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FINAL REPORT

ON

N.A.S.A. GRANT NAG 9-168

METEORITIC BASALTS,

to ALLAN H. TREIMAN.

Funded from 1986 through 1989

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SUMMARY

In the years 1986 through 1989, N.A.S.A. grant NAG9-168 was awarded to me as support in solving three particular problems in the geneses of basaltic meteorites: explain the abundances of siderophile elements in the SNC meteorite suite, of putative Martian origin; discover the magmatic origins and possibly magma compositions behind the Nakhla meteorite, one of the SNC meteorites; and a re-evaluation of the petrology of Angra dos Reis, a unique meteorite linked to the earliest planetary bodies of the solar nebula. As a direct result of N.A.S.A.'s support, I have been able to clarify the origins of these two igneous meteorites, with important planetogical implications.

Studies of the Angra dos Reis meteorite have been the most obviously successful. A re-evaluation of its petrography showed that the accepted scenario for its origin, as a cumulate igneous rock, was not consistent with the meteorite's textures (Treiman, 1989). More likely is that the meteorite represents a porphyritic igneous rock, originally with magma dominant. Geochemical studies of Angra dos Reis, published in abstract form and in pre-publications drafts, have shown that its bulk composition is consistent with an origin on a planetary body, and not as a direct solar-nebula condensate. Lithophile element abundances in Angra dos Reis are fractionated in a manner consistent with the types of igneous processes that occur in the Earth, Moon, and Mars (SNC meteorites). The fractionation could not have come from simple petrogenetic paths, but probably represents open-system behavior. Siderophile elements are strongly depleted in Angra dos Reis, consistent with the patterns expected from core formation in a fairly oxidizing planetary body. More data is being collected from a sample obtained under the auspices of the N.A.S.A. grant.

Studies of the Nakhla meteorite, of possible Martian origin, although difficult, have been successful. It became necessary to reject the basic categorization of Nakhla (to which I had subscribed): that it was a cumulate igneous rock. Detailed studies of the chemical zoning of Nakhla's minerals, coupled with the failure of experimental studies to yield 'expected' results, forced me to conclude that Nakhla is not a cumulate rock in the usual sense: a rock composed of igneous crystals and intercrystal magma. It seems clear (Treiman, 1990), that the crystal portion of Nakhla consists of xenocrysts from an equilibrated basaltic igneous rock, and that the magma among these crystals had absolutely nothing to do with the original formation of the crystals. This view of Nakhla is a radical departure from the accepted view, and is important for the petrology of the other SNC meteorites, and thereby petrogenesis on Mars.

Study of the siderophile element abundances in the SNC meteorite groups involved trying to find reasonable core-formation processes and parameters that would reproduce the observed abundances. Modelling was successful, and delimited a range of models which overlap with those reasonable from geophysical constraints.

PETROLOGY OF ANGRITE METEORITES

A major focus of grant-supported activity was the petrology of the unique achondrite meteorite Angra dos Reis, and the related newly-discovered angrites from Antarctica. The grant has supported study of Angra dos Reis from three directions: study of its petrography; experimental study of its phase equilibria and that of related compositions; and geochemical modelling of its trace element abundances. The first has yielded a published paper, the second has yielded a wealth of experimental data that will be submitted this year, and the third has yielded a paper in rough draft form.

Petrography of Angra dos Reis

In 1987, with support from this grant, I began a review of the petrology and petrography of Angra dos Reis. The meteorite consists of about 95% fassaite pyroxene with the remainder being whitlockite, olivine, spinel, and minor phases. The fassaite, whitlockite, and olivine occur both as megacrysts (up to 2 mm across) and as 0.1 mm sized matrix grains; spinel is only present as matrix-sized grains.

The accepted interpretation of the meteorite was that the matrix grains represented accumulated grains, and that the megacrysts grew poikilitically in the spaces among the cumulus grains (Prinz et al., 1977). In my 1989 paper on Angra dos Reis (see Appendix D), I questioned this standard interpretation, and showed that the proposed mechanism would not yield the observed texture. As an alternative, I proposed that Angra dos Reis was a porphyritic rock, with the megacrysts representing phenocrysts, and the matrix representing devitrified magma. This explanation is consistent with Angra dos Reis's textures, and with preliminary liquidus experiments. The composition of Angra dos Reis is completely molten at $1246 \pm 1^{\circ}C$, reasonable for igneous processes in an early, hot planetoid. Crystalline phases at lower temperatures were fassaite pyroxene and spinel, just as in Angra dos Reis. The apparent absence of olivine probably reflects its rarity in the experimental charges.

Other petrographic studies have been begun under this N.A.S.A. grant and are not yet complete. The shapes of the megacrysts in Angra dos Reis are important in the meteorite's interpretation, and I have mapped the phenocryst shapes in a series of more-or-less serial rock fragments in a thin section from the University of New Mexico. Another important petrographic tool is the distribution of spinel in the meteorite. Spinel should be present in material devitrified from magma, but possibly not in material formed from phenocrysts. These studies should be completed within the year.

Phase Equilibria

A second major portion of this N.A.S.A.-supported research is a study of liquidus phase equilibria relevant to the genesis of Angra dos Reis and the other angrites meteorites. This work is not ready for publication, but run results and chemical analyses are included in Appendix A as evidence of effort.

Essentially, the focus of these phase equilibria studies has been to outline the liquidus field for fassaite pyroxene (the major mineral in Angra dos Reis) plus or minus spinel, an essential constituent of the meteorite.

Work completed thus far under this grant has focussed on the pyroxene-spinel liquidus field in the system $CaO-MgO-Al_2O_3-SiO_2$ (CMAS). Although the system CMAS has been studied extensively in this century, the exact location and size of fassaite-bearing liquidi and the compositions of liquidus fassaites had not been established. The spinel-saturated fassaite liquidus in CMAS, shown in Figure 1, is really a minute field, very small in compositional and temperature extent. Pyroxene + spinel are stable on the liquidus between 1240°C and 1224°C. The geometry and compositions found here are consistent with most experiments in the literature, but the compositional extent of the pyroxene-spinel liquidus field is almost within the analytical and experimental errors: analytical error of $\pm$ 1% of the amount present, and perhaps 1% inhomogeneity of melt compositions within a charge.

However, Angra dos Reis and the other angrite meteorites contain TiO_2 and FeO, sufficient to alter the geometry and phase relations from those in CMAS. Under this grant, experiments into the effects fo TiO_2 and FeO have been begun, and would be continued under a current proposal to N.A.S.A.

Most of the data available so far are for the pyroxene-spinel liquidus surface in CMAS-TiO_2, CMAST. Experiments conducted under this grant, and experiments in the literature, allow an understanding of the effects of TiO_2: increase in the size of the pyroxene-spinel liquidus field, and a significant change in the geometry of the surface.

As TiO_2 is partitioned more into silicate melt that any of the other phases observed, temperatures on the liquidus surface will generally be lowered compared to CMAS. The temperature of the pyroxene-spinel liquidus will be lowered less than the other liqudus fields because fassaite pyroxene can accept significant amounts of Ti (presumaby as the component $CaTiAl_2O_6$) while essentially no Ti can enter plagioclase, olivine, or melilite.

But the most significant effect of Ti is on the compositions of the pyroxenes produced; presence of Ti in the pyroxenes shifts their composition enough to radically alter the nature of the liquidus reaction boundaries. In the projection of Figures 1 and 2, incorporation of Ti into the pyroxene causes it to leave the

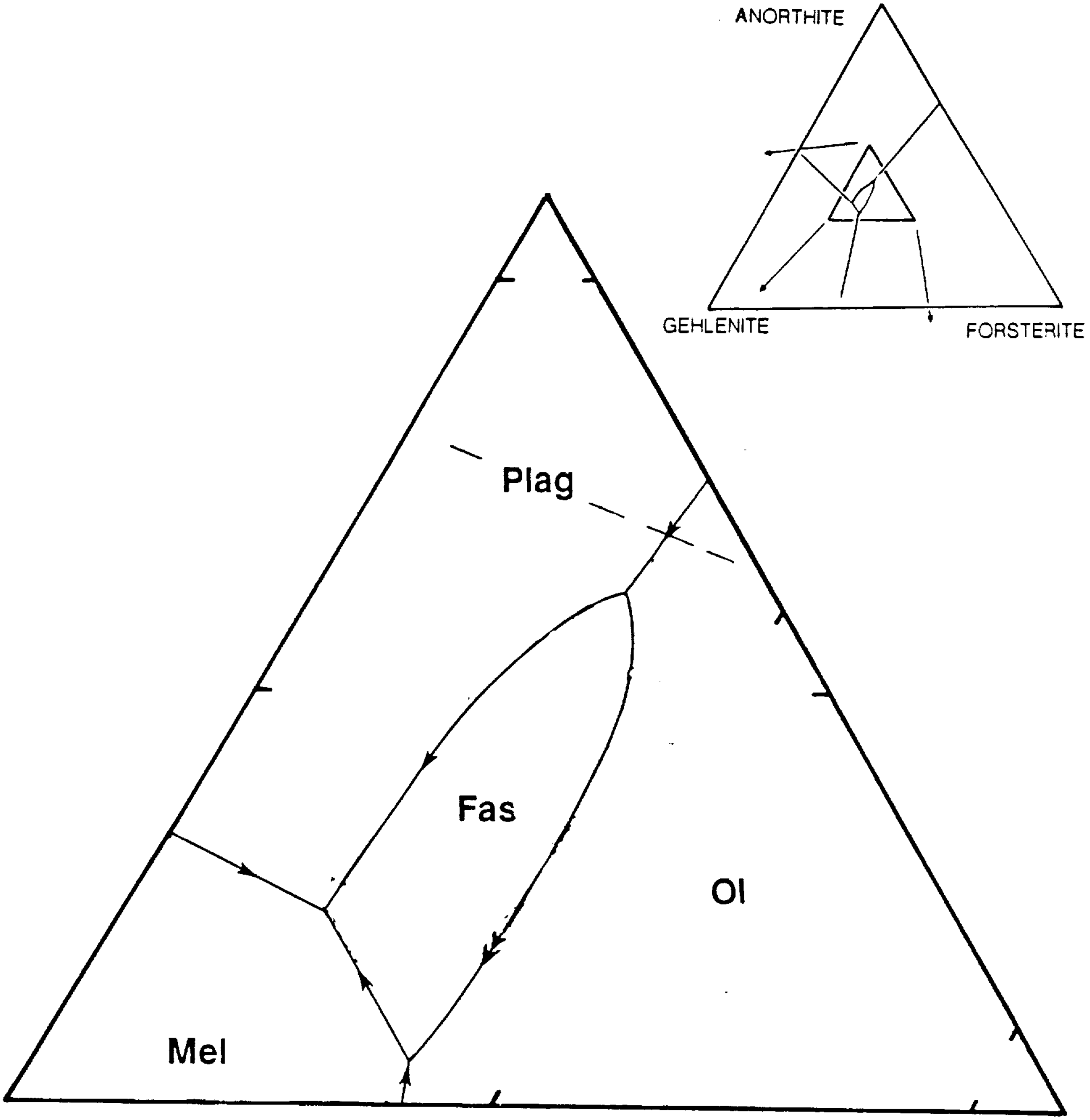

FIGURE 1. Geometry of the spinel-saturated liquidus surface in a portion of CaO-MgO-Al_2O_3-SiO_2, projected from spinel. The spinel-liquid-plagioclase-olivine-fassaite point is a distributary peritectic; melts passing through that point will arrive at the spinel-fassaite-plagioclase-melilite liquidus point, and then lose spinel-saturation. Dashed line is projection of diopside-CaTs join.

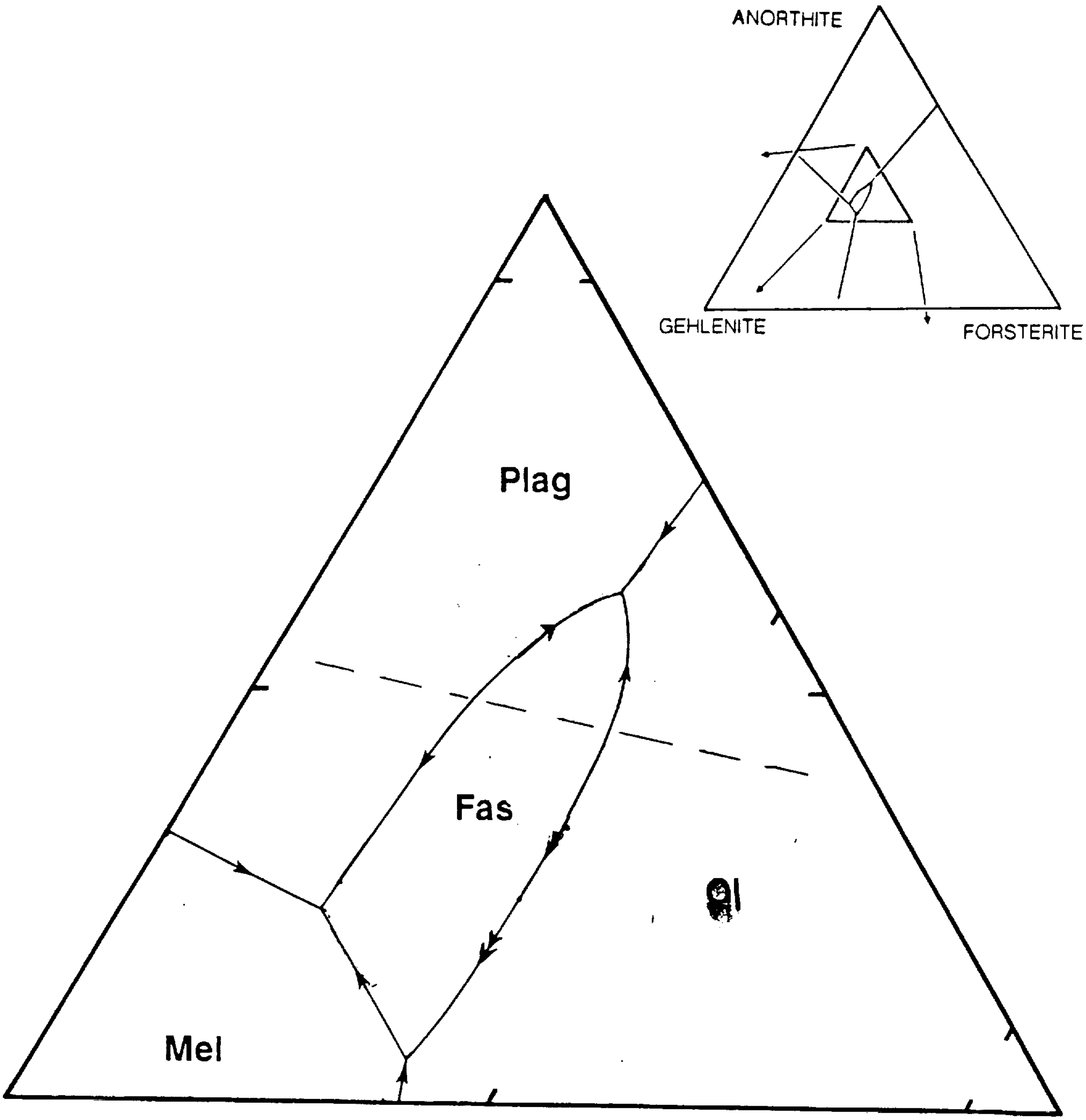

FIGURE 2. Geometry of the spinel-saturated liquidus surface in a portion of CaO-MgO-Al_2O_3-SiO_2-TiO_2, projected from spinel. The dashed line is the range of titanian aluminian pyroxenes possible. In this case, the reaction point spinel-melt-olivine-fassaite is cotectic (eutectic in this projection); melts which arrive at that point stay there. Thus, mineral assemblages like those in the angrite meteorites become reasonable.

Diopside-CaTs join and move toward the Gehlenite apex of the diagram. As the composition moves, it will enter pyroxene-spinel liquidus field; here the assemblage pyroxene-spinel melts congruently, and the melt-pyroxene-spinel-plagioclase-olivine point becomes a eutectic rather than a cotectic. This is, in fact, as observed in the antarctic angrites, possibly Angra dos Reis, most type B CAI's, and most Ca-Al chondrules. As more Ti enters the pyroxene, its composition will eventually project into the plagioclase or melilite liquidus field, yielding an different reaction geometry.

The effects of FeO on liquidus equilibria in CMAS-FeO, CMASF, has been explored little. It is likely that the spinel-saturated liquidus fields of olivine and fassaite would be expanded at the expense of those with plagioclase and melilite. The effect of Ti on Fe-bearing compositions, the system CMASTF, is more difficult to predict because of the effects of charge transfer: $Fe^{2+} + Ti^{4+} \Leftrightarrow Fe^{3+} + Ti^{3+}$ (Sack and Carmichael, 1982). An investigation of these and other effects has been proposed to N.A.S.A.

Geochemical Modelling

The third facet of work on Angra dos Reis, supported by this N.A.S.A. grant, is geochemical modelling of the meteorite's bulk composition. Two separate sets of models are involved here: one for the refractory lithophile elements, and one for the refractory siderophile elements (see abstracts in Appendix D). In both cases, modelling emphasizes the refractory elements because Angra dos Reis is strongly depeleted in volatile elements, both lithophile and siderophile.

Refractory lithophile elements in Angra dos Reis are not all abundant to the same CI-normalized level, but show significant fractionations based on cation size and valence. Figure 3 shows the abundances of refractory elements likely to be trivalent in Angra dos Reis as a function of ionic radius (an Onuma diagram). It is clear that elemental abundance is a smooth function of ionic radius, suggesting that igneous (silicate melt/solid) processing caused the present range of abundances.

Modelling element abundances in Angra dos Reis would be difficult if unusual or uncommon minerals (hibonite, perovskite, melilite), for which partitioning behaviour is poorly known, were present in its source area. However, there is no evidence for such unusual minerals; the element abundances in Angra dos Reis are similar enough to those of many terrestrial and lunar basalts that it is necessary only to consider fractionations involving common planetary minerals.

The first step in geochemical modelling was setting up a series of possible petrogenetic scenarios: combinations of partial melting, melt removal, and accumulation events. The second step was to estimate the range of likely compositions for the soruce

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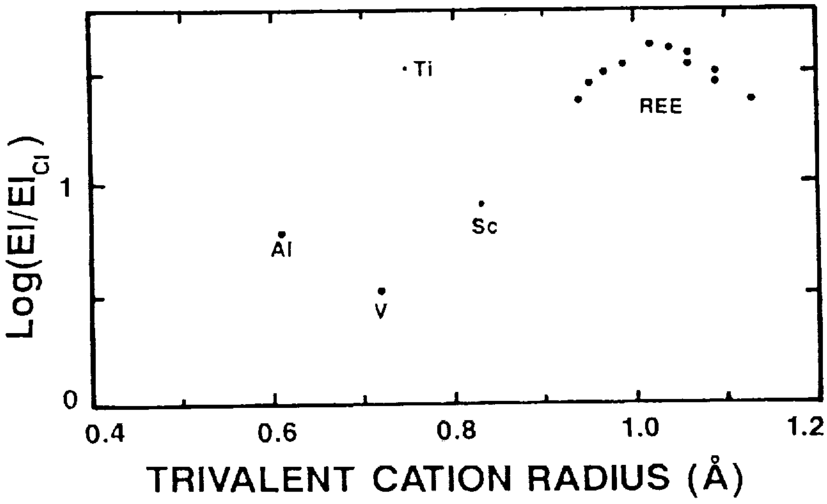

FIGURE 3. Abundances of trivalent refractory lithophile elements in the Angra dos Reis meteorite, as a function of trivalent ionic radius. Note the smooth dependence of abundance on radius; Ti was probably not trivalent during fractionations that led to Angra dos Reis.

region and subsequent solid assemblages, and quantify phase relations (eutectic/cotectic locations) within that range. The third step was to parametrize these models by the element distributions for the various processes with known partition coefficients. Finally, these models were entered into a computer, which performed exhaustive searches through the ranges of petrogenetic variables: original source composition, degree of partial melting, proportion of melt removed, proportion of phases in a cumulate.

The results of this geochemical modelling are straightforward: there are no simple petrogenetic paths from 'chondritic' source regions to the element abundance pattern of Figure 3. Either Angra dos Reis is a product of complex petrogenesis (e.g. more than three partial melting events) or it is a product of open system petrogenetic processes. It is clear that Angra dos Reis cannot be merely a large blob of planetary condensate (a super-CAI), somewhat differentiated. Angra dos Reis reflects the kind of complex petrogenesis one expects of planetary basalts, and it seems reasonable that Angra dos Reis is a fragment of an early planetoid rich in Ca and Al.

Siderophile Elements

Abundances of siderophile elements in basalts may retain the signatures of early metal-segregation events in a planetoid's history, and to that end Dr. J. Jones and I studied the abundances of siderophile elements in Angra dos Reis. Data included literature values, unpublished (soon to be published) data from Dr. Ander's group at the University of Chicago, and data being collected by Dr. H. Newsome, Univeristy of New Mexico. Our interpretations of siderophile abundances in Angra dos Reis were referred to in abstract form (see Appendix D), and are being prepared for publication.

In short, siderophile elements in Angra dos Reis are depleted below the abundances of lithophile elements of comparable volatility. For instance Ir is depleted by 10,000 compared to Ti and other refractory lithophiles. In general, the depletion of siderophile elements seems to correlate with their metal/silicate partition coefficients for fairly oxidizing circumstances: very close to the iron-iron oxide buffer. Thus, it seems reasonable that Angra dos Reis experienced the same type of metal segragations event(s), core formation perhaps, that are reflected in basalts from the Earth, Mars (SNC meteorites), and differentiated asteroids (eucrite meteorites).

CORE FORMATION: SNC PARENT BODY

Partially supported by this N.A.S.A. grant was publication of paper modelling the abundances of siderophile elements in the SNC meteorites. The focus of the work was to constrain core formation processes in the meteorites' parent planetoid (SPB=Mars?), for comparison with those thought to have occurred on Earth. Siderophile element abundances in the SPB were taken from Treiman et al. (1986), having been corrected for depletions through elemental volatility and silicate fractionations. It was possible to model core formation in the SPB as a very simple, single step event, with geophysically reasonable proportions of iron-rich metal and iron-sulfide liquid to form a core, and geologically reasonable proportions of these phases trapped in a silicate mantle. A copy of this paper is in Appendix D.

ORIGIN OF NAKHLA

The first work project funded under this N.A.S.A. grant was a study of the origin of the Nakhla meteorite, one ot the SNC meteorites of putative Martian origin. The original proposed work was primarily of phase eqilibrium experiments, which quickly proved that their founding assumptions were in error. The progress of this work has been a litany of ideas that yielded difficult or inconclusive answers. However, I feel I have finally found the key to unravelling Nakhla's petrogenesis: interpretation of the chemical zoning of its constituent minerals.

The study of chemical zoning in Nakhla, have produced a considerable revision of the petrogenetic history of Nakhla. Nakhla is an igneous rock, and has been considered as a simple augite-olivine cumulate with fine-grained mesostasis material among the cumulus crystals. I was able to show that much of the volume of these cumulus crystals was in fact post-cumulus overgrowths or replacement regions, and that only 40% of the meteorite truly was 'cumulus crystals'. However, the cumulus crystals are not phenocrysts. Their chemical zoning patterns and compositions suggest that they are xenocrysts, derived not from Nakhla's intercumulus magma but an earlier igneous body.

Thus, the petrogenesis of Nakhla is complicated enormously. It can no longer be considered a closed system body, but must contain at least two distinct components: magma and xenolith. Thus, it becomes very difficult, if not impossible to extract from Nakhla the composition of its parental magma, or even the identity of the rock from which its xenoliths derive.

Phase Equilibria

This N.A.S.A. grant, as originally funded, was to understand the origin of the Nakhla meteorite by determining the composition of its parental magma; in Treiman (1986) I had concluded that Nakhla's intercumulus magma could be considered its parental magma. I proposed to understand this intercumulus magma through phase equilibrium experiments on compositions between that of Nakhla itself and the composition of its cumulus phases.

Many liquidus equilibrium experiments conducted (Appendix B) and the results clearly did not agree with the conclusions expected if Treiman (1986) were entirely correct. Based on bulk and trace element compositions, I had predicted that Nakhla must consist of between 60% and 75% cumulus augite and olivine crystals, and 40-25% intercumulus magma. Experiments showed that all of these compositions had olivine alone as the liquidus phase, as predicted by the experiments of Longhi and Pan (1988?). The olivine-augite liquidus cotectic is at a mixture of about 60% melt and 40% crystals, and thus someof the basic premises behind Treiman (1986) must have been wrong. Rather than continue meaningless experiments, I sought other approaches to achieve the goal of the Grant: an understaning of Nakhla.

Field Study

In searching for the origin of Nakhla, I looked for terrestrial analogies: Earth rocks that are cumulates with fine-grained intercumulus mesostasis. Under this N.A.S.A. grant, I undertook reconaissance field studies of some likely terrestrial analogies to the Nakhlite meteorites, relying on published petrographic descriptions. The results of this facet of research have been somewhat disappointing. Although I have found a number of localities which contain rocks very similar to Nakhla, the actual volcanic environments of these rocks has not yet been clarified. So, they are of lesser use in understanding the origins of Nakhla. From such equivocal results, it is perhaps understandable that these field studies have yielded no publications.

The search for analogs to Nakhla was conducted in two months of field study near Matheson, northern Ontario, in the Abitibi greenstone belt (Archaean age). The Abitibi belt, a broad region of basaltic to intermediate volcanic and plutonic rocks, includes a number of published localities of rocks similar to Nakhla and the other Nakhlites. Rocks from two localities turned out to be quite analogous to the nakhlites: some samples from Theo's flow in the Munro township (Arndt, 1977) are dead ringers for Nakhla and Governador Valadares; and one horizon in the Dundonald sill, Dundonald township, is quite similar to Lafayette. Many other localities were investigated but were not similar to the nakhlites, despite their published descriptions.

From the field studies it is clear that the nakhlites are not unique products of a wholly Martian style of volcanism, but that similar rocks formed in a common tectonic/petrogentic terrane type on the young Earth. This in itself is a worthy piece of news, but I have been frustrated in going further, specifically in determining the igneous and volcanic environments that might give rise to the nakhlites. Fundamentally, the problem is that the vulcanology of the terrestrial occurrences has not been studied. Most of the volcanologic effort in the Abitibi belt has been spent on the komatiites, which are not directly relevant to the Nakhlites. So far, I have been unable to completely clarify the volcanology of the terrestrial occurrences.

Magmatic Inclusions

Magmatic inclusions, small bodies of magma or its derivatives trapped inside igneous crystals, have been useful in petrogenetic studies, and have been useful in understanding some of the other SNC meteorites (Floran et al., 1978; Treiman, 1985). The olivines of Nakhla contain many magmatic inclusions and I sought to constrain the origins of the olivines by chemical analyses of their inclusions. The inclusions in Nakhla's olivines are consist of olivines, strongly zoned pyroxenes, and opaque minerals in a glass matrix; I analyzed approximately fifteen of these inclusions by broad beam electron microprobe techniques; the results are given in Appendix C.

The results of the magmatic inclusion study are inconclusive. the analyzed compositions scatter widely, as could be expected from the inhomogeneous nature of the inclusions and the errors attendant on broad beam analyses of such material. On average, the magmatic inclusions appear to present differing minor element ratios than those likely for Nakhla's intercumulus magmas, but the differences are small and possibly of no statistical significance. Results of the magmatic inclusion study will be presented eventually for a publication.

Petrography and Mineral Zoning

Work on Nakhla supported by this grant has had its greatest success with study of the meteorite's petrographic and mineral chemistry. This work, in press in the Proceedings of the 20th Lunar and Planetary Science Conference (Treiman, 1990), is included in Appendix D and is excerpted here.

The augite and olivine phenocrysts in Nakhla are chemically zoned, a fact noted early for the augites but only confirmed for the olivines by Treiman (1986). Under this grant, I sought to understand the processes responsible for their zoning by detailed mineral chemical study of suitably oriented grains.

For this study, grains were chosen that were oriented so that crystal walls were perpendicular to the thin-section plane, and so that the cut of the section passed reasonably near the center of the crystal. Thus, measured zoning patterns would have real significance for crystal growth.

I found that the augites and olivines of Nakhla had very similar zoning patterns: cores, rims, overgrowths, and replacements. The cores of olivines and augites constituted 0.1 to 0.8 of the volumes of the crystals, and are of fairly homogeneous magnesian composition; these are the core regions referred to in previous studies. The rims of the crystals are chemically zoned, more ferroan to the outside. Their molar Mg/Fe ratios are linear functions of crystal volume, as predicted for crystals that grew during Rayleigh fractionation (Pearce, 1987). Rim zones grade outward into overgrowth zones, of constant ferroan composition. These zones seem to reflect the nucleation of a mineral that buffers Fe, as this zone is not apparent in the abundances of some minor elements. Replacement zones, found only in pyroxene, are regions where all of the preceeding zones have been obliterated and replaced wholesale by extremely ferroan compositions.

Thus, the rim, overgrowth, and replacement zones can reasonably be ascribed to processes within the present Nakhla meteorite: intercumulus growth and its reaction with magnesian crystals. But the cores have no place in this.

It was noted early that the olivine cores in Nakhla are too ferroan to have been in igneous equilibrium with the augites or with intercumulus magma, and this apparent disequilibrium has driven many of the hypotheses of Nakhla's origin. Berkley et al. (1980) suggested that the olivines are all intercumulus, but some olivines are considerably larger than the cumulus pyroxenes, and are thus unlikely to be filling holes among the pyroxenes. Longhi and Pan (1989) suggested that the olivines are ferroan because they have back-reacted with ferroan intercumulus melt, but the slopes of their zonings, Mg/Fe linear in crystal volume, is inconsistent with solid-state diffusional equilibration.

The best hypothesis for the olivines is that they are unrelated to the intercumulus magma: they are xenocrystic (Treiman, 1986). But the augite crystals have the same mineral zoning patterns as the olivine and thus seem to share the same petrogenesis; the augite cores are probably also xenocrystic. That the cores of both species are xenocrysts is consistent with their element distributions. As noted above the cores could not be in igneous equilibrium, but their compositions are consistent with sub-solidus metamorphic equilibrium!

Thus, one is forced to a difficult conclusion about the origin of Nakhla. It is a cumulate rock, but not a cumulate of its own phenocrysts. Nakhla is a cumulate, a sediment, of xenocrysts which must have been eroded from some augite-olivine cumulate rock (very similar to the Lafayette meteorite). Nakhla is not a closed-system rock. Its bulk chemistry reflects mixing of two (at least) components, and its isotopic characteristics should also. The fact that it has a well-defined age, concordant among all radio-chronometers, suggests that the magma and the xenolithic material were essentially contemporaneous and of the same initial isotope ratios. These results have significant implications for petrogenesis on Mars, which are being explored.

Implications for the Study of Mars

The studies supported by this grant have important implications for the geology of the SNC's parent planet, Mars by most accounts. I have presented some of these interpretations at workshops sponsored by N.A.S.A. and the L.P.I.: the MEVTV Workshop on Nature and Composition of Surface Units on Mars; and the Workshop on Mars Sample Return Science. In both cases, my presentations dealt with the observations that almost all of the SNC meteorites were cumulates of one kind or another. Such samples are poor probes of planetary interiors, compared to the relatively pristine basalt samples commonly available on the Earth. If one expects to retrieve the most geochemically meaningful samples with a Mars Sample Return Mission, one must avoid areas which yielded samples like the SNC meteorites, except EETA79001 (which includes one xenolith-free, non-cumulate lithology).

CONCLUSIONS

In raw numbers, the three years of research funded by N.A.S.A. grant NAG9-168 has produced three papers published or in press and many abstracts (see Appendix D), attendance and scientific participation at conferences, and a considerable fund of data awaiting fuller study. Of these data, I hope to bring three sets to publishable form and submission in the next year: liquidus phase equilibria in CMAST relevant to angrite and chondrule petrogenesis (Appendix A), geochemical modelling of lithophile element abundances in Angra dos Reis, and chemical analyses of magmatic inclusions in Nakhla's olivines. Other data sets are not so close to publication: siderophile elements in Angra dos Reis, geological inferences from the SNC meteorites, and field and volcanological studies.

The success of this grant, and its value to science attributable to N.A.S.A., funding cannot be measured merely by number of publications. The quality of the publications is critical, and I believe that two of the papers supported by this grant are truly important contributions, papers that have or will strongly influence thinking about igneous meteorites and rocks. The 1989 paper on Angra dos Reis is a fundamental revision of the paradigm for understanding the meteorite: from nearly monomineralic cumulate rock derived from basalt to porphyry derived from a CAI-like magma. On the origin of the Nakhla meteorite, the 1990 paper in press and abstracts leading up to it represent a new view on a much-studied stone. It can not be considered a closed-system stone, but a xenocryst-rich open-system mixture.

Finally, I would like to thank N.A.S.A., its officers, and its agents, for the award of grant NAG9-168. I appreciate the trust and confidence in my abilities show by it. The work supported by the grant, particularly that on Nakhla, has been slow in reaching fruitition and involved many dead-ends. But the final results have been significant and are, I feel worthy of the time and money expended.

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APPENDIX A: EXPERIMENTAL RESULTS IN CMASTF

Table A.1. Compositions of Experimental Charges

	SSA	SSB	SSC	SSD	SSE	SSF	AdMg
SiO2	38.82	39.16	39.93	40.84	40.64	40.43	44.91
TiO2	0.00	0.00	0.00	0.00	0.50	1.00	2.30
Al2O3	22.48	21.26	22.07	23.83	23.71	23.59	9.88
MgO	15.18	16.07	14.81	11.98	11.92	11.86	11.42
CaO	24.52	23.51	24.18	23.35	23.23	23.12	23.33

Table A.2. Run Results

Bulk	Run	T(oC)	Phases
SSA	0	1390	gl+sp
	1	1265	gl+sp
	2	1253	gl+sp
	4	1245	gl+sp
	5	1243	gl+sp+px
	3	1240	gl+sp+px+ol
	13	1232	gl+sp+px+ol
	11	1225	gl+sp+mel+an+px(?)
	12	1201	gl+sp+px+mel(?)
	6	1186	gl+sp+mel+pl+px
	7	1148	gl+ol+px+pl(?)
SSB	4	1317	gl+sp(+ol?)
	6	1315	gl+sp
	5	1310	gl+ol+sp
	3	1297	gl+ol+sp
	2	1272	gl+ol+sp
	1	1251	gl+ol+sp
	15	1238	gl+ol+sp
	14	1236	gl+ol+(px?)+sp
	13	1232	gl+ol+px+sp
	9	1230	gl+px+ol+sp(+me?)
	12	1227	gl+px+ol+(me)+sp
	16	1225	gl+ol+px+sp+me
	7	1223	(gl+px+me+sp)?
	11	1223	gl+px+me+sp
	8	1221	gl+px+me+sp
SSD	3	1251	gl+pl+sp
	2	1245	gl+(pl)+sp
	4	1245	gl+pl+sp
	1	1241	gl+pl+ol+sp
	7	1239	gl+px+pl+sp
	5	1236	gl+px+pl+sp
	9	1235	gl+(px)+pl+sp
	6	1231	gl+pl+px+sp

	10	1226	gl+pl+px+sp
	8	1222	gl+px+mel+pl (relict spinel)
SSE	2+	1386	gl
	3+	1352	gl+sp
	1,2	1270	gl+sp+pl
	3	1250	gl+sp+pl+px(?)
AdMg	5	1333	gl
	6	1319	gl
	13	1310	gl
	8	1295	gl+px
	7	1272	gl+px
	3	1260	gl+px
	2	1249	gl+px
	12	1243	gl+px
	11	1241	gl+px
	14	1241/0	gl+px
	10	1240	gl+px
	9	1239	gl+px
	1	1238	gl+px

Table A.3. Pyroxenes

Date	5.16/25.89						
Charge	SSB-9	SSB 9	SSB-9	SSB 11	SSB 11	SSB-16	SSB-16
Analysis	3	4	5	4	5	1	2
Si02	46.48	46.33	46.72	45.20	45.31	49.77	45.52
Al20	14.63	14.59	14.42	17.09	17.16	9.82	16.54
Mg0	13.03	13.15	13.32	11.78	11.95	15.00	12.13
Ca0	25.85	25.52	25.84	26.15	26.04	25.84	25.66
Total	99.99	99.60	100.29	100.21	100.46	100.43	99.85
cations per 6 oxygens							
Ca	1.001	0.992	0.997	1.011	1.004	0.994	0.994
Mg	0.706	0.715	0.607	0.638	0.645	0.808	0.658
Al	0.622	0.622	0.764	0.726	0.726	0.415	0.704
Si	1.680	1.680	1.573	1.631	1.631	1.787	1.646
Si+Al/2	1.991	1.991	1.955	1.994	1.994	1.995	1.998
Sum Cat.	4.009	4.009	4.011	4.006	4.028	4.005	4.002

Date							
Charge	SSB-16	SSB-16	SSB-16	SSD-1	SSD-1	SSD-5	SSD-5
Analysis	3	4	5	1	2	1	2
Si02	46.48	46.06	46.07	50.02	46.74	49.12	46.20
Al203	15.46	15.78	14.64	8.76	14.29	8.01	13.95
Mg0	12.59	12.39	12.72	14.58	12.48	15.46	12.81
Ca0	25.61	25.68	26.00	25.89	25.59	25.48	25.75
Total	100.14	99.91	99.43	99.25	99.09	98.06	98.72
cations per 6 oxygens							
Ca	0.988	0.994	1.013	1.008	0.998	1.006	1.010
Mg	0.680	0.671	0.694	0.795	0.681	0.855	0.703
Al	0.655	0.671	0.627	0.375	0.612	0.347	0.601
Si	1.674	1.664	1.676	1.818	1.701	1.810	1.692
Si+Al/2	2.002	1.999	1.989	2.005	2.007	1.984	1.993
Sum Cat.	3.998	4.000	4.010	3.996	3.993	4.017	4.007

Date			
Charge	SSD-5	SSD-5	SSD-6
Analysis	3	4	1
Si02	50.07	49.65	48.76
A1203	8.05	8.06	7.75
Mg0	15.33	15.33	14.91
Ca0	25.78	25.98	24.95
Total	99.22	99.02	96.28
Cations per 6 oxygens			
Ca	1.005	1.016	1.002
Mg	0.836	0.840	0.838
Al	0.344	0.346	0.337
Si	1.821	1.812	1.824
Si+Al/2	1.993	1.985	1.992
Sum Cat.	4.006	4.014	4.000

Table A.4. Melilites

Charge	SSB-11	SSB-11	SSB-16	SSB-16	SSB-16	SSB-16
Analysis	5	6	1	2	3	4
Si02	39.08	38.98	40.02	39.81	39.68	39.61
A1203	9.26	8.35	7.32	7.33	7.34	7.48
Mg0	10.60	10.81	11.33	11.52	11.17	11.13
Ca0	41.33	41.18	41.22	41.27	41.36	41.10
Total	99.27	99.31	99.88	99.92	99.55	99.32
Cations per 7 oxygens						
Ca	2.027	2.018	2.006	2.009	2.022	2.013
Mg	0.728	0.742	0.772	0.785	0.782	0.763
Al	0.445	0.450	0.391	0.392	0.394	0.402
Si	1.789	1.783	1.818	1.809	1.811	1.810
Si+Al/2	2.011	2.008	1.987	1.979	2.008	2.011
Sum Cat	4.988	4.992	4.987	4.995	5.009	4.988

Table 3. Glasses -

Charge	SSB-9	SSB-9	SSB-9	SSB-11	SSB-11	SSB-13
Analysis	3	4	5	4	5	1
SiO2	43.60	44.04	43.85	42.29	42.43	42.59
Al2O3	17.99	18.14	18.07	20.23	20.00	17.20
MgO	11.20	11.34	11.14	8.04	8.07	10.82
CaO	28.39	28.62	28.70	29.56	29.75	27.74
Total	101.18	102.15	101.76	100.13	100.26	98.34
Normalized to 4 cations						
Si	1.557	1.558	1.558	1.540	1.544	1.565
Al	0.756	0.755	0.755	0.876	0.856	0.744
Mg	0.600	0.602	0.594	0.439	0.440	0.597
Ca	1.087	1.085	1.093	1.154	1.160	1.093

Charge	SSB-13	SSB-14	SSB-14	SSB-16	SSB-16	SSB-16
Analysis	2	4	5	1	2	5
SiO2	42.93	43.18	42.48	43.03	42.62	42.76
Al2O3	17.50	17.78	17.59	18.81	17.77	17.67
MgO	10.83	10.84	10.35	10.30	10.46	10.67
CaO	27.95	28.18	29.12	29.04	28.76	28.63
Total	99.21	99.98	99.35	101.18	99.82	99.73
normalized to 4 cations						
Si	1.565	1.562	1.546	1.541	1.547	1.551
Al	0.751	0.757	0.753	0.792	0.784	0.754
Mg	0.592	0.588	0.567	0.553	0.549	0.518
Ca	1.092	1.093	1.136	1.114	1.119	1.113

Charge	SSB-16	SSD-1	SSD-1	SSD-1	SSD-1	SSD-7
Analysis	6	1a	2	3	4	1
SiO2	42.45	42.20	42.75	42.99	42.84	42.78
Al2O3	19.12	17.16	17.08	17.59	17.61	17.97
MgO	9.80	10.86	10.85	11.21	11.15	9.62
CaO	28.79	26.27	26.06	26.58	26.52	29.33
Total	100.15	96.49	96.74	98.37	97.85	99.70
Normalized to 4 cations						
Si	1.537	1.580	1.597	1.578	1.581	1.559
Al	0.814	0.756	0.751	0.760	0.764	0.770
Mg	0.532	0.610	0.608	0.617	0.617	0.526
Ca	1.117	1.054	1.044	1.045	1.038	1.145

Charge Analysis	SSD-7 2	SSD-7 3	SSD-5 1	SSD-5 2	SSD-5 3	SSD-6 1
SiO2	42.94	43.48	42.70	41.92	41.61	40.97
Al2O3	18.04	18.03	17.93	17.70	17.68	17.72
MgO	9.63	10.11	10.78	10.67	10.60	9.89
CaO	29.51	29.30	28.61	28.65	28.60	28.36
Total	100.13	100.92	100.02	98.95	98.49	96.93*
Normalized to 4 cations						
Si	1.558	1.563	1.544	1.532	1.528	1.529
Al	0.770	0.763	0.763	0.761	0.763	0.778
Mg	0.524	0.545	0.585	0.585	0.584	0.554
Ca	1.147	1.129	1.108	1.121	1.125	1.134

Charge Analysis	SSD-6 2	SSD-6 3	SSD-2 1	SSD-2 2
SiO2	40.60	40.77	43.87	42.43
Al2O3	17.43	17.29	17.84	17.67
MgO	9.65	9.77	11.14	10.87
CaO	28.40	28.30	25.99	26.13
Total	96.08*	96.13*	98.84	98.30
Normalized to 4 cations				
Si	1.532	1.537	1.604	1.583
Al	0.774	0.767	0.767	0.772
Mg	0.546	0.553	0.611	0.605
Ca	1.148	1.143	1.018	1.040

Table A.5.- Older Pyroxene Analyses

Date	11-18-88			1-25-89
Charge	SSA-11	SSA-11	SSA-10	SSB-9
Analysis	12	14	27	2
SiO2	47.84	47.67	45.18	45.16
Al2O	14.73	14.68	16.39	14.07
MgO	12.41	12.26	12.72	12.59
CaO	25.09	25.16	25.39	24.13
Total	100.06	99.76	99.68	95.95
cations per 6 oxygens				
Ca	0.974	0.971	0.986	0.970
Mg	0.668	0.662	0.577	0.709
Al	0.622	0.622	0.699	0.621
Si	1.717	1.717	1.637	1.695
Si+Al/2	2.028	2.028	1.987	2.005
Sum Cat.	3.981	3.972	3.898	3.995

APPENDIX B: EXPERIMENTAL RESULTS
NAKHLITE EXPERIMENTS

Table B.1. Compositions of Experimental Charges

	NakC	NakD'	Nak70	Nak60	NakBulk
SiO2	43.47	44.08	45.53	46.25	48.42
TiO2	0.73	0.60	0.57	0.55	0.51
Al2O3	4.38	3.26	2.71	2.43	1.60
Cr2O3	0.31	0.17	0.25	0.29	0.41
FeO	30.15	29.63	26.70	25.24	20.85
MnO	1.01	0.51	0.48	0.47	0.42
MgO	11.73	9.71	10.46	10.84	11.97
CaO	8.59	10.46	11.91	12.63	14.81
Na2O	1.09	0.90	0.77	0.71	0.51
K2O	0.44	0.28	0.32	0.34	0.40
P2O5	0.00	0.34	0.26	0.22	0.10

Table A.2. Critical Run Results (Most Runs are Omitted!)
All experiments run at 0.75-1.5 log units more oxidizing that Fe FeO

Bulk	Run	T(oC)	Phases
NakC			
	BU21	1345	gl
	BU20	1275	gl+ol
NakD'			
	BU55	1291	gl
	BU56	1282	gl+ol
Nak70			
	BU52	1298	gl
	BU48	1289	gl+px
Nak			
	BU46	1298	gl
	BU42	1293	gl+px (trace)
	BU44	1286	gl+px

APPENDIX C: CHEMICAL ANALYSES OF MAGMATIC INCLUSIONS

Inclusion[b]	1.1.1	1.1.2	1.1.3	1.2.1	1.2.2	1.2.3	1.3.1	2.2.1	2.2.2*	2.2.3	2.2.1	AVG.[c]
SiO_2	48.83	53.73	43.32	39.71	42.26	35.04	47.10	42.84	42.89	47.30	42.11	44.66
TiO_2	0.99	0.31	0.11	2.08	0.30	0.01	0.81	0.94	0.89	0.58	0.61	0.72
Al_2O_3	8.64	14.57	13.48	14.13	10.08	0.89	8.38	15.92	10.75	8.62	8.29	10.30
Cr_2O_3	0.24	0.04	0.26	0.00	0.20	0.99	0.08	0.00	0.06	0.14	0.19	0.20
FeO	15.52	13.15	13.05	21.61	18.20	38.64	18.93	16.93	13.72	20.45	27.15	20.03
MnO	0.35	0.32	0.35	0.33	0.47	0.38	0.53	0.26	0.32	--	0.47	0.38
MgO	5.70	3.09	8.66	6.30	9.71	11.04	8.02	4.74	6.79	10.96	9.59	7.69
CaO	15.55	6.11	18.36	8.91	16.37	12.63	13.21	13.29	14.07	9.21	9.26	12.48
Na_2O	1.10	2.39	0.99	1.01	0.95	0.13	1.28	1.82	1.41	1.47	1.69	1.32
K_2O	1.39	1.78	0.33	1.78	0.71	0.00	1.00	2.13	2.17	0.57	0.25	1.37
P_2O_5	1.39	1.14	0.63	1.08	0.67	0.05	0.65	1.13	0.89	0.51	0.39	0.78
(Sum	95.55	93.62	93.89	77.58	86.45	97.28	88.24	72.36	95.15	88.35	95.79	--)
Mg'	0.40	0.30	0.54	0.31	0.47	0.37	0.55	0.58	0.47	0.49	0.39	0.41
Diam. (mm)	0.062	0.011	0.019	0.075	0.020	0.006	0.069	0.200	0.058	0.066	0.018	

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[a] Electron microprobe analyses, defocussed beam, normalized to 100%. Sum shows analytical totals, which may be low because some inclusion surfaces are irregular.

[b] Identification numbers are "Harvard Univ. thin section of Nakhla . olivine number . inclusion number ".

[c] Numerical average, unweighted.

* Average of three analyses.

[redacted] Compositions of Phases in Magmatic Inclusions

Analysis[a]	2.2.2.1	2.2.1.6	1.2.1.7	2.2.2.2	2.2.1.2	2.2.1.3
Phase	Aug.	Aug.	Aug.	Glass	Glass	Ti-Mt.
SiO_2	49.28	47.45	47.32	64.41	67.67	0.19
TiO_2	1.07	1.19	1.03	0.14	0.11	19.12
Al_2O_3	1.98	3.80	2.96	17.00	16.11	6.28
Cr_2O_3	0.02	0.00	0.00	0.00	0.00	0.34
FeO	13.86	18.11	18.81	1.67	1.09	70.12
MnO	0.37	0.45	0.39	0.00	0.00	0.55
MgO	10.75	8.22	7.71	0.58	0.06	0.19
CaO	19.80	20.99	21.17	3.06	1.50	0.32
Na_2O	0.63	0.21	0.22	1.36	2.32	0.02
K_2O	--	--	--	5.11	4.51	--
P_2O_5	--	--	--	1.05	0.15	--
Sum	100.79	100.46	99.63	94.34	94.20	97.18
Mg'	0.58	0.45	0.41	0.38	0.09	--

[a] Identification numbers are: "Harvard Univ. thin section of Nakhla . olivine number . inclusion number . analysis number".

APPENDIX D:
PUBLICATIONS UNDER THIS GRANT

PUBLICATIONS

Treiman A.H., Jones J.H., and Drake, M.J. (1987) Core formation in the Shergottite Parent Body: a chemical model. *Proc. 17th Lunar Planet. Sci. Conf., Jour. Geophys. Res.* 92, Suppl., E627-E632.

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