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METEORITIC BASALTS: THE NAKHLITES, THEIR PARENTAL MAGMAS,
COOLING RATES, AND EQUIVALENTS ON EARTH

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1 SUMMARY

Funding for NASA grant NAG 9-168, titled "Meteoritic Basalts: the Nakhrites, their Parental Magmas, Cooling Rates, and Equivalents on Earth," was received at Boston University on July 1, 1986. Work on the grant began immediately, concentrating in three areas of the proposal: field study in Ontario, attendance at a scientific conference, and experimental petrology. Field work in Canada was successful in finding rocks similar to the nakhrites, and in teaching me about possible tectonic settings for the nakhrites. Attendance at the Geological Society of America conference was fruitful because of the many talks devoted to studies of cumulate igneous rocks. Laboratory work has progressed slowly, but has yielded an important constraint on the oxygen fugacity of nakhrite crystallization.

2 FIELD STUDY

Field study in northern Ontario was planned to compare cumulate rocks reported in the literature with the nakhrites in order to study the crystallization rates of the nakhrites and their possible geological settings. Three weeks were spent in the field in late July and early August, 1986, near Timmins, Ontario. Rocks studied were in the Abitibi greenstone belt (Archaean age). There, I collected suites of rocks from two areas, Munro and Dundonald townships. Augite rich cumulate rocks were reported in both areas, and I was able to collect many samples and verify reported field relations. Upon return to Boston, preparation of thin sections was begun. I have in hand and have examined thin sections of 20 of the most critical rocks; the remainder are in progress.

One occurrence of augite-rich cumulate rocks (in Munro township) is in the lower half of a 125 meter thick flow [Arndt, 1977]. The texture of this rock (Figure 1) is very similar to that of Nakhla (Figure 2) and of Governador Valadares [Berkley et al., 1980]. Both meteorites have more coarsely crystalline mesostasis (among the cumulus augite) than the Munro sample, suggesting that the meteorites cooled more slowly than the Munro flow. Likely geologic settings for Nakhla and Governador Valadares are thick flows (>200 meters ?) or very shallow intrusions (probably less than 100 meters deep).

Another occurrence of augite-rich cumulates is in the Dundonald township, where they form the middle third of a differentiated peridotite-pyroxenite-gabbro sill [Naldrett and Mason, 1968]. The augite cumulates from that sill have adcumulate textures, with little or no mesostasis material among the augite (Figure 3). This texture is very similar to that of Lafayette (Figure 4), suggesting that Lafayette formed in a similar sill. Depth of emplacement of the Dundonald sill is probably less than a kilometer.

Based on this field work, I am more confident of my previous conclusions [Treiman, 1986] that the nakhrites formed in a volcanic to sub-volcanic setting. Such arguments are presented in the accompanying abstract submitted to the 18th Lunar and Planetary Science Conference.



Fig. 1. Augite cumulate from flow. Thin section in plane light, 4 cm vertical size. Augite crystals in dark, altered glass (?).



Fig. 2. Nakhla meteorite, thin section in plane light, 2.3 cm vertical size. Euhedral augite crystals in finely crystalline mesostasis.



Fig. 3. Augite cumulate from sill, thin section in plane light, 1.8cm vertical size. Augite and altered olivine crystals (spotted) in adcumulate texture.



Fig. 4. Lafayette meteorite, thin section in plane light, 2.3 cm vertical size. Augite and olivine crystals in adcumulate texture.

3 CONFERENCE ATTENDANCE

In the fall, I attended the 98th annual conference of the Geological Society of America, held in San Antonio, Texas. The conference was useful to this work on nakhlites because of a featured session on "Layered Mafic Intrusions and Related Topics". Of particular interest was the work of Dr. C. Chalokwu, who has been studying different ways of retrieving magma compositions from cumulate igneous rocks.

Originally in the proposal, I had budgeted money to attend the conference of the Meteoritical Society in New York City. I was sick through that week, and so used the budgeted money to partially defray the costs of attending the Geological Society of America conference.

4 EXPERIMENTAL STUDIES

Experimental studies have progressed slowly in the last six months because of the demands of field work and teaching three classes. In the coming months, I will be able to devote much more time to experiments. The furnace is fully functional, and its thermocouple and oxygen sensor cells are functional and calibrated. As I write, the muffle tube assembly still has an air leak - this will be fixed shortly.

Re-examination of charges run last year has yielded a significant constraint on the oxygen fugacity during nakhlite crystallization; the fugacity was significantly below the FMQ buffer. The earlier experiments, run at FMQ, contain microphenocrysts of Cr-magnetite as the first crystallizing phase. In the nakhlite, magnetite is late, suggesting that the oxygen fugacity was well below FMQ. This inference is in accord with the intrinsic oxygen fugacity measurements of Delano and Arculus [1980], but not in accord with the mineral-chemical inferences of Reid and Bunch [1975].

5 NEXT SIX MONTHS

Work in the next six months will concentrate on three topics: experimental studies, continued interpretation of field data, and attendance at the 18th Lunar and Planetary Science Conference. Emphasis will be placed on experimental studies, as I am dissatisfied with my progress to date.

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7 PUBLICATION

Treiman A.H. (1987) Geology of the nakhlite meteorites: Cumulate rocks from flows and shallow intrusions. *Lunar Planet. Sci.* XVIII, submitted.

GEOLOGY OF THE NAKHLITE METEORITES: CUMULATE ROCKS FROM FLOWS
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The nakhlite meteorites, augite-rich cumulate igneous rocks, are part of the SNC suite which may have originated on Mars [1]. It is important to infer the original geological settings of the nakhlites to improve our understanding of their parent planet. Based on comparison of mineral textures of the nakhlites and comparable Earth rocks, the meteorites originated in thick flows and shallow intrusions of ultrabasic (picritic magma). One Earth environment where such rocks form, above mantle hot spots, is known from Mars.

The nakhlite meteorites (Nakhla, Lafayette, and Governador Valadares) are igneous rocks composed predominately of cumulus augite, with minor cumulus olivine and mesostasis (crystallized intercumulus magma) composed primarily of pyroxene, olivine, plagioclase, and magnetite [2,3]. The nakhlites (and Chassigny, a related olivine-rich cumulate) all crystallized at 1.25 \AA [4], and have similar parental magmas [3], similar initial isotope ratios [4,5], and similar cosmic ray exposure histories [6]. Although the nakhlites are similar, they are enough different that they must have come from separate igneous bodies. Nakhla and Governador Valadares have different initial Sr isotope ratios [4]; both meteorites have more (and finer grained) mesostasis than does Lafayette [2].

A critical feature in understanding the geology of the nakhlites is the texture of the mesostasis. If the rock cooled rapidly, its mesostasis will be abundant and glassy. If cooling was slower, the mesostasis will be less abundant and crystalline; the slower the rock cooled, the coarser-grained the mesostasis minerals (e.g., [7]). With very slow cooling, no mesostasis will be preserved and the final rock may be an adcumulate. Cooling rate can be related to depth of emplacement and thickness of the parent igneous body.

The textures of the nakhlite meteorites may be compared with those in igneous cumulate rocks from Earth, where the geologic setting and depth of emplacement are known. Augite-rich cumulate rocks are well preserved in portions of the Abitibi greenstone belt (Archaean age) of northern Ontario, and show textures nearly identical to those of the nakhlites. Augite cumulates comprise the lower half of a 125m thick flow [8], and their textures (Figure 1) are near identical to those of Nakhla (Figure 2) and Governador Valadares. Augite cumulates also comprise the middle third of a 300m thick sill [9], and their textures are adcumulate, with essentially no mesostasis material (Figure 3). These textures are comparable to those of Lafayette (Figure 4).

From comparison with Earth rocks, the nakhlites crystallized in thick flows (>125m) or in shallow intrusions (probably less than a kilometer deep) of basaltic to picritic magma. These conditions are reasonable if the nakhlites came from Mars, as volcanoes with thick lava flows and indirect evidence of shallow intrusions are common in the Tharsis region. The tectonic setting of Tharsis, a bulge above a mantle hot-spot, is better defined than those of greenstone belts [10]. Hot spot tectonics has been suggested as a cause of greenstone belt volcanism, and comparison of Tharsis with greenstone belts on Earth may provide insights into the tectonic development of both planets.

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