Significance of Ca-Al-rich silicate melt inclusions in olivine crystals from the Murchison type II carbonaceous chondrite

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Abstract. — The Murchison chondrite meteorite has been studied extensively. It consists of olivine-pyroxene aggregates and isolated crystals, which formed at high temperatures, in a hydrous, carbonaceous matrix, mainly layer lattice silicates, which formed at low temperatures. The olivine crystals contain Ca-Al-silicate melt inclusions. Several workers (Fuchs, Grossman, Olsen, and others) have proposed that the melt inclusions represent globules of melt formed by direct (metastable?) condensation from the solar nebula; they further have proposed that the globules were subsequently enclosed, while still viscous, by olivine crystals growing from a vapor phase (mainly hydrogen) at about 1170 °C and ≤ 10^{-3} atm. My studies of the inclusions indicate that this theory is incorrect, and that the inclusions and the olivine formed from a gas-bearing melt. The evidence is as follows: 1) glass (now phyllosilicatate) coats the outer faces of some sharply euhedral olivines; 2) pseudosecondary planes of troilit tell, glass and «vapor» inclusions are found in olivine; and 3) several ~ 300 μm iron-rich olivines were found that have thick, almost inclusion-free rims and sharply defined, more magnesian cores that are densely and uniformly crowded (~ 5 × 10^{10} cm^{-2}) with < 1 μm, mainly «vapor»-rich inclusions. These observations, and the lines of evidence presented by other workers, are most compatible with a relatively high temperature, two-stage formation of the olivine crystals from a gas-bearing, olivine-rich silicate melt containing some Ca and Al, rather than from a vapor phase.

Key words: inclusions, olivine, Murchison, carbonaceous chondrite, meteorite.

Sur la signification des inclusions fondues silicatees riches en Ca-Al dans les cristaux d'olivine de la chondrite carbonatée de Murchison type II.

Résulté. — La chondrite de Murchison est constituée d'agrégats et de cristaux isolés d'olivine et de pyroxène formés à haute température, inclus dans une matrice hydratée et carbonée formée surtout de phyllosilicates de base température. Les cristaux d'olivine contiennent des inclusions vitreuses de silicates alumino-calciques. Plusieurs auteurs (Fuchs, Grossman, Olsen, etc...) ont proposé que ces inclusions représentent les globules fondues formés par condensation directe (metastable?) de la nébuleuse solaire; les gouttes seraient ensuite englobées en veux visqueuses, par des cristaux d'olivine croissant à partir d'une phase vapeur (surtout hydrigène) vers 1170 °C et sous pression de ≤ 10^{-3} atm. Les observations suivantes suggèrent une cristallisation de l'olivine à partir d'un bain fondu contenant des gaz. 1) Présence de verre (maintenant phyllosilicates) couvrant les faces externes de cristaux euhédéraux. 2) Présence de plans pseudo-secondaires riches en inclusions de troilit, verre, «vapeur», dans l'olivine. 3) Présence de cristaux d'olivine riche en fer de 300 μm ayant une bordure nette d'épauvée d'inclusions et un cœur plus magnésien uniformément bougré (~ 5 × 10^{10} cm^{-2}) de fines (< 1 μm) inclusions « gazeuses ». Ces observations, jointes à d'autres, sont compatibles avec une histoire de cristallisation en deux étapes, à température relativement élevée, l'olivine croissant d'un bain silicaté plutôt que d'une phase vapeur.

Mots clés: inclusions, dolivine, Murchison, chondrite carbonatée, météorite.

INTRODUCTION AND NATURE OF THE PROBLEM

The Murchison meteorite was studied in detail by Fuchs et al. (1973), and has been the subject of considerable study and debate since (e.g., see Beckett et al., 1979; Grossman and Olsen, 1974; Jarosevich, 1971; Macdougall, 1979; McSween, 1977; Olsen and Grossman, 1978; Richardson and McSween, 1978). Murchison consists of two quite different materials: dispersed, light-colored particles (diameters ≤ 4.5 mm) of a relatively coarse-grained crystalline fraction over a range of high temperatures, and a very fine grained matrix formed at low temperatures. The matrix is a black, hydrous, carbonaceous material consisting mostly of hydrous layer lattice silicates (phyllosilicates) high in Mg and Fe, plus calcite, whewellite, gypsum, and a poorly defined sulfide phase. The low-temperature part of the sequence of environments or events that yielded this obvious bimodal distribution is itself a question of considerable consequence in understanding the origin of the solar system, but will not be addressed here. This paper deals only with the origin of certain parts of the high-temperature fraction.

Although Murchison is classed as a chondrite, it contains very few chondrules. Grossman and Olsen (1974) report that chondrules, which they define as «... objects containing the following unambiguous evidence of being the solidification products of rapidly-quenched molten droplets; interstitial glass and/or barred and/or radial crystalline textures»
condensation versus a melt origin of similar olivines in other C2 chondrites have been put forward in several other papers. Thus Desnoyers (1980) concluded that the olivines in the similar Niger I C2 meteorite formed by crystallization from a melt, but as I have examined only Murchison, my remarks are limited to it.

NATURE OF THE INCLUSIONS AND THEIR HOSTS

Host olivine.

Published studies of the Murchison meteorite show that the olivine crystals in it consist of several different populations, based on textural features or composition. The isolated grains of olivine exhibit a strong mode near pure forsterite (Fa < 1), but about 2/3 of the grains have fayalite contents spread rather uniformly over the range Fa 8-60 (Fuchs et al., 1973) (*). Some of the fayalitic olivines are normally zoned, with forsterite-rich cores, but some have reverse zoning with more fayalite-rich cores. Onuma et al. (1972) suggested on the basis of oxygen isotope work that there is no direct genetic relationship between the high-Fe and low-Fe olivines. Although many of the isolated olivine grains are broken fragments, a few are sharply euhedral; they break away from the soft matrix easily, and the euhedral facets appear slightly frosted.

Fuchs et al. (1973) reported a similar range of compositions for the olivine grains in the white inclusions and in the true chondrules, although most such olivines range from Fa 1 to 5. They also reported a few large (≤ 13 mm) xenolithic fragments. Most of these are of C3-chondrite type, again with the same range of olivine compositions (but with the mode at Fa 5-10) and one 1.2 mm fragment is of an "unknown meteorite type" (see below).

McSween (1977) classified the chondrules in the carbonaceous chondrites (including Murchison) into types I and II. The olivines in type I are subhedral to anhedral, homogeneous, forsterite-rich (Fa 0-9) grains in which FeO is negatively correlated CaO. Type II chondrules contain euhedral, porphyritic, zoned, more fayalite-rich olivines (Fa 12-36) in which FeO is positively correlated with CaO and MnO. The host chondrules also have specific differences in gross composition. Fuchs et al. (1973) also reported a positive correlation of FeO with CaO in zoned olivines, but found no correlation between CaO and fayalite content for the homogeneous grains. Hutchinson and Symes (1972) found no correlation between CaO and FeO in 140 analyses of 49 of the larger olivine grains in Murchison, but did note such a correlation on a few zoned crystals, in which the Fe-rich zones had a higher Ca content.

(*) At least one grain of Fa 85 was found, but apparently Fa 60 is the most fayalitic olivine normally found.
Beckett et al. (1979) found an overall bimodal distribution of compositions for grains in white inclusions (« aggregates »), and in isolated crystals (« matrix grains »): most show a sharp peak at Fa 0-1, and a smaller number of grains peak at ~ Fa 35. From these studies, and studies of the compositions of pyroxenes, they suggest that both white inclusions and isolated crystals come « from the same population » (sic), but that there must be different sources for this population.

Olsen and Grossman (1978) reported numerous measurements of the mean diameter of the various types of olivine grains. Most of those in true chondrules ranged from 5 to 25 μm, with a very strong maximum at 15 μm; most of the isolated anhedral grains ranged from 5 to 50 μm; the grains from aggregates were similar to the foregoing; and the relatively few isolated euhedral grains were larger still, with a maximum at 80 μm, and one > 1 mm. The true chondrules themselves were mainly 300-400 μm in diameter.

I wish to add two additional relatively rare but possibly significant categories to the above list of olivine populations: 1) olivine grains with inclusion-rich cores (see section entitled « Nature of the inclusions and their hosts »); and 2) densely packed, euhedral olivine crystals in porphyritic xenoliths (lithic fragments). Two of these xenoliths are shown in figures 13 and 14, and other presumably similar but smaller fragments were also recognized in the several slides of Murchison examined (e.g., figure 17). Most of these euhedral olivine grains are in the same size range as that found by Olsen and Grossman (1978) for isolated euhedral olivine crystals, 25-500 μm. The matrix for the olivine phenocrysts in both fragments is a dark yellow-brown material, presumed to have formerly been glass, now altered to phyllosilicates. It is thus very different from the phyllosilicate-rich but almost opaque general matrix for the fragments in this meteorite — see figures 13, 14, and 17. Several sprays of dark acicular crystals and a few sharp octahedra of greenishbrown spinel (20-30 μm) are also found between the olivine euhedra. These xenoliths are similar to the single 1.2 mm « unknown meteorite type » fragment reported by Fuchs et al. (1973). They describe the olivines in this fragment as « ... blocky, jointed pieces (some subhedral crystals) of pure forsterite set in a matrix of glass, with traces of troilite, metal, and euhedral chrome. The glass is partially devitrified into a dendritic pattern of submicron needles ». (p. 27). However, the photographs (their figure 17) show what appears to be sharply euhedral crystals of olivine, and hence are very similar to porphyritic xenoliths described above.

**Magmatic inclusion compositions**

This term is used to cover all types of inclusions of former fluids within crystals formed during magmatic processes (Roedder, 1979). Although it thus has a genetic connotation, it is used here for want of a better term. « Silicate melt inclusions » is an inadequate term in view of the range of phase compositions involved in individual inclusions. This range includes Ca-Al silicate melt (now glass), Fe metal (plus minor Ni), Fe sulfide (presumably troilite), and « vapor ». In addition, sharp octahedral crystals of spinel are present as inclusions. Individual inclusions may consist of only one, or of a wide range of ratios of these five very different composition materials.

**Ca-Al silicate melt inclusions.**

Fuchs et al. (1973) reported the presence of many glass inclusions, as much as 36 μm diameter, in olivine from Murchison. These inclusions consist of clear, colorless glass, plus a « vapor » bubble that occupies 0-14% of the individual inclusion. Some melt inclusions contained a sharp octahedron of spinel crystals from olivine-spinel white inclusions to 2.6% Cr₂O₃ and 0.6% FeO. In contrast, other spinel crystals from olivine-spinel white inclusions contain as much as 25% Cr₂O₃ and 11% FeO. Most melt inclusions contain no spinel, however, and no significant differences were found in the glass compositions of those with and without spinel. Some isolated spinel octahedra are embedded in olivine, without glass. Fuchs et al. (1973, p. 15) also reported that some silicate inclusions contain spherules of Fe metal or Fe sulfide, and that the interior walls of some « vapor » bubbles were « ... lined with an iron sulfide (presumably troilite) ».

The average composition of the 14 glass inclusions analyzed by Fuchs et al. (1973) is: SiO₂, 52.1; CaO 18.1, Al₂O₃ 21.6, FeO 1.3, MgO 4.2, MnO 0.03, K₂O 0.05, Na₂O 0.3, TiO₂ 0.8, Cr₂O₃ 0.2, sum 98.7. The CIPW norm for such a composition is ~ 60 wt. % anorthite, 27% diopside, and 13% quartz. With few exceptions, the compositions deviate little from this average. The largest variation was in FeO content; the average for 11 inclusions in Fa 0-1 host olivine was 0.17% and that for the other 3, all of which were in more Fayalitic olivine, was 5.3% FeO. Silicate inclusions having a very similar range in composition have been reported from the Niger I C2 meteorite (Desnoyers, 1980).

**Metal inclusions.**

Many olivine crystals contain one or more nearly spherical blebs of metal, and some contain many, mostly in the range of 5-10 μm diameter (Figure 10). All gradations exist between pure silicate melt and pure metal inclusions (Figure 8), and some silicate melt has apparently been trapped as the host olivine crystal grew around one or more metal blebs (Figures 9 and 10).

Fuchs et al. (1973) report unusually high Cr and P contents in metal from Murchison, 0.20-0.96 wt. % and 0.28-0.37 wt. % respectively. They indicate that they analyzed grains from within olivines both from white inclusions and true chondrules as well as isolated metal grains, and found no systematic chemical differences from these three sites (p. 9). Their Ni content ranges from 4.0 to 7.4 %, Co from 0.32 to 0.74, and Si, Mn and Cu were below detection limits (~ 0.05%).
Iron sulfide inclusions.

An Fe sulfide phase (presumably troilite) forms numerous opaque spherical inclusions in olivine, either isolated or within silicate melt inclusions (Figures 11, 12, 16). Only a few of these in the samples studied were accessible and large enough for electron microprobe examination; they showed major Fe and S only, plus minor Ni. I do not know how many of the other opaque spherules found in these olivines are Fe sulfide and how many are Fe metal, but the latter is probably much more abundant on the basis of those that are accessible to analysis. Fuchs et al. (1973) report spherules of Fe metal and of Fe sulfide in silicate melt inclusions, but do not indicate the relative abundances.

« Vapor » inclusions.

Many larger silicate melt inclusions contain large « vapor » bubbles, as large as 75 vol. % and other smaller inclusions appear to be 100 % « vapor ». This appearance of 100 % « vapor » may not be real, as the presence of a film of silicate melt lining the walls, even though constituting 25 vol. % would be difficult to see in small (2-3 μm) inclusions (Roedder, 1972, p. 14). A bubble formed by shrinkage on cooling of a silicate melt in an olivine bottle would be essentially a vacuum, but such a bubble would appear visually identical to a bubble with gas under pressure, so a series of inclusion bearing grains were crushed in oil on the crushing stage (Roedder, 1970). All were found to contain a vacuum, i.e., < 10⁹ molecules of non-condensable gas (Figures 18 and 19).

Magmatic inclusion occurrence.

The inclusions found in Murchison olivines fall in all three classes of inclusion origin: primary, pseudosecondary, and secondary. Primary inclusions represent material that is trapped by the growing crystal. Secondary inclusions represent fluids trapped as a result of rehealing of a fracture in a preexisting crystal; they may form at any time after the original crystallization. Pseudo-secondary inclusions form by the same processes of rehealing of a fracture in a preexisting crystal, but during the growth of the enclosing crystal, so that the healed fracture becomes covered with an additional layer of unfractured material. Most of the inclusions studied here are primary, as are most inclusions in meteoritic minerals, but planes of secondary and pseudosecondary inclusions are present in many grains (Figures 3, 11, and 12).

It would be of interest if certain types of inclusions were limited to certain populations of olivine, but the samples are inadequate to detect any correlation. Most special types of inclusions were rare, and hence the sampling was too limited to be certain as to what combinations of inclusion and host olivine do or do not occur.

Note: All are of samples from Murchison, in plain transmitted light except as noted. Scale bar dimensions given in μm.

Fig. 1. — Cored, rounded olivine grain from USNM 5347 mounted in index oil. See figures 2 and 3.

Fig. 2. — Polished section through cored olivine grain shown in figure 1. Core contains many inclusions of several types (see figure 3 for enlargement of central area). The diagonal line outlined by tiny primary inclusions (both spinel-rich and « vapor »-rich) near the core is a former crystal growth face. Large opaque inclusion in outer part is Ni-bearing Fe sulfide.

Fig. 3. — Detail from figure 2. Many of the smaller primary inclusions are silicate glass with a small (5-10 vol. %) vapor bubble (dark), but the larger inclusions are essentially all vapor, with a coating of glass that actually may amount to 25-30 wt. %. Some also have an opaque spherule (arrow). A plane of tiny pseudosecondary inclusions crosses the upper left corner.

Fig. 4. — Cored, roughly euhedral olivine grain from USNM 5347 viewed in strong lateral incident light plus a small amount of transmitted light (to show exterior grain outline). See figure 5.

Fig. 5. — Section through grain in figure 4, showing inclusion-free rim and inclusion-rich core. The core contains 1-2 vol. % of primary inclusions, mostly below 1 μm, spaced at ~ 2 μm intervals throughout, except in the « halos » near the larger inclusions. See figures 6 and 7.

Fig. 6. — Detail of one 9-μm inclusion from figure 5, showing ~ 65 vol. % vapor (dark, lower left), 2 % opaque spherule (probably sulfide), glass (clear, upper right), and inclusion-free halo. Some other smaller inclusions (arrow) have only 5-10 vol. % vapor. (Note — Although this particular inclusion is not at the surface, the polished surface intersects three other similar opaque spherules; all three were Fe sulfide with significant Ni. Two were in the core and one was in the rim.)

Fig. 7. — Detail of one 15-μm inclusion at edge of core in figure 5, showing ~ 45 vol. % vapor (dark, upper part), 52 % glass (clear), 3 % opaque spherule, and a pronounced inclusion-free halo in the surrounding cloud of tiny primary inclusions.

Fig. 8. — Four inclusions from isolated olivine crystals in USNM 5347, showing a wide range of ratios of glass (clear) to opaque spherule. Each has a dark shrinkage bubble as well. Figure 8a has no opaque spherule, only glass and a bubble estimated to be ~ 4 vol. %; figure 8b has ~ 40 vol. % opaque spherule and ~ 8 vol. % vapor; figure 8c has ~ 70 vol. % opaque spherule; and figure 8d has perhaps 90 % opaque spherule.

Fig. 9. — Pair of opaque spherules in USNM 5347, connected with a fillet of glass.

Fig. 10. — Isolated olivine grain from USNM 5377 with many opaque spherules of Fe metal, some with attached glass. Inclusion A contains a spinel crystal as well (see inset). Silicate melt in inclusion B seems to have been trapped as the crystal grew from right to left and surrounded the Fe metal spherule (see dark matrix at left, and inset at top, taken at a different plane of focus).
not occur. Thus only a few grains of olivine were found each of which contained a number of inclusions that had a regular ratio of silicate:« vapor »: sulfide (7) globule (e.g., figure 16). Another similar 252 μm grain in USNM 5347 contained 12 inclusions, each with ~ 23 vol. % « vapor » and 1-3 vol. % sulfide (?). Similarly, relatively few Fe sulfide inclusions were verified as such, but many others are believed to be Fe sulfide, even though very small.

Olivine crystals from true chondrules contain abundant but small silicate melt inclusions containing small « vapor » bubbles and uniform phase proportions (~ 15 vol. % « vapor » and 5 vol. % sulfide(?)), bleb; figure 20), and occasional metal inclusions. No « vapor »-rich (>= 15 %) inclusions were seen. The other three types of olivine occurrence, in white inclusions, as isolated grains, and in porphyritic xenoliths, all have inclusions of silicate melt, of metal, of sulfide(?), and of « vapor ». The sizes and abundances of these inclusion types vary widely from grain to grain, and the abundance of secondary or pseudosecondary inclusions varies (predictably) with the presence of fractures. Many grains, particularly the smaller ones, have no such fractures. The glass in glass inclusions within olivine crystals is completely clear and free of alteration, even though presumably equivalent glass just a few micrometers away is now a mass of phyllosilicates (Figures 13, 14, 17, and 20).

The most striking variations in inclusion concentration occur within single cored olivine grains. A number of these were handpicked from a sample of Murchison, and others were found in prepared sections. Most were isolated, Fe-rich olivine crystals ~ 0.3 mm in diameter (e.g., figures 1-7), but a similar grain was found in one of the porphyritic xenoliths (Figure 15). These cored olivines consist of a central core (~15-20 vol. %) that is densely and uniformly crowded with tiny, mostly « vapor »-rich inclusions, and a thick, almost inclusion-free rim (~80-85 vol. %). The rims have ~ 5-20 % more fayalite component than the cores. The core is sharply defined, with a crystallographically controlled outer shape; the interface with the rim is sometimes decorated with inclusions of both spinel and « vapor »-rich types. Most of the inclusions in the core are < 1 μm (many are ~ 0.4 μm), but their numbers are so large (e.g., ~ 5 x 10^16 cm^-3) that they constitute 1-2 vol. %. A very few larger inclusions are scattered through this « cloud » (e.g., figures 5-7) with an inclusion-free halo surrounding each. The contents of the smaller inclusions can only be estimated crudely, but most seem to be « vapor » filled. Almost all larger inclusions (10-15 μm diameter) have ~ 25-50 vol. % glass, « vapor » bubble (~ 50-80 vol. %), a brownish octahedron (spinel ?) of ~ 5 vol. % and an opaque sulfide(?) spherule (2-3 vol. %). As the latter two phases are rather regular in occurrence and volume percent, I believe that they

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**Fig. 11.** Isolated olivine grain in USNM 5377 showing planes of 0.5-1 μm pseudosecondary inclusions of mainly Ni-bearing FeS (verified by electron microprobe), but also including some « vapor » and some silicate glass, that formed when the olivine crystal fractured during its growth. After trapping of these inclusions, the crystal grew an additional, unfractured layer (the rim, see arrow) that is optically continuous with the core but slightly higher in fayalite. For a detail of a similar plane in another grain, see figure 12.

**Fig. 12.** Planes of small inclusions (probably pseudosecondary) of « vapor », sulfide and silicate melt in an isolated olivine crystal in USNM 5347, plus a few larger inclusions that may be primary.

**Fig. 13 and Fig. 14.** Porphyritic xenolithic fragments consisting of euhedral pyroxenes and olivines (with melt inclusions) in a yellow-brown matrix (presumed to have formerly been glass, now altered to phyllosilicate), containing a few sprays of dark accicular crystals (from devitrification ?) and several sharply euhedral greenish-brown spinel octahedra (black arrows). Note that the matrix within the fragments (white arrows) is translucent, whereas that outside is opaque. Sample USNM 5294; partly crossed polarizers.

**Fig. 15.** Detail on one crystal from figure 14, showing high concentration of primary inclusions in core of crystal. Four types of inclusions are present: « vapor », sharply euhedral green spinel octahedra, opaque spherules (Fe metal (?), and glass with small « vapor » bubble and a small (~ 2 vol. %) opaque spherule. Intermediate mixtures of these types are also present.

**Fig. 16.** Primary inclusion in isolated olivine grain from USNM 5347 containing ~ 32 vol. % « vapor » and ~ 25 % opaque spherule, presumably Fe sulfide, in glass (clear). This is one of 5 inclusions in the grain, each with the same phase ratio, within the precision of the measurement. This volume of « vapor » cannot be from shrinkage alone; it indicates that there has been considerable crystallization of olivine on the walls after trapping.

**Fig. 17.** Isolated euhedral olivine crystal from USNM 5294, with adhering glass, now a yellow mixture of layer lattice silicates. An unaltered clear glass primary inclusion is present but at a different level of focus (arrow). Another crystal is present in the same fragment (at the top, near the point). This fragment is essentially identical with the larger porphyritic xenolith fragments (Figures 13 and 14).

**Fig. 18 and Fig. 19.** Primary silicate melt inclusions in isolated olivine grains from USNM 5347, mounted in matching index oil (n ~ 1.64) on the crushing stage. Upper pictures, before crushing; lower pictures, after crushing. The dark « vapor » bubbles in three glass + « vapor » inclusions in figure 18 and in one inclusion consisting of glass (clear) + « vapor » (dark gray) + two opaque spherules in figure 19 all filled instantly and completely with oil, indicating that they contained no detectable non-condensable gas (i.e., < 10^8 molecules).

**Fig. 20.** Fragment of barred olivine chondrule from USNM 5347e. Numerous silicate melt inclusions consisting of clear glass, with ~ 15 vol. % « vapor » and 5 vol. % opaque bleb, presumably sulfide (see arrow on inset, which is an enlarged photograph of circled area), occur within the laths. The former glass between the laths is now a mass of light yellow-brown phyllosilicates, much more translucent than the essentially opaque matrix for the whole grain. Crossed polar.
are daughter phases, formed from the trapped melt and not accidentally trapped phases. Each such cored olivine contains at least some silicate melt inclusions with only small bubbles (≈ 5 vol. %, e.g., figure 3), and some of the cores are cut by planes of pseudosecondary inclusions of sulfide, silicate melt, or vapor (Figure 11).

**Lines of evidence for and against formation of the inclusions and their olivine hosts by condensation or by melt/crystal processes**

I believe that the available evidence, from my own work and that already published by others, favors formation of the host olivines (and their silicate melt inclusions) by crystallization from a gas-bearing melt, rather than by condensation from a vapor. The various lines of evidence for and against these two hypotheses are discussed below.

**Evidence for formation by condensation, with rebuttals.**

1. The Ca/Al weight ratio of the glass inclusions is 1.13, nearly that of 1.09 for all chondrites and basaltic achondrites, and hence represents primitive solid matter in the solar system, and not a magmatic differentiate (Fuchs et al., 1973, pp. 15 and 32).

**Rebuttal.**

Because the major crystalline phases that should separate early from melted solar system material are olivine and smaller amounts of Ca-poor pyroxene, the Ca/Al ratio in the residual liquid *should* stay the same as that of the bulk material.

2. Single and relatively large olivine crystals in the matrix are not associated with any other adhering crystalline material. Such a meteorite is unknown (Fuchs et al., 1973, p. 17).

**Rebuttal.**

If olivine is the major phase to crystallize from a meteoritic melt, as their bulk compositions indicate, a simple quenching before crystallization of the second phase would explain the observation. Furthermore, the «unknown meteorite type» found as a xenolithic fragment in Murchison (Fuchs et al., 1973, p. 27 and their figure 17) is a perfect example. If that had been quenched slightly faster, to avoid the dendritic crystals in the glass, and was subsequently disaggregated, it could yield the isolated olivine grains of Murchison, and particularly one such as my figure 17. Even if another phase such as chromite were present as separate crystals, disaggregation could easily cause separation.

3. «Most, if not all, of the components of C2s must have condensed from primordial matter. Thus, their silicates and metal must have been closely associated with a condensation process and not with a fractionating magma.» (Fuchs et al., 1973, p. 17).

**Rebuttal.**

This somewhat circular argument is cited by Fuchs et al. (1973) as one of the four «major difficulties» with a melt/crystal origin. Crystal fractionation, forming specific phases with individual compositions not equal to that of the whole system, can occur either in a condensing vapor or in a crystallizing liquid. The compositional differences between olivine and melt inclusion could be examples of either.

4. «The euclidian morphology... of many of the forsterite crystals suggests condensation from a vapor phase» (Fuchs et al., 1973, p. 32).

**Rebuttal.**

Beautifully euclidian olivines also grow from liquid in many terrestrial lavas and experimental runs; in fact olivine is usually sharply euclidian. During disaggregation, these crystals frequently break free of adhering glass along the glass/crystal interface, as is seen in many terrestrial volcanic sands. Olsen and Grossman (1974, p. 246-247) and Richardson and McSween (1978, figures 4 and 5) illustrate crystal faces on phenocrysts of olivine that have broken free of silicate matrix. Richardson and McSween (1978) propose alteration of mesostasis glass to friable «spinach phase» phyllosilicates as a mechanism by which euclidian olivines can be more readily separated from porphyritic chondrules, although Olsen and Grossman (1978, p. 12) claim this alteration does not cause weakening. The phyllosilicates in Murchison are obviously much poorer bonding agents than silicate glass.

5. Metallic Fe spheres are common as inclusions in the olivines of C2 chondrites, including Murchison (Fuchs et al., 1973; Olsen and Grossman, 1978). Analyses of metal grains from such meteorites show amounts of Ni, Co, Cr, and P compatible with condensation of metal at temperatures comparable with those at which forsterite condenses (1473° versus 1444 K; Grossman, 1972). The Cr content, in particular, is exceptionally high. «In fact, no other process has been proposed to account for the composition of these metal grains» (Olsen and Grossman, 1978, p. 123).

**Rebuttal.**

This is permissive evidence only, as such metallic Fe can form by a variety of processes. Most meteoritic metal analyses do not show the amounts of Cr and P found here (0.96 and 0.37 wt. %, maxima, respectively), and many show only trace Cr, but few analysts have looked for these elements. Unfortunately, the specific nature of the «metal grains» analyzed (e.g., in matrix or in forsterite) is not always stated. Wai and Wass (1970) reported as much as 0.26 wt. % Cr in metal from Nedaogola, and Richardson and McSween (1978) found only 0.35 wt. % in metal from Murchison. When analyzed for Cr, the metal grains in basaltic rocks from the moon not infrequently show significant amounts (0.2-0.4 wt. %). El Goresy et al. (1971) report 0.55-
700 K. (However, that for troilite would presumably drop as well.)

4. Fuchs et al. (1973) and Grossman and Olsen (1974) proposed that the anorthite-rich Ca-Al silicate melt blebs condensed at ~ 1350 °C (and forsterite at 170 °C), but Grossman (1972) shows that anorthite condenses at 1089 °C.

5. The reverse zoned olivines are difficult to explain by a condensation process.

6. To use the words that Fuchs et al. (1973, p. 32) applied to the melt/crystal theory of origin of the silicate melt inclusions, the condensation hypothesis seems to require «complicated, highly contrived conditions». Examples include the suggestion of large pressure drops (5-6 orders of magnitude) between condensation of the Ca-Al globules and condensation of the host forsterite, and 200 °C of metastable supercooking before nucleation of melt droplets.

7. The presence of round «vapor» inclusions in the olivine are difficult to explain. If the olivine grew from a vapor phase, and trapped portions of this vapor by some irregularities in growth, the cavities would normally be lined with crystal facets, as is common in many crystals grown from the vapor phase in both the laboratory and industry.

8. The apparent wetting phenomena between glass, olivine, and vapor are difficult to explain. Fuchs et al. (1973), Grossman and Olsen (1974) and Olsen and Grossman (1978) suggest that the glass inclusions (i.e., those having a small «vapor» phase) are round because they are condensed droplets that adhered to the growing olivine crystal surface and were enclosed with little change in shape. This would require that the melt did not wet the crystal (i.e., the contact angle was ~ 180°), yet the many melt inclusions with a small amount of melt and a large amount of «vapor» consistently show the melt wetting the olivine, thus forming a thin film over the inside of the cavity. (Such wetting relations are commonly observed in magmatic inclusions from normal melt/crystal equilibria).

Evidence for formation by melt/crystal processes.

1. Glasses high in Ca and Al occur as melt inclusions within or as layers between the laths of olivine (or pyroxene) in some typical barred or radial chondrules from other meteorites, where most would agree they are probably residual melts (e.g., Van Schmus, 1967). Very similar barred olivine «chondrules» (but with the interstitial glass crystallized to anorthite) have been found in a lunar igneous rock (Roedder and Weiblen, 1977b). Furthermore, McSween (1977) presented three pairs of analyses showing very similar compositions for the Ca-Al-rich glass inclusions in olivine and its chondrule mesostasis for three chondrules in the Kainsaz and Lance C3(O) carbonaceous chondrites. In contrast, Olsen and Grossman (1978) find that glass from Murchison chondrule mesostasis is much higher in SiO₂ and much lower in Al₂O₃ and CaO than that from Murchison olivines. Entirely apart from the probability that the small number of true chondrules in Murchison are not chemically representative of the presumed coarser porphyritic chondrules (?) or lithic fragments that may have yielded the isolated olivines, these glass compositional differences may well be explained by the mineralogy involved: the inclusions in olivine had to remain on an olivine subtraction line, whereas the interstitial glass in the chondrules may have followed quite different lines of descent.

2. The porphyritic olivine xenoliths described here, with altered matrix, provide a very likely candidate for disaggregation to yield the euhedral olivine phenocrysts that previously have provided much of the support for the condensation hypothesis.

3. An immiscible Fe sulfide melt is perfectly expectable in such meteoritic compositions. The solubility of sulfide in silicate melts increases with temperature and FeO content, and decreases with pO₂ of the melt (Skinner and Peck, 1969; Shima and Naldrett, 1975). In these meteoritic melts, even though the FeO content was low, pO₂ was very low and presumably the temperature was high.

4. The presence of planes of pseudosecondary inclusions in the cored olivines requires that these crystals, at least, fractured in the presence of an immiscible mixture of silicate and sulfide melts that could enter the fractures and cause healing.

5. A regular ratio of sulfide melt globule to silicate glass in groups of inclusions in the same grain requires the presence of a melt that was somewhat undersaturated in sulfide at the time, such near saturation is common in many terrestrial and lunar melts.

6. The trapping of minute vapor bubbles as a result of nucleation and growth of the new vapor phase on a liquid-solid interface is as common in geology and industry as it is in champagne. The vapor bubble protects the surface where it is attached from access to more nutrients for growth, and hence is enclosed as the host crystal continues to grow (Roedder, 1979).

7. The presence of round «vapor» inclusions is typical of gas inclusions trapped in many terrestrial magmatic environments.

Evidence against formation by melt/crystal processes, with rebuttals.

1. All melt inclusions trapped within a single host during fractional crystallization «should have the same composition», but those in Murchison do not (Fuchs et al., 1973, p. 16 and table 8). The compositions are called «substantially different» by Olsen and Grossman (1978, p. 125).

Rebuttal.

The only evidence presented for the statement consists of analyses from two grains. The largest differences in the first pair of analyses are for Al₂O₃,
1.97 wt. % Cr in metal from Apollo 11 and 0.1 —
> 2.0 % (with a caveat) for Apollo 12. Taylor et al.
(1971) report 0.42 wt. % from another Apollo 12 rock,
Melson et al. (1972) report 0.5 in rock 14053, and
Taylor and McCallister (1972) report 0.2-0.74 wt. %
Cr in metal of Apollo 15 basalts.

I see no great difficulty in getting the Cr in the
Murchison metal by reduction processes, particularly
if applied to a previously fractionated portion. In
addition, Olsen and Grossman (1978, p. 123) state
that metal of similar composition is found in the
olivine of chondrules that did form by melt/crystal
processes; in explanation, they suggest that the high-
Cr compositions were inherited from the preceding
condensation process, and survived the melting
process.

6. Some of the white inclusions in Murchison are
compositionally zoned, with olivine-rich cores and

Rebuttal.

Although this distribution is in keeping with the
relative condensation temperatures given by Gros-
man (1972) for forsterite and enstatite (1444 and
1349 K, respectively), this distribution could also be a
result of some particular sequence of events in the
actual aggregation process or processes. The specific
nature of the processes whereby meteoritic material
aggregated into the forms we now see is certainly not
simple, and is at present unknown.

7. The glass inclusions are nearly spherical (Olsen

Rebuttal.

Although condensation would yield spherical
droplets, most silicate melt inclusions formed during
most melt/crystal processes are close to spherical
(Roedder and Weiblen, 1971; Roedder, 1979).

8. Euhedral olivines possess morphological fea-
tures on their crystal faces that are characteristic of
condensation from a gas (Olsen and Grossman, 1974).

Rebuttal.

Considerable effort has been expended on this
aspect, but although there are morphological differ-
ences between the surfaces of olivine from various
localities, and even between different faces on the same
crystal, none of these differences have been shown to
be due to crystallization from gas versus liquid. From
the various SEM photographs published (see also
Richardson and McSween, 1978; Olsen and Gross-
man, 1978), it is quite apparent that 1) the surfaces
on various isolated olivine phenocrysts from Murchi-
son differ among themselves, and 2) many physical
and chemical variables may affect surface features
(Olsen and Grossman, 1974). It is also possible that
some of the surface features of the olivine (at this scale
are a result of etching during alteration of matrix glass
to phyllosilicates, even though there is no evidence of
significant replacement of olivine by phyllosilicates
(Richardson and McSween, 1978).

9. Some silicate melt inclusions contain 1-14 vol. %
vapor bubbles but others have none because of
"... bubble occupancy by vapors under varying
pressures » (Fuchs et al., 1973, p. 14).

Rebuttal.

I am not certain what is meant here, but I presume
this refers to varying ambient pressure during
condensation, which, however, would not affect the
volume percent of « vapor » phase forming in melt
inclusions on cooling. Nucleation of a shrinkage
bubble in a melt inclusion, if it occurs at all, may
occur at any stage in the cooling cycle. If it occurs
late, when the melt is highly viscous, only a small
bubble may form before quenching (Roedder, 1971,
1979). This, plus the trapping of primary gas bubbles
along with silicate melt in various ratios, can easily
yield the vapor bubble range found:

Evidence against formation by condensation.

1. If olivine crystals grew from a vapor, one would
expect them to be essentially all euhedral crystals, yet
the olivines in the white inclusion aggregates are
mainly anhedral. Yet Fuchs et al. (1973, p. 34)
indicate that at least the process of aggregation must
have been «... an exceedingly gentle, process... »,
while the particles were moving with «...near zero
relative velocities... » (presumably because of the
fragile nature of the aggregates).

2. Grossman and Clark (1973, table 3) calculated
the composition of condensates expected from the
solar nebula in terms of wt. % CaO, MgO, Al2O3,
and SiO2, at a pressure of 10^-3 atm., and various
temperatures. None of the compositions agrees with
that found in the melt inclusions. Fuchs et al. (1973,
table 8) show a composition for the melt inclusions
(average of 14 analyses, recalculated to 100 % from a
partial sum of 96 %) of SiO2-54, CaO-19, Al2O3-23,
MgO-4 wt. %. Grossman and Clark's data show that
high condensation temperatures are required at
10^-3 atm. to result in low MgO, but that even at
1500 K (1227 °C), the condensate consists of SiO2-19.9,
CaO-35.0, Al2O3-38.3 and MgO-6.8 %. SiO2
increases to 50. % if the temperature is dropped to
1300 K (1027 °C), but then CaO-4.1, Al2O3-4.3, and
MgO-41.6 %

3. Spherical Ni-bearing Fe sulfide globules occur
commonly as inclusions in both forsteritic and Fe-
rich olivine in Murchison. According to Grossman
(1972), troilite should condense (at 10^-3 atm. total
pressure) at 700 K (427 °C), but the host forsterite
condenses at 1444 K (1711 °C), ~ 750° higher.
Grossman also shows that the condensation tempera-
ture of forsterite drops as total pressure drops, but an
extrapolation of his figure 5 would suggest that
absurdly low pressures (~ 10^-18 atm) would be
required to drop the condensation temperature to
(24.5 \pm 2.9\%\), with the lower value from the analysis with the lowest total (96.1\%). The other grain is represented by three analyses, one of a homogeneous inclusion, and the other two of an inclusion that consists of two intergrown «phases» (seen in reflected light) that are not further described or categorized. The magnitude of most of the differences reported are such that they could be solely a result of the problems of electron microprobe analysis of small inclusions, but even if the differences are real, the original premise of Fuchs et al. is invalid, as such differences are expectable for inclusions even within single crystals (Roedder and Weiblen, 1977a; Roedder, 1979).

2. As above, all melt inclusions trapped within a single host should have essentially the same composition, but do not, as evidenced by observation of changes in the position of the «vapor» bubble in glass inclusions before and after heating (Fuchs et al., 1973, p. 16). Thus one inclusion showed a shift in bubble position after heating to between 1 200° and 1 300 °C, but bubbles in other inclusions did not move even after heating to 1 400 °C.

Rebuttal.

A change in the bubble position indicates either movement in the melt, or homogenization of the inclusion on heating and reenuclation in a different place on cooling. The nucleation of a «vapor» bubble in a homogenized inclusion occurs almost always at the solid/melt interface, and very commonly at a given point on that interface, presumably where some invisible nucleus lowers the activation energy to form the new phase and get it past the small-radius surface tension barrier (Roedder, 1971, 1979), so the data presented do not require different composition melts.

3. Aggregates of olivine grains that may contain glassy inclusions are loosely consolidated. This state of aggregation appears contrary to a magmatic origin (Fuchs et al., 1973, p. 17).

Rebuttal.

Many processes, some probably still unknown, occurred during the formation of the carbonaceous chondrites, but certainly there was impact, disaggregation and reaggregation, as evidenced by the isolated olivine grains, as well as by many other features of this and other meteorites (and the lunar regolith breccias?). These processes must have occurred at different places in the nebula, as evidenced by the different compositions of individual multiparticulate clasts and the isotopic data of Onuma et al. (1972). Furthermore, glass inclusions are also present in the olivines of the non-friable lithic fragments (my figures 15 and 17).

4. Olivines containing inclusions of glass occur in 1-2 mm chondrules in the Allende C3 meteorite. «Clearly, chondrules solidified as discrete systems of millimeter dimension and did not crystallize in a magma chamber» (Fuchs et al., 1973, p. 17).

Rebuttal.

Although this is one of the four «major difficulties» pointed out by Fuchs et al. (1973), the implication here that melt/liquid equilibria require a «magma chamber» is simply not true. Equilibria (metastable or stable) between melt and crystal have no size limitations.

5. «We noted... [that] postulating a magmatic state... requires complicated, highly contrived conditions that are contrary to the primitiveness of a meteoritic object such as Murchison» (Fuchs et al., 1973, p. 32).

Rebuttal.

Apart from the circular reasoning here (the materials are primitive because the meteorite is made of primitive materials), I can only point out that the (possible metastable) high-pressure condensation process proposed for the origin of the melt droplets, followed by their transport outward along the ecliptic plane to regions of much lower pressure and temperature where olivine crystals, growing from the vapor phase, enclosed the metastable, still soft glass droplets (Fuchs et al., 1973, p. 31-36), is certainly not free of complications and contrivance. Also, again, there is no requirement of a «planetary object» to have crystallization of olivine from a melt; this could have occurred in the chondrule-sized «systems» that presumably were disaggregated to form the isolated grains and possibly also, under somewhat different conditions, the materials now found in the white inclusion aggregates.

6. «If the white aggregates are interpreted as once-molten droplets (chondrules), then the glass inclusions trapped in the interiors of the olivine grains must be close to the initial composition of the liquid from which the olivine crystallized. This leads to the absurd conclusion that the bulk composition of these forsterite-enstatite aggregates is... equal to that of the trapped parent liquid» (Grossman and Olsen, 1974, p. 177).

Rebuttal.

The stated conclusion is indeed absurd. If melt/crystal equilibria are involved, the glass inclusions obviously must represent not the initial composition but the residue left after crystallization of large amounts of olivine (± pyroxene) from a melt. Part of this crystallization could well have occurred on the walls after trapping, as has been well established in many other occurrences of silicate melt inclusions in olivine (e.g., Roedder and Weiblen, 1970, p. 804; Roedder, 1979).

7. Forsterite is not the primary phase for melt compositions like the glass inclusions in the equilibrium system CaO-MgO-Al₂O₃-SiO₂ (Grossman and Olsen, 1974).

Rebuttal.

This criticism was adequately refuted by McSween (1977), who showed that although the glass composi-
tions do fall in the plagioclase field in the appropriate system, they lie essentially on olivine subtraction lines from the bulk composition of the chondrules. Thus, the liquid compositions in the inclusions could be achieved simply by failure to nucleate plagioclase on cooling, as is commonly observed.

8. Anhedral olivine chondrules, even if disaggregated, cannot yield the euhedral isolated olivine grains (Olsen and Grossman, 1978, p. 120).

Rebuttal.
Although this is true, there is nothing to prevent the disaggregation of porphyritic olivine xenoliths or chondrules, with euhedral olivines, which these same authors acknowledge to be one of the three unambiguous characteristics of chondrule origin (p. 111).

9. « We have never seen a euhedral crystal in any kind of true chondrule. They are all anhedral » (Olsen and Grossman, 1978, p. 124).

Rebuttal.
Although it seems of little consequence as to which source of euhedral olivines is disaggregated, lithic fragments or porphyritic chondrules, undissaggregated euhedral porphyritic chondrules do exist in Murchison.

10. « Only the (condensation) process... can result in (the) euhedral crystals of olivine in either aggregates or isolated in the matrix » (Olsen and Grossman, 1978, p. 120).

Rebuttal.
Not true. Disaggregation of either porphyritic chondrules (see above two items) or of porphyritic lithic fragments could yield them (e.g., figures 13 and 14).

11. The grain size of the euhedral isolated olivines is much larger than that of olivine in the chondrules and the white inclusions. This, plus the euhedral shape, precludes deriving them from these materials (Olsen and Grossman, 1978, p. 123).

Rebuttal.
It is true that even the euhedral olivines in the porphyritic xenoliths are too small to produce the largest isolated olivines. These isolated crystals must have been produced from a material (larger chondrules or impact melts?) that is not necessarily represented among the clasts present. Similar problems have bedeviled students of the polynictic lunar breccias, but do not require a condensation process.

12. «... Fuchs et al. (1973) found on olivine grain... with a single glass inclusion which contains an interface separating two different compositions. This is even more difficult to explain as trapped melt » (Olsen and Grossman, 1978, p. 125).

Rebuttal.
Although I personally doubt that these two are immiscible liquids (see item 1 above), if immiscibility has occurred, trapping both melts in a single inclusion is a very common process (Roedder, 1979).

13. There is a 15-fold greater Na₂O content in the residual glasses of CrXO chondrules (McSween, 1977) than in the inclusion glasses in isolated olivines from Murchison (Fuchs et al., 1973), and hence «... the glass blebs contained inside host olivine grains in C2 meteorites have had a different history from mesostasis glass that coexists with olivine inside true, melt chondrules » (Olsen and Grossman, 1978, p. 126).

Rebuttal.
This is true, but it is important to note that of all constituents in chondrule mesostasis glass, Na₂O varies the most. In fact, compositions ranging from essentially that of anorthite to albite, and even to nephelinite have been recorded. This variation may well be caused by the differences in the original condensation history or to later volatilization of Na₂O, and Kurat (1967) has reported large variations in the composition of glass with distance from the surface in single chondrules. Similar volatilization of Na₂O is a well-known problem in some experimental silicate melt studies, and has been experimentally verified using chondritic materials at 1300 °C (Goding and Muenow, 1977).

INTERPRETATION OF THE DATA:
A SCENARIO FOR THE ORIGIN
OF MURCHISON OLIVINES

The following interpretation is a sequence of events that I believe could yield the bizarre assemblage of minerals, textures, and inclusions constituting Murchison with a minimum of ambiguity, and still stay within most of the constraints placed on the sequence by the available data. It incorporates some features from several published papers, plus some novel items, but obviously it must be considered tentative at best. The carbonaceous chondrites have been around for more than 4 billion years; I suspect they will remain enigmatic, at least in part, for a few more years.

Spinel crystals nucleated first, then olivine crystals, from a very olivine-rich melt, the components of which presumably condensed originally from the solar nebula. The volume of melt could not have been smaller than chondrule drops of a size adequate to yield the largest individual olivine or porphyritic olivine xenoliths found (>1-2 mm). As olivine-rich melts nucleate and grow crystals easily, the apparent maximum size of olivine crystals present (~1-2 mm) effectively precludes any «magma chamber» of planetary size. Fe metal, either from the sweeping up of previous condensates or from precipitation by loss of oxygen, formed immiscible droplets in this silicate melt, which were then trapped by the growing olivine
crystals along with some of the early spinels and melt. No evidence proves or precludes a subsequent stage of impact melting and crystallization.

The silicate melt from which the olivines were growing contained much olivine, and only minor amounts of CaO, Al₂O₃, and excess SiO₂. On trapping in an olivine «bottle», additional crystallization of olivine and daughter crystals of spinel from the inclusion liquid enriched the residual liquid in Ca-Al silicate, and decreased its volume. Crystallization of the olivine on the walls resulted in a net volume decrease also, and this is reflected in the common occurrence of melt inclusions in olivine with regular phase ratios and 25-30 vol. % «vapor». Melt inclusions having smaller amounts of «vapor» phase could represent trapping of portions of melt from which most of the forsterite had already crystallized before trapping; the extreme examples, with only ~ 5 vol. % «vapor», represent trapping of an essentially pure Ca-Al-silicate melt, and the «vapor» bubbles in them represent essentially differential shrinkage of crystal host and melt on cooling.

Some of these olivine crystals, from a more Fe-rich region of precipitation, were subjected to altered conditions during growth, yielding the cored olivine crystals. In these melts, sulfur or other volatile species were present in sufficient concentration that the silicate melt was at saturation with respect to some vapor phase at the growing olivine front throughout growth of the core, and many vapor bubbles nucleated on the interface. These were trapped as «vapor» inclusions, in part along with silicate melt. Gravitational pressure was presumably negligible or zero, but the vapor pressure at this time had to be high enough to permit nucleation in spite of the surrounding nebula gas pressure and the small-bubble surface-tension barrier (Roedder, 1971). On cooling to room temperature, these volatiles condensed on the inclusion bubble walls (Fuchs et al., 1973, p. 15; Moore and Calk, 1971), leaving a vacuum. The larger silicate melt inclusions in the core, which were trapped along with vapor bubbles, were big enough to nucleate an immiscible sulfide phase and a spinel crystal on cooling, whereas the small silicate melt inclusions, which also happened to be without a trapped vapor bubble, were not large enough (Roedder, 1979).

After the growth of the cores, but prior to the growth of the rims, some of these crystals were fractured. The surrounding fluid, presumably an emulsion of immiscible Fe sulfide droplets in silicate melt, entered these cracks, and healed the fractures, forming planes of pseudosecondary inclusions. The absence of inclusions in the rims of these crystals suggests that this latter stage of crystallization was from a melt with a lower concentration of volatile species.

Some of the silicate melt that was trapped in inclusions was sufficiently rich in sulfide that it became saturated on cooling and precipitated globules of sulfide phase, yielding a constant phase ratio in each such inclusion. The silicate melt from which the olivine grew was very olivine rich, and the melt inclusions crystallized still more olivine on the walls, driving the composition toward the plagioclase primary phase field on the appropriate plagioclase-olivine-silica phase diagram. Failure to nucleate plagioclase when the composition reached the olivine-plagioclase boundary permitted the composition to continue to evolve along a metastable olivine extraction line («olivine control line») into the plagioclase primary phase field, as described by McSween (1977) (*).

Following crystallization of the bulk of the olivine, the small amount of residual liquid between the crystals had a composition similar to the present glass inclusions, and the texture probably resembled the porphyritic olivine xenoliths described above. These materials, plus some droplets that may have been subjected to a different cooling cycle, yielding the true chondrules, were then partly disaggregated and reaggregated to form the white inclusions. Some of the materials may have gone through several such cycles, and others may reprecipitate condensation from impact clouds (K. Fredriksson, personal communication, 1980). The compositionally zoned aggregates presumably resulted from changes in the environment during this process. The reaggregation might have occurred at high temperatures, permitting the small amount of glass particles and the glass adhering to the individual olivine fragments or euhedra to act as a cement. All such interstitial glass in the aggregates is now green or yellow-brown phyllosilicates.

These various materials (including some primary condensate particles and broken barred chondrules such as that in figure 9 in Olsen and Grossman, 1978) were then subjected to low-temperature alteration in the presence of water, which converted all exposed glass to yellow-brown or green layer-lattice silicates. After this, and some additional disaggregation to break apart altered porphyritic olivine xenoliths and thus free euhedral olivine phenocrysts (some with yellow-brown or green layer-lattice silicates still adhering), the materials were reaggregated along with finely divided carbonaceous matter, to yield the present black matrix between the clasts.

REMAINING PROBLEMS

Many unsolved problems, such as the exact nature of the aggregation process, are implicit in the arguments given above and do not need to be repeated here. A few of the more troubling questions should be mentioned, however.

1. Although condensation from the solar nebula to form a finely divided «smoke» consisting of a series of phases has been shown to be possible, based on calculated stability fields and assumptions on vapor

(*) It is important to note that in these olivine-rich compositions, it is necessary to crystallize only ~ 2.5 wt. % additional olivine, under metastable conditions, after the olivine-plagioclase boundary is reached, to achieve the glass compositions found. Much experimental silicate work is bedeviled by (or in some cases only possible as a result of) such metastable extensions of liquidus surfaces into regions where other stable phases failed to nucleate.
composition, temperature, and pressure, the mass transfer problems in the growth of millimeter-sized forsterite crystals from the amount of forsterite vapor present in $\leq 10^{-3}$ atm hydrogen at 171°C, and even more so, e.g., that of magnetite from such low-density hydrogen gas at 132°C (Grossman, 1972), has apparently not been addressed.

2. The inclusion-free halos surrounding the larger inclusions in the cored olivines (Figures 5, 6 and 7) present a paradox. Two possible explanations come to mind, but neither is very satisfying. If these inclusions represent a formerly much larger volume of olivine-rich melt, crystallization of this olivine on the walls could yield an inclusion-free zone, but hardly the diameter of those found. Another possibility is that these cored olivines formed with a relatively uniform distribution of small inclusions, but that by diffusion of ions (and holes) through the crystal during a long period of heating, driven by the resulting small reduction in surface energy, those inclusions that were slightly larger «ate up» the surrounding small inclusions, leaving an inclusion-free zone.

3. It has been suggested (O. James, personal communication, 1980) that the inclusions in the inclusion-rich cores in Murchison olivines might form from subsolidus precipitation. Thus the Ca, Al and Si of the melt inclusion glass phase might have been formerly present as trace constituents in the olivine structure, as has been proposed for some silicate inclusions in certain lunar olivines (Roedder and Weiblen, 1971; Bell et al., 1975). The occurrence of large numbers of minute silicate inclusions, possibly from subsolidus reactions, is also not rare in plagioclase form the lunar highlands. However, the relatively large volume percent of «vapor» in the Murchison inclusions, and particularly the sulfide phase, seem difficult to derive in this manner.

4. The presence of glass itself, both in Murchison and other meteorites. Even anhydrous alkali aluminosilicate glasses, probably the most viscous of all natural melts, have apparently crystallized during the cooling cycle of some lunar rocks. In Murchison, however, the glasses are anorthite-rich and should crystallize much more readily. Wood (1963, p. 165) has proposed a rapid process involving shock-wave melting and cooling to form chondrules, but it is hard to visualize a process whereby solar nebula material could cool slowly enough to precipitate out coarse (and even unzoned) crystals of refractory compounds, and then be quenched sufficiently fast that the residual Ca-Al-Si melt forms a glass.

5. The presence of «vapor» bubbles in fluid meteoritic materials that were presumably exposed to the solar nebula gas presents a difficult problem. Wood (1963, p. 176) states that bubbles have never (*) been observed in chondrules, so why should they be present during the crystallization of some of the Murchison olivines? A vapor bubble will form in a melt at essentially zero gravity only if the vapor pressure of gaseous species in the melt exceeds the combination of the effects of the external vapor pressure and the small-bubble surface tension barrier (surface tension increases greatly as bubble diameter decreases). In a melt in space, any such bubble is unstable, as its internal pressure will be greater than the external pressure by virtue of the surface tension increment. As a result, the volatiles forming the bubble should, with time, diffuse through the walls and permit the bubble to collapse to a smaller size, with even higher internal pressures. Perhaps the chondrules had enough time at temperature before crystallization to their present form to lose essentially all their volatiles, but the melts forming the Murchison olivines had not. Another possibility is that the vapor bubbles in the Murchison melts occurred either in a body larger than a chondrule, where diffusive loss would be slower, or in a still larger body, where depth and gravitational forces were adequate to hold even larger amounts of volatiles in and prevent loss. As pointed out above, the fine grain size of the olivines in Murchison seems to preclude the last possibility.

6. Most puzzling of all, but (fortunately) beyond the scope of this paper, is the nature of the alteration process, involving major metasomatism, to form the phyllosilicates.

CONCLUSIONS

An examination of the various types of magmatic inclusions in olivine of the high-temperature fraction of the Murchison carbonaceous chondrite has yielded data that seem most compatible with origin of these inclusions, and their host olivines, by melt/crystal processes, and that seem to preclude a mode of origin involving direct condensation of these olivines from solar nebula gas. The many lines of evidence for and against the two hypotheses of origin are presented and evaluated and a tentative multistage scenario is proposed to explain the rather strange assemblage of minerals, textures and inclusions in Murchison.

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