"NAKHLITES" ON EARTH: CHEMISTRY OF CLINOPYROXENITES FROM THEO'S FLOW, ONTARIO, CANADA

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The nakhlites (basaltic rocks rich in augite pyroxene) have been considered a uniquely martian phenomenon, testifying to fundamental differences between Mars and the Earth. However, very similar augite-rich basalt flows are present in Archaean terranes on Earth [1-4]. New chemical data confirm the similarity and extend it to trace elements. Like the nakhlites, the parent magmas of one such flow (Theo's) is LREE-enriched with minimal Eu anomaly, and depleted in the most incompatible elements. Clearly, nakhlite-forming petrogenesis on Mars had a terrestrial equivalent during the Archaean. Studies of these Earth basalts will clarify the nakhlites' origin, and the nakhlites will in turn clarify petrogenetic processes in the Archaean (and subsequent) Earth.

THE ROCKS: The nakhlite meteorites are volcanic or sub-volcanic clinopyroxenites with minor olivine and a fine-grained mesostasis [1,2,5]. Similar rocks occur sparingly in the Archaean on Earth [6]; the best studied example is Theo's flow, a clinopyroxenite flow in Munro Township, Ontario [3]. Clinopyroxenites of Theo's flow are nearly identical to the nakhlites in mineralogy, mineral proportions, grain sizes, and textural relations [1-4].

THEO'S FLOW: XRF bulk chemical analyses of a cumulate clinopyroxenite (TF-9) and a thin flow (TS-2) from the Theo's flow complex were obtained from a commercial laboratory (Table 1). Theo's flow was basaltic (~50% SiO_2) and strongly depleted in Al relative to Ca and Ti [6]. This magma is <u>not</u> a tholeiite, which typically have 13-16% Al_2O_3 and plagioclase near the liquidus; rather, such low-Al basalts are named "theolites" after Theo's flow [6].

Bulk trace element data were obtained by XRF and INAA using standard methods [7] (Figure 1). Minor and trace element abundances in the cores of TS-9 augites were obtained by laser ablation ICPMS [8] (Figure 1). Rocks of Theo's flow have MREE abundances near 15xCI, small depletions in LREE, stronger depletions in HREE, and minimal Eu anomaly. Compared to the lava TS-2, aphanitic pyroxenite P9-158 [4] seems evolved in having higher REE, Ti, Al, Fe, and Na, and lower Mg and Ca (Figure 1, Table 1). Theo's flow augite has a typical LREE-depleted pattern, slightly depleted in HREE, and with no Eu anomaly. Parent magma REE abundances were calculated from ICPMS data and appropriate $D^{augite/basalt}$ [10,11]. The inferred parent magma REEs are coincident with the bulk analyses of Theo's flow rocks (Figure 1).

COMPARISON: Clinopyroxenites from Theo's flow are nearly identical to nakhlites in texture [1-6] and chemistry: low Al, superchondritic Ca/Al and Ti/Al, LREE-enriched with a slight depletion in La-Ce, and minimal Eu anomaly [6,12-14]. Other critical trace element comparisons between TS-9 and Nakhla include Sc (48 vs. 53 ppm), Sr (~100 vs. ~60 ppm) and Co (60 vs. 50 ppm) [15]. If a Theo's flow pyroxenite fell from space, it would be classified as a nakhlite (until O isotopes and high Mg* showed its terrestrial origin).

There are significant differences between Theo's flow rocks and the nakhlites, e.g. lower Mg*. The very low Al contents of nakhlites, despite similar parent magma compositions (Table 1), suggests that they contain little intercumulus magma. Nakhla pyroxene has a more extreme HREE depletion, and a possible slight Eu anomaly [13]. But these are differences minor compared to their petrographic and chemical similarities.

COMPARATIVE PLANETOLOGY: The chemical similarities between the nakhlites and Theo's pyroxenites reflect similar parent magma compositions (Table 1), petrogeneses, and mantle compositions [6]. Al-depleted magmas, including theolites, Al-depleted komatiites (group II), and ferropicrites, were moderately common in the Archaean on Earth. The ferropicrites are notably similar to nakhlites and theolites in having high FeO contents and enrichments in the LREE [20,21]. In general, Al-depleted magmas must come from Al-depleted mantle source regions, and leave no residual aluminous phase(s), implying removal of an aluminous phase before magma generation [6,16,17]. Plagioclase was not involved for nakhlites nor theolites, as neither are depleted in Eu or Sr. Spinel removal has been proposed for nakhlites [6]; garnet removal has been invoked for Theo's flow [18], but cannot explain the Al-depletion of group-II komatiites [19]. And, why has Al-depleted mantle persisted on Mars, while it is apparently absent in the Earth (at least from magma producing regimes) after the Archaean [6]?

The ferroan yet primitive nature of ferropicrites and theolites raises a problem of mantle composition. The ferropicrites and theolites can be considered primitive as they have high Co and Ni abundances; thus, crystal fractionation had little effect on their Mg*, which then should reflect Mg* of their source mantles. Their source mantles had Mg*~75, much more ferroan than normal Earth mantle at Mg*~90 [17,21]. Clearly, the Earth's mantle had significant heterogeneities in Mg*. Could the source mantle for the nakhlites (and other SNCs) be as unrepresentative of the martian mantle as the theolite source mantle is of the Earth's mantle?

Table 1: "Nakhlites" and Parent Magmas

	1	2	3	4	5
SiO_2	49.53	50.95	50.4	48.61	50.2
TiO_2	0.83	0.90	1.14	0.33	1.0
Al_2O_3	5.74	6.95	9.5	1.60	8.6
Cr_2O_3	0.44	0.26	nd	0.29	0.1
FeO	10.20	10.17	12.8	20.89	19.1
MnO	0.19	0.18	0.20	0.50	0.4
MgO	12.78	11.64	9.1	12.02	4.0
CaO	14.46	12.46	10.2	14.84	11.9
Na_2O	1.03	1.91	3.8	0.46	1.2
K_2O	0.04	0.04	0.03	0.12	2.8
P_2O_5	0.06	0.07	nd	0.11	0.7
L.O.I.	2.35	1.83	2.0	---	---
Sum	97.65	97.36	99.2	99.77	100.00

1) Theo's Flow pyroxenite TS-9. 2) Pyroxenite lava (Marvin's Flow) TF-2. 3) Theo's Flow aphanite P9-158 [3]. 4) Nakhla [12]. 5) Nakhla parent magma [12].

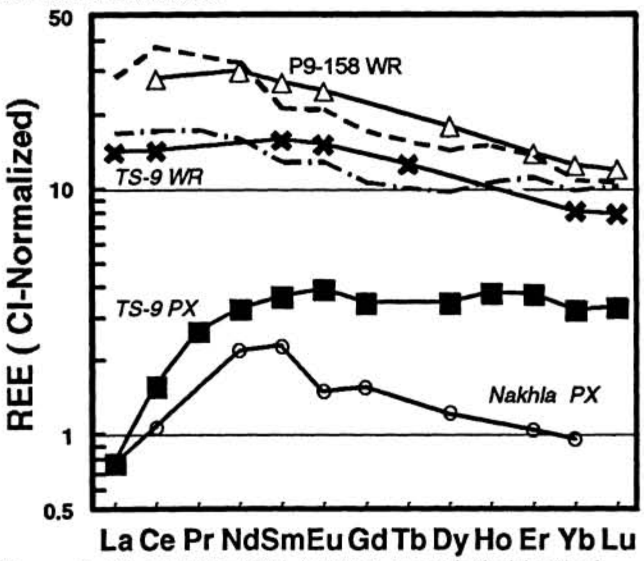

Figure 1. TS-9 WR by INAA; TF-2 essentially identical. Theo's flow aphanite P9-158 [9]. TS-9 pyroxene by laser ICPMS. Nakhla pyroxene by SIMS [13]. Dashed lines are TS-9 parent magma inferred from $D^{augite/basalt}$ [10,11].

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