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

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# Contents

# 1 SUMMARY

Funding for NASA grant NAG 9-168, titled "Meteoritic Basalts: the Nakhlites, their Parental Mamas, Cooling Rates, and Equivalents on Earth," was received at Boston University on July 1, 1986. One year of research has been completed. Proposed one-bar phase equilibrium experiments, designed to determine the compositions of the nakhlites' parental magmas, are in progress. Proposed field studies on Earth, designed to find occurrances of rocks like the nakhlites, were extraordinarily successful.

Other work supported in the past year by this NASA grant includes: attendance at the 1986 national meeting of the Geological Society of America; attendance at the 18th Lunar and Planetary Science Conference; completion and publication of a study of core formation in the SNC parent body; initiation of a study of the flux of SNC meteorites onto the Earth; and initiation of petrologic study of the Angra dos Reis achondrite.

# 2 WORK COMPLETED

## 2.1 One-Bar Experiments

Experimental studies were proposed to test the hypothesis of Treiman [1] that the nakhlites formed from ultrabasic magmas, and to estimate the rates at which those magmas cooled. Much of the past year has been spent in final assembly and calibration of the one-bar furnace facility. I now have a fully operational vertical muffle tube furnace (Deltech DT-31-VT-OS-C), equipped for controlled atmospheres and measurement of oxygen fugacity. The temperature controller allows for linear heating and cooling. Temperature is measured with a type-S thermocouple calibrated against the melting point of gold and a secondary standard thermocouple traceable to the National Bureau of Standards. Oxygen fugacity is measured with an yttria-stabilized zirconia electrode, calibrated accurate to $\pm 0.05$ log units $f(O_2)$ at the iron-wüstite buffer.

Equilibrium crystallization studies were initiated to determine the composition of Nakhla's intercumulus magma, the best available sample of the magma from which the nakhlites formed [1]. Starting materials are synthetic powders corresponding to calculated possible parent magmas. The powders are melted to glass beads on platinum loops. Experiments so far are syntheses, using these glass beads, at the temperatures of interest and oxygen fugacities slightly above the iron-wüstite buffer. Liquidus and cotectic temperatures will be confirmed by reversal experiments. A table of experimental results is included here as APPENDIX A.

Because Nakhla's intercumulus magma was saturated in augite and olivine, phase equilibrium experiments seek to determine the augite-olivine cotectic (i.e. melt compositions and temperatures where augite, olivine and melt are stable together). Liquidus temperatures for the intercumulus magma compositions are near 1300°C. The best-known to date, that of composition C [1], is $1282 \pm 10$°C. Olivine is the liquidus phase for compositions B, C and D (APPENDIX A), and

presumably for composition A which is richest in olivine component. This implies that the augite-olivine cotectic is at more augite-rich compositions than D. The augite-olivine cotectic is near 1260°C, based on results from compositions C and D.

Compositions A through D were calculated (by mass balance) for 20-40% intercumulus magma; D corresponds to the most intercumulus magma [1]. Because the cotectic is at compositions more augite-rich than D, Nakhla must have contained more than 40% trapped melt among the cumulus augite and olivines. This percentage is greater than originally suggested, and implies that the cumulus grains in Nakhla compacted little after settling. In retrospect, this seems reasonable. There would have been little gravitational force for compaction, because the densities of the grains and the melt were similar. Compaction would be further hindered by post-cumulus grain growth, which is documented in the nakhlites [1,2].

No oxide minerals were observed in the low-temperature (1125°C) runs, suggesting that oxygen fugacity in the experiments is lower than that experienced by the nakhlites. The intrinsic oxygen fugacity data of [3] are in accord with this limit.

## 2.2 Terrestrial Analogs to the Nakhlites and Chassigny

The nakhlites are unusual among igneous rocks because they are cumulates with fine-grained, quench-textured material (mesostasis) among the settled grains. To understand how the nakhlites formed, I looked for Earth rocks of similar mineralogy and texture as analogs to the meteorites. Based on literature descriptions, I proposed field study near Timmins (Ontario) to examine cumulate rocks in thick flows and shallow sills. The study was successful beyond expectations. Some of the cumulate rocks are nearly identical, mineralogically and texturally, to the nakhlite and Chassigny meteorites. If the Ontario rocks had not been metamorphosed, it would have been difficult to tell them from the meteorites. Preliminary results of the field study are given in [4] (see APPENDIX B for this paper and two related abstracts).

Field studies were conducted during the first three weeks of August, 1986 in northern Ontario. Base camp for field work was Kettle Lakes Provincial Park, Ontario, where I camped. The weather was good, and only one rainstorm (10 cm in one day) hindered study. Insect life was not a problem.

The first rock unit studied was the Dundonald Sill of Dundonald and Clergue Townships, Ontario [5]. It is a 300+ meter thick body of basaltic composition, differentiated from granophyric gabbro at its top to pryoxenite and dunite at its base. The sill is cut by faults, and has experienced greenschist facies metamorphism. Some samples of dunite and pyroxenite, possibly from the sill, are texturally similar to the Chassigny and Lafayette meteorites and are figured in [4]. The meteorite analogs occur in a fault block abutting gabbro and pyroxenite of the sill, but the sill's pyroxenite is significantly coarser-grained than the fault block's pyroxenite. The rocks of the fault block not be from the sill, but possibly from a 'komatiite' flow intruded by the sill.

The second rock unit studied was Theo's flow in Munro Township, Ontario [6]. The flow is wedge-shaped, 30-125 meters thick, and is differentiated to gabbro, cumulate pyroxenite, and

cumulate peridotite. The geologic structure near Theo's flow is unambiguous. Exposure of the flow is repeated by a fault, but the flow is not disrupted or folded. The whole region experienced mild metamorphism, but no penetrative deformation.

The pyroxenites of Theo's flow are texturally identical to the Nakhla and Governador Valadares meteorites, except for the effects of metamorphism. Photomicrographs of the rocks and the meteorites are given in [4]. The meteorites and these Earth analogs are all augite-rich cumulates with some cumulus olivine, have poikilitic olivine grains among the augite, and have quench-textured mesostases among their cumulus grains. Grain sizes in the mesostases are comparable, suggesting similar cooling rates and therefore similar geologic settings.

It seems fair to conclude that Nakhla and Governador Valadares formed in thick flows similar to Theo's flow. If one accepts that the nakhlites are from Mars, that planet must have had thick flows of basaltic (or ultrabasic) lava which differentiated in situ.

## 2.3 Petrography and Mineral Chemistry

Petrography and mineral chemistry have served as tools in experimental and field studies (above). Petrofabric studies in the preceeding proposal were delayed because the Department's universal stage has vanished. Dr. J. L. Berkley has kindly loaned me a replacement.

A noteworthy petrographic observation is that augites in the nakhlites (particularly Governador Valadares) contain magmatic inclusions, composed of glass, magnetite, olivine(?) and vapor bubbles. The vapor bubbles are of interest as possible hosts for noble gasses in the nakhlites [7]. I am in correspondence with Dr. T. Swindle, noble gas specialist at the University of Arizona, about the inclusions.

## 2.4 Flux of SNC Meteorites

The flux of SNC meteorites onto the Earth is important in understanding the mechanism of their ejection from Mars, and the dynamics of their transit to Earth. Recent studies have assumed a constant flux of SNC meteorites for millions of years [8,9], but without control on possible time dependence. Meteorite falls, finds, and Antarctic finds represent samples of the meteorite flux to Earth in different time periods, and the proportios of SNC meteorites in these populations indicates that the flux of SNC meteorites has been constant, at least over the last hundred thousand years.

Observed meteorite falls represent a sample of the meteorite flux within the last 200 years. Among the 959 recorded meteorite falls [10], four are SNCs for a flux proportion of 0.42%. Of basaltic meteorites, 7.7% are SNCs. Although large and metallic meteorites are probably over-represented, the proportions of falls may be close to the real proportions of meteorites falling onto the Earth today.

Among non-Antarctic meteorite finds, the best indicator of SNC flux is the proportion of SNC meteorites to basaltic meteorites of similar lithology, the HED suite. Stony meteorites are under-

represented because iron meteorites are distinctive and resistant to weathering. Basaltic meteorites may be further under-represented becuase they look so much like terrestrial basalts. Among the 42 finds of basaltic achondrites, 2 are SNC meteorites, for a proportion of 4.8%.

Among the Antarctic meteorites the best indicator of SNC flux is also the proportion of SNC meteorites to HED basaltic achondrites. Many Antarctic meteorites are paired and thus the number of cataloged meteorites does not represent the number of falls. Approximately 1100 separate stony meteorite falls may be represented [11,12] in the U.S. collections, possibly fewer because of the difficulty in pairing ordinary chondrites. The basaltic meteorites have been extensively studied and the 58 cataloged samples came from 32 falls. Of these, 2 are SNC meteorites for a fraction of 6.25%.

The present-day proportion of SNC meteorites to HED meteorites, 7.7%, is essentially identical to the SNC/HED proportions among non-Antarctic finds (4.8%) and Antarctic finds (6.25%). Taking the proportion of HED meteorites to stony meteorites from the fall data, one may infer that 0.4of stony meteorites (within the time sampled) have been SNCs.

Based on this assesment of the historical record, the flux of SNC meteorites has been constant for the last few hundred thousand years, the average age of the Antarctic meteorites. However, one cannot infer with certainty that the flux has been constant for even a few million years.

## 2.5 Angra dos Reis

The Angra dos Reis meteorite is a unique calcium-rich achondrite, composed almost entirely of fassaite pyroxene (Al-Ti augite). Dr. John H. Jones and I have begun a re-evaluation of the origin of Angra dos Reis, eleven years after the ADORABLES' studies [13]. My work will focus on petrology, and his work (included in an independent grant proposal) will focus on geochemistry.

Already complete is an abstract on textural relations in Angra dos Reis (see APPENDIX B). Textures of Angra dos Reis suggest that it is a quickly cooled or quenched magma with amoeboid phenocrysts. This interpretation is at variance with that of [13], and suggests that geochemical modelling of the meteorite must be revised.

In progress is a study of crystallization and phase equilibria of Angra dos Reis. In general, its crystallization is consistent with the phase equilibria for Fe-free fassaite pyroxene [14], modified for the effects of added iron.

## 2.6 Conference Attendance

This grant supported attendance at two conferences: the 98th annual meeting of the Geological Society of America (November 10-13, 1986; San Antonio, TX), and the Lunar and Planetary Science Conference (March 16-20, 1987; Houston, TX). Funds originally budgeted for attending the meeting of the Meteoritical Society were used to partially defray costs to the Geological Society meeting. I could not attend the Meteoritical Society conference because of illness.

My primary interest at the conference of the Geological Society of America was a session titled "Layered Mafic Intrusions and Related Topics." The session featured several talks useful in the interpretation of the nakhlites as cumulate rocks; of particular use was the talk by Dr. C. Chalokwu, who has been studying methods of retrieving magma compositions from igneous rocks.

At the Eighteenth Lunar and Planetary Science Conference, I presented a paper on the geological origins of the nakhlite and Chassigny meteorites (see APPENDIX B), and attended sessions on Martian geology, basaltic achondrites, and ureilites, among others. Of particular value were informal conversatons about noble gasses in the nakhlites, Angra dos Reis, and the geomorphology of Martian lava flows.

# 3 REFERENCES


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# 4 APPENDIX A: RESULTS OF EXPERIMENTS

| Run # | Comp. | T (°C) | Phases |
|---|---|---|---|
| BU-10 | B | 1291 | gl |
| BU-11 | C | 1291 | gl |
| BU-20 | C | 1273 | gl + ol |
| BU-14 | C | 1267 | gl + ol |
| BU-17 | C | 1244 | gl + ol + au |
| BU-16 | C | 1225 | gl + ol + au |
| BU-15 | C | 1155 | gl + ol + au + pl(?) + op |
| BU-13 | C | 1125 | ol + au + pl |
| BU-29 | D | 1268 | gl + ol |
| BU-27 | D | 1257 | gl + ol + au |
| BU-28 | D | 1250 | gl + ol + au + op |

Results of phase-equilibrium experiments on the origin of the nakhlites. Compositions are those of [3], and represent a range of possible intercumulus magmas in the Nakhla meteorite. Oxygen fugacities for compositions B and C are approximately 0.25 log units above the iron-wüstite buffer; for composition D, oxygen fugacity is 1 log unit above iron-wüstite. Abbreviations for phases present are: gl, glass; ol, olivine; au, augite; pl, plagioclase; and op, opaques.

# 5 APPENDIX B: PUBLICATIONS AND PREPRINTS

Treiman A.H., Jones J.H. and Drake M.J. (1987) Core formation in the Shergottite Parent Body and comparison with the Earth. Proc. 17th Lunar Planet. Sci. Conf. J. Geophys. Res. 92 Suppl., E627-E632.

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Treiman A.H. (1988?) Geology of the nakhlite and Chassigny meteorites: Equivalents on Earth and implications for Mars. Preprint for submission to Proc. 19th Lunar Planet. Sci. Conf.

Treiman A.H. (1988?) The textures and origin of Angra dos Reis: Still adorable after all these years? (abstract) Preprint for submission to Lunar Planet. Sci. XIX.