AN INCLUSION OF ALH-77004: A POSSIBLE SURFACE REGOLITH OF L CHONDRITE PARENT BODY

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Abstract: An inclusion in ALH-77004 (H4 chondrite) consists of four different constituents with varying degree of recrystallization; (1) moderately to highly recrystallized lithic and chondrule fragments (fayalite-rich group), (2) unequilibrated chondrules (fayalite-poor group), (3) fine-grained dark clastic matrix, and (4) particles of Fe-Ni metal, troilite, and chromite. From petrological examinations of these constituents, it is suggested that the inclusion was a surface regolith of the L chondrite parent body formed by repetitive impact cratering processes extended to various depths of the body.

1. Introduction

Meteorite regolith breccias are defined as clastic rocks that formed by shock lithification or sintering of hot glass of fragmental regolith materials once resided at the surface of a meteorite parent body (RUBIN *et al*, 1983; STÖFFLER *et al.*, 1980). They would provide information about the surface and the complex histories of the meteorite parent body, involving accretion, recrystallization, impact or shock, and mechanical mixing of various rock types.

Allan Hills-77004 chondrite has been classified as H4 chondrite, on the basis of petrographic examinations (SCORE *et al.*, 1981). Previous studies (*e.g.*, MARVIN and MASON, 1980) have noted the presence of inclusions, which were distinguished by their texture from the exterior of the chondrite. The author discovered in this meteorite sample an inclusion (1.4 cm in diameter) which consists of many submillimeter-size fragments, fine-grained silicate matrix, and particles of Fe-Ni metal, troilite and chromite. Although this inclusion is a part of ALH-77004 (H4 chondrite), the fragments included in the inclusion were probably derived from L chondrites with various degrees of recrystallization. These fragments may indicate that this inclusion was a surface regolith of L chondrite parent body.

In this paper, the author reports a petrographic study of fragments in the inclusion of ALH-77004 using electron microprobe techniques. In addition, he discusses the genetic model of the inclusion on L chondrite parent body.

2. Analytical Procedures

Polished thin section was studied under the microscope by both transmitted and reflected lights. Electron microprobe analyses of olivine, pyroxenes, plagioclase, metallic Fe-Ni, and chromite were made using a JEOL-5 electron probe microanalyzer with a focused beam with 15 kV accelerating voltage and 0.2×10^{-7}A specimen current. Standard Bence-Albee and ZAF correction procedures were employed after NAKAMURA and KUSHIRO (1970) and SWEATMAN and LONG (1969).

3. Results

The inclusion of ALH-77004 consists of four different constituents, namely (1) moderately to highly recrystallized lithic and chondrule fragments (fayalite-rich group), (2) unequilibrated chondrules (fayalite-poor group), (3) fine-grained dark clastic matrix, and (4) particles of Fe-Ni metal, troilite and chromite (Table 1). Results of studies

Table 1. Constituents of the inclusion of ALH-77004.

	Vol %	Olivine composition	Low-Ca pyroxene composition	Metamorphic grade
(1) Moderately to highly recrystallized lithic and chondrule fragments (fayalite-rich group)	55	Fa_{21-35} av. Fa_{24-25} heterogeneous	En_{80-75} Fs_{19-23} $Wo_{0.5-5}$	Type 4 to 6
(2) Unequilibrated chondrules (fayalite-poor group)	5	Fa_{8-20} heterogeneous	En_{90-80} Fs_{4-18} $Wo_{0.5-5}$	Type 3(?)
(3) Fine-grained dark clastic matrix	30			
(4) Particles of Fe-Ni metal, troilite and chromite	10			

of these four constituents are discussed in the following sections. Particular emphasis will be given to a discussion of the coexistence of unequilibrated, transitional, and highly-equilibrated materials in single inclusion in terms of the metamorphism hypothesis (DODD *et al.*, 1967; DODD, 1969; VAN SCHMUS and WOOD, 1967).

Inclusion of ALH-77004 consists of about 55% (in vol %) recrystallized lithic and chondrule fragments, 5% unequilibrated chondrules, 10% particles of metals, troilite and chromite, and 30% fine-grained dark clastic matrix, in which all the fragments are embedded.

Some fragments have been slightly shocked to the same degree: fractured silicates with undulose extinction, and 'fizzed' troilites (spheres with metal-troilite melt texture; SCOTT, 1982) are rarely found in thin section. These features may suggest that the shock occurred mostly before compaction of the inclusion.

3.1. *Moderately to highly recrystallized lithic and chondrule fragments (fayalite-rich group)*

It appears that about 55% of the inclusion is made up of round to oblong 'chondrules' with all textural varieties, and lithic and chondrule fragments. These rounded to angular fragments of various sizes (up to 1.2 mm in apparent diameter) are usually distinguishable from the dark clastic matrix, but fine-grained (<0.1 mm) fragments are difficult to distinguish from mineral fragments in the matrix. Fragments of this group are composed of a highly-recrystallized assemblage of olivine, low-Ca pyroxene, metallic nickel-iron and troilite with minor plagioclase and accessory high-Ca clinopyroxene and chromite.

They show evidence of varying degree of recrystallization, which has proceeded to type 6 (VAN SCHMUS and WOOD, 1967) where chondritic textures are essentially destroyed in some fragments and clear plagioclase is microscopically visible. Usually feldspar occurs in small, often turbid areas or in the interstices among large olivine and orthopyroxene crystals.

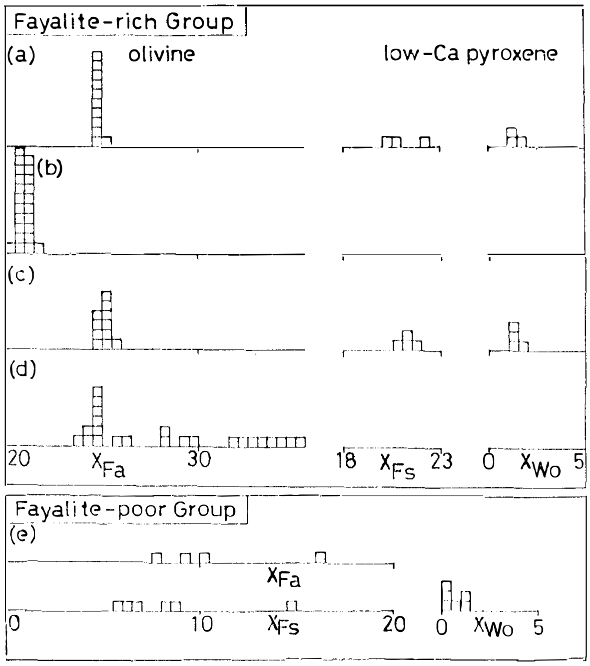
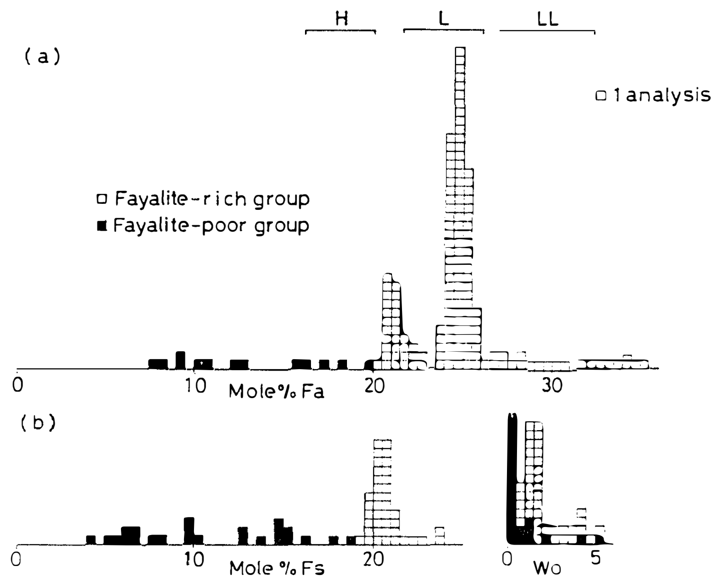


Fig. 1. Histograms of the mole % fayalite, ferrosilite and wollastonite contents of olivine and low-Ca pyroxene in five representative fragments in the inclusion of ALH-77004 chondrite. (a), (b) and (c): moderately to highly-recrystallized lithic fragments of fayalite-rich group; (d): a lithic fragment of fayalite-rich group with exceptionally heterogeneous olvine compositions; (e): a microporphyritic chondrule of fayalite-poor group. One square denotes one analysis.

Silicate mineral grains are usually homogeneous in each fragment, but fragment-to-fragment compositional variations are noted (Fig. 1). Olivine and low-Ca pyroxene exhibit strong peaks in the composition-frequency diagram at about Fa_{24-25} and Fs_{20}, respectively. In addition to these peaks, there are broad 'unequilibrated backgrounds' (Fig. 2), indicating that grains with compositions considerably different from these peaks are included. Furthermore, high-Ca clinopyroxene, microcrystalline plagioclase, and chromite are variable in composition from grain to grain. Representative chemical analyses of these minerals are given in Table 2. Average compositions of olivine (Fa_{24-25}) and low-Ca pyroxene ($Fs_{20}Wo_1$) are close to the averages and are within the ranges for equilibrated L-group chondrites ($Fa_{21.6-26.0}$; $Fs_{17.9-21.7}$, WASSON, 1974; KEIL and FREDRIKSSON, 1964), suggesting that most of the fragments of the



Fg. 2. Histograms of the mole % fayalite, ferrosilite and wollastonite contents of olivine and low-Ca pyroxene in fragments of fayalite-rich and fayalite-poor groups in the inclusion of ALH-77004 chondrite. For comparison, compositional ranges of olivine in type 4–6 ordinary chondrites are shown (WASSON, 1974; KEIL and FREDRIKSSON, 1964).

Fa-rich group were derived from L-group chondrites.

Texture and mineral compositions as well as presence of microcrystalline plagioclase indicate that most of fragments of this group belong to petrologic types 4 to 6, when the classification of VAN SCHMUS and WOOD (1967) is applied.

3.2. *Unequilibrated chondrules (fayalite-poor group)*

The unequilibrated chondrules of Fa-poor group are round in shape and are embedded in the clastic matrix. Their mineralogy indicates that they resemble a chondrule of type 3 unequilibrated chondrite. In a thin section examined only four chondrules of this group are found. These chondrules have a microporphyritic texture, consisting of subhedral to euhedral olivine and/or low-Ca pyroxene phenocrysts set in a fine-grained, microcrystalline groundmass. Subhedral to euhedral olivine and low-Ca pyroxene grains vary in composition and are more magnesian and heterogeneous than those of Fa-rich group, showing normal compositional zoning (Figs. 1 and 2). The compositional ranges of olivines and low-Ca pyroxenes of this group are Fa_{8-20} and $Fs_{4-18}Wo_{0.5-1}$, respectively. Representative chemical analyses of these minerals are given in Table 2. In addition, large low-Ca pyroxene phenocrysts in a pyroxene-porphyritic chondrule contain some olivine inclusions large enough for electron-microprobe analysis, whose composition is Fa_{24-27}.

3.3. *Fine-grained dark clastic matrix and particles of Fe-Ni metal, troilite, and chromite*

The dark-colored matrix of the inclusion is composed mainly of angular to subangular mineral fragments. The author defines the matrix of the inclusion as the grain size fraction smaller than about 30 μm. The matrix contains particles of metals, sul-

Table 2. Electron microprobe analyses of the silicate and oxide phases in the inclusion of ALH-77004.

	1	2	3	4	5	6	7	8
SiO_2	38.1	55.0	66.1	40.6	58.4	—	—	—
TiO_2	—	.32	—	—	n.d.	2.72	2.24	3.11
Al_2O_3	—	.31	20.5	—	n.d.	5.37	3.22	4.47
Cr_2O_3	n.d.	.17	—	.16	.43	55.5	60.5	56.8
V_2O_3	—	—	—	—	—	.96	.81	.97
FeO*	22.7	13.6	—	9.02	4.25	31.0	29.6	31.2
MnO	.56	.51	—	.50	19	.97	1.00	.87
MgO	38.4	30.1	—	49.1	36.6	2.81	3.17	2.72
CaO	n.d.	.95	2.14	.14	.12	—	—	—
Na_2O	—	—	9.51	—	—	—	—	—
K_2O	—	—	1.14	—	—	—	—	—
NiO	.14	—	—	.43	—	—	—	—
Total	99.90	100.96	99.39	99.95	99.99	99.33	100.54	100.14
Si	.995	1.954	2.928	.996	1.993	—	—	—
Ti	—	.009	—	—	n.d.	.073	.060	.083
Al	—	.013	1.068	—	n.d.	.226	.135	.188
Cr	n.d.	.005	—	.003	.011	1.569	1.700	1.598
V	—	—	—	—	—	.023	.019	.023
Fe	.496	.404	—	.185	.122	.926	.882	.928
Mn	.013	.015	—	.011	.006	.029	.030	.026
Mg	1.496	1.594	—	1.795	1.862	.150	.168	.144
Ca	n.d.	.036	.102	.003	.005	—	—	—
Na	—	—	.817	—	—	—	—	—
K	—	—	.065	—	—	—	—	—
Ni	.003	—	—	.009	—	—	—	—
O	4	6	8	4	6	4	4	4
Total cation	3.003	4.029	4.979	3.002	3.999	2.996	2.994	2.990
	$Fa_{24.9}$			$Fa_{9.3}$				
		$Wo_{1.8}$	$An_{10.4}$		$Wo_{0.3}$			
		$Fs_{19.9}$	$Ab_{83.0}$		$Fs_{6.1}$			
		$En_{78.4}$	$Or_{6.6}$		$En_{93.6}$			

*: Total Fe as FeO; —: not analyzed; n.d.: not detected.
1: Olivine from Fa-rich group; 2: low-Ca pyroxene from Fa-rich groups; 3: plagioclase from Fa-rich group; 4: olivine from Fa-poor group; 5: low-Ca pyroxene from Fa-poor group; 6: matrix chromite; 7: chromite in chondrule rim; 8: matrix chromite.

fide, and chromite. The compositions of olivine and low-Ca pyroxene show peaks in the ranges characteristic of equilibrated L chondrites and are similar to those of the fragments of Fa-rich group. These features suggest that the matrix materials were also derived mainly from equilibrated L chondrites.

Most of the metallic Fe-Ni occur as a subround to irregular assemblage of homogeneous kamacite and compositionally-zoned taenite. The latter shows normal, M-shaped Ni profiles and sometimes contains plessite. Kamacite and taenite show more variations and enrichment in Co content than those in most equilibrated L chondrites (AFIATTALAB and WASSON, 1980); in kamacite Co ranges from 0.8 to 1.4 wt % and Ni from 5 to 7.5 wt % with an average of 1.2 wt % Co and 6.0 wt % Ni, whereas in taenite

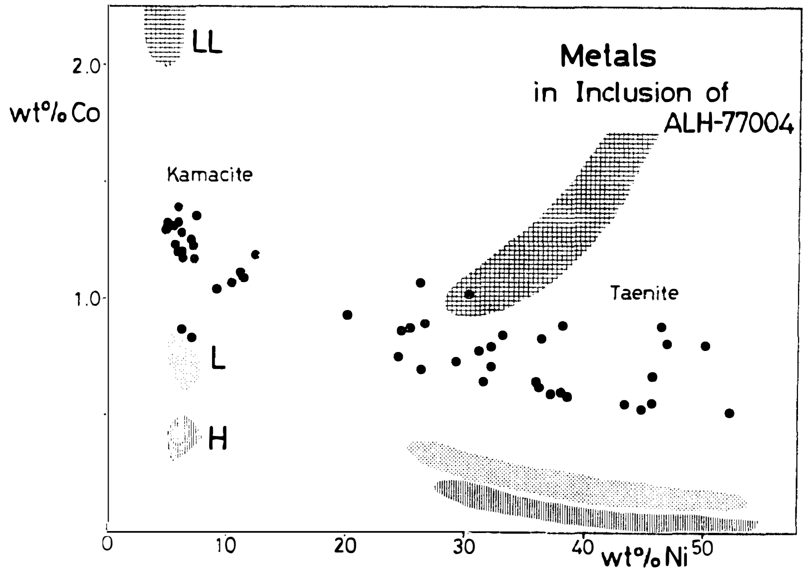


Fig. 3. Compositions of kamacite and taenite in the inclusion of ALH-77004 chondrite. For comparison, the ranges of average compositions of kamacite and taenite for equilibrated ordinary chondrites are shown (AFIATTALAB and WASSON, 1980).

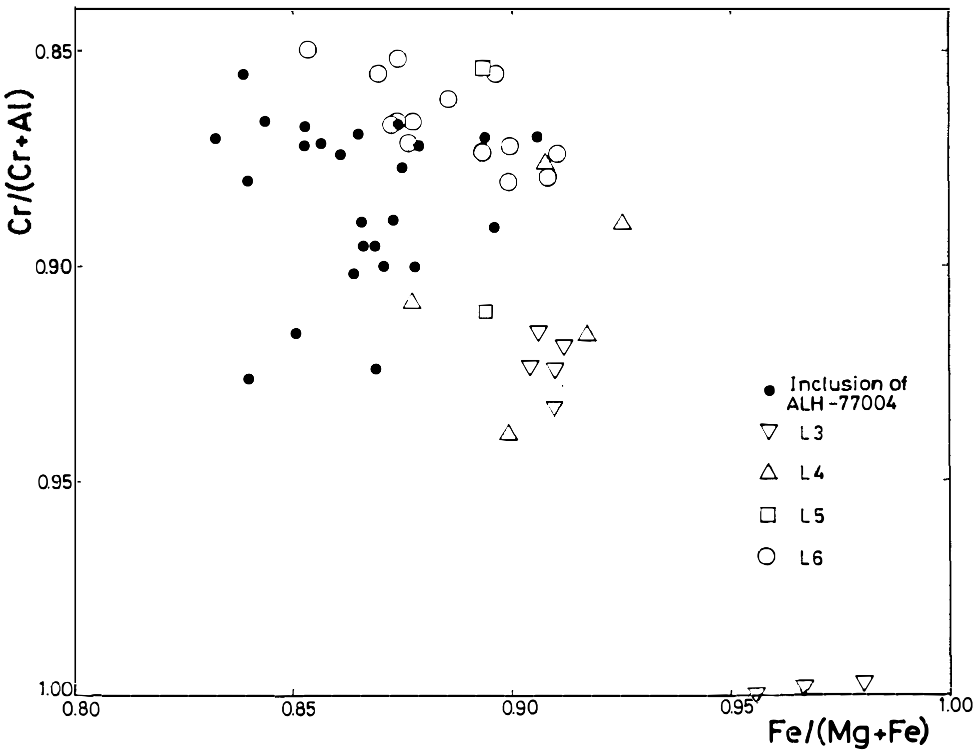


Fig. 4. Core composition of chromites in the inclusion of ALH-77004 chondrite. For comparison, the data of chromite compositions from L chondrites (Khohar, Bishunpur, Krymka, Barratta, Goodland, McKinney, Atarra, Bald Mountain, Lua, Ergheo, Kyushu, Modoc, Walters, New Concord, Harleton: BUNCH et al., 1967; Alfianello, Colby, Leedy: CURTIS and SCHMITT, 1979; Pampa del Infierno: BOCTOR et al., 1982; Yamato-74191: KIMURA et al., 1980; Yamato-74190, -74354, -74362: NAGAHARA, 1979; B80010629-L: OHTA and GRIFFIN, 1982) are also shown. Total Fe as FeO.

Co ranges from 0.5 to 1.1 wt % and Ni from 20 to 52.5 wt % with an average of 0.8 wt % Co and 30.0 wt % Ni (Fig. 3).

Chromite occurs mostly in the matrix and rarely in olivine of fragments of Fa-rich group as fine-grained inclusions. It frequently coexists with Fe-Ni metal and troilite. The compositions are variable from grain to grain and the range is somewhat wider than that of chromite in equilibrated ordinary L chondrites (BUNCH *et al.*, 1967) (Fig. 4). Representative chemical analyses of chromite are given in Table 2.

4. Discussion

As described above, the major portion of the inclusion of ALH-77004 is composed of chondritic materials of L group with petrologic types 4, 5, and 6. Furthermore, small amounts of unequilibrated chondrules of Fa-poor group are mingled with these well-recrystallized L chondritic materials. Clearly, the fragments contained in the inclusion have not suffered from annealing for a long time at relatively high temperatures, since such a process would have equilibrated all the constituents of the inclusion.

It is suggested that these fragments of the inclusion could only be formed when the fragments of L chondrites resided for some time at the surface of the parent body, where they were comminuted to submillimeter size, mixed and turned-over by impacts, and new materials were continuously excavated and supplied. In the conventional onion-shell models (ANDERS, 1978; MIYAMOTO, 1979), it is assumed that radioactive internal heating after accretion would have produced a shell-like structure of the L chondrite parent body with highly-recrystallized type 6 materials in the core surrounded successively by shells of types 5–3. Repetitive impact cratering processes would have uncovered recrystallized materials of the L chondrite parent body and mixed them with the near-surface unequilibrated material to form the inclusion of ALH-77004. The mixture of highly-recrystallized (petrologic type 6) rounded to angular, abraded lithic fragments of various sizes, the unequilibrated microporphrytic chondrules, particles of metal, troilite and chromite, and the dark fine-grained clastic matrix portion is readily explained by this process.

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References

AFIATTALAB, F. and WASSON, J. T. (1980): Composition of the metal phases in ordinary chondrites; Implications regarding classification and metamorphism. Geochim. Cosmochim. Acta, **44**, 431–446.

ANDERS, E. (1978): Most stony meteorites come from the asteroid belt. Asteroids: An Exploration Assessment, ed by D. MORRISON and W. C. WELLS. Houston, NASA Conf. Publ. 2053, 57–75.

BOCTOR, N. Z., BELL, P. M., MAO, H. K. and KULLERUD, G. (1982): Petrology and shock metamorphism of Pampa del Infierno chondrite. Geochim. Cosmochim. Acta, **46**, 1903–1911.

BUNCH, T. E., KEIL, K. and SNETSINGER, K. G. (1967): Chromite composition in relation to chemistry and texture of ordinary chondrites. Geochim. Cosmochim. Acta, **31**, 1569–1582.

CURTIS, D. B. and SCHMITT, R. A. (1979): The petrogenesis of L-chondrites; Insights from the chemistry of minerals. Geochim. Cosmochim. Acta, **43**, 1091–1103.

DODD, R. T. (1969): Metamorphism of the ordinary chondrites; A review. Geochim. Cosmochim. Acta, **33**, 161–203.

DODD, R. T., VAN SCHMUS, W. R. and KOFFMAN, D. M. (1967): A survey of the unequilibrated ordinary chondrites. Geochim. Cosmochim. Acta, **31**, 921–951.

KEIL, K. and FREDRIKSSON, K. (1964): The iron, magnesium, and calcium contents of coexisting olivines and rhombic pyroxenes of chondrites. J. Geophys. Res., **69**, 3487–3515.

KIMURA, M., YAGI, K. and ONUMA, K. (1980): Opaque minerals in the Yamato-74191 chondrites. Mem. Natl Inst. Polar Res., Spec. Issue, **17**, 95–103.

MARVIN, U. B. and MASON, B. (1980): Catalog of Antarctic meteorites, 1977–1978. Smithson. Contrib. Earth Sci., **23**, 50 p.

MIYAMOTO, M. (1979): Thermal evolution of the ordinary chondrite parent body. Proc. 12th Lunar Planet. Symp. Tokyo, Inst. Space Aeronaut. Sci., Univ. Tokyo, 92–98.

NAGAHARA, H. (1979): Petrological studies on Yamato-74354, -74190, -74362, -74646 and -74115 chondrites. Mem. Natl Inst. Polar Res., Spec. Issue, **15**, 77–109.

NAKAMURA, Y. and KUSHIRO, I. (1970): Compositional relations of coexisting orthpyroxene, pigeonite and augite in a tholeiitic andesite from Hakone Volcano. Contrib. Mineral. Petrol., **26**, 265–275.

OHTA, Y. and GRIFFIN, W. L. (1982): Preliminary studies of 3 Yamato meteorites. Papers presented to the Seventh Symposium on Antarctic Meteorites, 19–20 February 1982. Tokyo, Natl Inst. Polar Res., 3–5.

RUBIN, A. E., SCOTT, E. R. D., TAYLOR, G. J., KEIL, K. and ALLEN, J. S. B. (1983): Nature of the H chondrite parent body regolith; Evidence from the Dimmitt breccia. Proc. Lunar Planet. Sci. Conf. 13th, Pt 2, A741–A754 (J. Geophys. Res., **88**, Suppl.).

SCORE, R., SCHWARZ, C. M., KING, T. V. V., MASON, B., BOGARD, D. D. and GABEL, E. M. (1981): Antarctic meteorite descriptions 1976–1977–1978–1979. Antarct. Meteorite Newsl., **4**(1), 144 p.

SCOTT, E. R. D. (1982): Origin of rapidly solidified metal-troilite grains in chondrites and iron meteorites. Geochim. Cosmochim. Acta, **46**, 813–823.

STÖFFLER, D., KNÖLL, H. D., MARVIN, U. B., SIMONDS, C. H. and WARREN, P. H. (1980): Recommended classification and nomenclature of lunar highland rocks —A committee report. Proc. Conf. Lunar Highlands Crust, **12**, 51–71.

SWEATMAN, T. R. and LONG, J. V. P. (1969): Quantitative electronprobe microanalysis of rock-forming minerals. J. Petrol., **10**, 332–379.

VAN SCHMUS, W. R. and WOOD, J. A. (1967): A chemical-petrologic classification for the chondritic meteorites. Geochim. Cosmochim. Acta, **31**, 747–765.

WASSON, J. T. (1974): Meteorites; Classification and Properties. New York, Springer, 316 p.

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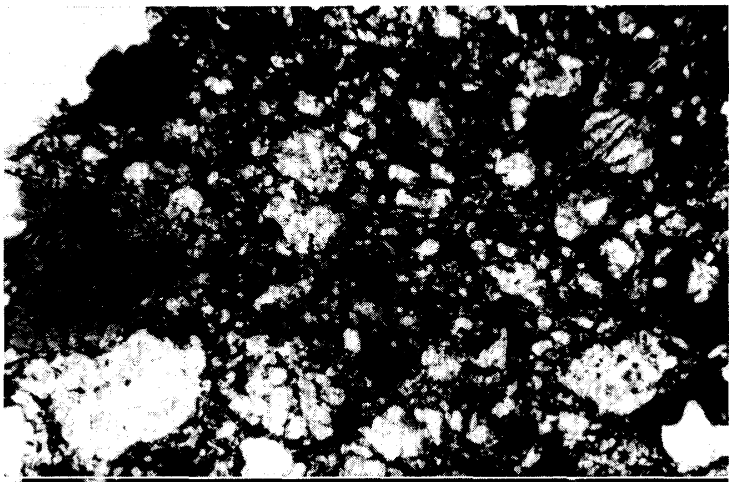

Photo 1. Photomicrograph of thin section of the inclusion of ALH-77004 chondrite. Moderately to highly-recrystallized lithic fragments are embedded in the fine-grained dark clastic matrix. Transmitted light. Width 3.6 mm.

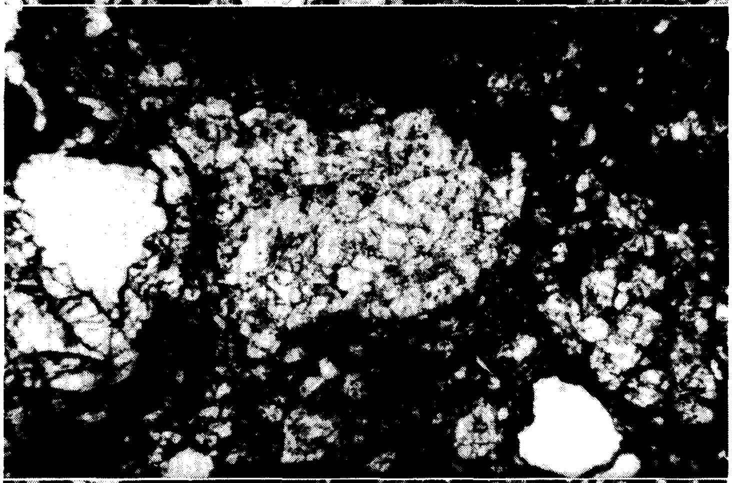

Photo 2. Photomicrograph of a subangular lithic fragment of fayalite-rich group. Texture, mineral compositions and presence of microcrystalline plagioclase indicate that the fragment was derived from L6 chondrite. Transmitted light. Width 1.8 mm.

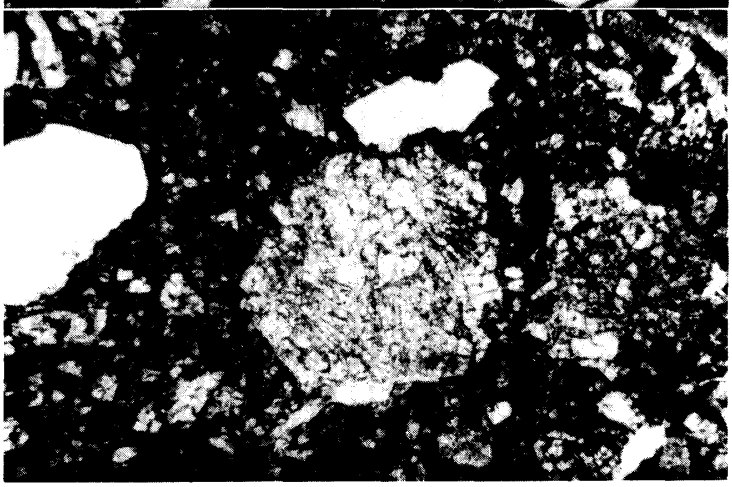

Photo 3. Photomicrograph of a rounded lithic fragment of fayalite-rich group embedded in the dark clastic matrix. Clear plagioclase grains are microscopically noted in the interstices of olivines and low-Ca pyroxenes. Transmitted light. Width 1.8 mm.