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Frontier Mountain meteorite specimens of the acapulcoite-lodranite clan: Petrography, pairing, and parent-rock lithology of an unusual intrusive rock

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Abstract–In this paper we reconstruct the heterogeneous lithology of an unusual intrusive rock from the acapulcoite-lodranite (AL) parent asteroid on the basis of the petrographic analysis of 5 small (<8.3 g) meteorite specimens from the Frontier Mountain ice field (Antarctica). Although these individual specimens may not be representative of the parent-rock lithology due to their relatively large grain size, by putting together evidence from various thin sections and literature data we conclude that Frontier Mountain (FRO) 90011, FRO 93001, FRO 99030, and FRO 03001 are paired fragments of a medium- to coarse-grained igneous rock which intrudes a lodranite and entrains xenoliths. The igneous matrix is composed of enstatite ($Fs_{13.3 \pm 0.4}$ $Wo_{3.1 \pm 0.2}$), Cr-rich augite ($Fs_{6.1 \pm 0.7}$ $Wo_{42.3 \pm 0.9}$), and oligoclase ($Ab_{80.5 \pm 3.3}$ $Or_{3.2 \pm 0.6}$). The lodranitic xenoliths show a fine-grained (average grain size 488 ± 201 μm) granoblastic texture and consist of olivine $Fa_{9.5 \pm 0.4}$ and Fe,Ni metal and minor amounts of enstatite $Fs_{12.7 \pm 0.4}$ $Wo_{1.8 \pm 0.1}$, troilite, chromite, schreibersite, and Ca-phosphates. Crystals of the igneous matrix and lodranitic xenoliths are devoid of shock features down to the scanning electron microscope scale. From a petrogenetic point of view, the lack of shock evidence in the lodranitic xenoliths of all the studied samples favors the magmatic rather than the impact melting origin of this rock.

FRO 95029 is an acapulcoite and represents a separate fall from the AL parent asteroid, i.e., it is not a different clast entrained by the FRO 90011, FRO 93001, FRO 99030, and FRO 03001 melt, as in genomict breccias common in the meteoritic record. The specimen-to-meteorite ratio for the AL meteorites so far found at Frontier Mountain is thus 2.5.

INTRODUCTION

The rare primitive achondrites of the acapulcoite-lodranite (AL) clan are important rocks because they convey significant information on melting and differentiation processes in the asteroid belt early in the history of the solar system (e.g., Mittlefehldt et al. 1998; Mittlefehldt 2005).

In this paper we discuss the pairing of 5 small (<8.3 g) meteorite specimens belonging to the AL clan, which were found in the Frontier Mountain blue ice field, Antarctica (Fig. 1 and Table 1). They include one acapulcoite, Frontier Mountain (FRO) 95029 (Grossman 1997), 3 specimens originally classified as lodranites, FRO 90011 (McCoy et al. 1993), FRO 99030 (Grossman 2000), and FRO 03001 (Russell et al. 2004), and the igneous (the term "igneous" is used in this paper to strictly describe rocks or minerals with textures indicating solidification from molten material) member FRO 93001 (Folco et al. 2006); the latter carries evidence for very high degree melting processes and thus it may considerably increase our understanding of differentiation mechanisms operating on the AL parent asteroid. Pairing is discussed on the basis of the direct comparison of new petrographic data from FRO 90011, FRO 95029, FRO 99030, and FRO 03001 with literature data for FRO 93001 (Folco et al. 2006). In particular, we will show how meteorites that appear unrelated in thin section are actually fragments of the same fall, as in the case of the 3 lodranites FRO 90011, FRO 99030, and FRO 03001, and the igneous-textured FRO 93001. This pairing allows us to reconstruct the heterogeneous lithology of the parent rock, to better constrain petrogenesis, and to plan future investigations avoiding unnecessary duplicate analyses of such small and important specimens. Furthermore, the pairing results contribute to the long-term, ongoing studies (e.g., Fioretti and Molin 1996; Welten et al. 1999, 2001, 2006a, 2006b; Smith et al. 2000) aiming at establishing the actual number of individual meteorites found at Frontier Mountain (~700 specimens so far found) (Folco and Zeoli 2005), with

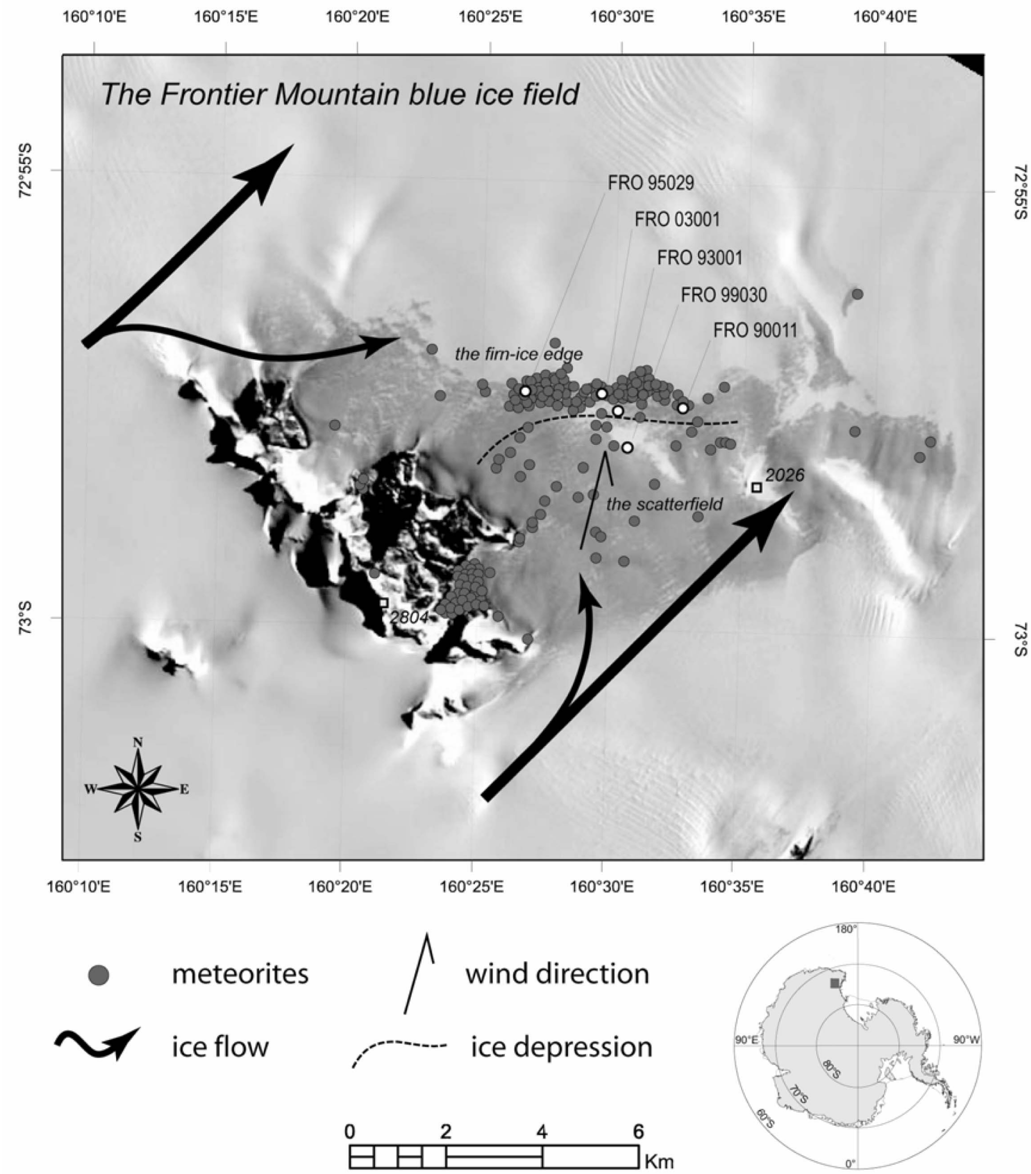

Fig. 1. Meteorite distribution map of the Frontier Mountain blue ice field showing find location of the FRO 93001, 95029, 90011, 99030, and 03001 meteorite fragments studied in this work. For details about the meteorite concentration mechanism the reader is referred to Folco et al. (2002).

implications for the meteorite concentration mechanism, the flux of meteorites to Earth, and on the petrogenesis of complex meteorite breccias.

SAMPLES AND ANALYTICAL METHODS

New petrographic observations were carried out on samples from the FRO 90011, FRO 95029, and FRO 99030 meteorites in the collection of the Museo Nazionale dell'Antartide in Siena (MNA-SI). Main masses were first inspected under the stereographic microscope for macroscopic characterization. One polished thin section representative of each meteorite specimen (FRO 90011,04, FRO 95029,03, FRO 99030,01, and FRO 03001,01) was then prepared for petrographic analyses. Textural and mineral compositional data were obtained using the optical microscope (in both transmitted and reflected light) and a Philips XL30 microanalytical scanning electron microscope (SEM-EDS) at the MNA-SI. Mineral mode for FRO 95029 was determined through counting 142 points on a 300 μm grid in the SEM-EDS. The mode for the other meteorites was not determined, since their large grain size relative to specimen size prevents the obtainment of representative estimates of mineral abundances. Mineral compositions, reported in Tables 2–6, were determined with a JEOL JXA 8600 electron microprobe fitted with 4 wavelength dispersive spectrometers at the CNR Instituto di

Table 1. Meteorite fragments of the AL clan from the Frontier Mountain blue ice field studied in this work.

Name	Mass (g)	Main lithology observed in thin section	Class: This work	Class: Literature	SS#	W§
FRO 90011	1.8	Large orthenstatite enclosing lodranitic xenoliths	Intrusive breccia	Lodranite (McCoy et al. 1993)	S1	W1
FRO 93001	4.84	Coarse-grained, enstatite-augite-oligoclase-rich igneous rock entraining lodranitic xenoliths	Intrusive breccia	Unique igneous rock (Folco et al. 2006)	S1	W1
FRO 95029	4.6	Homogeneous, typical acapulcoite	Acapulcoite	Acapulcoite (Grossman 1997)	S1	W1
FRO 99030	8.3	Large lodranitic metal xenoliths	Intrusive breccia	Lodranite (Grossman 2000)	S1	W1
FRO 03001	1.46	Lodranite impregnated by a two-pyroxene melt	Intrusive breccia	Lodranite (Russell et al. 2004)	S1	W1

#Following Stöffler et al. (1991).
§Following Wlotzka (1993).

Table 2. Compositions of olivines in FRO 90011, FRO 95029, FRO 99030, and FRO 03001 (oxides wt% and, in parentheses, standard deviations). Literature data for FRO 93001 (Folco et al. 2006) are reported for comparison.

	FRO 90011	FRO 93001	FRO 95029	FRO 99030	FRO 03001
Textural type	granoblastic	granoblastic	granoblastic	granoblastic	granoblastic
N	4	73	17	5	11
SiO_2	41.4 (0.3)	41.2 (0.3)	41.1 (0.16)	41.0 (0.3)	41.4 (0.2)
TiO_2	<0.04	<0.04	<0.04	<0.04	<0.04
Al_2O_3	<0.04	<0.04	<0.04	<0.04	<0.04
FeO	9.11 (0.32)	9.67 (0.51)	8.47 (0.20)	9.27 (0.76)	9.11 (0.43)
MnO	0.48 (0.05)	0.54 (0.05)	0.49 (0.06)	0.48 (0.08)	0.48 (0.05)
MgO	49.7 (0.3)	49.2 (0.5)	50.8 (0.2)	48.9 (0.4)	49.1 (0.2)
CaO	0.03 (0.01)	<0.03	0.03 (0.02)	0.04 (0.01)	0.03 (0.01)
NiO	<0.04	<0.04	<0.04	<0.04	<0.04
Cr_2O_3	<0.05	<0.05	<0.05	<0.05	0.06 (0.04)
Total	100.72	100.61	100.89	99.69	100.18
Endmembers	$Fa_{9.3\ (0.3)}$	$Fa_{9.9\ (0.6)}$	$Fa_{8.6\ (0.2)}$	$Fa_{9.6\ (0.7)}$	$Fa_{9.5\ (0.4)}$

N = number of analyses.

Table 3. Compositions of enstatites in FRO 90011, FRO 95029, FRO 99030, and FRO 03001 (oxides wt% and, in parentheses, standard deviations). Literature data for FRO 93001 (Folco et al. 2006) are reported for comparison.

	FRO 90011	FRO 93001	FRO 95029	FRO 99030	FRO 03001	
Textural type	igneous	igneous	granoblastic	nd	granoblastic	igneous
N	13	10	27	6	5	10
SiO_2	57.8 (0.5)	56.3 (0.5)	57.4 (0.5)	56.7 (0.5)	57.8 (0.7)	56.6 (0.6)
TiO_2	0.15 (0.03)	0.17 (0.01)	0.26 (0.05)	0.14 (0.03)	0.15 (0.03)	0.15 (0.04)
Al_2O_3	0.36 (0.07)	0.39 (0.03)	0.36 (0.04)	0.32 (0.04)	0.24 (0.03)	0.32 (0.03)
FeO	8.29 (0.11)	8.41 (0.13)	6.05 (0.22)	8.28 (0.47)	8.16 (0.27)	8.75 (0.35)
MnO	0.53 (0.34)	0.54 (0.04)	0.57 (0.04)	0.54 (0.08)	0.52 (0.05)	0.42 (0.13)
MgO	32.0 (0.1)	31.8 (0.3)	34.8 (0.3)	31.5 (0.4)	31.8 (0.2)	31.5 (0.2)
CaO	1.33 (0.48)	1.66 (0.13)	0.85 (0.15)	1.42 (0.08)	0.93 (0.06)	1.45 (0.08)
Cr_2O_3	0.39 (0.26)	0.47 (0.03)	0.28 (0.06)	0.44 (0.05)	0.31 (0.07)	0.36 (0.09)
Na_2O	0.07 (0.06)	0.13 (0.09)	<0.07	<0.07	<0.07	<0.07
Total	100.92	99.87	100.57	99.34	99.91	99.55
Endmembers	$Fs_{13.0\ (0.6)}$ $Wo_{2.5\ (0.5)}$	$Fs_{13.3\ (0.4)}$ $Wo_{3.1\ (0.2)}$	$Fs_{9.5\ (0.3)}$ $Wo_{1.6\ (0.3)}$	$Fs_{13.2\ (0.6)}$ $Wo_{2.7\ (0.2)}$	$Fs_{12.7\ (0.4)}$ $Wo_{1.8\ (0.1)}$	$Fs_{13.7\ (0.5)}$ $Wo_{2.7\ (0.1)}$

nd = not determined.
N = number of analyses.

Table 4. Compositions of augites in FRO 90011, FRO 95029, FRO 99030, and FRO 03001 (oxides wt% and, in parentheses, standard deviations). Literature data for FRO 93001 (Folco et al. 2006) are reported for comparison.

	FRO 90011	FRO 93001	FRO 95029	FRO 99030	FRO 03001
Textural type	igneous	igneous	granoblastic	nd	igneous
N	8	10	8	3	16
SiO_2	54.4 (0.3)	53.8 (0.5)	54.6 (0.3)	53.8 (0.4)	54.1 (0.4)
TiO_2	0.36 (0.06)	0.32 (0.04)	0.67 (0.03)	0.36 (0.09)	0.36 (0.04)
Al_2O_3	0.91 (0.09)	0.98 (0.21)	0.94 (0.02)	0.90 (0.05)	0.75 (0.09)
FeO	3.22 (0.19)	3.47 (0.12)	2.56 (0.13)	3.13 (0.16)	3.26 (0.13)
MnO	0.33(0.13)	0.30 (0.05)	0.32 (0.02)	0.22 (0.02)	0.20 (0.05)
MgO	17.1 (0.2)	17.7 (0.2)	18.1 (0.2)	16.7 (0.5)	17.4 (0.2)
CaO	21.1 (0.3)	20.2 (0.5)	21.2 (0.2)	21.4 (0.2)	21.3 (0.4)
Cr_2O_3	1.56 (0.18)	1.54 (0.09)	1.25 (0.06)	1.81 (0.02)	1.42 (0.09)
Na_2O	0.83 (0.08)	<0.02(0.09)	0.64 (0.06)	0.95 (0.10)	0.74 (0.13)
Total	99.81	98.31	100.28	99.27	99.53
Endmembers	$Fs_{5.8\ (0.3)}$ $Wo_{44.3\ (0.4)}$	$Fs_{6.1\ (0.7)}$ $Wo_{42.3\ (0.9)}$	$Fs_{4.6\ (0.2)}$ $Wo_{43.6\ (0.5)}$	$Fs_{5.5\ (0.3)}$ $Wo_{45.3\ (0.1)}$	$Fs_{5.6\ (0.3)}$ $Wo_{44.2\ (0.8)}$

nd = not determined.
N = number of analyses.

Table 5. Compositions of chromites in FRO 90011, FRO 95029, FRO 99030, and FRO 03001 (oxides wt% and, in parentheses, standard deviations). Literature data for FRO 93001 (Folco et al. 2006) are reported for comparison.

	FRO 90011	FRO 93001	FRO 95029	FRO 03001
Textural type	granoblastic	granoblastic	granoblastic	granoblastic
N	3	8	8	8
SiO_2	<0.07	<0.07	<0.07	<0.07
TiO_2	0.83 (017)	0.70 (0.17)	1.25 (0.12)	1.03 (0.05)
Al_2O_3	7.51 (0.87)	4.53 (1.65)	9.17 (0.18)	5.79 (0.05)
FeO	18.1 (0.7)	20.0 (0.9)	19.1 (0.51)	20.7 (0.5)
MnO	1.54 (0.20)	1.92 (0.25)	1.81 (0.40)	1.44 (0.15)
MgO	8.42 (0.05)	6.97 (0.79)	8.01 (0.10)	7.42 (0.16)
CaO	<0.02	<0.03	<0.02	<0.02
Cr_2O_3	60.4 (1.7)	64.8 (1.30)	58.1 (1.3)	62.9 (0.4)
ZnO	0.44 (0.09)	0.47 (0.10)		0.37 (0.08)
Total	97.24	99.91	97.43	99.77
Endmembers	$Ulvö_{2.2\ (0.2)}$ $Sp_{15.6\ (1.8)}$ $Chr_{83.3\ (2.1)}$	$Ulvö_{1.8\ (0.6)}$ $Sp_{11.2\ (1.8)}$ $Chr_{86.9\ (2.2)}$	$Ulvö_{3.2\ (0.2)}$ $Sp_{18.7\ (0.5)}$ $Chr_{79.7\ (0.7)}$	$Ulvö_{2.7\ (0.1)}$ $Sp_{11.8\ (0.3)}$ $Chr_{86.1\ (0.3)}$

N = number of analyses.

Geoscienze e Georisorse in Florence, following the experimental conditions described in Folco et al. (2006).

To discuss possible pairings with FRO 93001, a direct comparison with thin section FRO 93001,01 and literature data published in our previous work (Folco et al. 2006) was carried out.

RESULTS

FRO 90011

FRO 90011 is a meteorite specimen of 1.8 g (Table 1). Originally classified as acapulcoite (Wlotzka 1992), it was then re-classified as a typical lodranite (McCoy et al. 1993) due to its relatively coarse-grained (mafic silicates average grain size 538 µm) granoblastic texture and significant depletion of plagioclase (traces) and troilite (3 vol%) with respect to chondritic abundances. Petrographic descriptions were also reported by Maras et al. (1994) and McCoy et al. (1997).

FRO 90011 is locally coated with millimeter-sized patches of relatively fresh, black fusion crust with minor rusty haloes. The external surfaces uncovered by fusion crust reveal a granular texture, with fine- to medium-grained, brown-yellow to deep-green mafic silicates and lesser metal.

The FRO 90011,04 thin section studied in this work (Fig. 2a) measures ~4 × 4 mm and it is not the one used for the original classification reported in Wlotzka (1992) and previous petrographic works by McCoy et al. (1993, 1997) and Maras et al. (1994). The FRO 90011,04 thin section is dominated by a portion of a single crystal (i.e., a crystal larger

Table 6. Compositions of plagioclase in FRO 90011, FRO 95029 and FRO 99030 (oxides wt% and, in parentheses, standard deviations). Literature data for FRO 93001 (Folco et al. 2006) are reported for comparison.

	FRO 90011	FRO 93001	FRO 95029	FRO 99030
Textural type	igneous	igneous	granoblastic	igneous
N	5	50	9	6
SiO_2	66.7 (0.2)	64.3 (0.8)	63.1 (0.5)	64.5 (0.9)
TiO_2	<0.04	<0.04	0.06 (0.03)	<0.04
Al_2O_3	20.8 (0.3)	22.8 (0.6)	23.2 (0.2)	22.3 (0.5)
FeO	0.20 (0.04)	0.12 (0.01)	0.28 (0.12)	0.14 (0.10)
MnO	<0.07	<0.07	<0.07	<0.07
MgO	<0.07	<0.07	<0.07	<0.07
CaO	1.29 (0.21)	3.48 (0.59)	4.05 (0.14)	3.23 (0.65)
Cr_2O_3	<0.05	<0.05	<0.05	<0.05
Na_2O	10.4 (0.2)	9.41 (0.01)	8.87 (0.21)	9.67 (0.19)
K_2O	1.17 (0.10)		0.68 (0.07)	0.58 (0.09)
Total	100.56	100.11	100.24	100.42
Endmembers	$Ab_{87.6\ (0.8)}$ $Or_{6.4\ (0.5)}$	$Ab_{80.5\ (3.3)}$ $Or_{3.1\ (0.6)}$	$Ab_{76.8\ (0.5)}$ $Or_{3.9\ (0.4)}$	$Ab_{81.7\ (2.4)}$ $Or_{3.2\ (0.5)}$

N = number of analyses.

than the thin section) of orthenstatite (Fig. 2a) extending for 5 mm in maximum dimension with homogeneous composition, $Fs_{13.0\ \pm\ 0.6}$ $Wo_{2.5\ \pm\ 0.5}$ (Table 3; Fig. 3) and micrometer-thick [100] exsolution lamellae of Ca-rich pyroxene. It encloses a number of magmatic inclusions indicating crystallization from a melt; the inclusions are up to some tens of µm in size and mainly consist of tiny augite crystals set in an alkali feldspar groundmass.

One side of the igneous orthoenstatite crystal is in contact with a small polymineralic aggregate with fine-grained, homeoblastic texture (Fig. 2a) consisting mainly of olivine, $Fa_{9.3\pm0.3}$ (Table 2; Fig. 3), Fe,Ni metal and lesser troilite. The grain size measured on the 20 olivine crystals present ranges from 160 to 990 µm, with a mean value of 440 ± 202 µm (Fig. 4) close to the 540–700 µm range for lodranites defined by McCoy et al. (1996). Adjacent olivine crystals show well-developed 120° triple junctions. Reduction rims, decorated by enstatite plus troilite symplectites, are common in olivine. Traces of chromian (Cr_2O_3 = 1.56 ± 0.18 wt%) augite, $Fs_{5.8\pm0.3}$ $Wo_{43.9\pm0.4}$, plagioclase, $Ab_{87.6\pm0.8}$ $Or_{6.4\pm0.5}$, chromite (Tables 4–6; Fig. 3) and phosphates were also observed. Both mineral composition and texture indicate that this is a portion of a lodranitic rock (Krot et al. 2005; Mittlefehldt 2005); in particular, the chromite composition (fe# = 0.61, cr# = 0.88) falls in the AL field for primitive achondrites defined by Nehru et al. (1997). Lodranitic lithic fragments up to 500 µm in size are enclosed in the igneous orthoenstatite (Fig. 2b). They exhibit rounded and cuspate-lobate contours suggesting some igneous corrosion.

Silicates such as olivine and pyroxene exhibit sharp optical extinction, with minor irregular fracturing. Such features are diagnostic of unshocked meteorites, i.e., shock stage S1 according to the classification scheme for meteorites of chondritic mineralogy (i.e., including acapulcoites and lodranites) by Stöffler et al. (1991). Troilite and kamacite are monocrystalline as in unshocked or weakly shocked meteorites of chondritic mineralogy (Bennett and McSween 1996).

Following the classification scheme by Wlotzka (1993), which applies to meteorites with chondritic mineralogy, oxide haloes around a few metal grains, and limonitic products along cracks in mafic silicates rank FRO 90011 in the W1 category, corresponding to a low degree of weathering.

FRO 99030

FRO 99030 is a meteorite specimen of 4.6 g originally classified as a lodranite; however, as pointed out in Grossman (2000), classification was considered tentative because the thin section studied was clearly not representative of the parent lithology.

In hand specimen FRO 99030 is basically a flat piece of metal. One side is covered by black fusion crust with minor rusty patches; the other one is covered by a millimeter-thick and discontinuous layer of yellow-to-brown and lesser deep-green silicates.

The FRO 99030,01 thin section studied in this work is the same used for the original classification. It mostly consists of a 13 × 2.5 mm mass of metal discontinuously surrounded by some silicate crystals with compositions matching those of AL meteorites reported by Krot et al. (2005) and Mittlefehldt (2005). The latter include olivine ($Fa_{9.6\ \pm\ 0.7}$), orthoenstatite ($Fs_{13.2\ \pm\ 0.7}$ $Wo_{2.7\ \pm\ 0.2}$), Cr-rich augite ($Fs_{5.5\ \pm\ 0.3}$ $Wo_{45.3\ \pm\ 0.1}$; Cr_2O_3 = 1.81 wt%), and interstitial plagioclase (Fig. 5) of variable oligoclasic composition ($Ab_{15.0\pm2.8}$ $Or_{3.2\pm0.2}$) (Fig. 3; Tables 2, 3, 4, and 6). Metal is mostly kamacite with minor taenite, associated with lesser troilite, schreibersite, and chromite. The grain size of the 8 mafic silicate whole crystals (olivine only) present in thin section FRO 99030,01 (Fig. 4) ranges from 340 to 830 µm, with a mean value of 563 ± 180 µm in

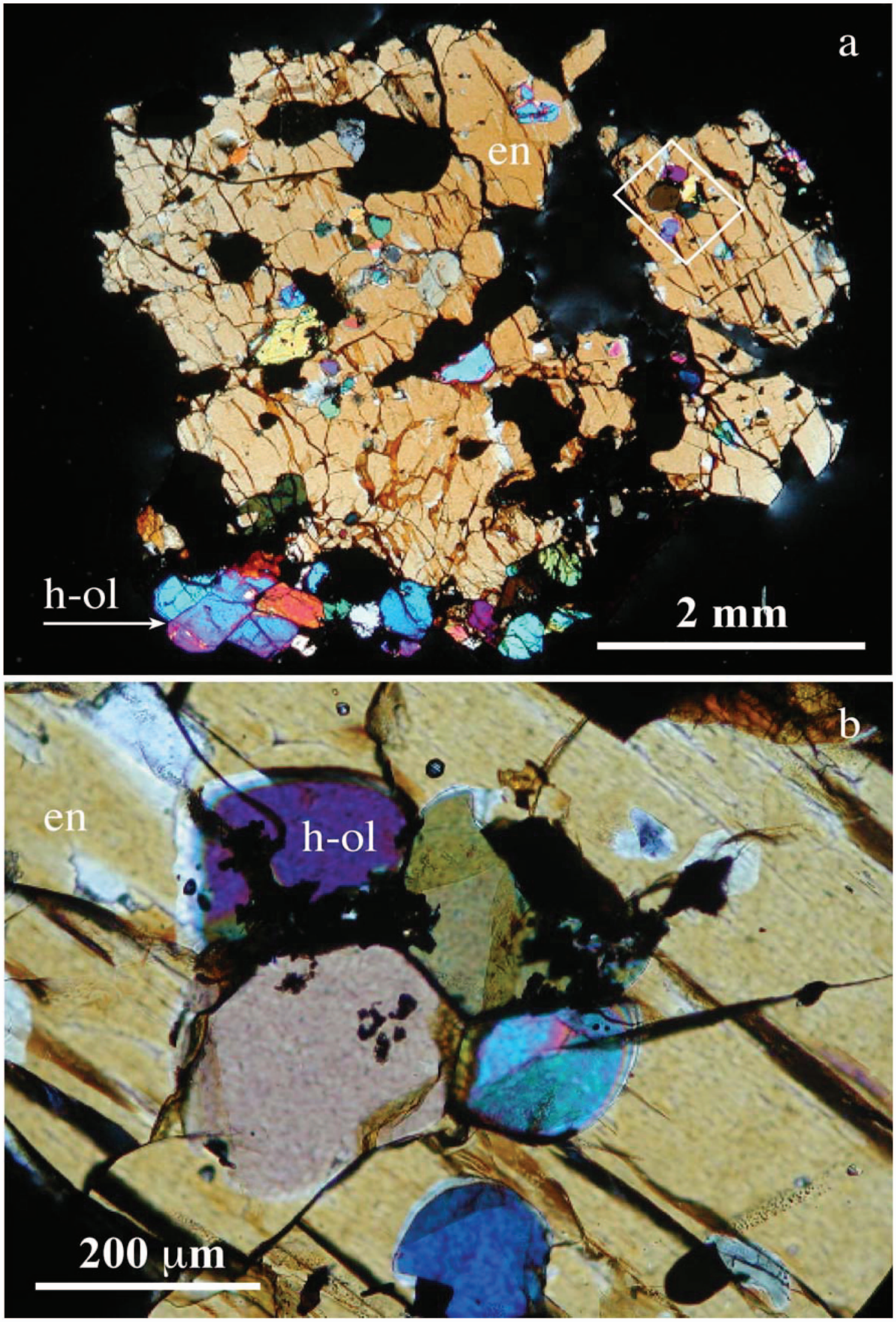

Fig. 2. a) Optical micrograph of thin section FRO 90011,04 showing a millimeter-sized portion of an orthoenstatite crystal (en) in contact with a lodranitic lithology (bottom left) mainly consisting of fine-grained, homeoblastic olivine (h-ol), plus metal and troilite masses. The orthoenstatite crystal encloses many polymineralic aggregates of the lodranitic lithology. The white rectangle defines the field of view of Fig. 2b. b) Optical micrograph (crossed nicols) from the FRO 90011,04 thin section showing a detail of the lodranitic inclusions (center) in the igneous orthoenstatite (en); the lodranitic inclusions consist mainly of granoblastic olivines (h-ol) showing igneous corrosion. Note the 120° triple junctions between adjacent olivine crystals and the rounded crystal boundaries abutting enstatite host.

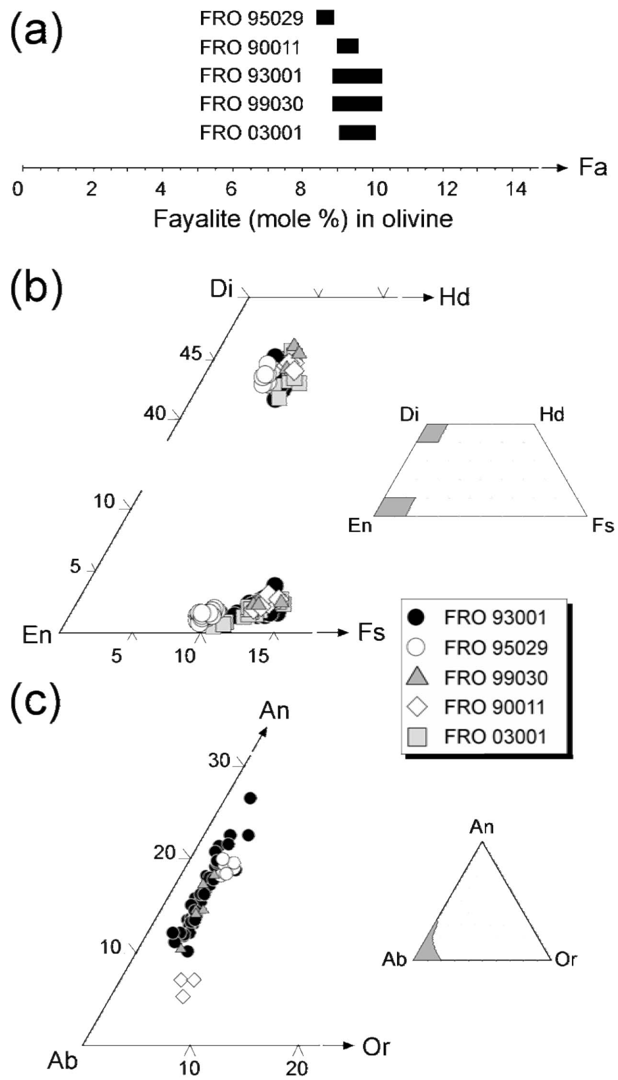

Fig. 3. Mineral composition of olivine, pyroxenes, and feldspars for FRO 90011, FRO 93001, FRO 95029, FRO 99030, and FRO 03001. a) Olivine Fa (mole%) distribution. b) Pyroxene quadrilateral. c) Feldspars ternary diagram. Data for FRO 93001 are from Folco et al. (2006).

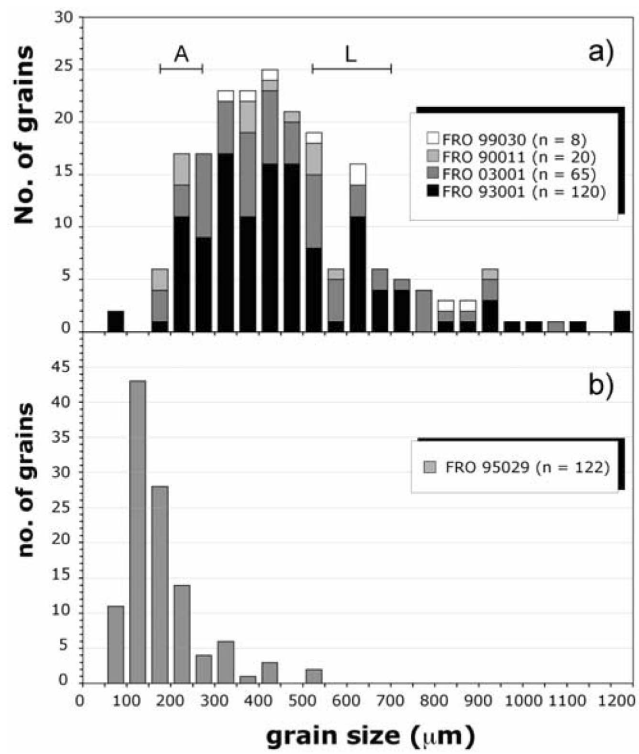

Fig. 4. Grain size distribution in FRO 90011, FRO 93001, FRO 99030, and FRO 03001 olivine (a), and FRO 95029 olivine and pyroxene (b). Data for FRO 93001 are from Folco et al. (2006). Typical ranges for acapulcoites (150–230 µm; A) and lodranites (540–700 µm; L) are from McCoy et al. (1996).

the range for lodranites defined by McCoy et al. (1996). The small size of the sample precludes the obtainment of additional textural details.

Both metal and silicates are devoid of shock deformation features at the optical microscope scale indicating shock level S1 following Stöffler et al. (1991). Minor amounts of secondary iron oxides replace metal indicating weathering grade W1 following Wlotzka (1993).

FRO 03001

FRO 03001 is a meteorite of 1.46 g which we originally classified as a lodranite (Table 1), appearing in a brief report in the Meteoritical Bulletin No. 88 (Russell et al. 2004).

FRO 03001 is an angular meteorite fragment covered by a rather fresh black fusion crust on all sides except one. The fusion crust exhibits a glassy appearance and little oxidation. The side of FRO 03001 devoid of fusion crust reveals a homogeneous lithology, consisting of yellow to brown and, occasionally, deep-green silicates with an overall fine-grained granular texture.

The FRO 03001,01 thin section studied in this work is the same one used for the original classification and measures ~5 × 3 mm. The thin section reveals a granoblastic texture (Fig. 6a) dominated by olivine, lesser amounts of Fe,Ni metal and traces of orthoenstatite, troilite, chromite and Ca-phosphates. Adjacent olivine crystals show well-developed 120° triple junctions. Granoblastic olivine and orthoenstatite have homogeneous composition $Fa_{9.5 \pm 0.4}$ and $Fs_{12.7 \pm 0.4}$ $Wo_{1.8 \pm 0.1}$, respectively (Tables 2 and 3; Fig. 3), and match the AL compositional ranges (Krot et al. 2005). The chromite composition (fe# = 0.61, cr# = 0.88; Table 5) falls in the AL field for primitive achondrites defined by Nehru et al. (1997). The grain size of granoblastic mafic silicates measured on 64 olivine crystals ranges from 150 to 1080 µm, with a mean value of 488 ± 201 µm (Fig. 4) which falls in the small grain size side of the range for lodranites defined by McCoy et al. (1996). Reduction rims, decorated by troilite plus enstatite symplectites, are common in olivine. They

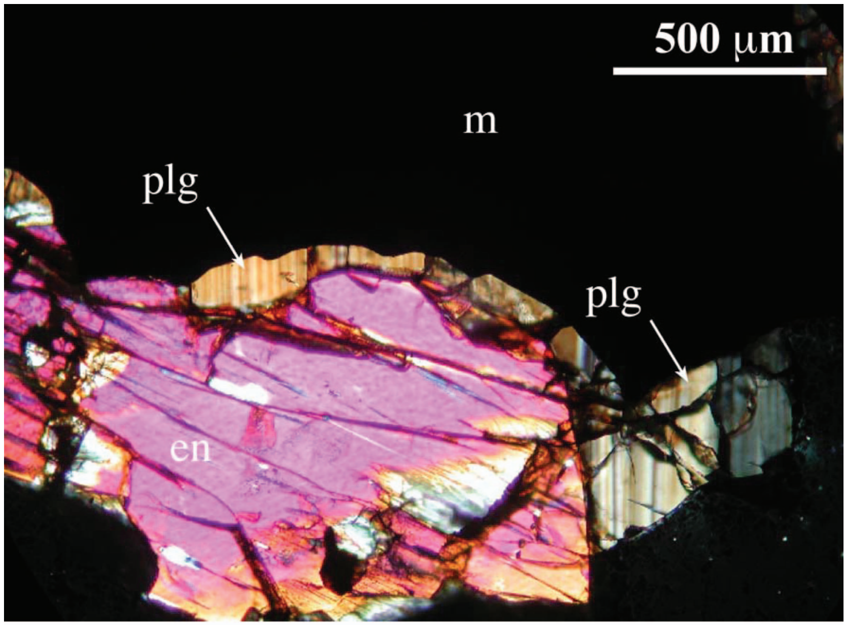

Fig. 5. Optical micrograph (crossed nicols) of orthoenstatite (en), interstitial plagioclase showing polysynthetic twinnings (plg), and metal (m) in FRO 99030,01 thin section.

are the likely reflection of olivine sulfidation as suggested for olivines in Lodran (Papike et al. 1995). Noteworthy is a large 2 × 2 mm troilite plus enstatite symplectitic region as a beautiful example of the mineralogy associated with the olivine sulfidation reaction; here (Fig. 6b) the replacement of olivine appears to be pervasive, leaving behind only few relic cores.

Besides the granoblastic assemblage, FRO 03001,01 thin section shows few crystals of augite and orthoenstatite with interstitial setting indicating crystallization from a melt. Augite is exsolved on [100] and has homogeneous bulk composition $Fs_{5.5 \pm 0.3}$ $Wo_{44.2 \pm 0.8}$ (Table 4; Fig. 3). Orthoenstatite is given by a relatively large (~1 mm in maximum dimension) crystal fragment at the margin of the thin section with a distinctly Ca-richer composition $Fs_{13.7 \pm 0.5}$ $Wo_{2.7 \pm 0.1}$ compared to granoblastic orthoenstatite (Table 3).

Mafic silicates, metal, and troilite do not bear evidence of shock deformation, which is consistent with the S1 shock level defined by Stöffler et al. (1991). Weathering products consist of minor oxide haloes around metal grains, indicating weathering grade W1 of the classification scheme by Wlotzka (1993).

FRO 95029

FRO 95029 is a half fusion-crusted angular meteorite fragment of 8.3 g (Table 1) originally classified as acapulcoite (Grossman 1997). The broken surface is crystalline, with a sort of mm-scale globular structure due to selective wind erosion. Silicate crystals appear brown-stained due to some terrestrial weathering. The fusion crust, flaked off in some places, shows degassing bubbles.

FRO 95029 exhibits a fine-grained, homeoblastic texture in the ~5 × 4 mm thin section FRO 95029,03 (Fig. 7). Olivine and orthoenstatite are the most abundant minerals comprising 28 and 40 vol%, respectively, with lesser amounts of Fe,Ni metal (mostly kamacite, with minor taenite), 20 vol% (the mode includes weathering products), plagioclase, 8 vol%, troilite, 2 vol%, Ca-phosphates, 2 vol% (mostly merrillite, and minor chloroapatite and fluoroapatite), and traces of augite and chromite (Table 7). When in mutual contact, olivine and orthopyroxene develop well-defined 120° triple junctions. Mafic silicate grain size based on 112 measured crystals ranges from 70 to 530 µm, with a mean value of 175 ± 90 µm (Fig. 4) which falls in the 150–230 µm range for acapulcoites defined by McCoy et al. (1996). Orthopyroxene and occasionally olivine typically show dusty cores (i.e., swarms of µm-sized metal inclusions). FRO 95029 is cross-cut by a network of µm-thick veinlets of metal plus troilite, which run along grain boundaries or cut through the crystals of all mineral phases but metal. Silicates and oxides have homogeneous compositions (Tables 2–6; Fig. 6). Olivine is $Fa_{8.6 \pm 0.2}$, with chondritic [Mn/Mg]. Orthoenstatite is $Fs_{9.5 \pm 0.3}$ $Wo_{1.6 \pm 0.3}$. The Fa and Fs values plot in the field of acapulcoites (Krot et al. 2005; Mittlefehldt 2005). Augite, $Fs_{4.6 \pm 0.2}$ $Wo_{43.6 \pm 0.5}$, is Cr-rich ($Cr_2O_3 = 1.25 \pm 0.06$ wt%) and plagioclase is oligoclase $Ab_{76.8 \pm 0.5}$ $Or_{3.9 \pm 0.4}$. The chromite composition (fe# = 0.58, cr# = 0.81) falls near the AL grouping for primitive achondrites defined by Nehru et al. (1997).

The sharp extinction in silicates indicates shock level S1 following Stöffler et al. (1991). Secondary iron oxides discontinuously rim metal grains and partially replace the metal in the veinlets, indicating weathering grade W1 following Wlotzka (1993).

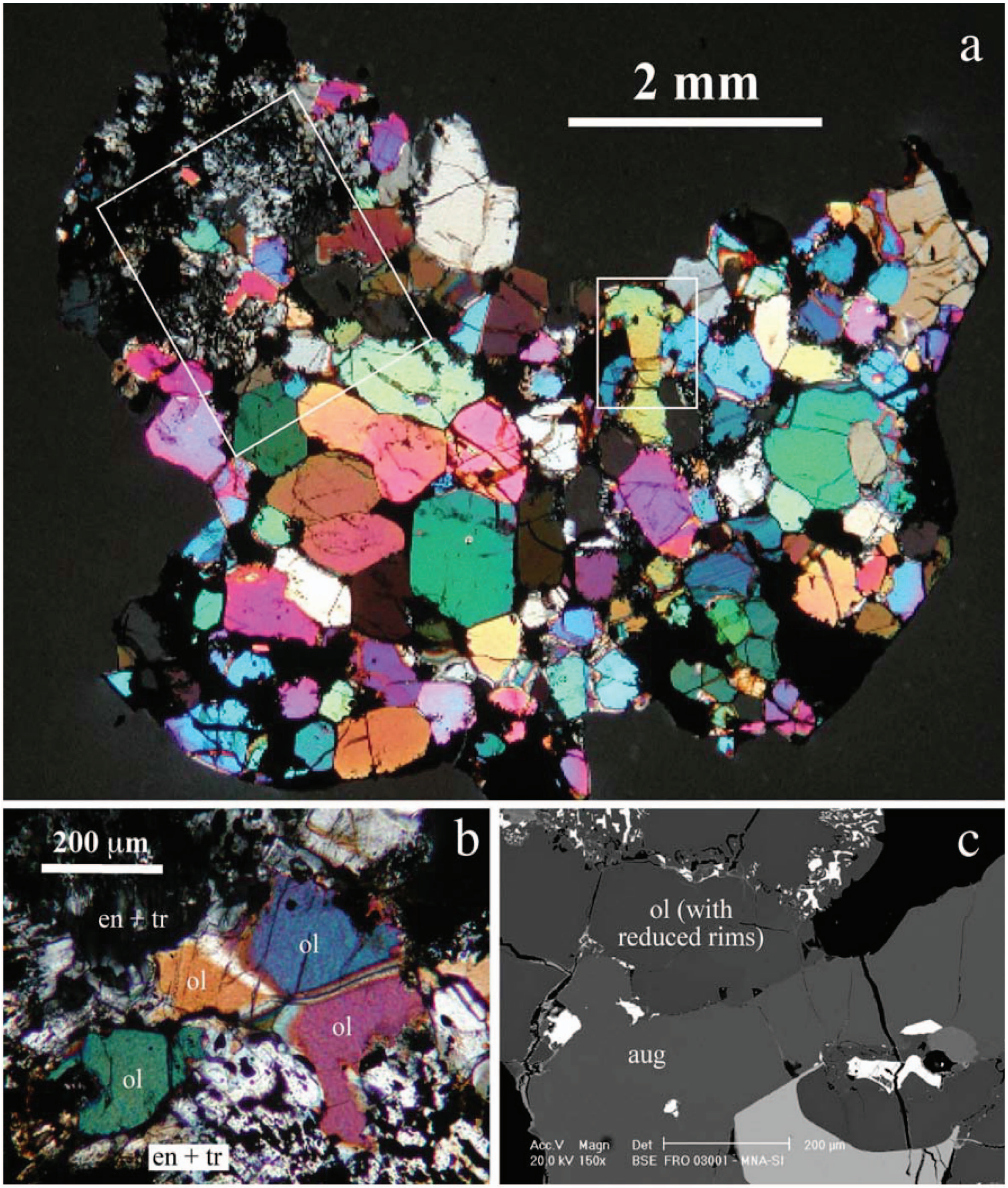

Fig. 6. a) Optical micrograph (crossed nicols) of thin section FRO 03001,01 showing the typical lodranitic texture. The white rectangles define the fields of view of Figs. 4b and 4c. b) Optical micrograph (crossed nicols) of the a reaction mineral assemblage observed in thin section FRO 03001,01, where olivine (ol) is pervasively substituted by enstatite plus troilite symplectites (en + tr). c) Backscattered electron image of interstitial augite impregnating the lodranitic assemblage in FRO 03001.

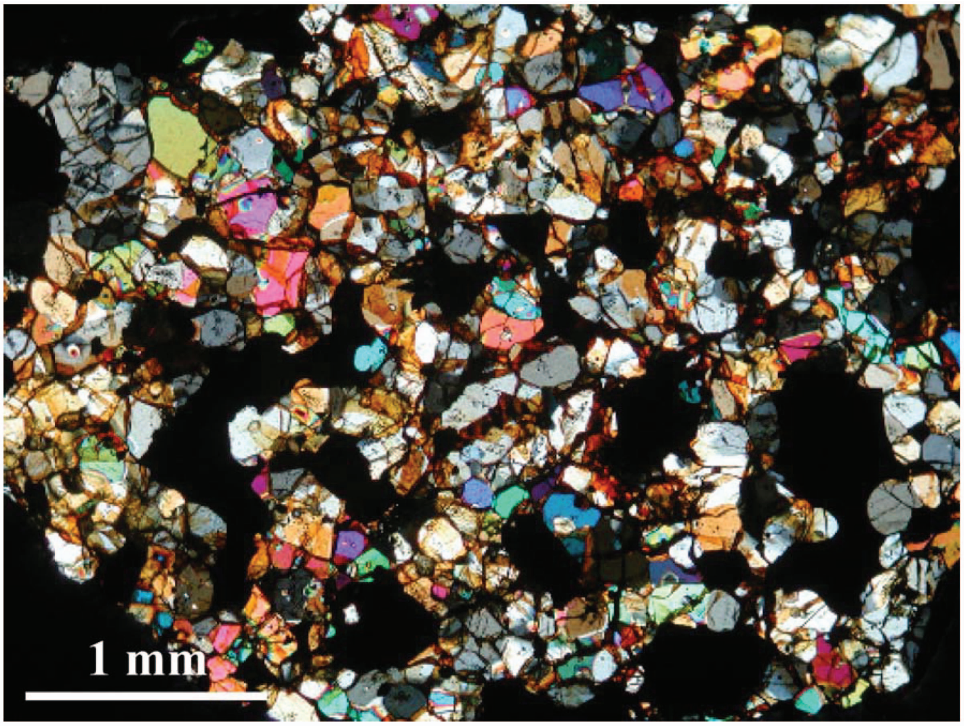

Fig. 7. Optical micrograph (crossed nicols) of FRO 95029,03 thin section showing the typical acapulcoitic texture, i.e., fine-grained and granoblastic.

DISCUSSION

Petrography Revisited

FRO 90011

Texture, mineral composition, shock, and weathering levels indicate that the granoblastic lithology observed at the edge of FRO 90011,03 thin section and in the form of small polycrystalline inclusions in the igneous orthoenstatite is part of the lodranitic assemblage described earlier by McCoy et al. (1993, 1997) and Maras et al. (1994) in different thin sections of this meteorite, whereas the relatively large (>5 mm) igneous orthenstatite crystal is here reported for the first time (Fig. 2a). We therefore conclude that FRO 90011 is a heterogeneous meteorite specimen consisting of a medium-grained (or coarser), enstatite-bearing igneous rock enclosing lodranitic lithic fragments, which undergo corrosion due to disequilibrium interaction with the surrounding melt (Fig. 2b).

FRO 99030

The available textural and mineral compositional data confirm the lodranitic affinity of this rock, in agreement with previous classification (Grossman 2000); however, the orthoenstatite composition is indistinguishable from that of the igneous pyroxene observed in FRO 90011 (Table 3), and the interstitial character of plagioclase (Fig. 5), indicative of precipitation from a melt, suggests a similar heterogeneous lithology consisting of lodranitic material intruded by a melt.

FRO 03001

On the basis of the above petrographic data, we confirm the previous report (Russell et al. 2004) that the lithology observed in FRO 03001,01 is that of an olivine-rich lodranite (Fig. 6a). A new finding is the large symplectitic region, which indicates that the reduction of mafic silicates in lodranites is not solely confined along grain boundaries and crystal cracks, but can locally be more pervasive, extending in domains up to several mm^2, with nearly complete replacement of olivine by enstatite plus troilite (Fig. 6b). In addition, we note that orthoenstatite and augite have an interstitial setting suggesting crystallization from a melt. As such we think that FRO 03001 consists of a lodranite locally impregnated by a melt (Fig. 6c), similar to FRO 90011 and FRO 99030.

FRO 95029

Our petrographic data confirm previous classification of FRO 95029 (Grossman 1997) as an unshocked and relatively fresh acapulcoite. Note, however, that FRO 95029 shows low abundances of plagioclase, augite, and troilite when compared to other acapulcoites (Table 7), whereas the geochemical systematic study of AL meteorites by Patzer et al. (2004) showed that FRO 95029 is depleted in Sc, Se,

Table 7. Mineral mode (vol%) of FRO 95029. Literature data, mean values, and ranges for acapulcoites is reported for comparison.

Minerals	FRO 95029 this work	Acapulcoites Yugami et al. (1998)[a]	Patzer et al. (2004)[b]	Grand mean[a, b]
Olivine	28	26.9 (25.2–28.4)	31.3 (29.0–38.0)	29.3 (25.2–38.0)
Enstatite	39	37.5 (32.4–41.1)	18.2 (11.0–28.0)	26.8 (11.0–41.1)
Augite	tr	5.5 (2.5–7.3)	7.9 (4.0–11.0)	6.8 (2.5–11.0)
Chromite	tr	tr	2.0 (0.4–4.0)	1.4 (0.2–4.0)
Plagioclase	8	14.0 (13.5–14.8)	11.5 (10.0–13.0)	12.6 (10.0–14.8)
Ca-phosphates	2	0.8 (tr–1.2)	1.0 (0.5–1.4)	0.9 (0.4–1.4)
Troilite	2	6.3 (3.9–8.7)	10.5 (7.7–15)	7.3 (3.9–15.0)
Fe,Ni metal	13	8.5 (5.7–15.0)	8.2 (4.4–15.0)	9.7 (3.5–29.0)
Schreibersite	–	tr	nd	nd
“Rust”[c]	7	nd	4.7 (0–23)	4.7 (0–23)

Abbreviations: tr = traces; nd = not determined.

[a]Data from Acapulco, Allan Hills 77081, Allan Hills 78230, and Yamato-8307.

[b]Data from Graves Nunataks (GRA) 98028, Northwest Africa (NWA) 725, NWA 1058, Dhofar (Dho) 290, and Thiel Mountains (TIL) 99002.

[c]= Limonitic mineral assemblages replacing metal phases as a result of terrestrial weathering.

and Zn with respect to chondritic abundances, suggesting some troilite loss only.

Pairings

Based on the petrographic descriptions of FRO 90011, FRO 99030, and FRO 03001 given above, and that of FRO 93001 reported in Folco et al. (2006), we argue that these 4 meteorite specimens from the Frontier Mountain blue ice field are paired. The apparent differences observed in thin sections are simply due to the fact that they are small fragments (cm-sized) of a relatively coarse-grained (grain size up to centimeters), heterogeneous (namely, inclusion-rich) rock.

According to Folco et al. (2006), FRO 93001 is an unshocked (shock level S1), little weathered (weathering grade W1), unique igneous rock of the AL clan consisting of orthoenstatite (Table 3), augite (Table 4), and oligoclase (Table 6) up to >1 cm in size enclosing polycrystalline aggregates of fine-grained homeoblastic olivine (Table 2), often associated with Fe,Ni metal, troilite, chromite (Table 5), schreibersite, and phosphates. Such aggregates appear to have undergone igneous corrosion and are interpreted as lodranitic xenoliths. This interpretation is based on the sharp textural contrast with the igneous host crystals (see Figs. 2 and 3 in Folco et al. 2006) and on the petrologic argument that the oligoclase-rich composition of the igneous mineral assemblage would require a source rock of acapulcoitic (or its chondritic precursor) composition, i.e., a chemical system which contained substantial amounts of Al, Ca, and Na, unlike the typical lodranitic one (Folco et al. 2006).

The lodranitic inclusions in FRO 90011, the lodranitic xenoliths in FRO 93001 and the lodranitic mineral assemblage in FRO 99030 are indistinguishable from the lodranitic lithology observed in FRO 03001 in terms of mineral compositions and mineral chemistry (Tables 2–6, and Fig. 3), olivine grain size (Fig. 4), mineralogy of the olivine reduction rims, as well as shock level. Likewise, the relatively large orthoenstatite crystal in FRO 90011 and the orthoenstatite, augite, and oligoclase crystals in FRO 99030 and FRO 03001 are igneous components of the igneous lithology described in FRO 93001 (Folco et al. 2006): they share common texture, mineral chemistry (Tables 2–6), exsolution microstructures, and they all are devoid of shock deformation features. Augite and plagioclase compositions may not perfectly overlap (Tables 4 and 6; Fig. 3): in pyroxene this is likely due to fact that we could not always resolve their fine exsolution lamellae at the electron microprobe scale; whereas for plagioclase, we suspect a large compositional range which is not always represented in our thin sections. The fact that all 4 fragments show the same weathering level is further evidence in support of their pairing. This pairing is also consistent with the meteorite concentration mechanism operating at Frontier Mountain (e.g., Folco et al. 2002). In spite of the complexity of the ice flow pattern and meteorite distribution due to glacial and wind drifts, we can hypothesize that, once arrived at the blue ice surface (either through exhumation by ice ablation after englacial transport or direct fall) in the “scatterfield” (Fig. 1), the 4 small (all <8.3 g; Table 1) fragments would have been wind-blown northeastward and trapped in the aeolian accumulation site called “the firn-ice edge,” with FRO 99030 showing a delayed on-ice transit time due to its flat shape, high density (it consists mainly of metal) and heaviest weight.

On petrographic grounds, FRO 95029 is a typical acapulcoite and thus we suggest that it is a distinct fall. However, mafic silicates in FRO 95029 and in the lodranitic lithology in FRO 90011, FRO 93001, FRO 99030, and FRO 03001 have similar mg# ~90 suggesting similar petrogenetic environment. As such, one may argue that FRO 95029 could be a different type of clast enclosed by the inclusion-rich

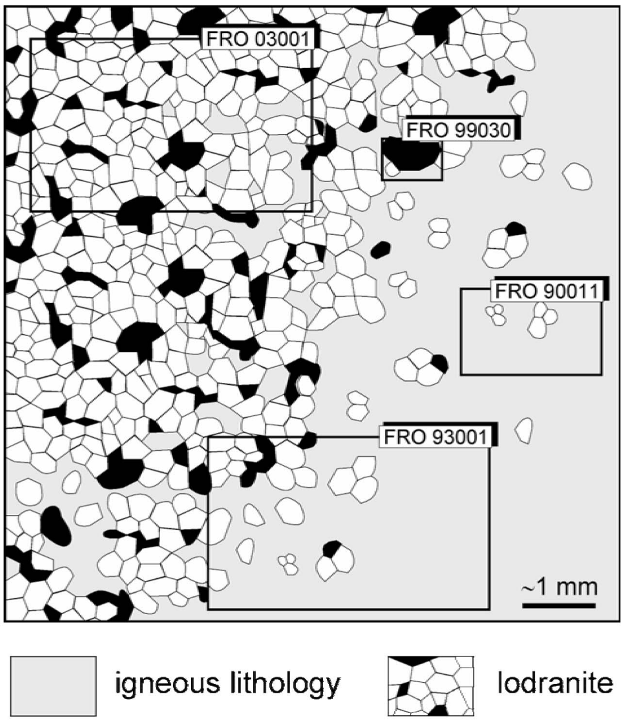

Fig. 8. Schematic representation of the parent-rock lithology resulting from the pairing of the FRO 90011, FRO 93001, FRO 99030, and FRO 03001 meteorite fragments: it consists of a medium- to coarse-grained gabbroic melt which intrudes a lodranite entraining xenoliths. Our petrographic investigation suggests that FRO 93001 and FRO 03001 are the best representative samples of the igneous lithology and the lodranite facies, respectively, as explained in the text. The black rectangles schematically outline the 4 thin sections discussed in this work.

FRO 90011-93001-99030-FRO 03001 igneous rock described above, since genomict breccias (i.e., breccias containing clasts belonging to the same meteorite group; e.g., Krot et al. 2005) are common in the meteoritic record (e.g., Bischoff and Stöffler 1992). Nevertheless, pairing is ruled out on the basis of noble gas data from literature. The cosmic-ray exposure (CRE) age calculated by Weigel et al. (1999) for FRO 90011 is ~6.5 Ma, whereas that calculated by Terribilini et al. (2000) for FRO 95029 is 4.59 ± 0.60 Ma. As shielding conditions were similar, the 35% difference in CRE age appears to be significant. Other evidence suggesting that they are different falls is that the radiogenic ^{4}He, and especially ^{40}Ar in FRO 90011 ($^{40}Ar = 512 \pm 35\ 10^{-8}\ cm^3$ STP/g) (Weigel et al. 1999), are much lower than in FRO 95029 (^{40}Ar = 4400 $10^{-8}\ cm^3$ STP/g) (Terribilini et al. 2000).

Our pairing results represent a contribution to the ongoing pairing studies (e.g., Fioretti and Molin 1996; Welten et al. 1999, 2001, 2006a, 2006b; Smith et al. 2000), which may have important implications on the meteorite concentration mechanism and flux of meteorites to Earth. In particular, we derive that the ratio between the number of specimens and the number of individual meteorites for AL meteorites from Frontier Mountain is 2.5. This value is similar to that of 3.7 derived for another achondritic meteorite group, i.e., ureilites; Welten et al. 2006b). On the basis of cosmogenic nuclide analyses, Welten et al. (2006b) inferred that the 11 ureilites so far found at Frontier Mountain belong to three distinct falls.

The Parent-Rock Lithology of FRO 90011, 93001, 99030, and 03001

Putting together pieces of information from the small FRO 90011, FRO 93001, FRO 99030, and FRO 03001 paired meteorite fragments, we can reconstruct their parent-rock lithology. This is an important outcome of the present study because it allows us to better constrain the petrogenesis of a rock that, together with Lewis Cliff (LEW) 86220, represents the only known silicate melts within AL meteorites, which are expected to provide significant clues on the early stages of igneous differentiation on rocky asteroids and planets. In particular, the petrologic study by Folco et al. (2006) demonstrated that FRO 93001 is the only evidence for very high-degree melting (≥35 wt%) on the AL parent body available in our laboratories, and provided the basis for discussing two petrogenetic scenarios: extensive anatexis and crystallization in a plutonic environment or shock melting due to cosmic impacts.

The parent-rock lithology resulting from the pairing of the FRO 90011, FRO 93001, FRO 99030, and FRO 03001 meteorite fragments can be described as an intrusive breccia given by a medium- to coarse-grained igneous matrix that contains lodranitic xenoliths. Figure 8 schematically illustrates the reconstructed lithology. The most representative description of the igneous matrix is that obtainable from FRO 93001,01 thin section and given by Folco et al. (2006), whereas that of the lodranitic xenoliths is provided by FRO 03001,01 thin section reported above (Fig. 6a). Accordingly, the igneous assemblage mainly consists of mm- to cm-sized crystals of orthoenstatite $Fs_{13.3 \pm 0.4}$ $Wo_{3.1 \pm 0.2}$ with [100] exsolutions of Ca-rich pyroxene, Cr-rich augite $Fs_{6.1 \pm 0.7}$ $Wo_{42.3 \pm 0.9}$ and oligoclase and $Ab_{80.5 \pm 3.3}$ $Or_{3.2 \pm 0.6}$ (Tables 2 to 6). The lodranitic assemblage has a medium-grained (average grain size 488 ± 201 µm; Fig. 4a) granoblastic texture and mainly consists of olivine $Fa_{9.8}$ with reduced rims, orthoenstatite $Fs_{12.7 \pm 0.4}$ $Wo_{1.8 \pm 0.1}$, Fe,Ni metal and minor amounts of troilite, chromite, schreibersite and Ca-phosphates, i.e., merrillite, Cl-apatite and F-apatite (Tables 2–5). The lodranitic xenoliths entrained by the igneous lithology are best shown in FRO 93001,01 and FRO 90011,04 (Figs. 2a and 2b) thin sections and consist of individual crystals or lithic fragments showing corrosion due to disequilibrium interaction with the surrounding melt. Both the igneous and lodranitic crystals are devoid of shock features (shock level S1) and very little weathered (weathering grade W1).

A number of petrogenetic constraints for discussing the origin of the FRO intrusive breccia can be derived from the present study. The oxygen isotopic composition measured on 2 aliquots of the FRO 90011 meteorite fragment by Franchi et al. (1992) are $\delta^{17}O = +0.83$ and $+1.12‰$, $\delta^{18}O = +3.81$ and $+3.64‰$. This data confirms that this rock is a sample of the AL parent asteroid, as inferred by Folco et al. (2006) on the basis of the sole mineral chemistry of FRO 93001.

Furthermore, in all the studied thin sections the lodranitic crystals are devoid of shock deformation features. This is an important piece of evidence, since it is a major argument in favor of the magmatic (rather than shock melting) origin proposed by Folco et al. (2006) for this intrusive breccia. Had this melt breccia actually formed by impact melting, the lodranitic xenoliths would show strong shock deformation as commonly observed in impact melt breccias (e.g., Bischoff and Stöffler 1992). Since this is not the case, our new petrographic evidence lends support to the plutonic scenario proposed earlier which envisages formation of the melt in a region of the AL parent asteroid with acapulcoitic composition, followed by migration and intrusion in its lodranitic region. In this scenario, the FRO intrusive breccia is possibly a sample from the contact with wall rocks, as shown in Fig. 8.

CONCLUSIONS

FRO 90011, 93001, 99030, and 03001 are small (<8.3 g) paired fragments of an unusual intrusive breccia from the AL parent asteroid consisting of a medium- to coarse-grained, enstatite-augite-oligoclase-rich, igneous rock intruding an olivine-rich lodranite. To date, this rock and LEW 86220 represent the only available silicate-rich melt material from the AL parent asteroid that may considerably increase our understanding of the melt generation and melt migration processes in the asteroid belt early in the history of the solar system. In particular, our data are consistent with melt generation in a region of the AL parent asteroid with acapulcoitic composition, followed by migration, intrusion, and impregnation of a lodranitic region. These findings corroborate previous arguments by Folco et al. (2006) based on their petrologic study of the FRO 93001 fragment.

FRO 95029 is an acapulcoite and represents a separate fall from the AL parent asteroid, i.e., it is not a different clast entrained by the FRO 90011, 93001, 99030, and 03001 melt as in the genomict breccias common in the meteoritic record.

The specimen-to-meteorite ratio for the AL meteorites so far found at the Frontier Mountain blue ice field is thus 2.5, similar to the 3.5 value inferred by Welten et al. (2006b) for another achondritic group (ureilites) well represented in the Frontier Mountain collection, the ureilites.

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