PETROGRAPHY AND CLASSIFICATION OF REFRACTORY INCLUSIONS IN THE ALLENDE AND MOKOIA CV3 CHONDRITES

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Abstract: More than 600 refractory inclusions in 22 thin sections of Allende and Mokoia were studied by optical and scanning-electron microscopy. Olivine-rich inclusions and Ca, Al-rich inclusions (CAI's) are aggregates of various combinations of three fundamental petrographic constituents: rimmed *concentric objects*, Ca, Si-rich *chaotic material*, and mafic *inclusion matrix*. A new classification system for refractory inclusions is developed that is based on the size and abundance of these three fundamental constituents. Olivine-rich inclusions consist primarily of inclusion matrix and are divided into two textural varieties: unrimmed olivine aggregates (Type 1A inclusions) and rimmed olivine aggregates (Type 1B inclusions). Many Type 1B inclusions contain Ca, Al-rich nodules that are aggregates of concentric objects. CAI's consist primarily of concentric objects and are divided into three varieties: unrimmed complex CAI's (Type 2 inclusions), rimmed complex CAI's (Type 3 inclusions), and simple CAI's (Type 4 inclusions). Simple and complex CAI's are divided into melilite-rich and melilite-poor varieties. Several varieties of refractory inclusions grade into each other chemically, mineralogically, and texturally. Our new classification system avoids several problems that are inherent to other classification systems, which use the term "coarse-grained" too restrictively for many simple CAI's and inaccurately for most melilite-rich complex CAI's.

1. Introduction

CV3 chondrites contain chondrules, olivine-rich and Ca, Al-rich inclusions (CAI's) (which we refer to collectively as *refractory inclusions*), and mineral fragments embedded in opaque, fine-grained matrix (McSWEEN, 1977a). Coarse-grained CAI's in Allende have been intensively studied, but until recently the fine-grained CAI's received little attention (KORNACKI, 1981a, b; MACPHERSON and GROSSMAN, 1982). In addition, refractory inclusions in other C3 chondrites have only recently been studied in detail (COHEN, 1981a, b; KORINA *et al.*, 1982; HUTCHEON and STEELE, 1982; IKEDA, 1982).

We report the results of a comprehensive petrographic survey of the refractory inclusions in the Allende and Mokoia CV3 chondrites. We identify their fundamental constituents, develop a new classification system for them, and discuss some relationships among refractory inclusions that have been obscured by other classification systems.

2. Methods of Observation

Seventeen thin sections of Allende and five thin sections of Mokoia were prepared from several fragments of each meteorite. Each thin section was studied by optical and scanning-electron microscopy (using a CWIKSCAN/100 field-emission scanning-electron microscope (SEM) equipped with a KeVex 500A X-ray energy-dispersive spectrometer (EDS)) and by electron-probe microanalysis (EPMA) (using MAC 400 and CAMECA MBX electron-probe microanalyzers).

All objects $>200\ \mu m$ in Allende and $>100\ \mu m$ in Mokoia were examined and identified as olivine- or pyroxene-rich chondrules, isolated mineral grains, opaque mineral complexes, or refractory inclusions. A total of 418 refractory inclusions in Mokoia and 189 refractory inclusions in Allende were studied. Minerals in these refractory inclusions were identified by their optical properties in plane polarized light, by backscattered electron (BSE) microscopy, and by semi-quantitative (EDS) and quantitative (EPMA) microanalyses.

3. Constituents of Refractory Inclusions

Refractory inclusions in Allende and Mokoia contain varying proportions of three distinct, fundamental petrographic constituents which we call *concentric objects*, *chaotic material*, and *inclusion matrix* (COHEN, 1981a, b; KORNACKI, 1981a, b).

Concentric objects are rounded, with a core-and-rim structure (Fig. 1A). The core consists of Al- and Ti-rich oxide minerals (hibonite, spinel, perovskite, ilmenite) and varying amounts of the Ca-rich silicates melilite and Ti-Al-pyroxene. Rimming the core are the following sequence of monomineralic layers: (1) an alkali-rich band of feldspathoids in Allende, or an Al-rich phyllosilicate (HAP; COHEN and KORNACKI, 1983) in Mokoia; (2) a band(s) of one or more clinopyroxenes (Al-diopside, Ti-Al-pyroxene, or hedenbergite) $\pm$ andradite; and (3) a layer of ferrous olivine (which is sometimes absent).

Chaotic material is a porous aggregate of fine-grained Ca-rich silicates (Mg-clinopyroxenes, hedenbergite, andradite, grossular, anorthite, and wollastonite) (Fig. 1B).

In Allende, inclusion matrix is a porous aggregate of ferrous olivine, salitic pyroxene, and feldspathoids (Fig. 1C). In Mokoia, a low-Al phyllosilicate, probably a trioctahedral montmorillonite, substitutes for the feldspathoids. We call this incompletely-characterized mineral LAP (COHEN and KORNACKI, 1983). The texture and mineralogy of inclusion matrix are similar to those of the opaque "meteorite matrix" in which refractory inclusions and chondrules are embedded. Inclusion matrix differs from meteorite matrix by being depleted in sulfide and metal grains and (perhaps) carbonaceous material (KORNACKI, 1982).

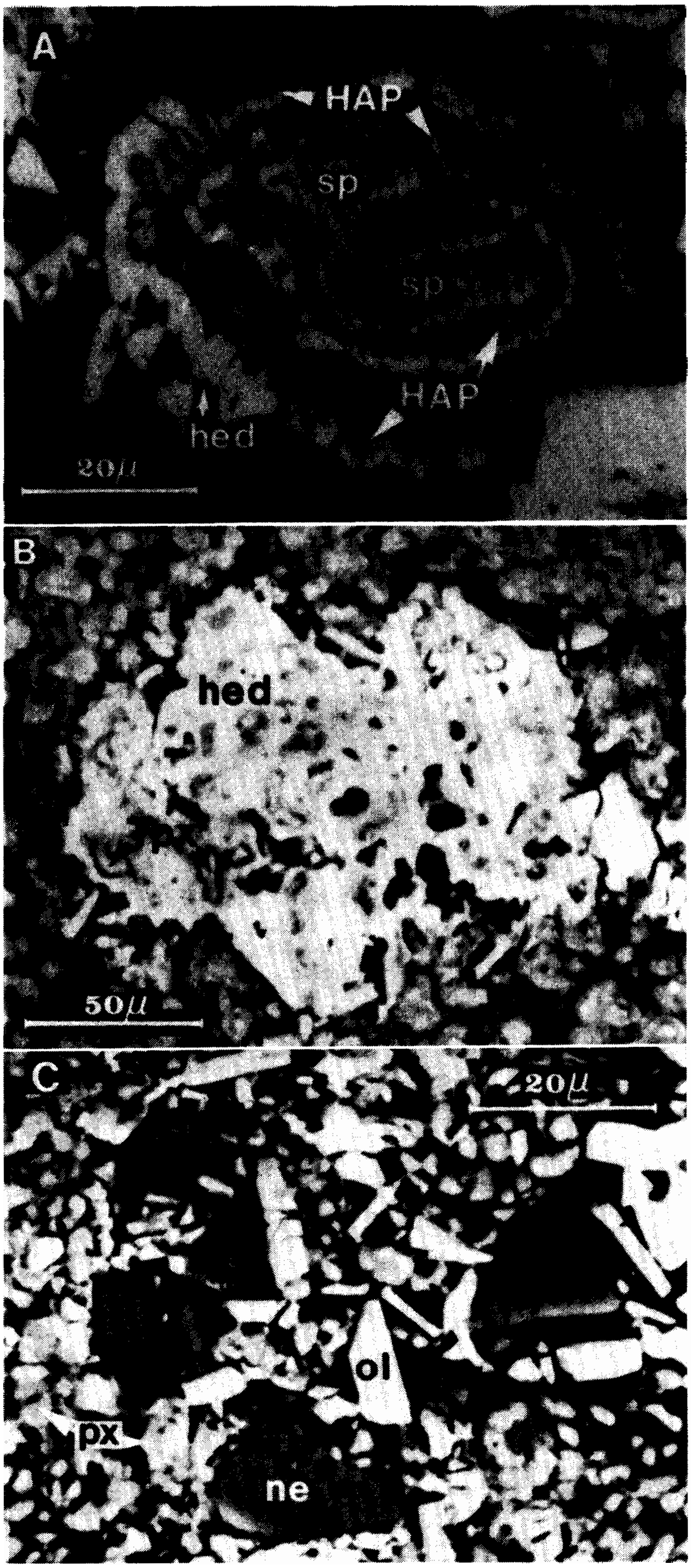

Fig. 1. Constituents of refractory inclusions in Mokoia (A, B) and Allende (C); BSE images. (A) Concentric object, (B) chaotic material, (C) inclusion matrix. HAP = high-Al phyllosilicate, hed = hedenbergite, ne = nepheline, ol = ferrous olivine, px = salitic pyroxene, sp = spinel, Tpx = Ti-Al-pyroxene.

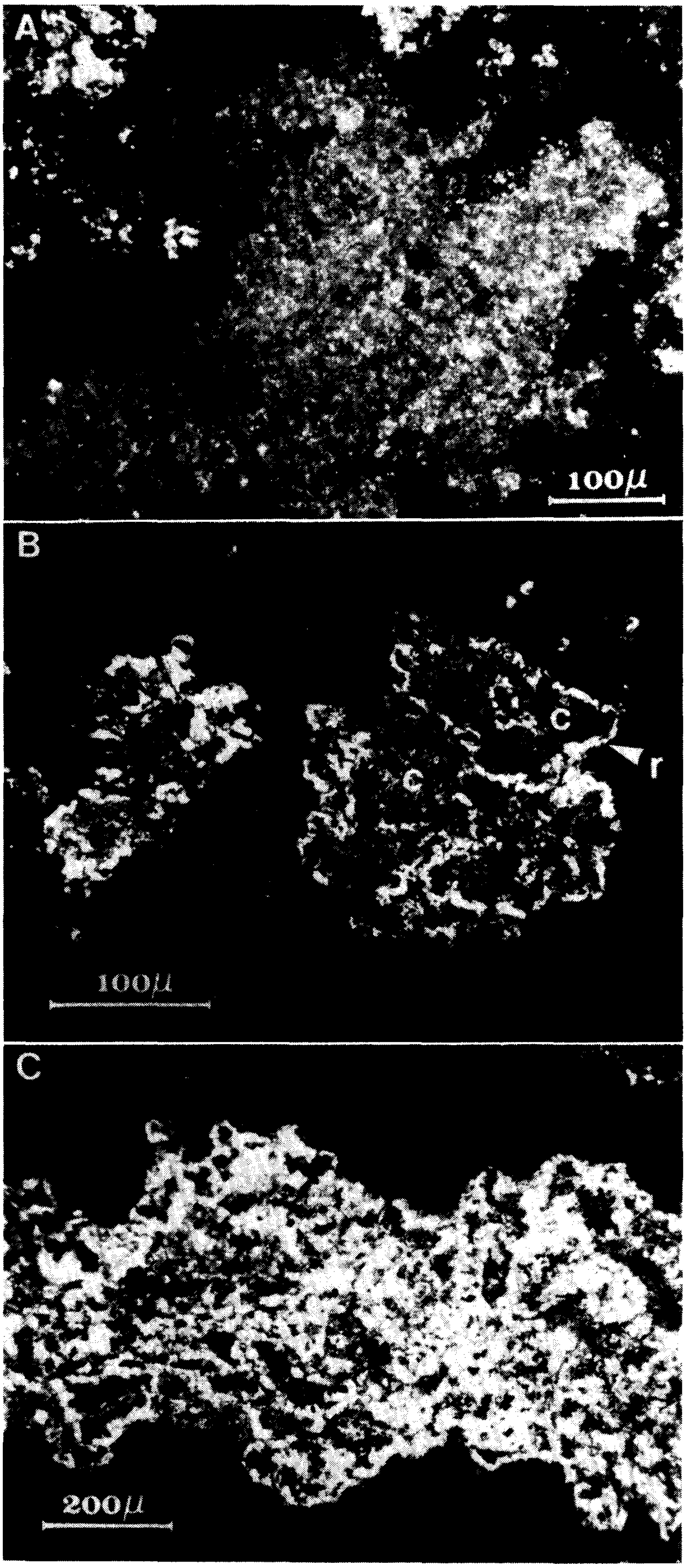

Fig. 2. Olivine-rich inclusions in Allende (A, C) and Mokoia (B); transmitted light photomicrographs. (A) Unrimmed olivine aggregate (Type IA inclusion). (B) This object is texturally intermediate between Type IA and Type IB inclusions. Cores (c) of inclusion matrix are surrounded by thin rims (r) of granular olivine. (C) Rimmed olivine aggregate (Type IB inclusion).

4. Classification and Petrography

4.1. Olivine-rich inclusions

There are two textural varieties of olivine-rich inclusions in Allende and Mokoia (Table 1). *Unrimmed* olivine aggregates (Type 1A inclusions) consist almost entirely of porous inclusion matrix (Fig. 2A). Some Type 1A inclusions have opaque cores of material that is mineralogically similar to opaque meteorite matrix (Fig. 3A). *Rimmed* olivine aggregates (Type 1B inclusions) are aggregates of rounded objects, each of which has a core of inclusion matrix and a rim of granular olivine (Fig. 2C). Rimmed olivine aggregates frequently contain Ca, Al-rich nodules that are aggregates of smaller concentric objects (Fig. 3B). Similar rounded objects in olivine-rich inclusions have been previously characterized as dark spheres (GROSSMAN and STEELE, 1976), Type IV chondrules (MCSWEEN, 1977b), or botryoidal nodules (IKEDA, 1982). Type 1B inclusions are equivalent to the amoeboid olivine aggregates (AOA's) of GROSSMAN and STEELE (1976) and BAR-MATTHEWS *et al.* (1979).

The two types of olivine-rich inclusions grade into each other texturally: intermediate varieties have very thin rims of granular olivine (Fig. 2B). The bulk compositions of unrimmed and rimmed olivine aggregates overlap (KORNACKI, 1982).

4.2. Ca, Al-rich inclusions

Three types of CAI's can be distinguished (Tables 1 and 2). *Simple* CAI's consist of a single concentric object. *Complex* CAI's are aggregates of concentric objects $\pm$chaotic material and inclusion matrix. Simple CAI's tend to be coarser-grained than complex CAI's, but the petrographic distinction we draw between them is based on the size and abundance of their constituent concentric objects, not on the size of individual mineral grains. Complex CAI's occur in unrimmed and rimmed varieties. There are two mineralogical varieties of simple and complex CAI's: melilite-rich and melilite-poor.

Unrimmed complex CAI's (Type 2 inclusions) are equivalent to the "fine-grained" CAI's of GROSSMAN *et al.* (1975), and the Type F and Type FAO inclusions of WARK (1979). They are aggregates of many tiny, rounded, spinel-rich concentric objects and chaotic material embedded in two types of matrix: olivine-rich inclusion matrix, or a spinel+clinopyroxene-rich matrix that is a debris of fragments of concentric objects (WARK and LOVERING, 1977), not simply a loose aggregate of individual crystals which formed separately (Figs. 4A–C). Some Type 2 inclusions are mineralogically zoned (Fig. 3C) (WARK, 1979), but their constituent concentric objects are so small that no prominent internal or external rims are visible by optical microscopy.

The other two types of CAI's (rimmed complex CAI's and simple CAI's) do have prominent external or internal rims, because they consist primarily of larger concentric objects than those that constitute Type 2 inclusions. Rimmed complex CAI's (Type 3 inclusions) are contorted, convoluted, botryoidal-to-sinuous aggregates of several concentric objects, and occur in two mineralogical varieties. Melilite-rich, rimmed complex CAI's (Type 3A inclusions) are equivalent to the "fluffy" Type A CAI's of MACPHERSON and GROSSMAN (1979) (Fig. 5A). Spinel-rich, rimmed complex CAI's (Type 3B inclusions) are equivalent to the "sinuous" Allende inclusion of DAVIS *et al.* (1980) and MACPHERSON *et al.* (1981), and the "nodular" and "banded" varieties of Murchison

Table 1. Suggested classification system for "fine-grained" refractory inclusions, related to earlier classifications.

This paper	Earlier classifications		
	Fine-grained CAI's[1,2]	Fine-grained, alkali-rich spinel aggregates (Type F)[3]	Fine-grained, irregular aggregates (Group II)[4]
Unrimmed complex CAI's (Type 2 inclusions) *Mineralogy*: See text	*Mineralogy*: spinel, clinopyroxene, sodalite, nepheline, grossular. May include small amounts of melilite, olivine, and plagioclase. *REE chemistry*: light REE ~20–50X chondritic. Heavy REE depleted relative to light REE.	*Core mineralogy*: spinel + perovskite ± hibonite. *Rim sequence*: nepheline + sodalite; diopside + Ti-Al-pyroxene; hedenbergite + andradite. (*REE chemistry* not employed.)	*Mineralogy*: spinel, clinopyroxene, melilite, grossular, nepheline, and sodalite. *REE chemistry*: light REE ~20–30X chondritic. Heavy REE depleted relative to light REE. Volatile REE (Eu, Yb) and refractory REE (Er, Lu) strongly depleted.
		Fine-grained, alkali-olivine aggregates (Type FAO)[3]	Fine-grained, irregular aggregates (Group III)[4]
		Mineralogy: intermediate between Type F and Type AO (below). (*REE chemistry* not employed.)	*Mineralogy*: spinel, clinopyroxene, grossular, sodalite, and nepheline. *REE chemistry*: light REE ~20X chondritic. Heavy REE not depleted relative to light REE. Only volatile REE (Eu, Yb) strongly depleted.
	Amoeboid olivine aggregates (AOA's)[5,6]	Fine-grained amoeboid olivine aggregates (Type AO)[3]	Fine-grained aggregates (Group IV)[4]
Unrimmed and rimmed olivine aggregates (Type 1 inclusions) *Mineralogy*: See text	*Mineralogy*: olivine, nepheline, sodalite, clinopyroxene. May include small amounts of anorthite and spinel. *REE chemistry*: usually relatively unfractionated (~8X chondritic). Group II REE patterns in "fractionated AOA's".	*Mineralogy*: olivine, nepheline, sulfides, spinel, and clinopyroxene. (*REE chemistry* not employed.)	*Mineralogy*: olivine. *REE chemistry*: relatively unfractionated (~5X chondritic).

References: (1) Grossman *et al.*, 1975 (2) Grossman and Ganapathy, 1976b (3) Wark, 1979 (4) Mason and Martin, 1977 (5) Grossman and Steele, 1976 (6) Grossman *et al.*, 1979

Table 2. Suggested classification system for "coarse-grained" refractory inclusions, related to earlier classifications.

This paper	Previously described inclusion types (various authors)	Petrographic characteristics: Core mineralogy	Rim sequence mineralogy	REE chemistry
Melilite-rich, rimmed complex CAI's (Type 3A inclusions)	"Fluffy" Type A CAI's[1-4]	mel poikilitically encloses sp and pv; ±hib; abundant fine-grained material	sp+pv; ne+sd±an±mel; Tpx +diop; hed+andr±wo	Complementary Group III and Group VI patterns (~10–20X chondritic)
Spinel-rich, rimmed complex CAI's (Type 3B inclusions)	"Sinuous" inclusion[5, 6]	sp+pv±mel	ne+an; diop+Tpx; hed+andr	Group II pattern
	"Compact" Type A CAI's[2]	mel poikilitically encloses sp and pv; ±hib; ±Tpx		n.d.
Melilite-rich, simple CAI's (Type 4A inclusions)	Type Bl CAI's[4, 7]	zoned mel and Tpx poikilitically enclose sp and pv	sp+pv; ne+ol; diop; well-developed hed	Usually Group I or Group V patterns (~10–20X chondritic)
	Type B2 CAI's[4, 7]	Tpx and mel poikilitically enclose sp and pv	Same as Type B1, but hed poorly developed	Same as Type B1
Melilite-poor, simple CAI's (Type 4B inclusions)	Type I CAI's[3, 8]	an+Tpx±sp±mel±ol	sp+pv; ne+sd; diop+Tpx+sf; ol	n.d.

References:
(1) Allen *et al.*, 1978
(2) MacPherson and Grossman, 1979
(3) Wark and Lovering, 1978
(4) Mason and Taylor, 1982
(5) MacPherson *et al.*, 1981
(6) Davis *et al.*, 1980
(7) Wark and Lovering, 1982a
(8) Hutcheon, 1982

Key:
an = anorthite
andr = andradite
diop = diopside
hed = hedenbergite
hib = hibonite
mel = melilite
ne = nepheline
ol = olivine
pv = perovskite
sf = sulfides
sp = spinel
Tpx = Ti-Al-pyroxene
wo = wollastonite
n.d. = not determined

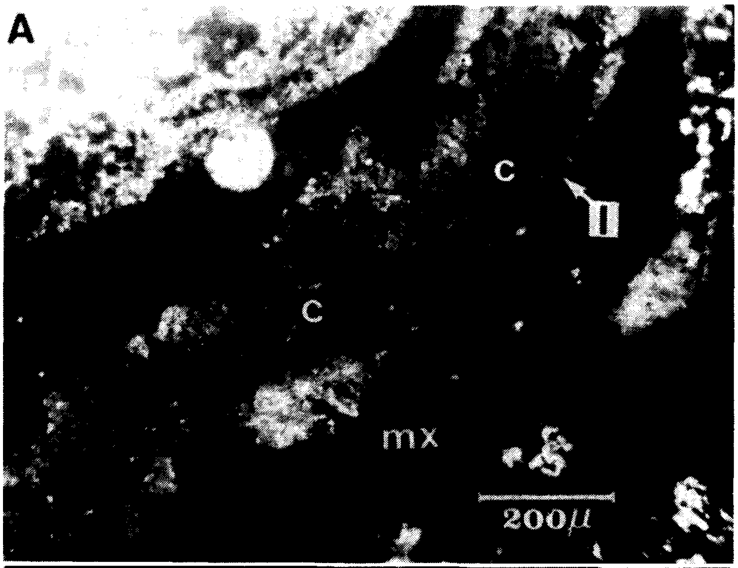

Fig. 3A. Olivine-rich Allende inclusion with an opaque core (c) of material similar to meteorite matrix (mx), surrounded by a thin layer (l) of porous inclusion matrix; transmitted light photomicrograph.

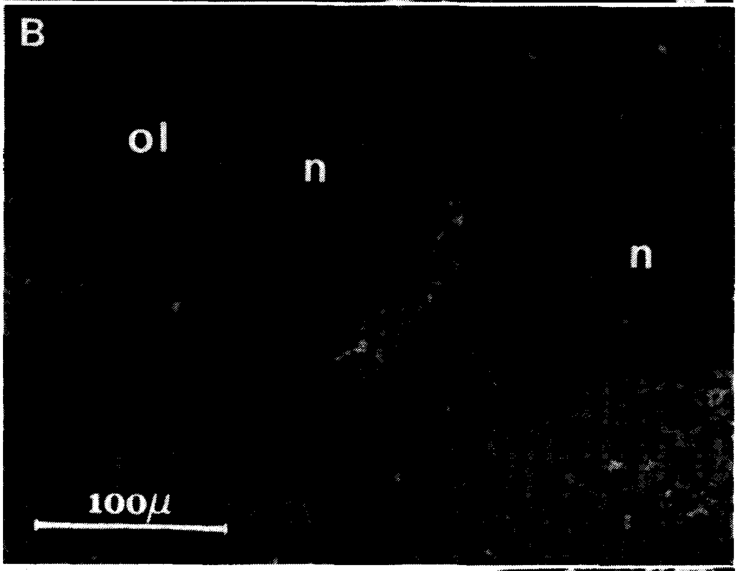

Fig. 3B. Complex Ti-Al-pyroxene-rich nodules (n) in a rimmed olivine aggregate (ol) from Allende; BSE image.

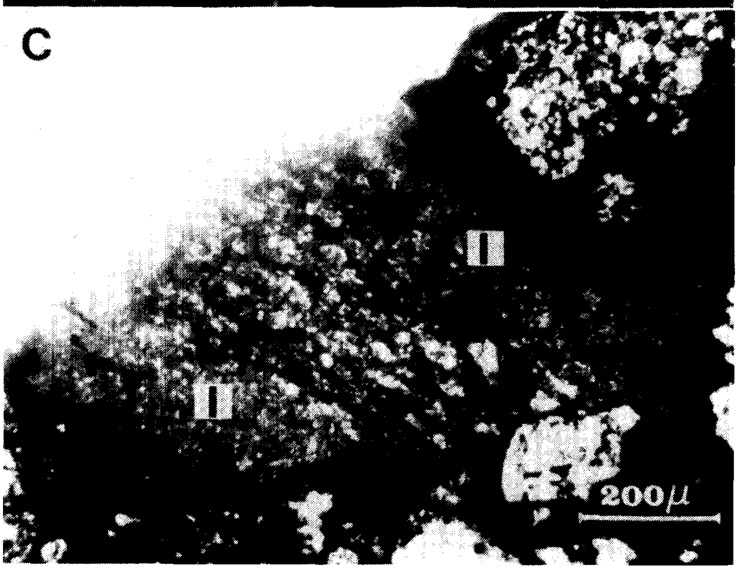

Fig. 3C. Zoned Type 2 inclusion from Allende; transmitted light photomicrograph. Concentric objects and fragments of chaotic material (bright) are embedded in inclusion matrix (gray). A layer of inclusion matrix (l) surrounds the inclusion.

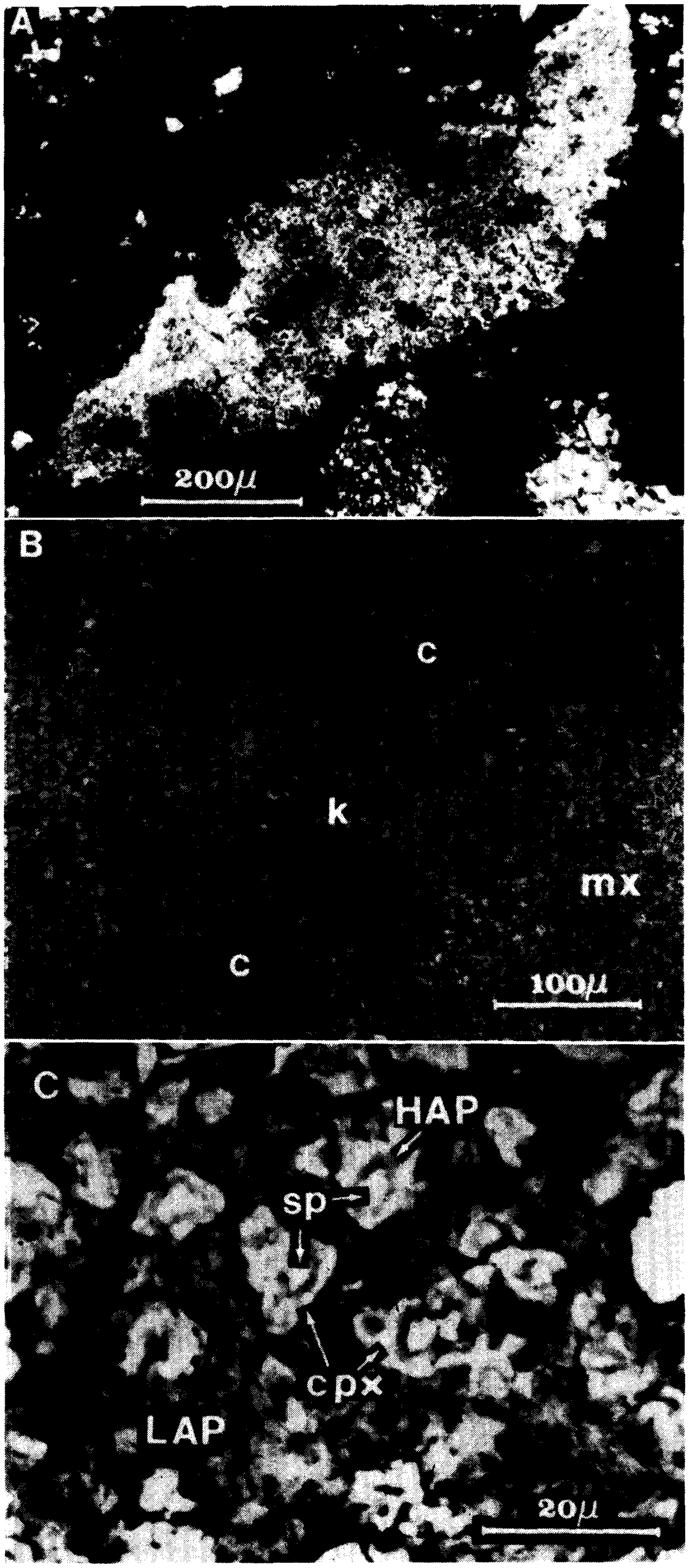

Fig. 4. Unrimmed complex CAI's (Type 2 inclusions) in Mokoia (A, C) and Allende (B). A: transmitted light photomicrograph; B, C: BSE images. (A) This unrimmed complex CAI is an aggregate of tiny concentric objects. (B) Spinel-rich concentric objects (c) containing rounded perovskite crystals (bright) are embedded in chaotic material (k); mx = meteorite matrix. (C) Concentric objects in Mokoia contain Mg-spinel (sp), high-Al phyllosilicate (HAP) and diopsidic pyroxene (cpx). Inclusion matrix contains a low-Al phyllosilicate (LAP).

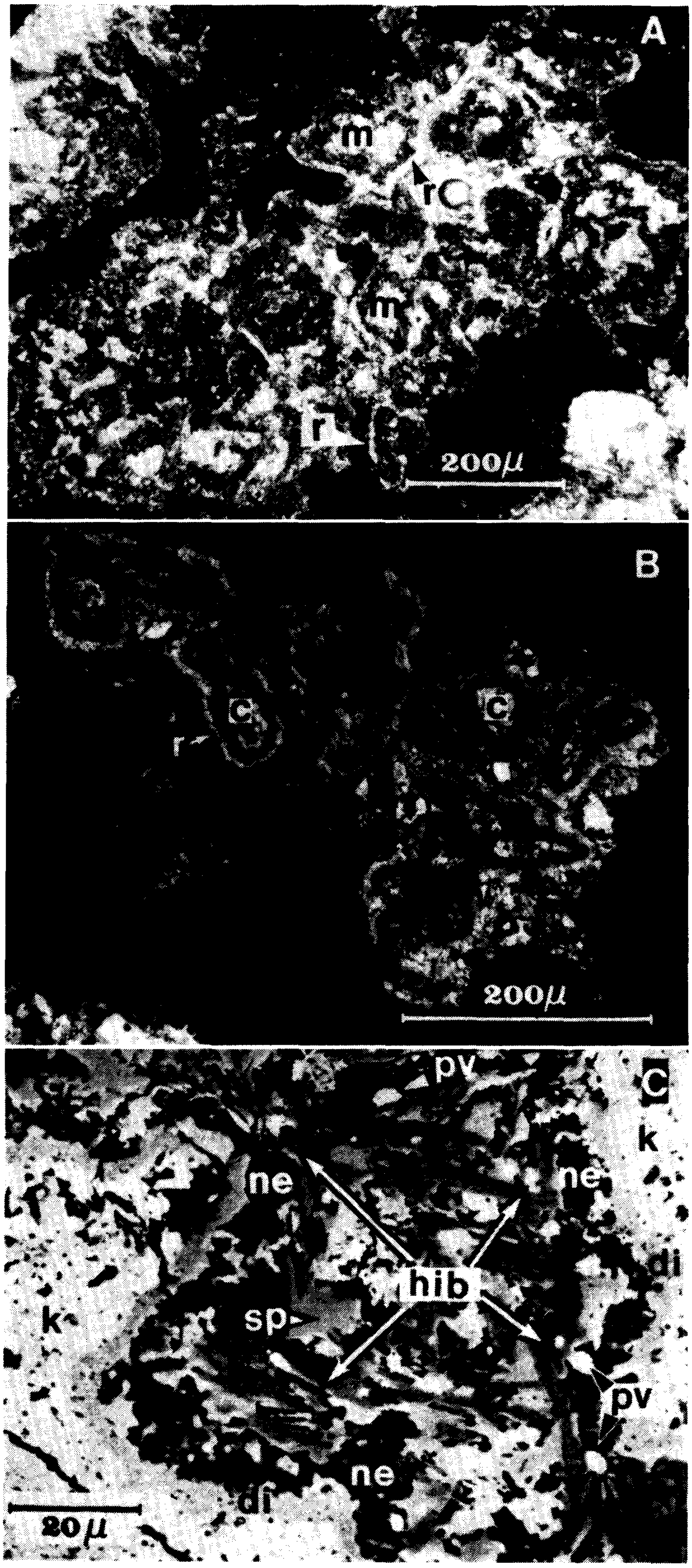

Fig. 5. Rimmed complex CAI's (Type 3 inclusions) in Allende. A, B: transmitted light photomicrographs; C: BSE image. (A) This melilite-rich, rimmed complex CAI (Type 3A inclusion) is a botryoidal aggregate of concentric objects containing coarse-grained melilite (m), abundant fine-grained material (gray), and pyroxene-rich rims (r). (B) This spinel-rich, rimmed complex CAI (Type 3B inclusion) is a botryoidal aggregate of concentric objects (c) rimmed by feldspathoids (dark) and clinopyroxene (r). (C) Detailed mineralogy of a concentric object in a Type 3B inclusion; di = Al-diopside, sp = Fe-bearing spinel, hib = hibonite, k = chaotic material, ne = nepheline, pv = perovskite.

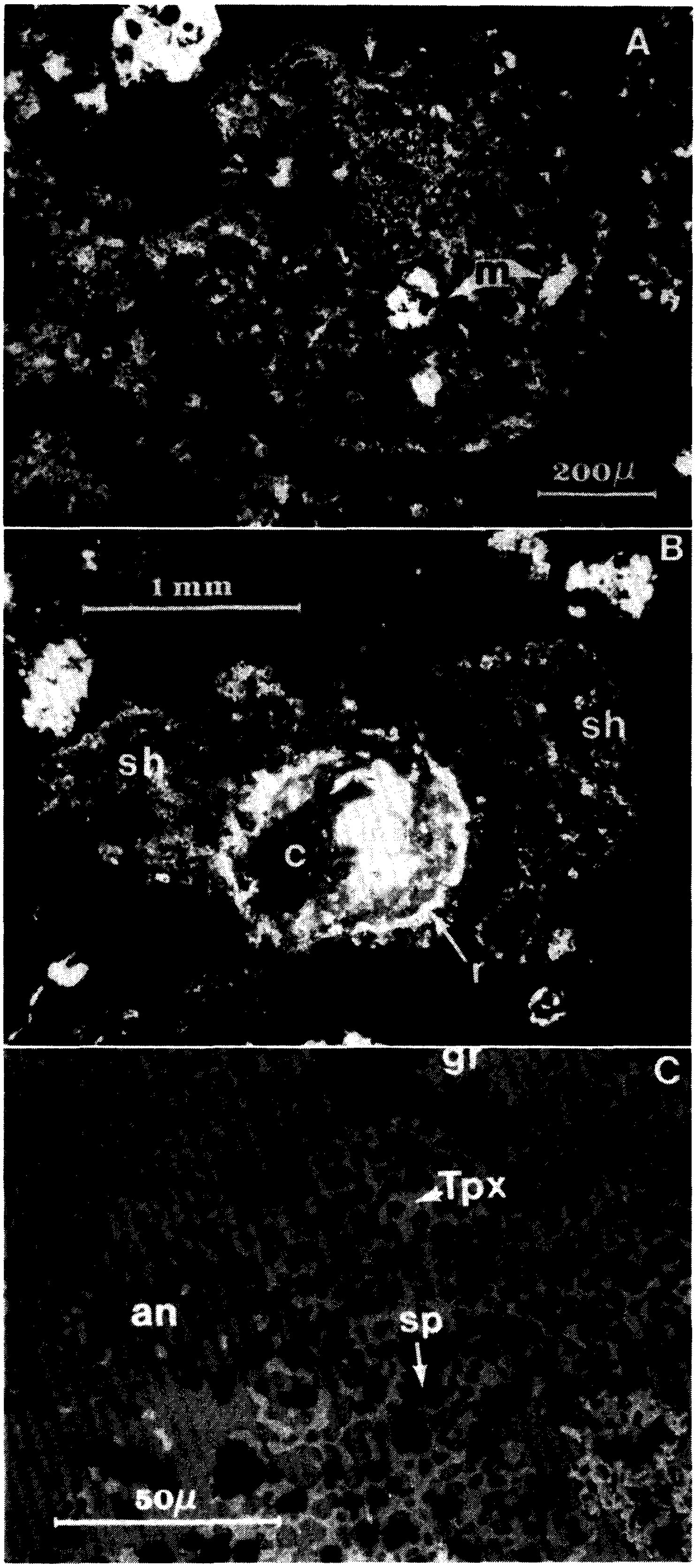

Fig. 6. *Simple CAI's (Type 4 inclusions) in Allende. A, B: transmitted light photomicrographs; C: BSE image. (A) This melilite-rich simple CAI (Type 4A inclusion) has a core of melilite (m) and Ti-Al-pyroxene (gray) that poikilitically enclose spinel, and thin rims (r) of feldspathoids and clinopyroxenes. (B) This unusual object has a rimmed (r) simple CAI in its core (c) that is mantled by an irregular shell (sh) of sulfide-bearing olivine. An oval bubble and epoxy fill an irregular hole in the CAI (bright). (C) Melilite-poor simple CAI's (Type 4B inclusions) have unusual sintered, fine-grained textures; an=anorthite, gr=grossular, sp=Mg-spinel, Tpx=Ti-Al-pyroxene.*

spinel-pyroxene aggregates (BAR-MATTHEWS *et al.*, 1980; MACPHERSON *et al.*, 1983) (Figs. 5B, C).

There are also two mineralogical varieties of simple CAI's (Type 4 inclusions), most of which have been interpreted to be igneous objects (WARK and LOVERING, 1982a; HUTCHEON, 1982). Melilite-rich simple CAI's (Type 4A inclusions) are equivalent to the Type B CAI's of GROSSMAN (1975) and (perhaps) some of the "compact" Type A CAI's of MACPHERSON and GROSSMAN (1979) (Fig. 6A). One Type 4A inclusion observed in Allende is particularly unusual: this composite object consists of a central simple CAI that is mantled by an irregular shell of chondrule-like material (composed principally of granular ferrous olivine and (Fe, Ni)-sulfides) (Fig. 6B). The second variety is melilite-poor (Type 4B inclusions); they are equivalent to the Type I CAI's of GROSSMAN and GANAPATHY (1976a). These simple CAI's consist primarily of fine-grained Al-clinopyroxene + anorthite ± spinel (Fig. 6C). Type 4A inclusions can be characterized as melilite-rich chondrules (MASON and TAYLOR, 1982). Type 4B inclusions can be characterized as "basaltic" chondrules (WLOTZKA and PALME, 1982).

5. Discussion

5.1. Gradational relationships among refractory inclusions

The classification system for refractory inclusions developed by GROSSMAN (1975), GROSSMAN *et al.* (1975), and GROSSMAN and STEELE (1976) emphasizes mineralogical and textural differences between discrete classes of objects. More recently, it has been recognized that many refractory inclusions are composite objects, which grew by incorporating smaller objects and chemically distinct constituents (WARK, 1979, 1980; WARK *et al.*, 1979; WARK and LOVERING, 1977, 1980, 1982b; COHEN, 1981a, b; KORNACKI, 1981a, b; COHEN *et al.*, 1983). Because refractory inclusions are aggregates of three fundamental components, several of the different varieties of inclusions grade into each other chemically, mineralogically, and texturally (KORNACKI, 1983). This can be demonstrated by analyzing one gradational sequence in detail: unrimmed/rimmed olivine aggregates→unrimmed complex CAI's→(spinel-rich) rimmed complex CAI's.

We have observed a continuous gradation in the composition, mineralogy, and textures of irregular, fine-grained refractory inclusions in Allende and Mokoia. Olivine-rich inclusions (Type 1A and Type 1B inclusions) grade into unrimmed complex CAI's (Type 2 inclusions; the "fine-grained" CAI's of GROSSMAN *et al.* (1975)) as the abundance of olivine-rich inclusion matrix decreases and the proportion of spinel-rich concentric objects increases. MCSWEEN (1977b) noted that the bulk chemistry of fine-grained refractory inclusions in CO3 chondrites vary continuously between olivine-normative and spinel + clinopyroxene-normative end members; these are the most abundant minerals in inclusion matrix and concentric objects. The class Type FAO was coined by WARK (1979) for fine-grained Allende inclusions mineralogically intermediate between olivine-rich aggregates (his Type AO) and unrimmed complex CAI's (his Type F). IKEDA (1982) also described refractory inclusions in the ALH-77003 C3 chondrite that are mineralogically intermediate between fine-grained CAI's and olivine-rich inclusions.

Trace-element analyses support this intepretation. Highly-fractionated Group II REE patterns and refractory trace-element depletions (GROSSMAN and GANAPATHY, 1976b; MASON and TAYLOR, 1982) are characteristic of, but are not limited to, "fine-grained" CAI's. GROSSMAN and GANAPATHY (1976b) and GROSSMAN *et al.* (1979) identified olivine-rich inclusions, which they classified as "fractionated AOA's", with these chemical features. GROSSMAN *et al.* (1979) suggested that these inclusions are mixtures of an olivine-rich component (equivalent to our inclusion matrix) and Group II CAI material (equivalent to our spinel-rich concentric objects). The absolute abundance of refractory trace elements in fractionated AOA's is intermediate between those in unfractionated AOA's and fine-grained CAI's, which supports this interpretation.

Some *coarse-grained* CAI's have chemical characteristics that demonstrate their relationship to *fine-grained* CAI's. The bulk composition and Group II REE pattern of a coarse-grained, rimmed complex CAI analyzed by DAVIS *et al.* (1980) are identical to those of fine-grained CAI's (our unrimmed complex CAI's). The simplest interpretation is that the two textural varieties of spinel-rich complex CAI's ("fine-grained" unrimmed CAI's and "coarse-grained" rimmed CAI's) grade into each other as the size and abundance of their constituent concentric objects increase.

5.2. *The nature of "coarse-grained" CAI's*

We have argued that classifying refractory inclusions on the basis of their mineral grain size obscures some fundamental relationships among them. We also note that the term "coarse-grained" is too restrictive to describe many simple CAI's, and inappropriate to describe most melilite-rich complex CAI's (the "fluffy" Type A CAI's of MACPHERSON and GROSSMAN (1979)).

Many simple CAI's are coarse-grained Ca, Al-rich chondrules that cooled relatively slowly (a few °C/hr) (STOLPER *et al.*, 1982; PAQUE and STOLPER, 1983). It seems reasonable that some droplets of CAI composition would have cooled faster than others. Simple CAI's that formed from these droplets would not be coarse-grained: they would have fine-grained, cryptocrystalline, or glassy textures. Inclusions with these textures have been described, but largely because meteoriticists tend to interpret only coarse-grained CAI's as igneous objects, their petrogenesis has been controversial. BLANDER and FUCHS (1975) described fine-grained CAI's that probably crystallized from melts; WARK and LOVERING (1978) described Type I CAI's with "chilled" textures; MARVIN *et al.* (1970) described a glassy CAI. Obviously, none of these objects are coarse-grained inclusions. Because they are segregated from coarse-grained CAI's on the basis of their grain size, possible relationships among them have been obscured and largely ignored (even though they only may have had different thermal histories).

We also suggest that ALLEN *et al.* (1978) and GROSSMAN (1980) describe and classify "fluffy" Type A CAI's as "coarse-grained" on the basis of a *petrological* interpretation, rather than from objective *petrographic* criteria (KORNACKI and COHEN, 1983). CG-11, the only "fluffy" Type A CAI described in detail, contains 77 vol% fine-grained material (ALLEN *et al.*, 1978). It is inaccurate to describe an object in which fine-grained material is three times more abundant than coarse-grained minerals as "coarse-grained". The use of that term is based on the petrological interpretation that coarse-grained melilite has been extensively altered in these inclusions (ALLEN *et al.*, 1978;

MACPHERSON *et al.*, 1981). Petrographical descriptions of CAI's should be based on objective, observable properties of the inclusions, and the simple fact is that most melilite-rich complex CAI's contain fine-grained material in greater abundance than coarse-grained melilite (Fig. 5A). The use of mineral grain size to classify CAI's that contain both coarse- and fine-grained constituents has led to confusion, making inter-laboratory comparisons of melilite-rich complex CAI's difficult (*e.g.*, KORNACKI (1981a, b) and MASON and TAYLOR (1982) describe many "fluffy" Type A CAI's as medium-grained). Melilite-rich complex CAI's can be described as "fluffy", but most of them are simply not coarse-grained.

6. Conclusions

Refractory inclusions in the Allende and Mokoia CV3 chondrites are aggregates containing varying proportions of three fundamental constituents: concentric objects, chaotic material, and inclusion matrix. Concentric objects are rounded objects that have cores of spinel+perovskite and various amounts of the Ca-rich silicates melilite and Ti-Al-pyroxene. They are rimmed by monomineralic bands of (primarily) feldspathoids or a high-Al phyllosilicate (HAP) and clinopyroxene(s). Chaotic material is a fine-grained aggregate of (primarily) Ca-rich silicates. Inclusion matrix is a porous aggregate of ferrous olivine, salitic pyroxene, and feldspathoids or a low-Al phyllosilicate (LAP).

Olivine-rich inclusions consist primarily of inclusion matrix. The two textural varieties are unrimmed and rimmed olivine aggregates (Type 1A and Type 1B inclusions), which grade into each other. Concentric objects form Ca, Al-rich nodules in many Type 1B inclusions. Some olivine-rich inclusions have opaque cores of material similar to meteorite matrix.

CAI's are classified into three varieties on the basis of the size and abundance of their constituent concentric objects. Complex CAI's are aggregates of smaller concentric objects and occur in two textural varieties: unrimmed (Type 2 inclusions) and rimmed (Type 3 inclusions). Simple CAI's (Type 4 inclusions) consist of a single concentric object. Complex and simple CAI's occur in melilite-rich and melilite-poor varieties.

Several varieties of refractory inclusions grade into each other chemically, mineralogically, and texturally. One such gradational sequence is: unrimmed/rimmed olivine aggregates→unrimmed complex CAI's→(spinel-rich) rimmed complex CAI's.

The term "coarse-grained" is too restrictive to describe many simple CAI's, and is used inaccurately to describe most melilite-rich complex CAI's ("fluffy" Type A CAI's). Advantages of our classification system are that it is based on the recognition of the fundamental petrographic constituents of refractory inclusions, not on mineral grain size, and that it uses clearly defined and readily applied petrographic criteria.

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References

ALLEN, J. M., GROSSMAN, L., DAVIS, A. M. and HUTCHEON, I. D. (1978): Mineralogy, textures and mode of formation of a hibonite-bearing Allende inclusion. Proc. Lunar Planet. Sci. Conf. 9th, 1209–1233.

BAR-MATTHEWS, M., MACPHERSON, G. J. and GROSSMAN, L. (1979): An SEM-petrographic study of amoeboid olivine aggregates in Allende. Meteoritics, **14**, 352.

BAR-MATTHEWS, M., MACPHERSON, G. J., GROSSMAN, L., TANAKA, T. and KAWABE, I. (1980): Spinel-pyroxene aggregates in Murchison. Meteoritics, **15**, 262.

BLANDER, M. and FUCHS, L. H. (1975): Calcium-aluminum-rich inclusions in the Allende meteorite; Evidence for a liquid origin. Geochim. Cosmochim. Acta, **39**, 1605–1619.

COHEN, R. E. (1981a): A study of the Mokoia C3(V) carbonaceous chondrite and the origin of CAI's. Lunar and Planetary Science XII. Houston, Lunar Planet. Inst., 163–165.

COHEN, R. E. (1981b): Refractory inclusions in the Mokoia C3(V) carbonaceous chondrite. Meteoritics, **16**, 304.

COHEN, R. E. and KORNACKI, A. S. (1983): Phyllosilicates in refractory inclusions in the Mokoia C3(V) chondrite. Lunar and Planetary Science XIV. Houston, Lunar Planet. Inst., 128–129.

COHEN, R. E., KORNACKI, A. S. and WOOD, J. A. (1983): Mineralogy and petrology of chondrules and inclusions in the Mokoia CV3 chondrite. Geochim. Cosmochim. Acta, **47**, 1739–1757.

DAVIS, A. M., TANAKA, T., GROSSMAN, L., MACPHERSON, G. J. and ALLEN, J. M. (1980): A sinuous inclusion from Allende; Trace element analysis of a rim. Meteoritics, **15**, 279–280.

GROSSMAN, L. (1975): Petrography and mineral chemistry of Ca-rich inclusions in the Allende meteorite. Geochim. Cosmochim. Acta, **39**, 433–454.

GROSSMAN, L. (1980): Refractory inclusions in the Allende meteorite. Ann. Rev. Earth Planet. Sci., **8**, 559–608.

GROSSMAN, L. and GANAPATHY, R. (1976a): Trace elements in the Allende meteorite—I. Coarse-grained, Ca-rich inclusions. Geochim. Cosmochim. Acta, **40**, 331–344.

GROSSMAN, L. and GANAPATHY, R. (1976b): Trace elements in the Allende meteorite—II. Fine-grained, Ca-rich inclusions. Geochim. Cosmochim. Acta, **40**, 967–977.

GROSSMAN, L. and STEELE, I. M. (1976): Amoeboid olivine aggregates in the Allende meteorite. Geochim. Cosmochim. Acta, **40**, 149–155.

GROSSMAN, L., FRULAND, R. M. and MCKAY, D. S. (1975): Scanning electron microscopy of a pink inclusion from the Allende meteorite. Geophys. Res. Lett., **2**, 37–40.

GROSSMAN, L., GANAPATHY, R., METHOT, R. L. and DAVIS, A. M. (1979): Trace elements in the Allende meteorite—IV. Amoeboid olivine aggregates. Geochim. Cosmochim. Acta, **43**, 817–829.

HUTCHEON, I. D. (1982): The Mg isotopic compositions of igneous-textured refractory inclusions from C3 meteorites. Meteoritics, **17**, 230–231.

HUTCHEON, I. D. and STEELE, I. M. (1982): Refractory inclusions in the Adelaide carbonaceous chondrite. Lunar and Planetary Science XIII. Houston, Lunar Planet. Inst., 352–353.

IKEDA, Y. (1982): Petrology of the ALH-77003 chondrite (C3). Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 34–65.

KORINA, M. I., NAZAROV, M. A. and ULYANOV, A. A. (1982): Efremovka CAI's; Composition and origin of rims. Lunar and Planetary Science XIII. Houston, Lunar Planet. Inst., 399–400.

KORNACKI, A. S. (1981a): Are CAI's condensates or distillation residues? Evidence from a comprehensive survey of fine- to medium-grained inclusions in the Allende meteorite. Lunar and Planetary Science XII. Houston, Lunar Planet. Inst., 562–564.

KORNACKI, A. S. (1981b): Are CAI's condensates or distillation residues? Evidence from a comprehensive survey of fine- to medium-grained inclusions in the Allende meteorite. Meteoritics, **16**, 341–342.

KORNACKI, A. S. (1982): The origin of inclusion and meteorite matrix in the Allende C3(V) chon-

drite. Meteoritics, **17**, 236–237.
KORNACKI, A. S. (1983): Geochemical, mineralogical, and textural relationships among Allende refractory inclusions and olivine chondrules. Lunar and Planetary Science XIV. Houston, Lunar Planet. Inst., 391–392.
KORNACKI, A. S. and COHEN, R. E. (1983): The nature of "coarse-grained" CAI's. Lunar and Planetary Science **XIV**. Houston, Lunar Planet. Inst., 395–396.
MACPHERSON, G. J. and GROSSMAN, L. (1979): Melted and non-melted coarse-grained Ca-, Al-rich inclusions in Allende. Meteoritics, **14**, 479–480.
MACPHERSON, G. J. and GROSSMAN, L. (1982): Fine-grained spinel-rich and hibonite-rich Allende inclusions. Meteoritics, **17**, 245–246.
MACPHERSON, G. J., GROSSMAN, L., ALLEN, J. M. and BECKETT, J. R. (1981): Origin of rims on coarse-grained inclusions in the Allende meteorite. Proc. Lunar Planet. Sci. Conf. 12B, 1079–1091.
MACPHERSON, G. J., BAR-MATTHEWS, M., TANAKA, T., OLSEN, E. and GROSSMAN, L. (1983): Refractory inclusions in the Murchison meteorite. Geochim. Cosmochim. Acta, **47**, 823–839.
MARVIN, U. B., WOOD, J. A. and DICKEY, J. S., Jr. (1970): Ca-Al rich phases in the Allende meteorite. Earth Planet. Sci. Lett., **7**, 346–350.
MASON, B. and MARTIN, P. M. (1977): Geochemical differences among components of the Allende meteorite. Smithson. Contrib. Earth Sci., **19**, 84–95.
MASON, B. and TAYLOR, S. R. (1982): Inclusions in the Allende meteorite. Smithson. Contrib. Earth Sci., **25**, 30p.
MCSWEEN, H. Y., Jr. (1977a): Petrographic variations among carbonaceous chondrites of the Vigarano type. Geochim. Cosmochim. Acta, **41**, 1777–1790.
MCSWEEN, H. Y., Jr. (1977b): Chemical and petrographic constraints on the origin of chondrules and inclusions in carbonaceous chondrites. Geochim. Cosmochim. Acta, **41**, 1843–1860.
PAQUE, J. M. and STOLPER, E. (1983): Experimental evidence for slow cooling of Type B CAIs from a partially molten state. Lunar and Planetary Science, XIV. Houston, Lunar Planet. Inst., 596–597.
STOLPER, E., PAQUE, J. and ROSSMAN, G.R. (1982): The influence of oxygen fugacity and cooling rate on the crystallization of Ca-Al-rich inclusions from Allende. Lunar and Planetary Science XIII. Houston, Lunar Planet. Inst., 772–773.
WARK, D. A. (1979): Birth of the presolar nebula; The sequence of condensation revealed in the Allende meteorite. Astrophys. Space Sci., **65**, 275–295.
WARK, D. A. (1980): Allende CAI 3643—A layered record of protosolar nebula condensation. Lunar and Planetary Science XI. Houston, Lunar Planet. Inst., 1202–1204.
WARK, D. A. and LOVERING, J. F. (1977): Marker events in the early evolution of the solar system; Evidence from rims on Ca-Al-rich inclusions in carbonaceous chondrites. Proc. Lunar. Sci. Conf. 8th, 95–112.
WARK, D. A. and LOVERING, J. F. (1978): Classification of Allende coarse-grained Ca-Al-rich inclusions. Lunar and Planetary Science IX. Houston, Lunar Planet. Inst., 1211–1213.
WARK, D. A. and LOVERING, J. F. (1980): More early solar system stratigraphy; Coarse-grained CAI's. Lunar and Planetary Science XI. Houston, Lunar Planet. Inst., 1208–1210.
WARK, D. A. and LOVERING, J. F. (1982a): The nature and origin of type Bl and B2 Ca-Al-rich inclusions in the Allende meteorite. Geochim. Cosmochim. Acta, **46**, 2581–2594.
WARK, D. A. and LOVERING, J. F. (1982b): Evolution of Ca-Al-rich bodies in the earliest solar system; Growth by incorporation. Geochim. Cosmochim. Acta, **46**, 2595–2607.
WARK, D. A., WASSERBURG, G. J. and LOVERING, J. F. (1979): Structural features of some Allende coarse-grained Ca-Al-rich inclusions; Chondrules within chondrules? Lunar and Planetary Science X. Houston, Lunar Planet. Inst., 1292–1294.
WLOTZKA, F. and PALME, H. (1982): A refractory-rich "basaltic" chondrule from Ornans. Abstract Volume, Conference on Chondrules and their Origins. Houston, Lunar Planet. Inst., 62.

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