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ON THE ORIGIN OF ISOLATED OLIVINE GRAINS IN TYPE 2 CARBONACEOUS CHONDRITES

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The origin of olivine grains isolated in the matrix of C2 carbonaceous chondrites is an important problem. If these grains are condensates from a solar nebular gas, they contain compositional, isotopic and physical features that further elucidate that process. If, however, they are grains released by the breakup of chondrules, then many important condensation features have been lost during the melting that took place to form chondrules.

In evaluating these two possibilities, care must be taken to determine which inclusions in C2 meteorites are actual chondrules and which are aggregates of grains that have never undergone melting. The two main types of aggregates, pyroxene-rich and pyroxene-poor, are forty to fifty times more abundant than chondrules. Four scenarios are presented to account for the kinds of aggregates and isolated grains seen in the Murchison C2 meteorite. An analysis of these scenarios is made in light of olivine crystal morphology, comparison of composition of glass inclusions inside olivine grains with interstitial glass in true chondrules and size distributions of olivines, isolated, in aggregates and in chondrules.

It is concluded that no scenario that includes a chondrule-making step can account for the observed population of isolated olivine grains. An origin by direct condensation, partial comminution, aggregation and accretion best accounts for the sizes and morphological features observed.

1. Introduction

Although there are details of chondrules that remain unexplained, the present consensus is that they represent rapidly-quenched melt droplets [1]. In unequilibrated chondrites, the following petrographic characteristics are the only unambiguous evidence for such an origin: spheroidal shape and the presence of interstitial glass with porphyritic, barred or radiating crystalline textures.

In ordinary chondrites, there is little question about what is a chondrule, or chondrule fragment, what is matrix and what are clasts. In the C2 and C3 meteorites, however, there are a number of types of inclusions that cannot be readily classified in an unambiguous manner. One way around this, that has been used in the past, is to call all, or most, of them chondrules in spite of the fact that they do not all satisfy the above petrographic criteria. The trouble with this is that the word *chondrule,* used in this loose manner, should no longer carry with it the aforementioned genetic connotation. The origins of the many types of inclusions seen in C2 and C3 meteorites are not at all clear at the present time. In the Murchison C2 meteorite, for example, we can distinguish about a dozen kinds of inclusions on the basis of morphology, texture and mineralogy. These include three kinds of "true" chondrules: (1) granular, anhe-

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dral olivine with pyroxene and glass; (2) barred olivine and glass; and (3) radiating pyroxene with glass. The first and second kinds are the most common; but, in all, true chondrules are very sparse and make up less than 0.5 volume percent of Murchison. Most of the inclusions in Murchison show no obvious textural evidence of ever having been melt droplets, i.e. chondrules, or divitrified chondrules. Fuchs et al. [2] noted differences between true chondrules and other inclusions that are aggregates of grains. Chondrules break free of the soft, phyllosilicate matrix intact, while other inclusions do not. The latter are as soft and mechanically weak as the phyllosilicate matrix surrounding them and are usually irregular in shape, although some may also be spheroidal. Also, while chondrules are tough and resistant to scraping and crushing, individual grains can easily be scraped loose from aggregates with a needle. Fuchs et al. [2] also described a population of abundant, isolated, single grains of olivine in the Murchison matrix. The majority of these are crystal fragments, but occasional euhedral crystals are found.

2. The problem

The origin of the aggregates and isolated grains is the problem of interest. If high-temperature phases that condensed directly from a solar nebular gas were accumulated as aggregates and single grains on the parent bodies of carbonaceous chondrites and were not altered since, then their chemical and morphological features are relics of the condensation process and can be studied to further illuminate that process [3,4]. If, on the other hand, all high-temperature phases in these meteorites are now, or once were, inside chondrules, i.e., have been melted, then we cannot expect to find many condensation features retained in them. Such a possibility has been advocated by McSween [5] for C3 meteorites and Richardson and McSween [6] for C2's. In those papers, the isolated grains are envisioned as resulting from the breakup of chondrules. The purpose of this paper is to examine critically the petrographic evidence bearing on these two alternative models. It is not our aim in this paper to account for all of the kinds of inclusions in Murchison but, rather, to concentrate only on that fraction of the high-temperature material (>90%) which contains features that we believe are indicative of a direct condensation origin. Other inclusions undoubtedly have different origins.

3. Inclusions

Aggregates in C2 meteorites are commonly irregular in outline, though some may be rounded or spheroidal (Fig. 1). We recognize two main types which we call pyroxene-rich and pyroxene-poor and which, together, comprise 80% by volume of all the aggregates in Murchison.

Pyroxene-rich aggregates. Pyroxene-rich aggregates are usually irregular in shape and consist of rounded, poikilitic olivine grains inside anhedral, twinned, low-Ca clinopyroxene laths (Fig. 2). Commonly, the core of such an aggregate consists of a cluster of olivine grains, with little or no pyroxene (Fig. 3). Had these aggregates formed by random fragmentation of once-larger objects, they would not exhibit the repetitious occurrence of this core-rim arrangement. Within the olivines are micrometer-sized blebs of Ca-, Al-rich glass that are usually spherical to ellipsoidal, but may be elongated. The glass blebs may contain minute gas bubbles. In addition, the olivines may contain micrometer-sized beads of Cr-rich, Fe-Ni alloys. The chemical composition of these metal beads is consistent with an origin by condensation [3]. No glass or metal was observed within the pyroxenes. In the interstices between the pyroxenes in the interiors of the aggregates are patches of pale green to dark, muddy green, brown or yellowish phyllosilicates; these may comprise a significant to a minor proportion of the volume of any particular aggregate. The textural relations between the high-temperature silicates and the phyllosilicates are optically obscure; however, in a few cases, the latter appear to be direct alteration products of olivine or pyroxene. Commonly associated with these are rounded clumps of black phyllosilicate. A noteworthy feature of these aggregates is the relative paucity of phyllosilicates from the rim regions.

Pyroxene-poor aggregates. Pyroxene-poor aggregates are often rounded. A wide range of textural varieties are observed, containing anhedral, subhedral and, rarely, euhedral olivine crystals. Rarely, pyroxene

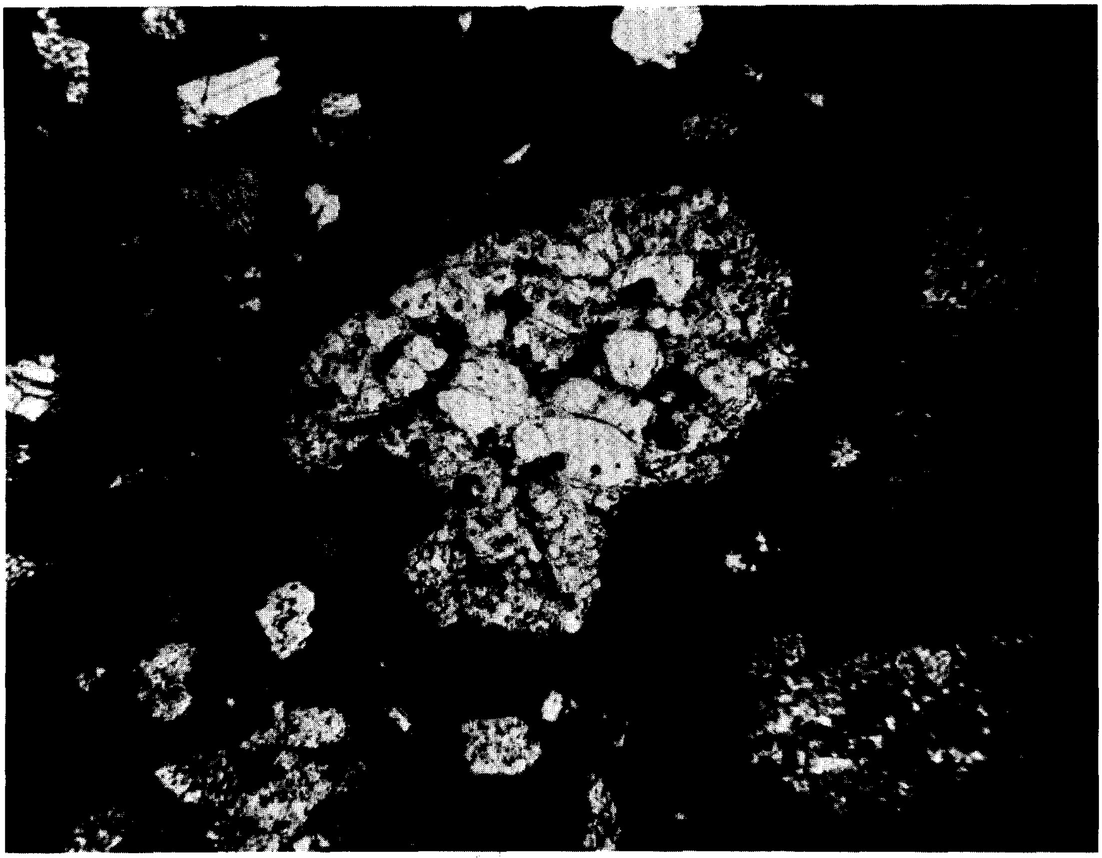

Fig. 1. Pyroxene-rich aggregate from Murchison. This aggregate has the highly irregular shape typical of most aggregates. Surrounding it are broken fragments of aggregates, as well as typical fragments of isolated olivine grains. Aggregate is 525 μm in longest dimension.

grains occur between the olivine grains. Within any particular anhedral cluster, olivine grains exhibit a wide range of sizes (Fig. 4). Olivines in these aggregates may also contain the Ca-, Al-rich glass blebs and Cr-rich, Fe-Ni alloys described in the pyroxene-rich aggregates, although many are free of these inclusions. In the interiors of the aggregates, between the grains, green phyllosilicate patches are very common. Altogether, pyroxene-poor aggregates are much less abundant than pyroxene-rich ones.

Both pyroxene-rich and pyroxene-poor aggregates are always rimmed with a dense coating of black phyllosilicate, distinctive because, compared to the surrounding matrix phyllosilicates, it is relatively free of chips of high-temperature phases. The rim always follows the outline of the aggregate, however irregular or intricate it may be. This is a general feature of many types of inclusions in C2's, including true chondrules.

Isolated grains. In a series of random microscope traverses over three ultrathin sections of Murchison, of 460 isolated grains encountered, there were 2.5 times more olivines than pyroxenes. The vast majority of isolated grains in the matrix are angular fragments, as can be seen in the ultrathin section pictured in Fig. 5. Isolated euhedral crystals of olivine are at least an order of magnitude less abundant than these. In this regard, we question the statement of Richardson and McSween [6] that isolated C2 olivines "appear more commonly as euhedral crystals rather than broken fragments". Euhedral olivines possess morphological features on their crystal faces that are characteristic of

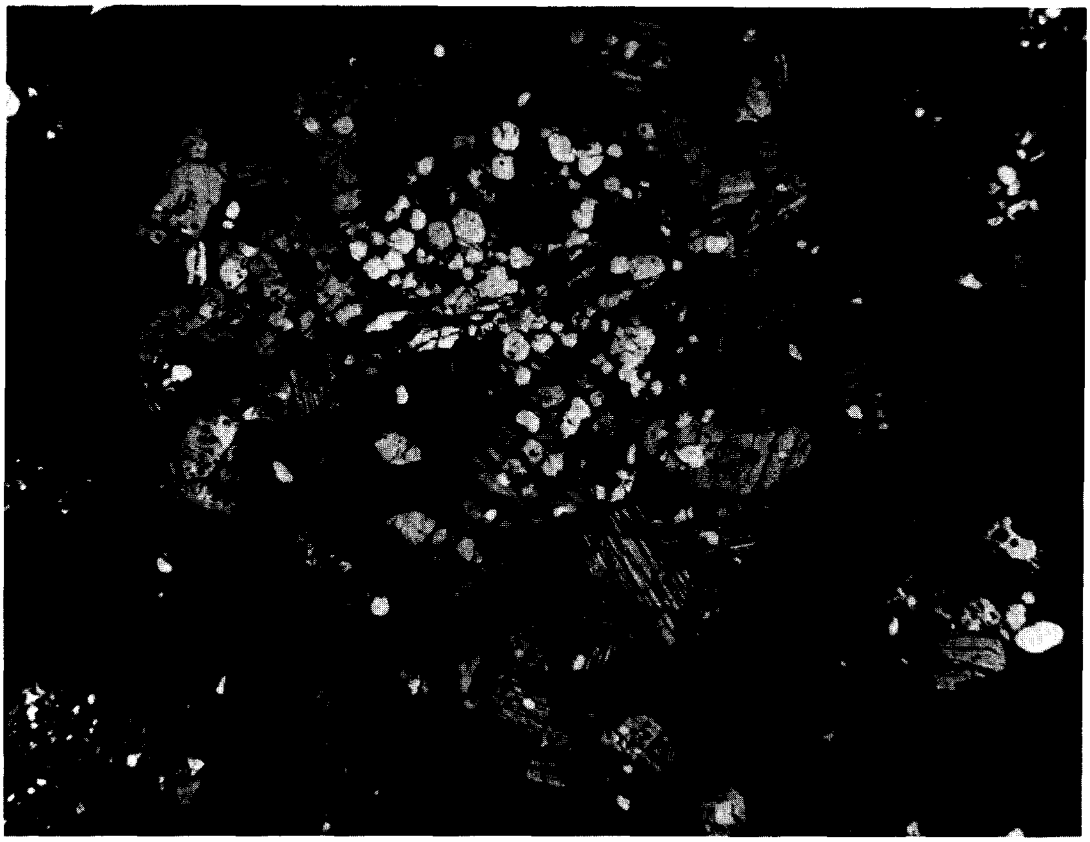

Fig. 2. Pyroxene-rich aggregate in Murchison. Center of aggregate consists of a cluster of both euhedral and anhedral olivines. Away from the center, olivine occurs as rounded grains, poikilitic inside twinned clinopyroxene. Outer edges are relatively olivine-free. Aggregate has typical irregular shape and is 735 μm in longest dimension.

condensation from a gas [4] (Fig. 6B). Isolated olivines also contain Ca-, Al-rich glass and Cr-rich alloys, discussed earlier, which Grossman and Olsen [3] interpreted as primary condensation features.

Chondrules. In rare instances, true chondrules are found (Fig. 7). Most of these consist of granular, anhedral olivine and pyroxene grains embedded in glass. The pyroxene is commonly clinoenstatite to clinohypersthene, but, in some cases, may be pigeonite to augite. The interstitial glass varies in composition from chondrule to chondrule, but is generally Al-, Si-rich and different, on the average, from the glass blebs found inside olivine crystals isolated in the matrix and within the aggregates described above (Table 1). Some chondrules consist of bars of forsterite, interlayered with glass, so-called barred olivine chondrules. In both kinds of chondrules, the glass may be partially to wholly replaced by green phyllosilicates. Fuchs et al. [2] suggested a metasomatic process whereby the glass is hydrated and altered to phyllosilicate, leaving the olivine unaffected. Fuchs et al. recognized that this presents a major mass balance problem, the conversion of a Ca-, Al-rich glass to an Fe-, Mg-, H_2O-rich phyllosilicate. There is at present no clear understanding of how this process could have taken place. Richardson and McSween [6] suggested that this alteration process resulted in the loss of mechanical strength of chondrules and promoted their breakup. They argued it was a critical step in a process that released olivine grains into the matrix.

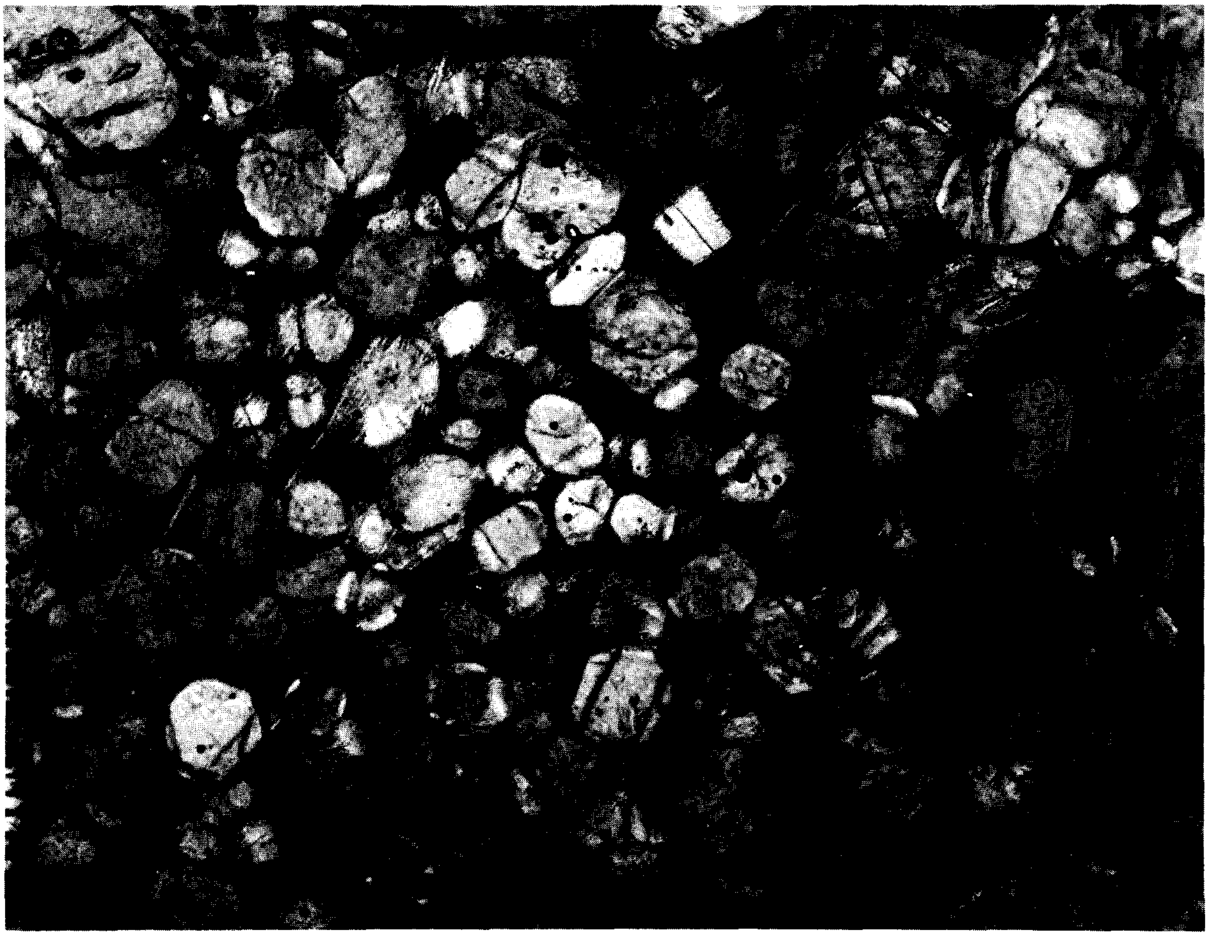

Fig. 3. Center of pyroxene-rich aggregate in Essebi, showing loose cluster of euhedral olivine crystals containing beads of metal and glass. Between the olivine grains are a few fibers of phyllosilicates and a large amount of pore space. Field of view is 630 μm in its long direction.

Finally, a third type of true chondrule has been observed that consists of thin blades of pure enstatite, with or without spinel. These are so rare that they will not be discussed further.

4. Scenarios

The complexity of C2 meteorite petrography makes it difficult to account for all the observed features by simple arguments. The basic question is whether physical and chemical features are present in the high-temperature minerals that reflect their origin by condensation from a solar nebular gas or whether most such features have been destroyed by a magmatic, chondrule-making stage. We shall summarize processes envisioned by different workers with a series of schematic diagrams (Fig. 8).

Fig. 8A. Collisions of grains of high-temperature condensates form barred chondrules [7] consisting of forsterite and siliceous glass, which are observed in Murchison. At low nebular temperatures, <400°K, phyllosilicates become stable. The glass in the chondrules reacts either with the nebular gas while the chondrules are still suspended in the nebula or with

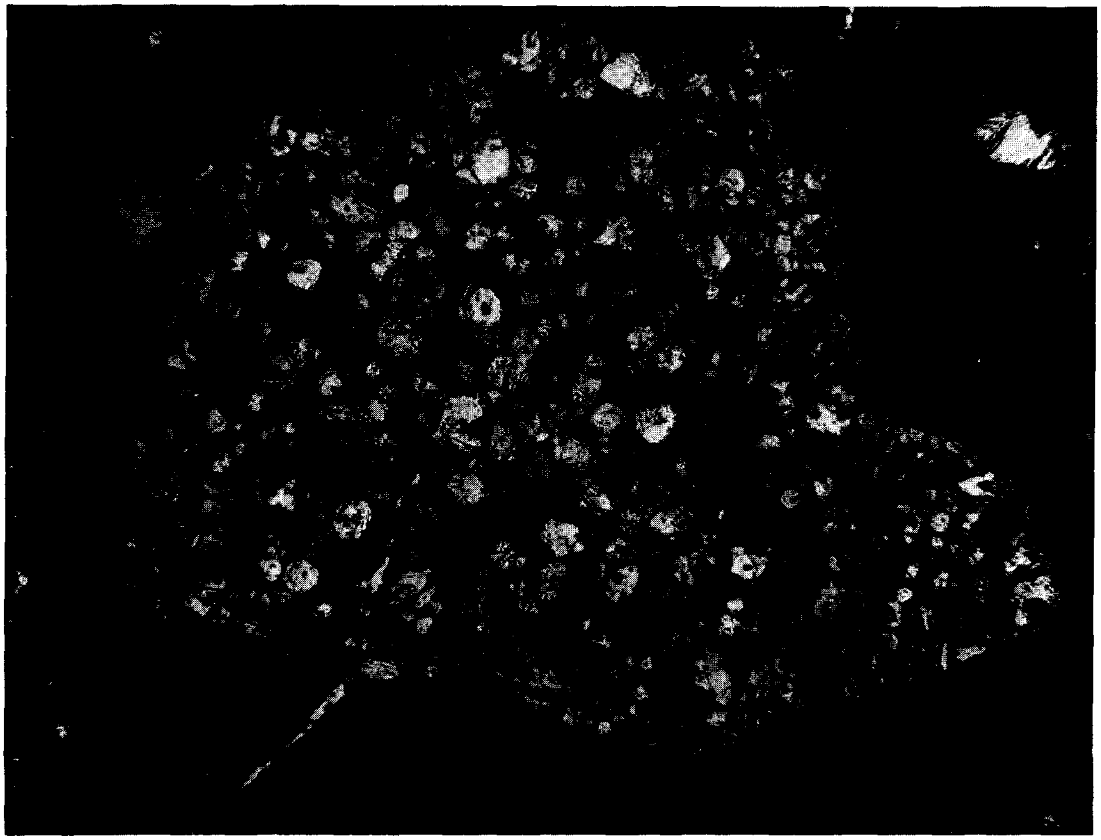

Fig. 4. Pyroxene-poor aggregate in Murchison. Anhedral grains of olivine showing a wide range of sizes. Some pyroxene is present at the outer edges. Aggregate is 0.8 mm in its longest dimension.

Fig. 5. View of isolated olivine grains and fragments of broken pyroxene-rich aggregates in Murchison. Note that isolated grains are all fragmental. Isolated euhedral crystals are rare. Field of view is 1.4 mm in its long direction.

TABLE 1

Glass compositions

	Average of 9 C3 glasses [5]	Average of 14 Murchison glasses in olivines [2]	Average of 8 Murchison glasses in true chondrule mesostasis (this work)
SiO_2	50.4	52.1	69.1
Al_2O_3	19.8	21.6	15.7
FeO	5.5	1.3	0.6
MgO	5.7	4.2	3.2
CaO	13.1	18.1	9.8
NaO	4.4	0.3	1.0
K_2O	0.1	0.05	0.03
TiO_2	–	0.8	0.1
Cr_2O_3	–	0.2	0.1
Sum	99.0	98.7	99.6

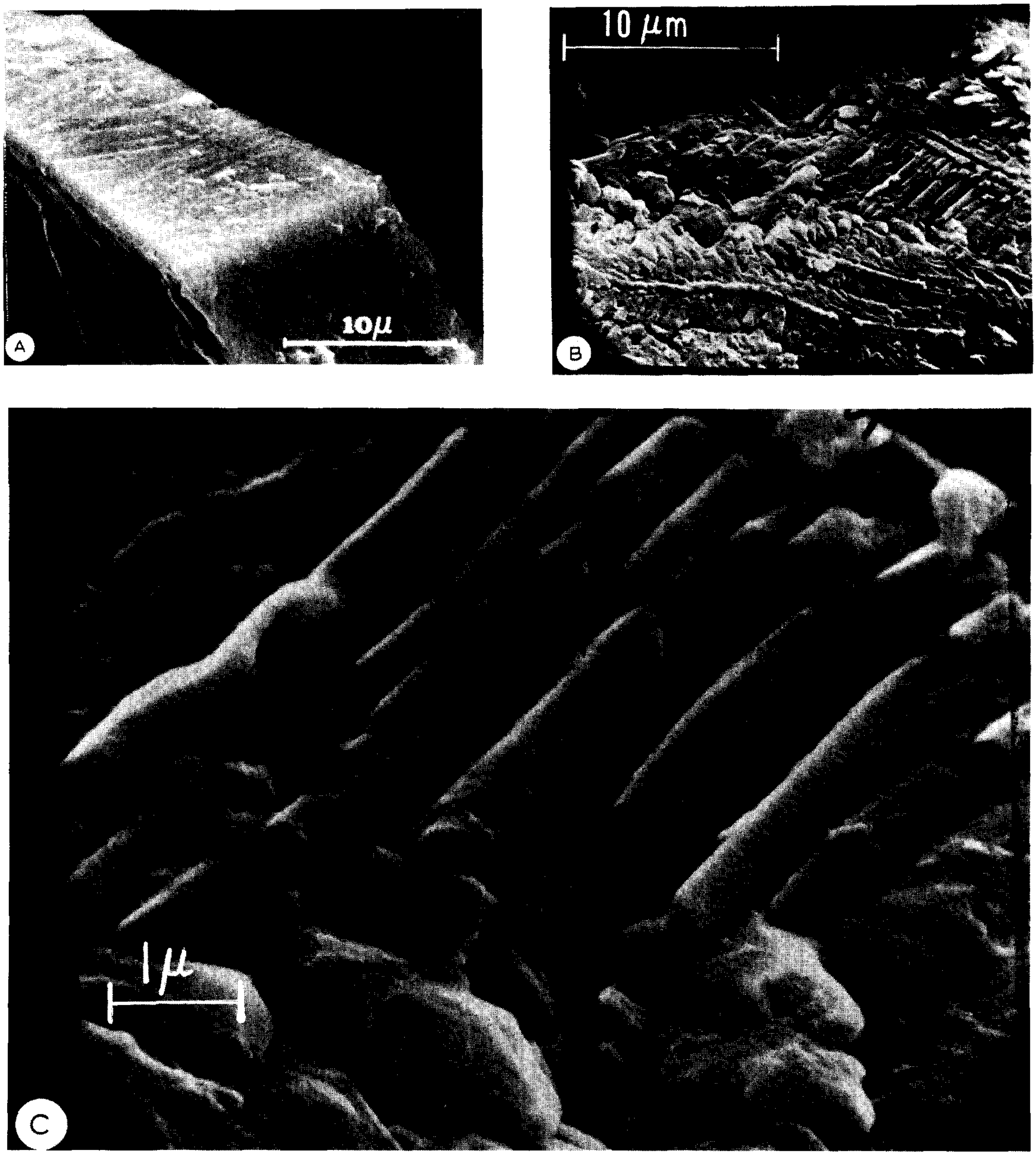

Fig. 6A. Isolated olivine bar from barred olivine chondrule. This photograph is reproduced from Richardson and McSween [6]. They state the "bar exhibits surface ridges and tubular forms similar to the surfaces of crystals suggested to be vapor condensates" B. Crystal face of euhedral olivine from Murchison photographed at same scale as 6A. This surface exhibits the kind of surface texture attributed to formation by condensation. It is clearly different from the surface shown in 6A. For further discussion, see section 5.2. C. Same crystal face as in 6B, magnified 4×, illustrating that the parallel ridge morphology persists down to a very small scale.

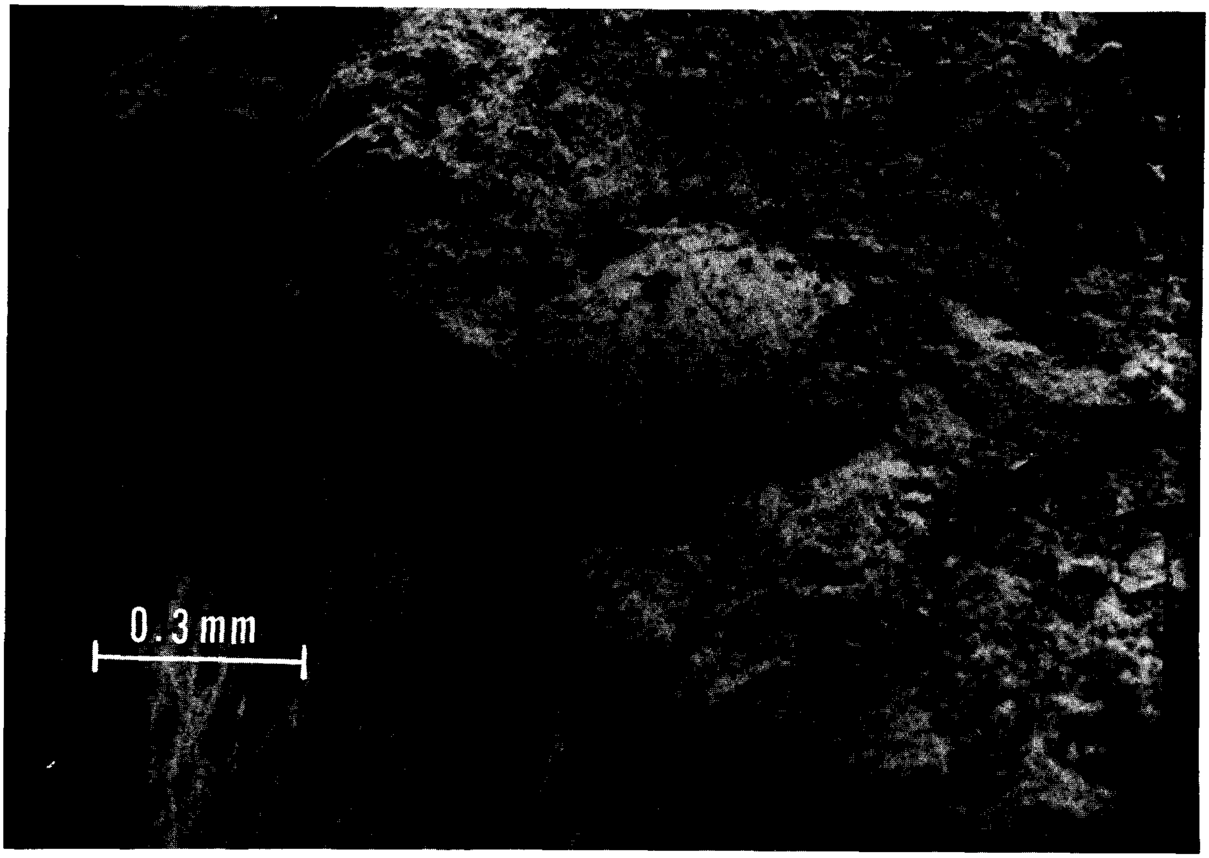

Fig. 7. True chondrule embedded in matrix of Murchison. Note that the chondrule breaks free of the matrix.

hydrated silicate-bearing material in the regolith of a parent body after accretion to form green phyllosilicates. The resultant loss of mechanical strength causes the chondrule to break up, releasing platy fragments of olivine [6]. These fragments could mix with phyllosilicate dust and collect into aggregates. Those that do not aggregate end up as isolated platy fragments. Aggregates of plates are never observed in C2's but isolated plates in matrix have been seen, though they are quite rare. We conclude that barred chondrules do not contribute in any significant way to the population of isolated olivine fragments in the matrix. Especially, this scenario cannot account for the isolated euhedral crystals seen.

Fig. 8B. Collisions of high-temperature condensate grains form granular chondrules of anhedral olivine and pyroxene in siliceous glass [7]. Like the barred chondrules, their glass is altered after phyllosilicates become stable in the nebula. The chondrules break up and mix with phyllosilicates to form aggregates of anhedral grains with rims of black phyllosilicates as well as isolated anhedral fragments in the matrix. This scenario can account for some of the pyroxene-poor aggregates observed and the smaller isolated anhedral grains in the matrix.

Fig. 8C. Euhedral olivine crystals condense at high temperature. Collisions between them cause fragmentation of some, leaving a small number of others unbroken. Some of the crystals and fragments accrete into pyroxene-free clusters. Those which fail to do so react later with the nebular gas at lower temperature, 1350°K at 10^{-3} atm [8], to form pyroxene. Smaller olivines are completely consumed by this reaction, while vestiges of the larger ones remain as rounded,

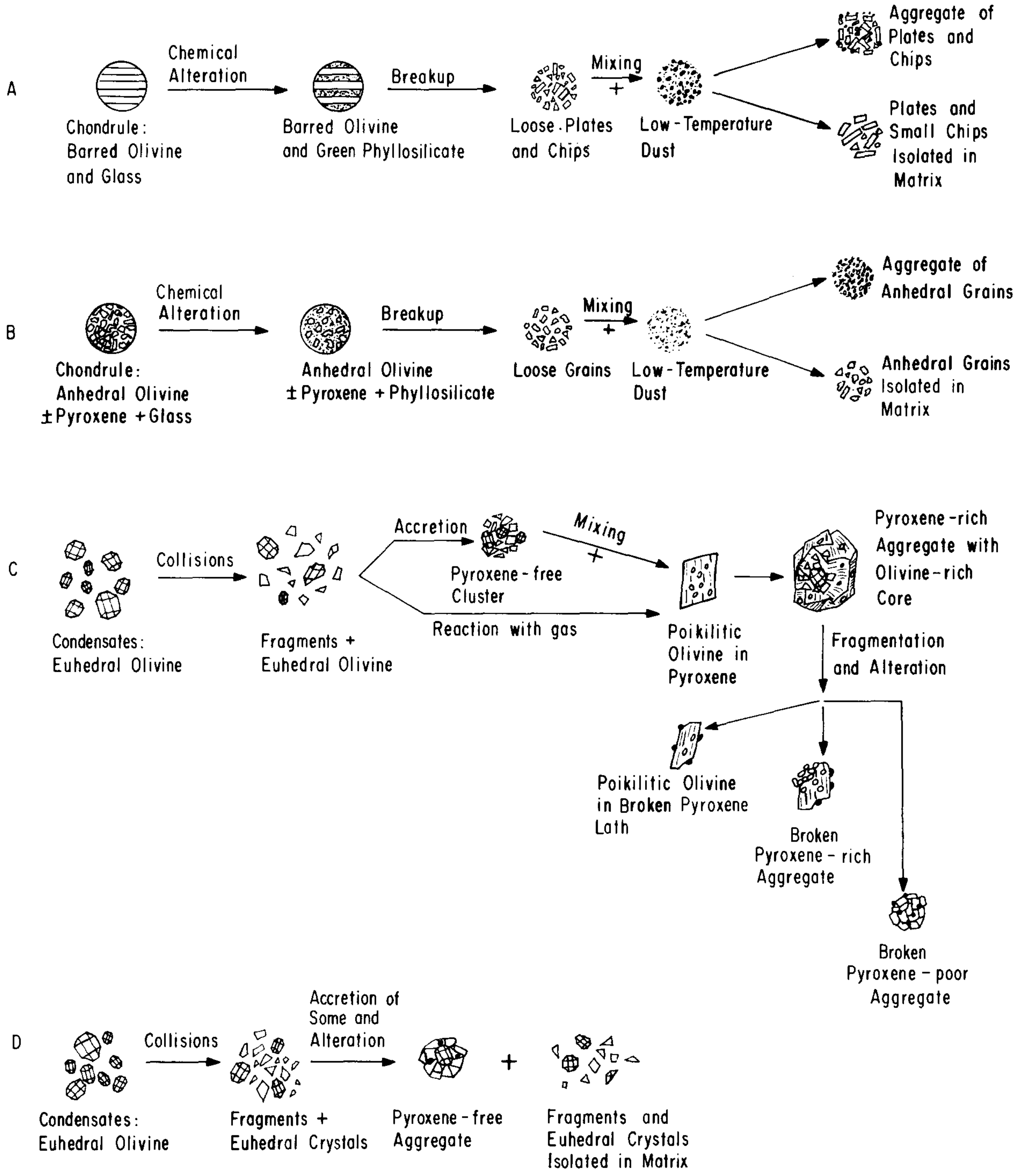

Fig. 8. Scenarios which can possibly lead to petrographic features observed in C2 chondrites. A. Hydration of glass in barred chondrules yields plates and chips of olivine. B. Hydration of glass in granular chondrules leads to anhedral olivine grains. C. Condensation of olivine followed by pyroxene yields pyroxene-rich aggregates, pyroxene laths with poikilitic olivine and some pyroxene-poor aggregates. D. Condensation of olivine leads to pyroxene-free aggregates, euhedral olivine crystals and their fragments.

poikilitic grains inside pyroxene. Laths of pyroxene, some containing poikilitic olivine, accrete onto the outsides of the olivine-rich clusters, perhaps during condensation, to form pyroxene-rich aggregates. Occasionally, pyroxene laths cluster together without any free olivine to form pyroxene-rich aggregates lacking olivine-rich cores. Some laths may fail to accrete altogether, but instead, undergo collisional fragmentation to form single, broken crystals of pyroxene with olivine inclusions which are found in the matrix. These, together with broken pieces of both pyroxene-poor and pyroxene-rich aggregates, can also form by fragmentation of the latter. Finally, low-temperature alteration of olivine and pyroxene to phyllosilicates occurs at the margins of all these objects and in the interstices between the crystals in the aggregates. All of the aggregates produced in this scenario occur in Murchison; the pyroxene-rich aggregates are, by far, the most abundant.

Fig. 8D. This scenario begins in the same way as that described in Fig. 8C. In this case, however, olivine grains fail to react to form pyroxene. Some cluster into pyroxene-free aggregates, while others remain as isolated fragments and euhedral crystals. Later reaction to form phyllosilicates occurs as above. It is necessary to propose this scenario, in addition to that illustrated in Fig. 8C, in order to produce isolated, euhedral olivines which have not reacted to form pyroxene. Such crystals, though rare, are, nevertheless, conspicuous in Murchison.

The conversion of olivine to pyroxene in Fig. 8C is an equilibrium process. Why it did not occur in the scenario described in Fig. 8D requires comment. One possibility is that the gas temperature dropped very rapidly through the pyroxene stability field in the region of the nebula where these euhedral olivines originated. Another is that the euhedral olivines were transported rapidly from their condensation site to a lower-temperature region below the pyroxene stability field. Oxygen isotopic data [9] support the latter idea, in that olivine and pyroxene in C2's appear to have condensed in a different region from the phyllosilicates.

The result of this analysis is as follows. While the process illustrated in Fig. 8A and B can take place, they cannot generate euhedral olivine crystals, nor can they generate the most common type of inclusion seen, namely, rounded, poikilitic olivine grains in pyroxene with some interstitial phyllosilicates. These processes encounter additional difficulties in the light of some other observations we have made. First, because fragments make up 21 volume % of Murchison and chondrules only constitute <0.5%, the process of chondrule hydration and degradation envisioned by Richardson and McSween [6] must have been extraordinarily efficient, requiring >97% conversion of chondrules to fragments. Second, Richardson and McSween regard hydration of interstitial glass in chondrules as an important factor in lowering the mechanical strength of the chondrules and promoting their degradation. Yet, we have observed that barred olivine chondrules in which the glass is hydrated show a strong tendency to break across the bars, rather than through the soft phyllosilicates parallel to them, as shown in Fig. 9. This suggests that the hydration mechanism is not as crucial as Richardson and McSween believe. In this regard, we note an apparent inconsistency between this process and the one proposed by McSween [5] for C3(O) chondrites. In that paper, McSween argues that isolated olivine fragments formed during breakup of chondrules; however, there is no evidence whatsoever for hydration of the glass in chondrules of these meteorites.

The end result of the process illustrated in Fig. 8B and D can be identical if no euhedral olivine grains are present initially in the one shown in 8D. That is, an aggregate of anhedral olivine fragments with interstitial phyllosilicates, or anhedral olivine grains isolated in the matrix, can result from either process. There is probably no petrographic way to tell them apart. Only the process in Fig. 8D, however, can result in euhedral crystals of olivine in either aggregates or isolated in the matrix.

5. Observations

5.1. Grain size distribution

The sizes of olivine grains in different petrographic settings provide additional constraints on their modes of origin. The sizes of aggregates, olivines within them, barred chondrules and isolated olivines in the matrix were measured in Murchison with a calibrated reticule while traversing approximately 290 mm^2 of three ultrathin polished sections in a rectangular grid pat-

Fig. 9. Fragment of barred olivine chondrule in Murchison. The glass has been converted to green phyllosilicates. Apparently, this process did not facilitate breakage of the chondrule, since the fracture surface does not run along a phyllosilicate bar. Instead, it cuts across bars.

tern. In addition, granular chondrules and isolated euhedral olivine crystals were excavated from hand specimens and their dimensions measured. Polished sections were made of these chondrules and the olivines within them were measured. The longest and shortest dimensions of each object were averaged. These data are summarized in Table 2 and illustrated in Fig. 10.

Isolated euhedral olivine crystals in the matrix range from 53 to 1100 μm in size. Isolated anhedral

TABLE 2

Sizes of objects in Murchison (in μm)

	Isolated olivine grains in matrix (>2 μm)		Whole chondrules	Olivine grains in chondrules	Whole aggregates	Olivine grains in aggregates	
	euhedral	anhedral				pyroxene-rich	pyroxene-poor
Range	53–1100	2–318	175–1081	2–135	47–1239	4–308	12–234
Mean	267	34	420	15	223	36	36
Sample size	12	305	27	632	99	191	73

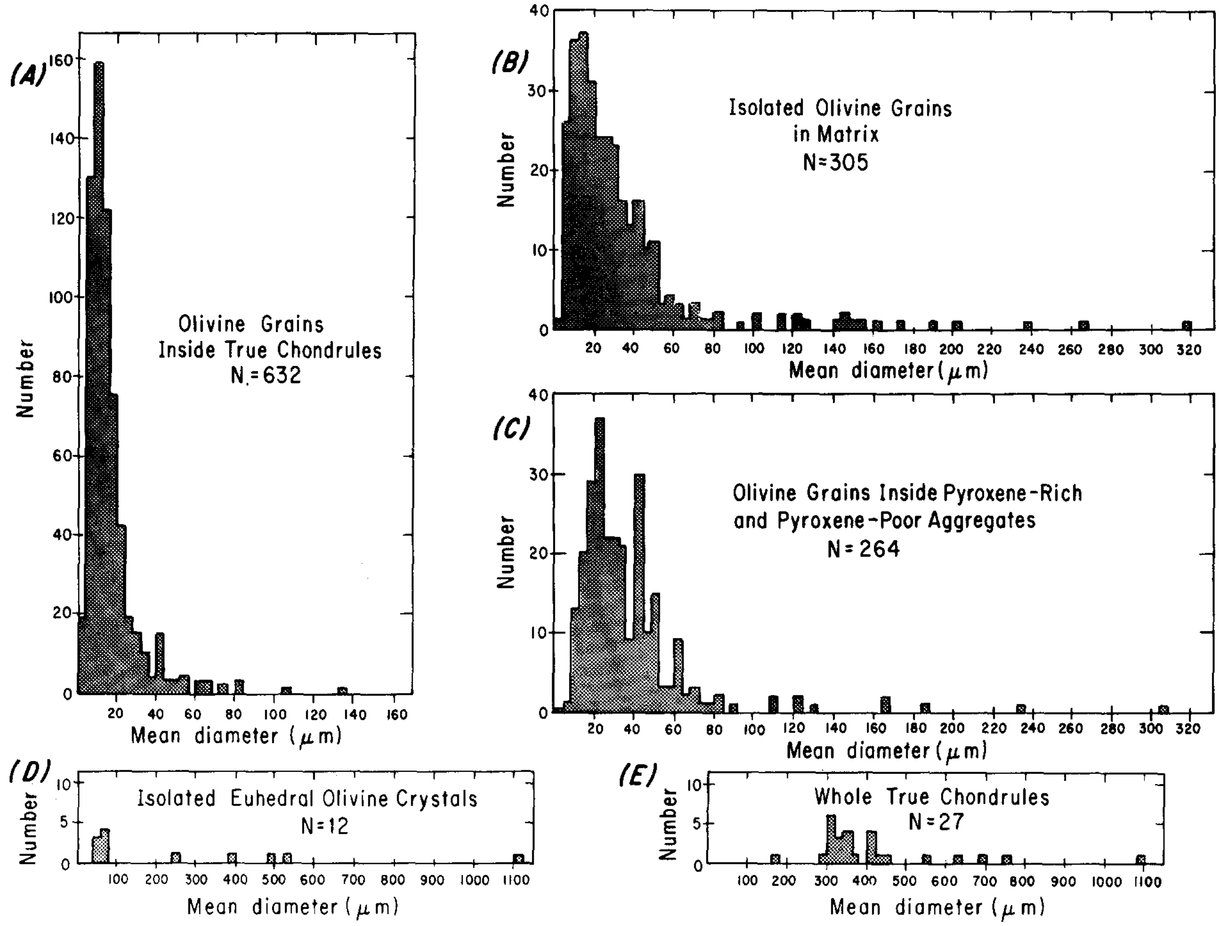

Fig. 10. Grain size distributions of olivines in various petrographic settings in Murchison. Isolated olivines and olivines in aggregates have distributions which are similar to one another, but different from that for chondrule olivines. Isolated euhedral olivines are sometimes very large. One is larger than the largest entire chondrule found.

fragments in the matrix range downward to submicrometer sizes; however, it was only feasible to measure those grains >2 μm. The average size of these is 34 μm, but the true average of the entire population of fragments must, of course, be less than this. Because of the ways in which they were sampled, the relative proportion of euhedral olivine crystals to anhedral fragments reported here (Fig. 10) is not a true measure of their relative abundance in the bulk meteorite. In fact, we believe that euhedral crystals are relatively under-represented in this study.

The largest true chondrule found thus far is 1081 μm and is made up of olivine grains necessarily smaller than that. Twenty-seven chondrules range from 175 to 1081 μm in diameter. Six hundred and thirty-two olivine grains, none euhedral, within the 21 granular chondrules among these average 15 μm in size, considerably less than that for the fragments in the matrix. There are two reasons for this. The grain size distributions shown in Fig. 10A, B for both types of olivine are characterized by long tails stretching out to large sizes. The tail for the isolated olivines is longer than that for those inside chondrules, with 4% of the isolated ones larger than the largest chondrule olivine. Furthermore, although large numbers of olivines of both types have sizes between 4 and 20 μm, 80% of those inside chondrules are <20 μm, while only 43% of the isolated ones are <20 μm. It is highly unlikely that the grain size distribution of the angular olivine fragments in the matrix was produced by the breakup of granular chondrules, even if no comminution of the olivines takes place during this process, because most of the matrix olivines are larger than most of the chondrule olivines. Even stronger arguments can be made against such an origin for the isolated euhedral olivines. All twelve of those measured are >52 μm in size, while only 2% of chondrule olivines are bigger than this. In fact, one isolated euhedral olivine crystal is larger than the largest entire chondrule found! Furthermore, these euhedral crystals cannot be made by fragmentation of chondrules that contain within them only anhedral grains.

Barred olivine chondrules are another type of chondrule found rarely in Murchison. These contain 4–20 μm thick forsterite plates interlaminated with glass. Lengths and widths of the plates are comparable to the diameters of these chondrules, 175–450 μm. It is conceivable that breakup and comminution of this kind of chondrule could have produced the grain size distribution of the angular olivine fragments, but again *no* euhedral olivines can result.

Pyroxene-rich and pyroxene-poor aggregates contain olivines with similar size-frequency distributions. Their combined grain size distribution, shown in Fig. 10C, is characterized by a broad peak between 10 and 50 μm and a long tail to 310 μm. This distribution is quite similar to that for the isolated matrix olivines, although there is a tendency for the latter to be slightly smaller. While 43% of the isolated grains are <20 μm in size, only 24% of the olivines in aggregates are smaller than this. This could be accounted for if olivines which aggregated and those which did not initially had similar grain size distributions and if some of the matrix olivines suffered additional fragmentation during breakup of aggregates.

We have seen that breakup and comminution of barred chondrules can produce the grain size distribution observed among anhedral olivine fragments in the matrix of Murchison. Similarly, these processes, acting on the aggregates, can account for the smaller olivine fragments. But neither the shapes nor the sizes of the isolated euhedral olivines can be produced by breakup of chondrules or aggregates. These crystals must have been produced by an independent process. Grossman and Olsen [3] and Olsen and Grossman [4] argued that this process was direct condensation from the solar nebula and suggested detailed explanations in terms of this process for the Ca-, Al-rich glass beads and particularly the Cr-rich metal grains contained within the olivines. In fact, no other process has been proposed to account for the compositions of these metal grains. Since the same Ca-, Al-rich glasses and Cr-rich alloys are also found in the isolated, anhedral olivine grains, we suggest that the latter originated simply by fragmentation of the isolated euhedral olivine crystals, as illustrated in Fig. 8D. This scenario is in distinct contrast to the origin suggested by Richardson and McSween [6] who postulated that all the isolated olivines in C2 meteorites were produced by the breakup of chondrules.

True chondrules contain metal beads with the same characteristic Cr-rich compositions as those in the isolated fragments. We do not believe that this should be taken as evidence that chondrules were the progenitors of the isolated olivines for, as argued above, this is precluded on other grounds. In our model, the source material for chondrules consists of aggregates and individual olivine grains, both of which contain Cr-rich metal condensate inclusions. During chondrule formation, rapid, isochemical melting would produce immiscible metal melts which would crystallize into metal beads having the same compositions as their metal precursors.

5.2. Morphology

It appears that Richardson and McSween [6] regard some of the aggregates as altered true chondrules and that such "chondrules" are the major source for isolated olivine grains in the matrix. In addition to the fact that the sizes of the isolated, euhedral olivines cannot be accounted for by breakup of aggregates, several other objections appear. First, as pointed out earlier, aggregates are most often highly irregular in shape (Fig. 1). Chondrules observed in C2's, on the other hand, are spherical or ellipsoidal. It could be argued that the irregular shapes of the aggregates are due to abrasion and breakage of once-spherical chondrules. Certainly, small fragments of the abundant pyroxene-rich aggregates can be recognized as such in the matrix of Murchison by their poikilitic textures. On the other hand, broken fragments of objects known to be true chondrules on the basis of their barred and radiating textures are still recognizable as segments of spheroidal objects retaining portions of their original curved rims (Fig. 9). If aggregates were once true chondrules, it is puzzling that they break by chipping from their edges, destroying their original rounded outlines, while obvious true chondrules are transected, leaving circular segments. Second, aggregates generally contain only small, discontinuous patches of phyllosilicates. An essential feature of the Richardson-McSween model is that the absence of interstitial glass in aggregates is due to its alteration to phyllosilicates. If these aggregates were indeed originally chondrules, we can only conclude that these "chondrules" had remarkably little interstitial glass. Furthermore, the size-frequency distribution of olivine grains in granular chondrules is substantially different from that of olivines in aggregates (Fig. 10). Eighty percent of chondrule olivines are <20 μm in size, but only 24% of olivines in aggregates are smaller than this. To account for this, Richardson and McSween would have to argue that only the finer-grained chondrules escaped complete alteration, which strains credibility. Finally, we recall the pyroxene rims so common in the abundant pyroxene-rich aggregates. If these objects were once true chondrules, i.e. quenched molten droplets, cooling and crystallization would have begun on the outside and proceeded inward with time. This would imply that the poikilitic olivines in the rim regions crystallized first, then the pyroxenes which enclose them and, finally, the olivine in the cores. Such a crystallization sequence, low-iron pyroxene followed by low-iron olivine, is completely at variance with any known phase diagram and, in fact, cannot even be accounted for by any non-equilibrium crystallization path. We conclude on the basis of all these facts, that aggregates were never chondrules.

Let us examine critically the evidence used by Richardson and McSween [6] to support their model of a chondrule origin for all isolated olivine grains in C2 meteorites.

They refer to the work of Olsen and Grossman [4] who suggested that surface decorations on crystal faces of isolated euhedral olivines in Murchison were produced during condensation from a solar nebular gas. That work showed that crystal faces of lunar and terrestrial magmatic olivines are smooth, while those of a terrestrial sublimate olivine are patterned. Richardson and McSween attempt to weaken this argument by citing examples of chondrule olivines in Murchison with the same decorations. First, they illustrate the edge of a bar from a barred olivine chondrule and state that it shows a surface pattern "similar to the surfaces of crystals suggested to be vapor condensates". We reproduce here their fig. 12, our Fig. 6A, alongside a photomicrograph of the kind of surface pattern discussed in our 1974 paper, Fig. 6B. This comparison shows clearly that neither the scale nor the complexity of the features in their photograph approach those that we illustrate here and discussed in 1974. Furthermore, insufficient information is given in their paper for us to judge whether the surface they illustrate is an indexable crystal face or merely an uneven fracture surface. Fig. 6C, a higher magnification view of a portion of Fig. 6B, shows that the parallel ridge pattern seen in the latter figure persists on a very fine scale. Also, in their fig. 5, they show a scanning electron photomicrograph of a euhedral olivine projecting from the surface of a broken "porphyritic chondrule" and surrounded by phyllosilicates. They state, and we agree, that its surface, illustrated in their fig. 6, is decorated in the same way as the isolated euhedral olivines. Where we differ is in the genetic interpretation of this olivine and the object in which it resides. We have never seen a euhedral crystal in any kind of true chondrule. They are all anhedral. Broken aggregates, however, occasionally do show olivine euhedra projecting from them, just as Richardson and McSween illustrated. It is apparent that the object they have illustrated is not a true chondrule, but is what we call an aggregate. The difference between these is not merely semantic. Olivines from true chondrules crystallized from a melt. From the arguments discussed above, aggregates are neither altered true chondrules nor are they assemblages of olivines released from altered true chondrules. Rather, we believe that the aggregates are clusters of vapor condensates. Indeed, Richardson and McSween themselves are troubled by this possibility, for they state, "The model we are advocating obviously depends on our *assumption* (our italics) that objects such as in (their) fig. 1 are altered true chondrules, rather than mechanically rounded olivine aggregates". In other words, they do not *know* for any petrographic, physical or chemical reasons whether the inclusions they studied are chondrules or not. Olsen and Grossman did not photograph crystal surfaces from aggregates, but only from euhedral crystals isolated in the matrix. Aggregates of euhedral crystals that condensed from a gas and then aggregated in the manner described in Fig. 8C would be expected, of course, to have the same crystal surface features as euhedral crystals that did not end up in aggregates.

5.3. Glass

Fuchs et al. [2] discovered blebs of glass included in both isolated and aggregated olivines in Murchison. They noted that the compositions of these glasses are not in equilibrium with olivine at liquidus temperatures and concluded that the glasses cannot be bits of melt trapped during magmatic crystallization. In addition, Fuchs et al. noted that within single olivines are glass blebs with substantially different compositions, an observation difficult to explain by the hypothesis that the glass represents trapped, complementary melt. Moreover, Fuchs et al. also found an olivine grain with a single glass inclusion which contains an interface separating two different compositions of glass on either side. This is even more difficult to explain as trapped melt. Several characteristics of these glass inclusions thus argue against their origin as blebs of complementary magma and, therefore, against crystallization of their host olivines from a chondrule melt.

If, however, the glass blebs are original condensates from a solar nebular gas or the products of nebular melting of solid condensates as suggested by Fuchs et al. [2] and Grossman and Olsen [3], one glass bleb, formed at one time and place, could contact and adhere to another bleb formed at a later time and/or different place. At temperatures above the condensation point of olivine, glasses of these compositions would still be plastic. Such an event must have been rare, for only one instance of the adhesion of two glasses to one other has been seen. Single olivine grains having discrete glass bleb inclusions of different compositions occur more often, indicating that condensing olivine nucleated on previously formed glass beads and incorporated beads during growth. The beads are very small, ranging downward from 36 μm to a few micrometers. Many of them, especially the smaller ones, are nearly spherical. The larger ones, however, are often distorted in shape, stretched and elongated [2]. At the condensation temperature of forsterite, 1430°K at 10^{-3} atm, glasses in this composition range would still be plastic and distortion during crystallization of overgrowing olivine, especially parallel to crystallographic surfaces, might be expected.

In objects which he regarded as chondrules in C3(O) chondrites, McSween [5] analyzed glass inclusions in olivine and glass interstitial to olivine and found these to be similar in composition to one another. He concluded that the glass inclusions originated as trapped, complementary melts and suggested that this origin be extended to the glass in C2 olivines because of what he considered to be similarities between these compositions and those reported by Fuchs et al. [2] for glass inclusions in Murchison olivines.

Table 1 compares the average composition of McSween's C3 glasses with that of the fourteen glasses from Fuchs et al. [2]. Contrary to McSween's contention, significant differences exist between these compositions. Specifically, Na_2O is higher in the average of the C3 glasses by a factor of 15, FeO by a factor of 4 and MgO by nearly 40%. In addition, CaO is higher in the average of the C2 glasses by 38% and Al_2O_3 by 10%. In Fig. 11 we have plotted weight percent Na_2O against weight percent CaO for the individual analyses of the nine C3 glasses of McSween [5] and the fourteen C2 glasses of Fuchs et al. [2]. These data points fall into two distinct and well-separated groups; there is no overlap. Thus, it is unwarranted for McSween to extend his model for C3 meteorites to C2's on the basis of what he regards as "similar" compositions of glass inclusions in olivines.

As noted already, McSween [5] shows that the compositions of interstitial glass and glass inclusions in C3 chondrules are similar. They fall into a relatively small area in a triangular plot of normative olivine-anorthite-silica. In Fig. 12, the same ternary used by McSween [5], we have plotted eight analyses of *interstitial* glasses in four true chondrules in Murchison and fourteen glass *inclusions* inside olivine crystals from Fuchs et al. [2]. These plot over a considerably wider range than McSween's plot for C3's. The glass inclusions in Murchison show a clustering of ten points in the same region as McSween's C3 glasses; however, four analyses are more silica-rich than his. Only one of the true chondrule interstitial glasses plots close to the region of McSween's C3 glasses,

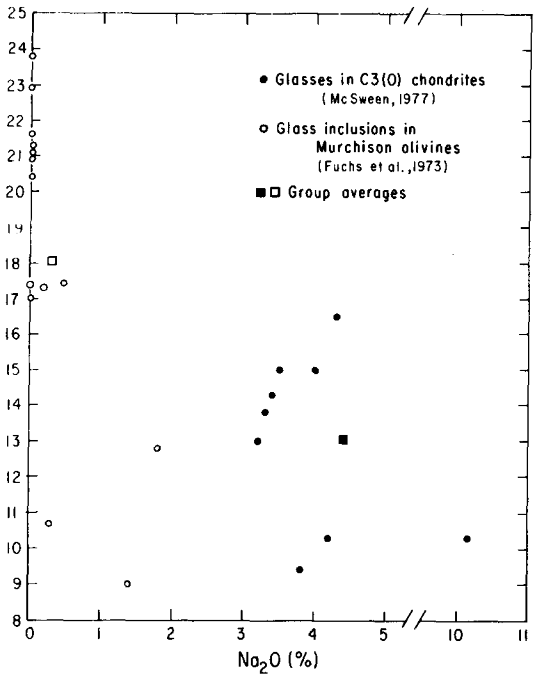

Fig. 11. Very large differences in composition exist between the glasses in C3(O) chondrites reported by McSween [5] and those glass inclusions in Murchison olivines reported by Fuchs et al. [2].

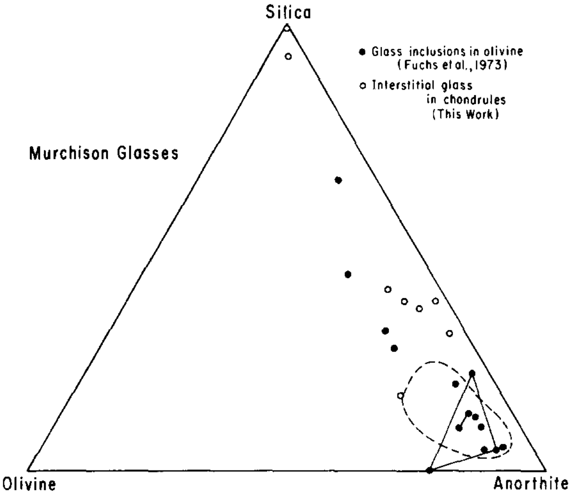

Fig. 12. In Murchison; glass inclusions in olivine have different compositions from interstitial glasses in chondrules. Lines connect glass compositions found within single olivine grains. The dashed region outlines the field of C3(O) glasses reported by McSween [5].

while five plot in a higher-silica area and two analyses plot close to the silica apex. Although both types of glass show a wide range of SiO_2 contents, it is apparent that the majority of chondrule glasses concentrate in different regions from the glass inclusions. Incidentally, no glass inclusions were observed by us within olivine grains in true chondrules. They are, however, not precluded.

From the comparison of these glasses, it is clear that 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, melted chondrules. The high Ca and Al contents in the glass blebs are similar to those of high-temperature condensates [10]. The high-silica, low-lime, interstitial glasses in true chondrules show some similarities to high-silica glasses that are fractionated from shock-formed melts in ordinary chondrites [11,12].

By virtue of the data plotted in Figs. 11 and 12, and the averages listed in Table 1, it is clearly impossible to relate McSween's [5] arguments for C3 meteorites to C2's on the basis of glass compositions. Because McSween [5] argues that "evidence for C1 and C2 olivines having crystallized from a melt accrues primarily from the presence of glass inclusions and similarities in composition to chondrule olivines", we are forced to agree with him that "there is no petrographic evidence that C2 olivine aggregates were ever molten". In his next paragraph, McSween goes on to say "some similarities between olivines in C1 and C2 meteorites and those in C3(O) chondrites may suggest that olivines in all the carbonaceous chondrites formed by the same mechanism, that of crystallization from a chondrule melt, but other petrographic data argue against this hypothesis." It is clear from his statements that McSween himself is unsure of the extension of his argument from C3 to C2 meteorites. The dissimilarities in glass compositions and other petrographic differences between these two types of chondrites rule out application of his model to C2 meteorites. We favor an origin by direct condensation, as discussed in Grossman and Olsen [3] and Olsen and Grossman [4].

6. Conclusions

On the basis of the foregoing data and discussion, it is clear that the great majority of isolated olivine grains in the matrix of C2 meteorites like Murchison never underwent melting in a chondrule-making stage, as envisioned in the model of Richardson and McSween [6]. These isolated crystals, isolated crystal fragments and aggregates can be accounted for in a most straightforward manner by direct condensation from a solar nebular gas. As such, their trace element and isotopic compositions and other features are directly related to condensation processes.

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