a). (19) Irving *et al.* (2002).

type of shergottite. A variety of terms (*e.g.*, "mixed shergottite," "transitional shergottite" and "picritic shergottite") are currently being used in the literature to describe this new type. Here I suggest that we adopt the descriptive name "olivine–phyric shergottite".

The basaltic shergottites Shergotty, Zagami, Queen Alexandra Range (QUE) 94201, Los Angeles and NWA 480 (as well as recent finds NWA 856 and Dhofar 378, described only in abstracts) consist predominantly of clinopyroxene (pigeonite and augite) and plagioclase (now shock-produced glass or maskelynite), and have basaltic or diabasic textures. The absence of olivine (except for late fayalite) in these rocks and in crystallization experiments on their bulk compositions, as well as their low *mg#* (=100 × molar Mg/[Mg + Fe]) values of approximately 23–52, indicate that they crystallized from fractionated magmas (Stolper and McSween, 1979). Shergotty and Zagami contain cumulus pyroxene (Stolper and McSween, 1979; McCoy *et al.*, 1992). Crystallization experiments on their bulk compositions produce pyroxenes that are more magnesian than the natural ones, and show that they are not multiply saturated with pyroxene and plagioclase (Stolper and McSween, 1979). In contrast, QUE 94201 and Los Angeles may represent magma compositions. Their higher plagioclase contents relative to Shergotty and Zagami suggest that they are closer to multiple saturation (McSween *et al.*, 1996; Rubin *et al.*, 2000), and the zonation patterns of pyroxenes in QUE 94201 have been reproduced in experiments on its bulk composition (Mikouchi *et al.*, 2001a; McKay *et al.*, 2002).

The lherzolitic shergottites Allan Hills (ALH)A77005, Lewis Cliff (LEW) 88516 and Yamato (Y)-793605 (as well as recent finds YA 1075 and Grove Mountains (GRV) 99027, described only in abstracts) are cumulate rocks consisting predominantly of coarse-grained olivine and poikilitic pigeonite (McSween *et al.*, 1979a,b; Treiman *et al.*, 1994; Harvey *et al.*, 1993; Ikeda, 1994, 1997). Their plagioclase contents are much lower than those of the basaltic shergottites, they contain chromite in addition to the titanomagnetite found in the basaltic shergottites, and their bulk *mg#* values (~70) are much higher. Their modal mineralogy (40–60% olivine) dictates their classification as lherzolites. It is interesting to note, however, that their designation as shergottites came about unofficially. When ALHA77005 was discovered, McSween *et al.* (1979a,b) pointed out that its dominant mineralogy was consistent with early crystallization from inferred primary shergottitic magmas (only Shergotty and Zagami were known at this time), and suggested that it was a cumulate formed earlier than the shergottites from the same or a similar magma. The idea that ALHA77005 was closely related to the shergottites was generally accepted, and it came to be referred to in the literature as one of them (*e.g.*, Shergotty Consortium, 1986; Lundberg *et al.*, 1990). The explicit term "lherzolitic shergottite" became prevalent after the third of these rocks was recognized (*e.g.*, Ikeda, 1997). Although some authors (Treiman *et al.*, 1994) have argued against calling them shergottites (preferring "martian lherzolite"), "lherzolitic shergottite" is now widely accepted (*e.g.*, review by McSween and Treiman, 1998) and used in official meteorite descriptions (*e.g.*, Russell *et al.*, 2002).

EETA79001, though immediately considered to be a shergottite (McSween and Jarosewich, 1983) and now classified as a basaltic shergottite (McSween and Treiman, 1998), has always been recognized as unique. EETA79001 consists of two lithologies separated by an obvious contact (Steele and Smith, 1982; McSween and Jarosewich, 1983). Lithology B (EET-B) is a clinopyroxene–plagioclase rock resembling other basaltic shergottites. Lithology A (EET-A), however, is distinct from either the basaltic or the lherzolitic shergottites. It consists of megacrysts of olivine (Fo_{81-53}), orthopyroxene, and chromite in a fine-grained groundmass of pigeonite and plagioclase. Original descriptions of EET-A (McSween and Jarosewich, 1983; Steele and Smith, 1982) noted that its groundmass resembles the basaltic shergottites while its megacryst assemblage resembles lherzolitic shergottites, and petrogenetic studies of EET-A largely focused on modelling it as a mixture of these shergottite types. Textural and compositional characteristics of the olivines (corroded-looking shapes and irregular zonation contours) suggested disequilibrium with the groundmass, which (together with the fact that some composite olivine–orthopyroxene megacrysts were observed) led to the idea that these megacrysts are xenolithic remnants of assimilated ultramafic material. McSween and Jarosewich (1983) calculated that the groundmass of EET-A could be produced by mixing ~10% olivine, 26% orthopyroxene and 0.5% chromite with a magma similar to EET-B. However, Wadhwa *et al.* (1994) calculated that the energy required to assimilate 36% ultramafic material was more than could plausibly be provided by latent heat of crystallization. An alternative model discussed by McSween and Jarosewich (1983) and McSween (1985) was magma mixing, with the megacrysts originating as phenocrysts from one of the magmas. Wadhwa *et al.* (1994) proposed that a phenocryst-bearing magma similar to bulk ALHA77005 was mixed with a basaltic magma resembling EET-B. Mittlefehldt *et al.* (1999) showed that the lherzolitic endmember in such a model must be poorer in incompatible trace elements than bulk ALHA77005, and was therefore probably cumulate material with little or no trapped melt. Based on this conclusion, they argued that magma mixing is an implausible mechanism for forming EET-A, and suggested that the energy constraints of assimilation could be satisfied by impact melting. Although no one model has been generally accepted for the origin of EET-A, the idea that its megacrysts are in some sense xenolithic has, and some authors (*e.g.*, Treiman, 1995) have even referred to them as lithology X.

DaG 476, which was discovered in the Libyan Desert in 1998/1999, is a porphyritic olivine basalt consisting of large olivines, lesser orthopyroxene, and chromite grains in a fine-grained groundmass of pigeonite and plagioclase (Zipfel *et al.*, 2000), and was thus the first example of a lithology like EET-A to be found as a whole meteorite. Its similarities to

EET-A immediately led to its classification as a shergottite, and to discussion of mixing models for its petrogenesis (Zipfel *et al.*, 2000; Folco *et al.*, 2000; Mikouchi *et al.*, 2001b; Wadhwa *et al.*, 2001). However, in the case of DaG 476, a xenolithic origin for its megacrysts seems less compelling. For example, it has a higher abundance of olivine crystals (25 *vs.* 12 vol%), most of which are euhedral or subhedral, and composite olivine–orthopyroxene megacrysts have not been observed. Furthermore, olivine compositions are more restricted (Fo_{79-62}) and disequilibrium with the groundmass is less pronounced. Zipfel *et al.* (2000) argued that DaG 476 cannot be modeled as a mixture of known lherzolitic and basaltic shergottites because its *mg#* and abundances of many trace elements (Ni, Co, Cr, Sc, Zn, Na, Ga) are nearly as high as in the lherzolitic shergottites, and concluded that its olivine and chromite are probably phenocrysts rather than xenocrysts. Nevertheless, as discussed by Mikouchi *et al.* (2001b) and Wadhwa *et al.* (2001), bulk DaG 476 cannot be a melt composition because olivine crystallizing from such a melt would be considerably more magnesian that that observed in the rock.

SaU 005 was found in the desert of Oman approximately a year after the discovery of DaG 476 in Libya. It is similar to DaG 476 in texture and mineral compositions, bulk chemical composition, and exposure age (Zipfel, 2000; Dreibus *et al.*, 2000; Gnos *et al.*, 2002; Goodrich, 2002, unpubl. data). Nevertheless, detailed petrographic differences between the two meteorites (Gnos *et al.*, 2002; Goodrich, 2002, unpubl. data), and the large distance between the two sites at which they were found (Zipfel, 2000), indicate that they are not paired.

Dhofar 019 was found in Oman in 2000. First descriptions showed that it is mineralogically and texturally similar to EET-A, DaG 476 and SaU 005 (Taylor *et al.*, 2000; Mikouchi and Miyamoto, 2001), except that its olivines are much smaller than in those rocks and the megacryst/groundmass distinction is less pronounced (Lentz and McSween, 2001). Nevertheless, apparent chemical disequilibrium between the most magnesian olivine (Fo_{60}) and pyroxene (*mg#* = 70) suggested that the olivine might be xenocrystic (Taylor *et al.*, 2000). Further investigations, however, revealed larger olivines zoned from ~Fo_{72} cores to Fo_{44} rims, suggesting that Dhofar 019 may be the product of a strongly fractionally crystallized magma (Cahill *et al.*, 2002), or of open-system crystallization involving influx of more magnesian melt (Lentz and McSween, 2001).

NWA 1068 was found in the Moroccan Sahara in 2001 (Barrat *et al.*, 2002a). Like DaG 476 and SaU 005, it has a porphyritic texture of olivine crystals (Fo_{72-42}) in a fine-grained pigeonite–plagioclase groundmass. Barrat *et al.* (2002a) note that the olivines appear broken and corroded, and suggest that they are xenocrysts derived from disrupted cumulates similar to lherzolitic shergottites.

The most recently discovered olivine–phyric martian basalt, NWA 1195 (obtained in Morocco in 2002) is particularly notable in that its olivines show the same compositional range as in EET-A (Irving *et al.*, 2002). However, in contrast to EET-A, most olivine grains are euhedral to subhedral, suggesting that they are phenocrysts. Irving *et al.* (2002) proposed that this sample represents the least magmatically evolved martian lava yet discovered.

Despite the fact that only first descriptions are available for some of these shergottites, it is clear that EET-A, DaG 476, SaU 005, Dhofar 019, NWA 1068 and NWA 1195 share petrographic features (olivine–porphyritic textures, presence of chromite in addition to titanomagnetite and ilmenite, and low augite contents) that distinguish them from both the basaltic and lherzolitic shergottites. Although they can technically be classified as basaltic shergottites on the basis of modal plagioclase abundance, this classification obscures their essential differences from rocks such as Shergotty and QUE 94201. Other terms such as "mixed," "transitional," "picritic" and "olivine–phyric basaltic" shergottite have been used to describe them in recent papers and abstracts. Clearly, some of these terms have petrogenetic implications, which in my view is not appropriate. Our understanding of the petrogenetic processes by which these rocks formed, and their petrologic and geochemical relationship to the basaltic and lherzolitic shergottites, is still young. The evidence for mixing in EET-A has naturally suggested similar origins for the others. However, these rocks differ from one another in the abundance, compositions and textures of their olivine, the presence or absence of orthopyroxene, and degree of apparent disequilibrium between olivine crystals and groundmass. These differences have suggested petrogenetic models other than mixing. These meteorites should be designated by a simple name that is descriptively meaningful and does not have petrogenetic implications. "Olivine–phyric shergottite" meets these requirements.

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