THE GOVERNADOR VALADARES NAKHLITE AND ITS RELATIONSHIP TO OTHER NAKHLITES. J. L. Berkley[1], K. Keil[1], M. Prinz[2], and C. B. Gomes[1], [1]Dept. of Geology and Inst. of Meteoritics, University of New Mexico, Albuquerque, NM 87131, [2]Dept. Mineral Sci., Am. Mus. Nat. Hist., New York, NY 10024.

INTRODUCTION. The Governador Valadares (GV), Minas Gerais, Brazil nakhlite (find, 1958) [1] is a cumulate augite achondrite with a pronounced mineral elongation lineation also noted in the other two known nakhlites, Nakhla (N) and Lafayette (L) [2]. Nakhlites are of great interest since they have very young ages (! 1.3×10^9 years) [3-6], which appear to correspond to the time of the most recent igneous crystallization and, thus, raise serious questions regarding current ideas on meteorite parent body differentiation. We studied PTS of all nakhlites by petrographic and electron microprobe techniques for the purpose of characterizing, comparing, and interpreting the origin of these rare achondrites. We present new compositional data on many phases as well as universal stage mineral orientation patterns for augite which confirm a cumulate origin for nakhlites. In addition, we present evidence which suggests that each nakhlite represents a unique meteorite, although all originated from a common source and formed under similar conditions.

PETROGRAPHY AND MINERAL CHEMISTRY. Cumulus cpx. The principal mineral in GV is subhedral to euhedral aug (En38.9Fs22.6Wo38.5), compositionally similar to aug in the other nakhlites (Fig. 1; Table 1). Little compositional variation exists from grain to grain and core regions are essentially homogeneous. All nakhlites display some limited FeO/MgO-enrichment in aug grain rims (generally not more than 1.0 mole% Fs difference, core to rim), probably caused by reaction with intercumulus liquid during post-cumulus crystallization. The major difference in aug core compositions is in Al_2O_3 which is similar between GV (0.81 wt.%) and L (0.91 wt.%), but lower in N (0.66 wt.%). Elongated aug grains with aspect ratios of about 3.3:1 display preferred orientations in all nakhlites (Fig. 2), expressed as high concentrations of horizontal points (near stereonet margin) for X and Z optical directions with Y displaying high vertical concentrations (near center). The distribution, especially of X, around the outer portions of the diagrams (and shown to a lesser degree for more diffuse Z patterns) suggests the existence of a weak foliation accompanying the strong mineral elongation lineation that is visible in PTS. These orientation patterns not only compare remarkably between individual nakhlites (Fig. 2), but are also similar to terrestrial cumulus clinopyroxene patterns [7], with the lineation probably resulting from flow during or after crystal settling. Olivine. Anhedral ol (equant grains up to 2 mm dia.) is a relatively minor phase in nakhlites. It occurs in two size ranges in N (and possibly, L; see below); large grains (1-2 mm dia.), and minute grains (10-100 ¢m) intergrown with plag and other mesostasis phases. The smaller grains tend to be more Fa-rich than the larger variety, Fa77 and Fa67, respectively (Fig. 1). Only the larger type was observed in GV (Table 1) and are zoned in GV (more Fa-rich rims), but zoning is minor or absent in other nakhlites. Reaction rims of low-Ca cpx (pig) occur on some ol grains in L. Ol in all nakhlites is generally veined or mantled by a brownish-red alteration product identified by [2] and here as iddingsite, an hydrous, ferric iron-rich assemblage of smectite clay and hydrous iron oxides commonly associated with low-temperature alteration of terrestrial ol, but generally unknown in meteorites. Although ol in all nakhlites is quite similar in major element composition (Fig. 1; Table 1), CaO in large L ol grains is significantly lower (0.23 wt.%) than in the other two nakhlites, both of which average

over 0.4 wt.% CaO. The Fa-rich nature of nakhlite ol compared to more MgO-rich cumulus aug (Fig. 1) rules out a cumulus origin for the ol. The majority of nakhlite ol is surely a post-cumulus, interstitial phase, although some more forsteritic ol of cumulus origin may have gone unnoticed. Minor Mesostasis Phases. Mesostasis areas in nakhlites are characterized in most cases by semi-radiating intergrowths of plag (An23-36Ab60-68Or3-9) ± alkali-feldspar (An4-6Ab20-42-Or52-76), cpx (mainly ferro pig with some subcalcic ferroaug and ferroaug; Fig. 1), titanomagnetite with ilmenite lamellae, and minor sulfides (pyrite, troilite, chalcopyrite) and chlorapatite. Pure SiO_2 occurs in minor amounts in N and GV but was not observed in L. High-SiO_2, feldspar-normative glass occurs as a major constituent of mesostasis areas in L but occurs in very minor amounts in other nakhlites. Mesostasis areas in nakhlites are highly reminiscent of interstitial variolitic intergrowths in quickly chilled terrestrial oceanic basalts, as well as certain meteoritic and lunar basalts. In L these areas are coarser grained than in other nakhlites, however, [2] noted coarse as well as fine-grained areas in N, so these apparent differences (and some others) may be due to sampling. Most mesostasis areas are composed principally of plag-cpx-opaque phase intergrowths, however, in some areas in N the cpx is absent; Fa-rich ol occurs instead. A similar situation may have occurred in L, since some mesostasis areas contain pig-plag intergrowths, but others contain iddingsite-plag assemblages. This iddingsite represents an alteration of olivine. These differences in phase assemblages from one interstitial area to another demonstrate independent crystallization of isolated post-cumulus liquid pockets commonly observed in cumulate rocks.
DISCUSSION AND CONCLUSIONS. We conclude that sufficient differences exist between the three nakhlites that appear to be outside the ranges that one might reasonably assume to be due to sampling to establish them as separate and distinct meteorite specimens. However, we stress the need for further investigations on different portions of these meteorites to confidently eliminate the chance for sampling problems. This conclusion is important since N and L have long been suspected to be pieces of the same meteorite. However, GV displays more similarities to N in terms of mineralogical and petrological properties than does L. The close similarity of major element compositions of cumulus aug and interstitial ol (Fig. 1; Table 1) and the nearly identical mineral orientation patterns (Fig. 2) and other common textural and mineralogical features in nakhlites, clearly demonstrate a common origin for all. The distinguishing features can be summarized as follows: (1) CaO is significantly lower in large ol grains in L than in other nakhlites (Table 1); (2) compositions of interstitial cpx are dramatically more En-rich in L than in the other nakhlites (Fig. 1); (3) mesostasis areas in L are more coarse grained and glass-rich than in the other nakhlites; and (4) Al_2O_3 in cumulus aug differs between individual nakhlites (Table 1). That nakhlites represent wholly unmetamorphosed (and unshocked) igneous rocks was documented by [2] and is reaffirmed here. The occurrence of euhedral cumulus aug crystals, the preservation of pig, glass, and delicate quench crystals and chemical zoning in silicate grains are not compatible with an intensive metamorphic event as proposed by [4]. It is clear that an igneous cumulate stage was the latest event to affect the nakhlites prior to their dispersion into space. Igneous crystallization obviously occurred under relatively highly oxidizing conditions as compared to most other achondrites. This is suggested by the presence of iddingsite (allowing for the possibility of pre-terrestrial H_2O involvement), titanomagnetite, pyrite, lack of Ni-Fe metal, and the partitioning of Ni into ol [2]. In this respect nakhlites are similar to the Shergottites [8] which are

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two-px cumulates, and the ol cumulate, Chassigny [9], which also display evidence for crystallization under more terrestrial-like conditions. The nakhlites evolved from a highly differentiated melt as evidenced by their light rare earth-enriched abundance patterns (4x chondrites) [10] and their highly FeO (and probably Fe_2O_3)-SiO_2-alkali-rich mesostasis (Fig. 1). In these respects they differ little from highly differentiated terrestrial basalts. The nakhlites appear to have undergone a two-stage cooling history, cooling relatively slowly during aug accumulation to form only slightly zoned or homogeneous euhedral crystals, followed by the quenching of the intercumulus mesostasis into delicate variolitic intergrowths. One possible mechanism for this might be sudden surface or near surface extrusion of a deeper-formed crystal-liquid mush, which is also consistent with cpx orientation patterns (Fig. 2).

We do not find any evidence that the nakhlites represent impact melts, such as obviously foreign mineral phases or lithic fragments; however, we cannot rule out this process or an origin as internally-derived melts. On the other hand, the moon is known to have ceased production of internally-generated melts (mare basalts) about two billion years prior to nakhlite formation which tends to mitigate against internal generation of nakhlite magmas in a lunar or smaller-sized parent body. Were conclusive evidence forthcoming for internal nakhlite generation, current ideas which propose relatively small-sized meteorite parent bodies might warrant reevaluation.

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Table 1. Average electron microprobe analyses of mafic silicate phases in nakhlites. GV=Governador Valadares; N=Nakhla; L=Lafayette: analyses 1-3, cumulus aug; 4-6, interstitial cpx; 7-9, large ol. ——not determined, ND-not detected. All analyses represent core values.

	1	2	3	4	5	6	7	8	9
	GV	N	L	GV	N	L	GV	N	L
SiO2	51.3	51.3	51.2	48.3	46.9	51.4	34.0	32.9	32.9
TiO2	0.17	0.23	0.29	0.42	0.35	0.23	——	——	——
Al2O3	0.81	0.66	0.91	0.35	0.57	0.29	——	——	——
Cr2O3	0.36	0.37	0.29	0.11	<0.05	<0.01	<0.09	<0.04	<0.10
FeO	14.0	13.9	12.9	36.6	37.9	29.4	49.9	51.1	50.2
MnO	0.37	0.43	0.38	0.95	1.00	0.47	0.71	0.76	0.77
MgO	13.5	13.5	13.3	8.6	6.1	12.3	14.3	14.4	14.1
CaO	18.6	18.1	18.7	4.2	5.2	4.6	0.44	0.41	0.23
Na2O	0.17	0.17	0.15	<0.04	<0.07	<0.06	——	——	——
Total	99.29	98.70	98.20	99.55	98.00	98.70	99.35	99.51	98.30
En	38.9	39.3	39.1	26.7	19.6	38.3	Fo 33.8	33.5	33.4
Fs	22.6	22.7	21.3	63.9	68.4	51.5	Fa 66.2	66.5	66.6
Wo	38.5	37.9	39.6	9.4	12.0	10.2			

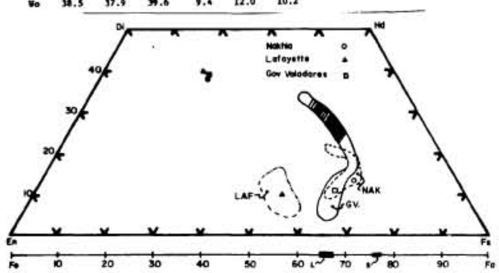

Figure 1. Molar pyroxene and olivine compositions in nakhlites. Filled symbols = avg. cumulus cpx cores; open symbols = avg. mesostasis cpx; enclosed areas = mesostasis range (hatched = no pts.). L = large ol range; S = small ol range in N.

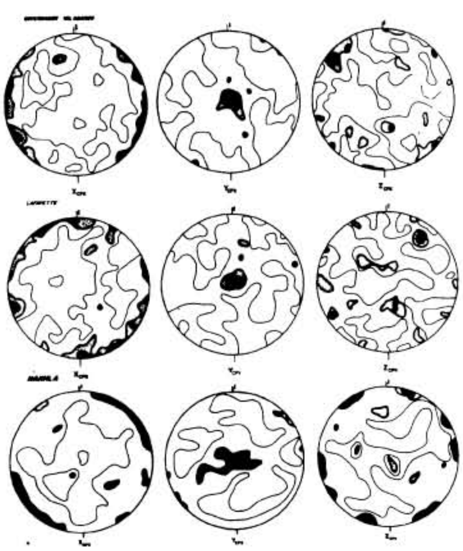

Figure 2. Stereonet diagrams of cumulus augite indicatrix orientations. I = lineation (visually determined ; black = highest concentration; stipled = intermediate concentration; open = low or zero concentration.