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Partial melting and melt migration in the acapulcoite-lodranite parent body

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Abstract—We review petrologic evidence that the acapulcoites and lodranites formed by <1 vol% to probably >20 vol% whole rock partial melting of a chondritic precursor material. At low degrees of partial melting, only Fe,Ni-FeS cotectic melting occurred. Migration distances for partial melts were short, resulting in the formation of acapulcoites with essentially chondritic troilite and plagioclase contents, but achondritic textures. At high degrees of partial melting, both Fe,Ni-FeS and basaltic (plagioclase-pyroxene) partial melts formed, and the melts may have migrated out of the source rock. The partial melt residues, which are more or less depleted in Fe,Ni-FeS and plagioclase, are the lodranites. Melt migration was complex: most acapulcoites, which experienced relatively low degrees of partial melting, lost little if any of the partial melt. One acapulcoite, LEW 86220, represents a unique case in which Fe,Ni-FeS and basaltic partial melts appear to have migrated from a lodranite source region into a cooler acapulcoite region, where they were trapped. In cases of the relatively high degrees of partial melting experienced by lodranites, melts may have been partly, selectively, or totally removed from the rocks, and Fe,Ni-FeS and/or basaltic partial melts may have been removed to different degrees and may, in fact, have been trapped on occasion in greater than chondritic proportions. We model vein and dike formation and melt migration by calculating the excess pressures and vein and dike sizes for varying degrees of partial melting. Our calculations are broadly consistent with observations, indicating that melt migration is inefficient at low degrees of partial melting and extremely efficient at high degrees of partial melting. Although the size of the acapulcoite-lodranite parent body and the volatile contents of the chondritic precursor rocks are poorly constrained, the lack of basaltic rocks in the world's meteorite collections complementary to the lodranites suggests that basaltic partial melts may have been accelerated off the body by explosive volcanism of the type envisioned by Wilson and Keil (1991) and ejected into space. The diversity of rocks from the acapulcoite-lodranite parent body may provide a basis for better understanding the diverse range of spectral subtypes recognized among the S-type asteroids. *Copyright* © 1997 Elsevier Science Ltd

1. INTRODUCTION

Recent studies of acapulcoites and lodranites (e.g., McCoy et al., 1996, 1997, and references therein) were aimed towards understanding the genesis of these rocks and the petrologic history of their parent body. From such studies, a number of general findings and conclusions have become apparent: acapulcoites and lodranites have essentially identical oxygen isotopic compositions and, on this basis, can be distinguished from other meteorites, including winonaïtes and ureilites (e.g., Clayton et al., 1992); acapulcoites and lodranites also have similar mineralogies, mineral compositions, thermal histories, and cosmic ray exposure ages. These data suggest that acapulcoites and lodranites are rocks from a common parent body. Furthermore, acapulcoites are relatively fine-grained and tend to have chondritic proportions of troilite and plagioclase, whereas lodranites are relatively coarse-grained and tend to be depleted in troilite and/or plagioclase relative to chondritic precursor rocks. In general, plagioclase and troilite contents are related to the degree of partial melt-

ing that these rocks experienced and to the degree of extraction of partial melts from these rocks. Acapulcoites and lodranites are the residues of partial melting, with acapulcoites having been heated to temperatures sufficiently high for Fe,Ni-FeS cotectic melting to take place, but not high enough for silicate partial melting. Lodranites were heated sufficiently to experience both Fe,Ni-FeS cotectic and silicate partial melting (e.g., McCoy et al., 1997). This heating and incipient partial melting of acapulcoites and lodranites took place early in the history of the solar system, as is indicated by ancient ³⁹Ar-⁴⁰Ar ages of two acapulcoites of 4.51 (Acapulco) and 4.52 Ga (Monument Draw), and of one lodranite of 4.49 Ga (Gibson; Bogard et al., 1993). Cooling from high temperature was rapid and possibly complex. Finally, it should be noted that nine acapulcoites are known representing five fall events and twelve lodranites representing ten distinct fall events. Thus, acapulcoites and lodranites are a numerically significant group of meteorites.

In this paper, we study the processes of partial melting and melt migration in the acapulcoite-lodranite parent body. We model the processes of crack and dike formation and melt migration as a consequence of heating (after the model developed by Wilson and Keil, 1991, 1996a,b; Muenow et

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al., 1992, 1995; Keil and Wilson, 1993), compare the results of these calculations with observations, and explore the migration of these melts within and from the source regions. We also examine meteorites in which partial melts appear to have been trapped, such as LEW 86220, which we interpret to be an acapulcoite whose excessively high Fe,Ni metal, troilite, and plagioclase contents suggest that it served as a trap for Fe,Ni-FeS cotectic and basaltic partial melts produced elsewhere on the acapulcoite-lodranite parent body. We also consider the fate of partial melts which reached the surface of the parent body. We suggest that the acapulcoite-lodranite parent body was sufficiently small and that volatile contents of the putative chondritic precursor material of the acapulcoites-lodranites were sufficiently high that a significant proportion of the basaltic partial melts may have been driven off the parent body by explosive volcanism. We also measured volatile contents in Acapulco and Lodran to gain insight into the fate of volatiles with increasing degree of partial melting. Finally, we use the diversity of rocks on the acapulcoite-lodranite parent body, which appear to have resulted from different degrees of partial melting, in an attempt to interpret the composition and parentage of S-asteroids.

2. SAMPLES AND TECHNIQUES

Because of its unique composition, we studied LEW 86220 in detail by examining polished thin section LEW 86220,4 in transmitted and reflected light and by determining mineral compositions with Cameca Camebax and Cameca SX-50 electron microprobes at the University of Hawaii; corrections were made using a manufacturer supplied PAP ZAF program. Natural and synthetic minerals of well-known compositions were used as standards. The maximum dimensions of twenty-five mafic silicate grains in the acapulcoite host of LEW 86220,4 were measured to determine the average grain size of this lithology. Of these grains, twenty-three were randomly selected, and we also sought the largest and smallest grains. Inclusion of these grains did not significantly affect the average grain size. Olivines poikilitically enclosed in pyroxenes were not included in these measurements, since they did not grow by the same mechanism as other grains. Polished thin sections LEW 86220,3 (JSC) and, 2 (Smithsonian) and the main mass of the Smithsonian stone were also briefly examined: all have similar textures. The volatile contents of a sample of Acapulco (81.59 mg) and one of Lodran (80.35 mg) were determined using dynamic high-temperature mass spectrometry following the procedures of Muenow et al. (1992).

3. PARTIAL MELTING AND MELT MIGRATION IN THE ACAPULCOITE-LODRANITE PARENT BODY

We and others have previously shown that acapulcoites and lodranites have experienced a wide range in their degree of partial melting as a result of heating by nonimpact related processes, and we estimated the degree of partial melting experienced by individual meteorites (McCoy et al., 1996, 1997, and references therein); details for individual meteorites and arguments against shock melting are, therefore, not repeated here. Although acapulcoites and lodranites appear to represent a continuum in their degrees of partial melting, we found it useful for modeling and descriptive purposes to group these rocks rather arbitrarily into four groups, representing, respectively, <1, 2–3, ~5, >10% partial melting of the whole rock. We should hasten to add that these groupings are at times somewhat obscured, because while rocks

may have experienced partial melt removal, they have occasionally been infiltrated by migrating melt, independent of the degree of partial melting the rocks themselves have experienced. This complicates estimation of the degree of partial melting which, in fact, is based not only on texture, but also on abundance of partial melt products such as Fe,Ni-FeS cotectic and plagioclase (basaltic) partial melts. We will make reference to these subtleties below and return to this point later when discussing LEW 86220. For each of the four groups, we briefly examine the petrologic features indicative of partial melting and melt migration, list the meteorites in this category, and compare the results of modeling of partial melting and melt migration with the petrographic evidence. Photographs of thin sections and hand specimens of typical examples of each category of degree of partial melting are shown in Fig. 1.

Modeling of crack formation and propagation and migration of melt given below follows the computational models of Wilson and Keil (1991, 1996a,b), Muenow et al. (1992), and Keil and Wilson (1993). These authors showed that expansion due to partial melting creates pressures in rocks that can be accommodated first by migration of gas and/or melt into voids (if any are present) and then by elastic compression of both the liquid and the solid. This compression requires the development of a pressure in excess of the ambient compressive stress level, and when this excess pressure exceeds a value closely related (Rubin, 1993) to the tensile strength of the rocks, typically ~5–15 MPa (Jaeger and Cook, 1979), the rocks will fracture and crack formation will begin. With increasing degrees of partial melting, cracks will grow, propagate (Pollard, 1987), and become interconnected. Eventually, very large liquid-filled cracks (dikes) will reach the surface, where eruptions will occur. Even very small amounts of gas present in the erupting melt will cause explosive disruption in the absence of a significant atmosphere. If the gas content is large enough, eruption velocities will exceed the escape velocities of asteroid-sized meteorite parent bodies, and melts will leave the parent body.

3.1. <1 vol% Partial Melting

3.1.1. Observations

Most acapulcoites have approximately chondritic modal abundances of troilite and plagioclase and, thus, experienced very low degrees of partial melting (McCoy et al., 1996). Fe,Ni metal and troilite veins in acapulcoites are 1–5 μm in width and $\leq 140 \mu\text{m}$ in length and crosscut all silicate phases, including plagioclase, indicating the formation of small amounts of Fe,Ni-FeS cotectic partial melt. The veins are not intimate mixtures of Fe,Ni metal-troilite but discrete segments of these two phases, probably formed during immiscibility of the two components upon cooling. A consequence of this segmented texture is that some veins appear in the plane of the thin section as only troilite or, more rarely, only Fe,Ni metal. These veins are very similar to those produced during heating for 1 week at 900°C of the Krymka (L3) chondrite (Ikramuddin et al., 1977; McSween et al., 1978).

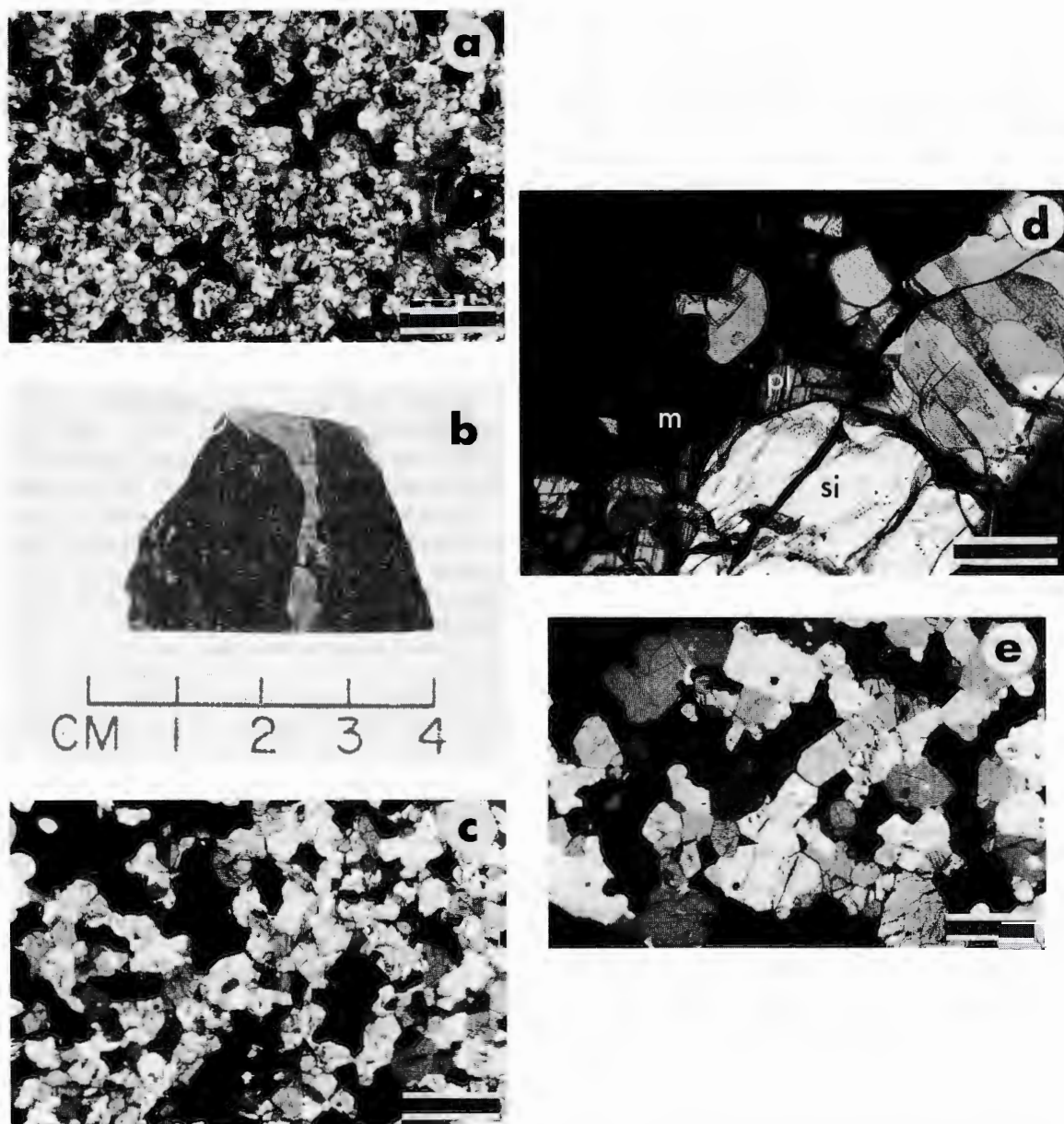


Fig. 1. Transmitted light photomicrographs in crossed polars (a), (c) to (e) and macrophotograph (b) of examples of acapulcoites and lodranites that have experienced different degrees of partial melting. (a) Acapulco. This and most acapulcoites experienced <1 vol% partial melting, with melting at the Fe,Ni-FeS cotectic, but no silicate partial melting. Melt migration distances are small (tens of μm), and the bulk compositions of the rocks remained mostly unchanged. Grain growth in the absence of silicate partial melting was limited, resulting in a relatively fine-grained rock. Scale bar = 1 mm. (b) Hand sample of the acapulcoite Monument Draw, in which partial melting of the Fe,Ni-FeS cotectic reached ~ 3 vol%. The Fe,Ni-FeS cotectic melt migrated into μm - to cm-sized veins. Silicate partial melting did not occur. (c) The lodranite EET 84302 experienced ~ 5 vol% partial melting. This rock is severely depleted in FeS, suggesting removal of nearly the entire volume of the Fe,Ni-FeS cotectic melt. Plagioclase textures suggest silicate partial melting and very local migration of a basaltic (plagioclase-pyroxene) partial melt. Grain growth was more efficient in the presence of a silicate partial melt, resulting in a medium-grained rock. Scale bar = 1 mm. (d) Lodranite Yamato 8002 experienced >10 vol% partial melting, with removal of almost the entire Fe,Ni-FeS cotectic melt as well as extensive formation of a basaltic (plagioclase-pyroxene) partial melt. The latter migrated to fill areas between mafic silicates, as evidenced by plagioclase grains (pl) interstitial to Fe,Ni metal (m) and silicates (si). Dark material to the upper left is epoxy. Scale bar = $250 \mu\text{m}$. (e) Lodran experienced >20 vol% partial melting and is depleted in troilite and devoid of plagioclase, indicating very efficient removal of the Fe,Ni-FeS cotectic and the basaltic melts. Extensive partial melting fostered grain growth so that the partial melt residue (Lodran) became coarse-grained. Scale bar = 1 mm.

The crosscutting relationship between the Fe,Ni-FeS veins and plagioclase in Acapulco implies that temperatures were insufficient to melt silicates. The small average grain sizes of mafic minerals of acapulcoites (150–200 μm ; Fig. 1a) are consistent with the absence of silicate partial melts, which would have fostered grain growth. We note, however, that some authors (e.g., Zipfel et al., 1995) have advocated extensive silicate partial melting in Acapulco. These authors argued that one consequence of this extensive partial melting is an overabundance and inhomogeneous distribution of phosphates and commensurate fractionation of the bulk REE pattern of the rock from chondritic values. We suggest instead that the P overabundances and fractionated REE pattern are entirely consistent with low degrees (<1 vol%) of partial melting. In both Acapulco and Monument Draw (<2–3 vol% partial melting), phosphates are found as veins, often associated with Fe,Ni-FeS melts, suggesting that phosphates were mobilized during melting near the temperature of the Fe,Ni-FeS cotectic ($\sim 980^\circ\text{C}$; Kullerud, 1963). Acapulcoites may have served as traps for P-rich melts produced elsewhere on the acapulcoite-lodranite parent body, thus explaining both the P overabundance and fractionated REE patterns. A more comprehensive discussion of both viewpoints is given by McCoy et al. (1996).

If acapulcoites originally contained ~ 5 wt% troilite, the total cotectic melt (consisting of ~ 85 wt% troilite and ~ 15 wt% Fe,Ni metal; Kullerud, 1963) would comprise ~ 6.1 wt% or ~ 4.3 vol% of the rock (assuming a bulk density of ~ 3500 (Keil, 1962) and a density of the melt of ~ 5100 kg/m^3). However, petrologic studies suggest that the extent of partial melting in most acapulcoites was much less than this value. Acapulco, Yamato 74063, ALH A77081, ALH A81261, ALH A81315, ALH 78230, ALH A81187, and ALH 84190 all exhibit rare Fe,Ni metal-troilite veins which comprise <1 vol% of the whole rock. We cannot unequivocally dismiss the possibility that larger (100 μm) metal-troilite grains which occur in acapulcoites were also molten, but as yet, no supporting evidence has been found. Thus, we suggest that most acapulcoites experienced <1% partial melting.

3.1.2. Modeling

At 1% partial melting, pockets of Fe,Ni-FeS melt will form at grain boundaries. Since porosity is low, only elastic compression of the liquid and solid can compensate for the pressure increase. Partial melting of 1% would generate excess pressures of ~ 10 MPa which can exceed the tensile strength of the rock (~ 5 – 15 MPa; Jaeger and Cook, 1979), and cracks will form. At this low level of stress, crack lengths will be on the order of the grain size (~ 200 μm). Excess pressures of 10 MPa in a crack 200 μm long would result in a crack width of ~ 0.2 μm . For 10 MPa excess pressures to enlarge cracks, a 1 μm wide crack would need to be ~ 20 mm long. These modeling results are broadly consistent with the petrographic observations: Fe,Ni metal-troilite veins in acapulcoites are ≤ 140 μm in length and about 1 μm in width. The unreasonably long length needed to widen cracks at a relatively low excess pressure of ~ 10 MPa caused by ~ 1 vol% of partial melting means that most cracks would

not grow very much and, thus, the melt would be trapped in situ. As a result, no partial melt was removed from the rock and the bulk Fe,Ni-FeS and plagioclase contents of the acapulcoites would remain unchanged and chondritic, consistent with observations.

3.2. ~ 2 – 3 vol% Partial Melting

3.2.1. Observations

As is the case with other acapulcoites, Fe,Ni metal-troilite veins crosscut silicate phases in Monument Draw, indicating partial melting at the Fe,Ni-FeS cotectic, but without silicate partial melting. Thus, the degree of partial melting was certainly no more than ~ 6 wt% (~ 4.3 vol%). The presence of cm-sized metal veins in Monument Draw (Fig. 1b) implies that this acapulcoite did experience a higher degree of partial melting than most acapulcoites. Examination of the largest available hand sample indicates that the largest vein is at least 6 cm in length, but this vein has been truncated on both ends by fusion crust; the original length is, therefore, unknown. It seems unlikely that the apparent high modal abundance of Fe,Ni metal relative to troilite in the veins of Monument Draw visible in hand specimen is a measure of the degree of partial melting (high metal content would imply higher than cotectic temperatures and, hence, higher degrees of partial melting). Although troilite-rich networks are found in the silicates adjacent to the cm-sized veins, the overall ratio of troilite/Fe,Ni metal is not in cotectic proportions. In this context it is important to note that we found apparently metal-rich veins in samples of the Krymka chondrite that were heated to 900°C (McSween et al., 1978), well below the melting point of Fe,Ni metal ($\sim 1550^\circ\text{C}$). Some veins which apparently contained only Fe,Ni metal were also found in the acapulcoites which experienced <1% melting. It appears that the presence of apparently nearly troilite-free metal veins in Monument Draw, other acapulcoites, and the artificially heated samples of Krymka may be an artifact of poor sampling in two dimensions or the result of separation of the two immiscible liquids at low temperatures and does not require melting at temperatures above the Fe,Ni-FeS cotectic of $\sim 980^\circ\text{C}$. There are also Fe,Ni metal-troilite grains in Monument Draw which are not associated with this vein and, hence, were probably not molten. The presence of a significant proportion of melted and unmelted Fe,Ni-FeS suggests to us that partial melting probably reached 2–3 vol%, although this estimate carries considerable uncertainties. Monument Draw is the sole acapulcoite in this category. Note that Monument Draw, just like Acapulco, contains phosphates in proportions greater than chondritic abundances (McCoy et al., 1996). As is the case with Acapulco, some of these phosphates occur in vein-like objects and probably represent trapped liquid produced by partial melting elsewhere on the acapulcoite-lodranite parent body.

3.2.2. Modeling

Monument Draw obviously experienced significant coalescence of melt and growth of cracks. At 3% partial melting, excess pressures in grain-edge melt pockets would be

~40 MPa. Such pockets would enlarge if they were 1.25 mm in length. While most cracks would be less than this, presumably some small fraction were this size and did enlarge. At this point, enhanced melt migration would occur. If a vein were 1 mm wide and isolated, pressures of 40 MPa would point to lengths of ~250 mm. Cracks of this length would almost certainly interact with smaller cracks and pressures would decrease. If the pressure decreased to 10 MPa, veins 1 mm in width would be on the order of 1 m long, but the observed lengths of such veins in the relatively small hand specimens available provide only a minimum value for their length in the original parent body. However, it appears that the presence of cm-sized veins in Monument Draw is broadly consistent with the model calculations based on ~3 vol% partial melting.

3.3. ~5 vol% Partial Melting

3.3.1. Observations

Two lodranites, EET 84302 and Gibson, appear to have experienced ~5 vol% partial melting. EET 84302 has only 0.1 vol% troilite (with 13.1 vol% Fe,Ni metal and 11.4 vol% plagioclase), suggesting nearly complete removal of the cotectic Fe,Ni-FeS melt. This depletion suggests partial melting of at least 6 wt% or 4.6 vol%. However, there are also indications that partial melting may have gone beyond cotectic melting of Fe,Ni-FeS and may have included some silicate partial melting and the generation of a basaltic melt caused by the partial melting of some plagioclase and pyroxene. Indirect evidence for silicate partial melting comes from the grain size of the rock (340 μm ; Fig. 1c), which is significantly larger than that of acapulcoites (150–200 μm) and may reflect grain growth in the presence of a small amount of silicate partial melt. Furthermore, the shapes of some plagioclase grains, which pinch between and partially surround mafic silicates, indicate precipitation from a melt and, hence, are consistent with some silicate partial melting.

Gibson is even coarser grained (540 μm) than EET 84302 and also exhibits plagioclase that pinches between mafic silicates, indicative of some silicate partial melting. Although troilite abundances are low (0.5 vol%), the extensive weathering experienced by the rock, which contains 19.4 vol% hydrated iron oxides of terrestrial origin, places greater uncertainties on our estimate of the amount of cotectic melt that was removed, and hence, on the degree of partial melting experienced by this rock.

3.3.2. Modeling

Modeling of melt migration at degrees of partial melting in excess of 5 vol% becomes complex. With the onset of silicate partial melting, melt migration involves both Fe,Ni-FeS and basaltic partial melts. These melts would be immiscible and so one would occur as droplets within the other, whichever was present in the larger amount locally. Since the densities of these melts differ dramatically (~5100 kg/m³ for the Fe,Ni-FeS cotectic melt and ~2800 kg/m³ for the basaltic partial melt; Wilson and Keil, 1996b), they would tend to migrate to opposite ends of a given dike. If we assume that volatiles were also present in the melt, the

gas bubbles would rise through both components to the leading edge of the cracks. When two cracks intersect, a complex set of distribution conditions would arise. Thus, modeling the process of melt migration is difficult. It is clear, however, that EET 84302 must have contained significant proportions of cracks, perhaps ranging upwards in size from a few m long and a few tens of mm wide to at least 1 km long and 1 m wide, and migration and loss of the Fe,Ni-FeS melt occurred through these cracks and dikes. It is interesting to note that significant loss of the Fe,Ni-FeS melt does not occur until the onset of silicate partial melting. Apparently, silicate partial melting opens pathways that allow melt migration, thus generally resulting in a change of the bulk troilite content of the rock.

3.4. >10 vol% Partial Melting

3.4.1. Observations

Most lodranites appear to have experienced in excess of 10% partial melting, although there are considerable complications and uncertainties in estimating the precise degrees of partial melting due to incomplete and complex melt migration patterns of partial melts from meteorite to meteorite. Lodranites seem to represent the residues of partial melting of a chondritic source material, where partial melt removal, in spite of uniformly high degrees of partial melting of >10 vol%, ranges from very little to nearly complete removal of partial melts. An example of a rock where partial melts may have nearly completely migrated out of a lodranite, leaving a rock depleted relative to chondrites in troilite and plagioclase, is MAC 88177. This rock contains no plagioclase and only 1.9 vol% troilite (McCoy et al., 1997). In other cases, silicate (plagioclase-pyroxene) basaltic partial melts may have been largely removed, whereas some portions of the Fe,Ni-FeS partial melts have been retained. Examples in this category are Lodran (Fig. 1e), Yamato 74357, LEW 88280, FRO 90011, Yamato 791491, and Yamato 791493 (paired), which are highly depleted in plagioclase (mostly zero to trace amounts; one meteorite; Yamato 791493 1.6 vol%), but have only moderately depleted modal troilite contents (2.4–4.1 vol%; McCoy et al., 1997) and bulk S concentrations (Dreibus et al., 1995). In these lodranites, removal of the silicate partial melt alone would account for >15 vol% partial melting (assuming 10 vol% plagioclase in the precursor material and a basaltic partial melt with >55% plagioclase, depending on the plagioclase composition; McCoy et al., 1997). Other rocks are somewhat depleted in plagioclase and are strongly depleted in troilite. For example, Yamato 8002 and Yamato 75274 (paired) contain 6.9 vol% plagioclase but only 0.2 vol% troilite (McCoy et al., 1997). The strongest evidence for silicate partial melting in these relatively plagioclase-rich lodranites comes from plagioclase textures: numerous plagioclase grains in these rocks poikilitically enclose mafic silicates, indicating that basaltic (plagioclase-pyroxene) partial melts occupied much of the interstitial portions of lodranites like Yamato 8002 (Fig. 1d). The coarse grain size of these lodranites (700 μm) is also consistent with significant grain growth in the presence of a silicate partial melt. The depletions in troilite, together with signifi-

cant silicate partial melting as indicated by plagioclase textures, suggests that these lodranites experienced in excess of 10% partial melting.

Clearly, migration of partial melts in the lodranite source region was a very complex process. We should add that the above conclusions are based on two assumptions, namely that the precursor material to the lodranites had roughly similar troilite and plagioclase contents as the ordinary chondrites and that these constituents were relatively homogeneously distributed throughout the chondritic precursor material of the lodranites. We and others have previously argued in favor of the former assumption (e.g., McCoy et al., 1997, and references therein), and we suggest that the latter assumption is also reasonable. We base this assertion on the apparent relative homogeneous nature of the parent bodies of the ordinary chondrites, as suggested by the relatively homogeneous nature of H, L, and LL chondrites (e.g., Keil, 1962; Jarosewich, 1990).

3.4.2. Modeling

Modeling suggests that for >10 vol% partial melting, melt migration should have been extremely efficient (see Introduction above). Pressures within melt pockets would have been ~100–300 MPa (in the range of 10–20% partial melting), and all melt pockets with initial lengths greater than 100 μm would have grown. Since the grain size of the lodranites prior to the onset of silicate partial melting would have been in excess of this value, as judged by the grain size of acapulcoites, almost all of the melt pockets would have grown considerably. As a consequence, a very efficient network would have formed and melt migration would have occurred. At ~20 vol% partial melting, melt migration would have more closely resembled porous flow, rather than migration through isolated or interconnecting conduits.

As discussed in the case of EET 84302 (5% partial melting), modeling melt migration in the presence of immiscible Fe,Ni-FeS and silicate partial melts is difficult. It seems clear that while we would expect these melts to leave their immediate source region upon formation, it is not clear that they will migrate together. Rather, it is likely that they will separate out as they move towards the surface. We would also note that these melts, as they migrate upward, travel through regions which have had their own partial melts removed. These migrating melts can be trapped at this stage. Indeed, several authors (Nagahara, 1992; Mittlefehldt et al., 1996) have advocated trapping of basaltic and/or Fe,Ni-FeS melts to explain the abundances or textures of plagioclase and/or troilite in lodranites, a view with which we agree in principle for some meteorites. Further, previous authors (e.g., Fukuoka et al., 1978; Palme and Chakraborty, 1995) have also argued that melting affecting the lodranites was a nonequilibrium process, consistent with rapid melt removal of the type envisioned here.

4. MELT MIGRATION OUTSIDE THE SOURCE REGION

Once partial melts are removed from the immediate source regions (the lodranites), they may have migrated substantial distances in the acapulcoite-lodranite parent body, perhaps

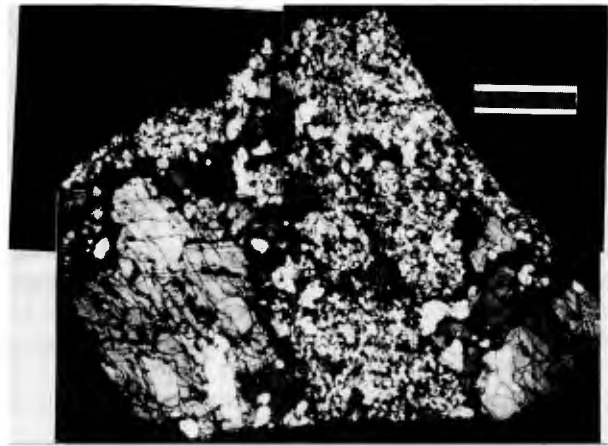


Fig. 2. Transmitted light photomosaic in crossed polars of LEW 86220. Scale bar = 2 mm. The rock is composed of an acapulcoite host region (fine-grained), into which has been intruded a coarse-grained, gabbroic, Fe,Ni-FeS-rich partial melt, presumably derived from partial melting of a lodranite source region elsewhere on the acapulcoite-lodranite parent body.

meters to kilometers. We might expect to find some remnants of these migrating partial melts, either in the form of coatings on the walls of dikes which pinched almost closed after erupting to the surface of the parent body, or as much thicker melt veins which were unable to reach the surface. We have identified one such rock, the unique meteorite LEW 86220. This small meteorite measures $4 \times 1.5 \times 1$ cm and weighs 25.0 grams. It was initially described as an iron meteorite with silicate inclusions (Martinez and Mason, 1988). However, examination of the hand sample by our group showed that it is not a typical iron with silicate inclusions. As initially noted by Martinez and Mason (1988), the metal in this rock has a string-like texture, rather than forming a matrix into which silicates are embedded, as is the case for most iron meteorites with silicate inclusions. Furthermore, mafic silicates (olivine of $\text{Fa}_{7.4}$; pyroxene of $\text{Fs}_{9.1}$) are more FeO-rich than those typically found in IAB irons, which are the most abundant group of iron meteorites with silicate inclusions. The oxygen isotopic composition of LEW 86220 silicates ($\delta^{18}\text{O} = 3.75\text{‰}$, $\delta^{17}\text{O} = 0.73\text{‰}$, $\Delta^{17}\text{O} = -1.22\text{‰}$) confirms its link to the acapulcoite-lodranite parent body, not to any of the groups of irons with silicate inclusions (e.g., IAB, IIICD) (Clayton and Mayeda, 1996). The meteorite consists of two different lithologies (Fig. 2), one of acapulcoite composition and grain size, the other of Fe,Ni metal, troilite, and plagioclase-augite (basaltic-gabbroic) composition and with a very coarse grain size. The boundaries between them are neither regular nor irregular, as in breccias. Instead, the precise boundaries are difficult to define, and it appears that the acapulcoite lithology was solid when it was intruded by Fe,Ni-FeS-silicate partial melts. The acapulcoite lithology is relatively fine-grained ($150 \pm 70 \mu\text{m}$) and consists of olivine ($\text{Fa}_{7.4 \pm 0.2}$, $N = 6$), orthopyroxene ($\text{Fs}_{9.1 \pm 0.2}$, $\text{Wo}_{1.8 \pm 0.2}$, $N = 5$), clinopyroxene ($\text{Fs}_{3.8}\text{Wo}_{43.7}$), plagioclase ($\text{An}_{15.1 \pm 1.1}$), metallic Fe,Ni, and troilite. Modal analyses were not conducted due to the small area of the rock in the polished thin section and the difficulty in determining the precise

boundaries between the lithologies in the optical microscope. However, the acapulcoite host does not appear to be depleted in either troilite or plagioclase, relative to chondritic values. The coarse-grained gabbroic lithology consists of highly zoned plagioclase ($An_{8.6-18.5}$, mean $_{13.8\pm 3.5}$, $N = 10$), clinopyroxene ($Fs_{3.9\pm 0.2}$, $Wo_{43.4\pm 0.7}$, $N = 7$), metallic Fe,Ni, and troilite as major phases, with minor orthopyroxene ($Fs_{9.6\pm 0.3}$, $Wo_{2.1\pm 0.4}$, $N = 3$). One plagioclase grain in this lithology is 9 mm in diameter and clinopyroxene grains are typically 1–3 mm in maximum dimensions. Troilite occurs predominantly within the large plagioclase grains, and metallic Fe,Ni is concentrated at boundaries between the two lithologies.

The mineralogy, texture, and distribution of the two lithologies suggests that LEW 86220 represents an acapulcoite host into which Fe,Ni-FeS cotectic and basaltic partial melts were intruded. We reject an in situ origin for the gabbroic lithology, since the acapulcoite host does not appear to be depleted in either plagioclase or troilite. We envision that the chondritic source region was heated to $\sim 1250^\circ\text{C}$, at which point the Fe,Ni-FeS and basaltic components would be molten and would migrate upwards, leaving a lodranite residue. The distance over which this melt migrated is uncertain, but could have ranged from hundreds of meters to kilometers, considering that the considerably hotter lodranite source regions were probably not in the immediate vicinity of the somewhat cooler acapulcoite rocks. When the melt passed through an acapulcoite region, represented by the host of LEW 86220, which was from ~ 100 – 300°C cooler than the lodranite source region, the melt cooled and was trapped. Although the acapulcoite region was at a lower temperature than the melt, it was still relatively warm, causing the boundary between the host and melt to be diffuse rather than distinct. Cooling rates were slow enough to allow crystallization of a coarse-grained lithology, yet fast enough to produce marked zoning in the plagioclase. We have measured the metallographic cooling rate of LEW 86220 (using the revised calibration of Willis and Goldstein, 1981) and, although the data points scatter widely, they suggest that the rock cooled very rapidly ($\sim 10^3^\circ\text{C/Myr}$; Fig. 3) in the temperature range of 600 – 400°C , as did all other acapulcoites and lodranites.

5. REMOVAL OF PARTIAL MELTS FROM THE PARENT BODY

The rather unique properties of LEW 86220 suggest that migration of melt indeed occurred over some significant distances in the acapulcoite-lodranite parent body and that these melts sometimes were trapped in the form of veins and dikes in the body. However, an unknown but possibly large portion of the partial melts, particularly the low density (i.e., the basaltic-plagioclase-pyroxene) partial melts may have reached the surface of the parent body. Although our sampling of the acapulcoite-lodranite parent body is undoubtedly unrepresentative and limited, it is noteworthy that no plagioclase-pyroxene basalts of compositions complementary to the lodranites are amongst the meteorites in the world's meteorite collections. We, therefore, suggest that these basaltic partial melts may have been removed from the parent body by explosive volcanism, as was previously argued to explain

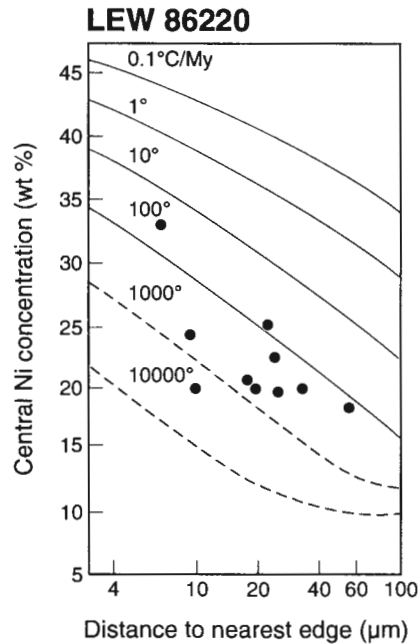


Fig. 3. Plot of central Ni content vs. distance to nearest edge for taenite grains in LEW 86220. Curves for cooling at 0.1 – 100°C/Myr are from Willis and Goldstein (1981). Curves for 1000 – 10000°C/Myr are approximate. Although data points scatter widely, it appears that LEW 86220, like all other acapulcoites and lodranites, experienced very rapid cooling ($\sim 10^3^\circ\text{C/Myr}$). This cooling probably occurred in an asteroidal fragment some tens of kilometers in diameter after parent body breakup.

the lack of basalts in the world's collections complementary to the aubrites (Wilson and Keil, 1991; Muenow et al., 1992) and to the ureilites (Warren and Kallemeyn, 1992; Scott et al., 1993). Keil and Wilson (1993) and Muenow et al. (1995) have also argued that if differentiating parent bodies contained volatile abundances comparable to those of type 3 ordinary chondrites, even dense Fe,Ni-FeS partial melts could be removed by this process, explaining the apparent sulfur depletions in the metal cores of the many parent bodies of the igneous iron meteorites. In analogy, one might speculate that some portion of the Fe,Ni-FeS partial melt might also have been removed by this process from the acapulcoite-lodranite parent body, although it is equally likely that this body has an intact S-bearing metal core that has not yet been broken up and, thus, not been sampled by meteorites.

In order for explosive volcanism to have expelled pyroclast-gas mixtures from the acapulcoite-lodranite parent body early in the history of the solar system, at least three criteria must have been met: (1) partial melts must have been produced; (2) the parent body must have had a relatively low escape velocity, i.e., it must have been relatively small (< 100 km in radius); and (3) the precursor material must have contained sufficient volatiles (several hundred ppm) that were retained in the body until the onset of partial melting, so that when these melts reached the parent body surface, expansion of the volatiles would accelerate the pyroclast-gas mixtures to velocities in excess of the escape velocity of the parent body.

We have shown above that partial melting has occurred on a large scale on the acapulcoite-lodranite parent body, so the first criterion was clearly fulfilled. We now consider cooling rates of acapulcoites and lodranites as a potential source of data that could constrain the size of the parent body. Zipfel et al. (1995) have argued for cooling rates of $\sim 50\text{--}100^\circ\text{C}/\text{Myr}$ for Acapulco between 900 and 1000°C . This rate suggests a minimum size for its parent body of ~ 20 km in radius, calculated using the equation of Haack et al. (1990). Bogard et al. (1993) argued for an average cooling rate in excess of $10^\circ\text{C}/\text{Myr}$ from $\sim 1000^\circ\text{C}$ to Ar closure, implying that the rocks cooled in a body at least ~ 65 km in radius. Metallographic cooling rates are of limited value in inferring the parent body size during melting, since they reflect lower-temperature cooling ($600\text{--}400^\circ\text{C}$), perhaps after breakup of the parent body (McCoy et al., 1996). These rates for acapulcoites and lodranites of $\sim 10^3\text{--}10^5^\circ\text{C}/\text{Myr}$ (McCoy et al., 1996, 1997) imply objects smaller than ~ 10 km in radius. We should caution, however, that the above calculated estimates of parent body radii assume that the rocks were located in the very center of this body. The body could, of course, have been larger, if these rocks had not been located in its very center, as is very likely. Thus, the acapulcoite-lodranite parent body radius is very poorly constrained: it was certainly several tens of km in radius, but we know of no evidence that would suggest that it may have been more than 100 km in radius. Thus, the second requirement is also likely to have been fulfilled.

Finally, for explosive volcanism to have accelerated pyroclast-gas mixtures off the acapulcoite-lodranite parent body, the precursor material needed to contain at least several hundred ppm of total volatiles that were retained in the parent body until the onset of partial melting. Although we and others have presented evidence that the precursor material to the acapulcoites and lodranites was chondritic material (e.g., McCoy et al., 1996, and references therein), no unadulterated precursor material is known to exist in the world's meteorite collections. Thus, it is impossible to reliably constrain the volatile contents of this precursor material, but we can make what we consider to be reasonable estimates based both on what we know about volatile contents of chondrites and the volatile contents we measured in Acapulco and Lodran. If the precursor material to the acapulcoites-lodranites was anything like unequilibrated ordinary chondrites, then our previous measurements (Muenow et al., 1995) suggest that ample volatiles would be released at partial melting temperatures to drive explosive volcanism. However, we also suggest that measurements of volatile contents in Acapulco (<1 vol% Fe,Ni-FeS, not silicate partial melting, and partial melts were not removed) and Lodran (>20 vol% Fe,Ni-FeS and silicate partial melting, and partial melts were removed to differing degrees) might show trends which would lend support to the suggestion that the precursor material contained volatiles that may have played a role in explosive volcanism on, and removal of partial melts from, the acapulcoite-lodranite parent body. We would expect that Acapulco, which has been heated to lower temperatures and has not lost partial melts, would have higher volatile abundances than Lodran, which has been heated to higher temperatures and has lost part of its partial melt including volatiles.

TABLE 1. Abundances and release temperatures for volatiles in Acapulco and Lodran.

Volatile	Acapulco		Lodran		Source
	Release Temperature ($^\circ\text{C}$)	Abundance (ppm)	Release Temperature ($^\circ\text{C}$)	Abundance (ppm)	
Contaminants					
H ₂ O	$\sim 150\text{--}450$	580	$\sim 150\text{--}400$	600	Physically Adsorbed
CH ₄	345-505	200	--	--	Organic Contaminant
C ₂ H ₆	345-505	480	--	--	Organic Contaminant
CO ₂	250-550	1940	375-575	300	Organic Contaminant Carbonate Decomposition
Indigenous					
CO	1165-1250	630	--	--	Reduction Product
CO ₂	$\sim 1100\text{--}1200$	110	1085-1128	100	Unknown
S	1000-1300	16000*	1035-1250	11800*	Troilite Decomposition
Cl	1150-1300	250*	1100-1250	10*	Phosphate Decomposition?
Na	1075-1300	1130*	--	<10	Feldspar Decomposition

* Probably not all released at temperatures within the operating limits ($<1300^\circ\text{C}$).

Indeed, as we will show below, amounts of released CO are much higher in Acapulco than in Lodran, and this species is released at the temperatures of silicate partial melting of Lodran. Thus, these trends are comforting: while they do not prove that sufficient volatiles were present to drive pyroclastic volcanism, the trend is consistent with the model presented here.

Acapulco and Lodran were also chosen because they are the only falls of their types and thus, are likely to be less contaminated by terrestrial volatiles than highly weathered finds. However, as our measurements indicate, even these falls contain what appear to be terrestrial contaminants (Table 1). These include physically adsorbed H₂O (with a possible contribution from hydrates), low-molecular weight hydrocarbons, and CO₂. Physically adsorbed H₂O is released between ~ 150 and 450°C and comprises ~ 600 ppm of both meteorites. Low-molecular weight hydrocarbons (CH₄, C₂H₆; Fig. 4a) were observed only in Acapulco and probably resulted from contamination by cutting fluids or other handling. The lack of such contaminants in Lodran probably reflects the fact that the material we analyzed was removed from a larger piece by breaking, rather than cutting. Both Acapulco and Lodran release CO₂ at temperatures between 250 and 575°C , but this gas is much more abundant in Acapulco (1940 ppm) than in Lodran (300 ppm). The presence of large amounts of low-temperature CO₂ in association with low-molecular weight hydrocarbons in Acapulco suggests that much of the CO₂ results from organic contaminants. In contrast, the low abundances of CO₂ in Lodran most likely result from decomposition of carbonates. Small amounts of CO₂ from Acapulco could also be due to the decomposition of carbonates. These carbonates are probably not indigenous. Lodran fell in India in 1868 and has been subjected to a long, if not particularly harsh, period of weathering in the terrestrial atmosphere. The 300 ppm of CO₂ in Lodran would correspond to only ~ 0.07 wt% CaCO₃.

Volatile species which appear to be indigenous to the meteorites include CO, CO₂ (that portion released at high temperature, $>1085^\circ\text{C}$), S, Cl, and Na (Table 1; Fig. 4). Among these, the abundant CO is probably the most important in the context of explosive volcanism. Acapulco released 630 ppm of CO over a relatively narrow temperature interval between 1165 and $\sim 1250^\circ\text{C}$ (Fig. 4a). Lodran did

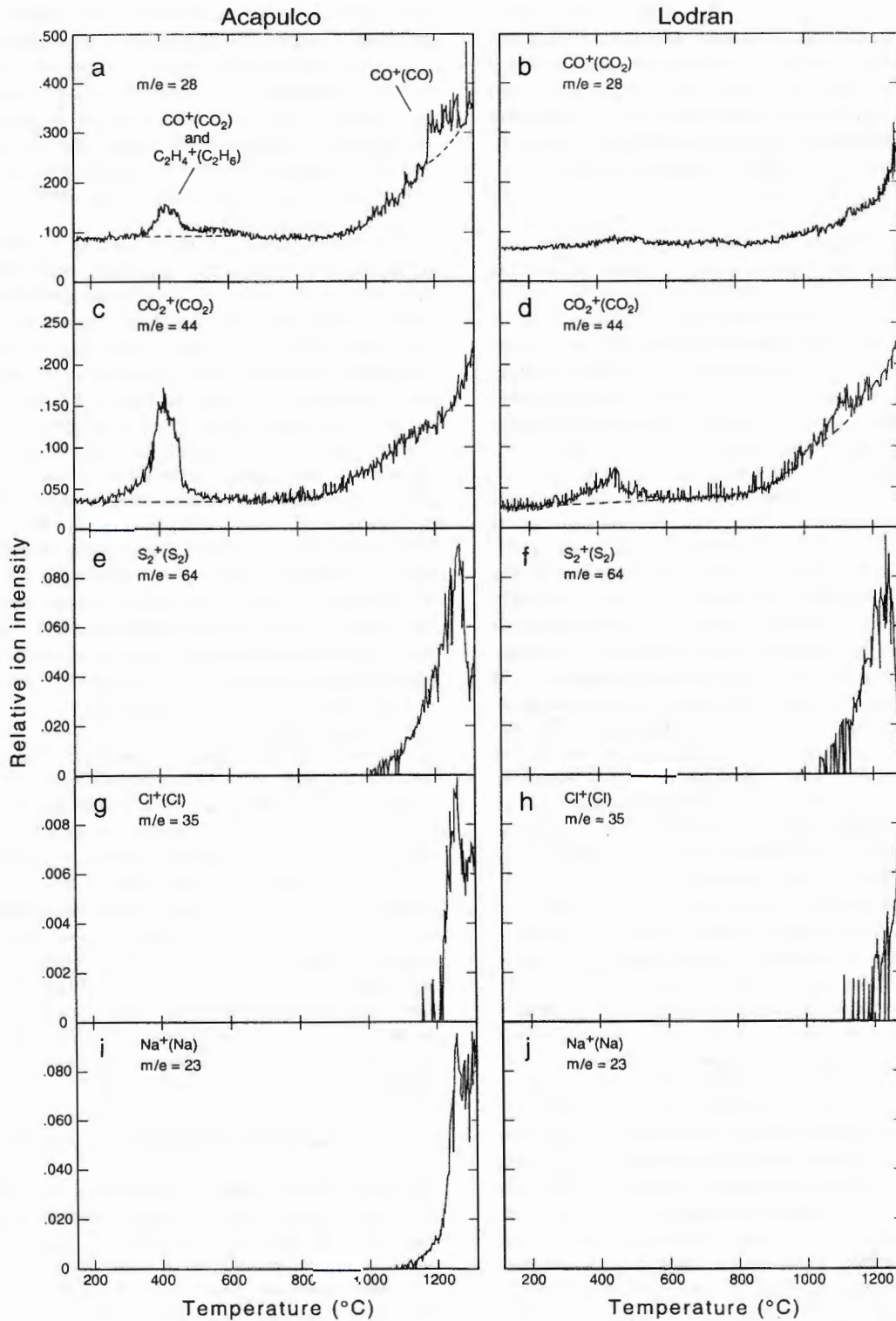


Fig. 4. Mass pyrograms for volatiles released from Acapulco and Lodran between ~100–1300°C. Each graph shows relative ion intensity vs. temperature for different mass/charge ratios. Indicated is the ion measured, its neutral molecular precursor, and the mass/charge ratio. Dashed lines indicate background levels. No background is present for Na, S, and Cl. For each volatile, Acapulco and Lodran are plotted to the same scale. Volatiles: (a,b) indigenous CO, contaminant CO₂ and C₂H₆; (c,d) CO₂; (e, f) S₂; (g,h) Cl; (i, j) Na.

not release any CO (Fig. 4b). The source of this CO in Acapulco is uncertain, but it probably results from reduction of mafic silicates by graphite, with release of CO. Degassing experiments on a heated mixture of San Carlos olivine and graphite employing the same procedure used in the present study produced abundant CO at approximately the same temperature (Muenow et al., 1995). Acapulcoites are known to contain graphite (Schultz et al., 1982; El Goresy et al., 1994, 1995). The lack of CO in Lodran, which experienced much higher partial melting than Acapulco, suggests that all graphite has reacted during partial melting to form CO and has escaped from the rock, presumably together with some of the partial melt. The temperature range for CO degassing is the same range in which lodranites experienced partial melting and loss of melt. Thus, degassing of CO during melting was possibly the major driving force for explosive volcanism. Indigenous CO₂ is released in both meteorites around 1100°C and comprises approximately 100 ppm (Fig. 4c,d). The source of this CO₂ is uncertain. Incomplete release of S, Cl, and Na also occurs in both meteorites up to the maximum operating temperature of the experimental system of ~1300°C. Sulfur is almost certainly the decomposition product of troilite, with Acapulco (16000 ppm) releasing more S than Lodran (11800 ppm) (Fig. 4e, f). This result is broadly consistent with the depletion of troilite in Lodran relative to Acapulco, although the small sample sizes and incomplete gas releases make this conclusion uncertain. Acapulco (250 ppm) and Lodran (10 ppm) both release Cl in the temperature interval between ~1100–1300°C (Fig. 4g,h). The major carrier of Cl in acapulcoites is chlorapatite, and the release of Cl may represent decomposition of this phase. Finally, Na (Fig. 4i, j) is released during decomposition of feldspar in Acapulco and of the late-stage melt products described by Bild and Wasson (1976) in Lodran, where plagioclase is absent. The differences in Na and Cl abundances are not surprising given the well-known depletion of phosphates and plagioclase in Lodran relative to Acapulco.

A point worth considering is the role that other volatiles not measured in the present study may have played in the history of the acapulcoite-lodranite parent body. One notable feature of both acapulcoites and lodranites is their relatively high abundance of trapped noble gases (McCoy et al., 1996, 1997, and references therein). This, at first sight, seems in conflict with the assertion that these rocks lost volatiles during partial melting and movement of these melts through the parent body and, in some cases, off the parent body, possibly as the result of explosive volcanism. However, it has been suggested that in acapulcoites, trapped noble gases are stored, at least in part, in bubbles (Kim and Marti, 1994; Takaoka et al., 1994). These authors suggest that noble gases were released during heating, but were re-trapped in these bubbles. Thus, the high concentrations of trapped gases may reflect migration within the body, but not loss at the surface. The database on other volatile elements, such as Zn and Br is, unfortunately, very limited. Zipfel and Palme (1993) report data for two acapulcoites (99–243 ppm Zn; 0.36–1.90 ppm Br) and two lodranites (65–144 ppm Zn; 0.09–0.24 ppm Br), suggesting that lodranites are slightly depleted in Zn and substantially depleted in Br relative to acapulcoites. The Br depletion in the lodranite MAC 88177 (0.07–0.08

ppm) relative to the acapulcoite ALH A88187 (0.9–1.1 ppm) was confirmed by Mittlefehldt et al. (1996). Thus, the presence of trapped noble gases in acapulcoites and lodranites does not appear to be in conflict with the suggestion that these rocks experienced various degrees of partial melting, and the lower abundances of volatile elements such as Zn and Br in lodranites relative to acapulcoites are consistent with the postulated higher peak temperatures for lodranites compared to acapulcoites.

In summary, we suggest that a possibly significant portion of the basaltic (plagioclase-pyroxene) partial melts could have been accelerated off the acapulcoite-lodranite parent body by the type of pyroclastic volcanism envisioned by Wilson and Keil (1991). The evidence that acapulcoites and lodranites experienced partial melting is convincing. It is also convincing to us that in acapulcoites these melts remained in the source rocks, whereas in lodranites they were, at least in part, removed from their source regions. However, the size of the acapulcoite-lodranite parent body is very poorly constrained, but we know of no evidence that suggests that it was larger than ~100 km in radius. The most poorly constrained parameter is the volatile content of the chondritic precursor material of the acapulcoites-lodranites. Although it is not unreasonable to assume that volatile contents resembled those of typical unequilibrated chondritic material, the lack of such unadulterated precursor material from the acapulcoite-lodranite parent body renders this assumption uncertain. Therefore, the most compelling evidence that explosive volcanism actually accelerated pyroclast (partial melt)-gas mixtures off the acapulcoite-lodranite parent body is in the apparent lack of basaltic (plagioclase-pyroxene) rocks complementary to the lodranites in the world's meteorite collections. Since many lodranites are depleted in plagioclase relative to likely chondritic precursors, the lack of such rocks suggests that these partial melts or their crystallization products must have been removed from the parent body early in the history of the solar system, so that none would be preserved to today. We suggest that the process that removed these melts was explosive pyroclastic volcanism. However, other scenarios, such as extrusion of basaltic partial melts on the surface of the parent body, crystallization of basalts from these melts, and removal of the basalts by corrosive impacts over time, cannot be ruled out.

6. IMPLICATIONS FOR S-ASTEROIDS

A major focus of asteroid studies over the past 20 years has been the attempt to link classes of asteroids (defined by their reflection spectra) with classes of meteorites. One of the most vigorously debated of these potential links is that with the S-asteroids. One group of investigators suggests that the abundant S-type asteroids are the parent bodies of the ordinary chondrites, the most abundant type of meteorite falling on Earth (e.g., Feierberg et al., 1982). The poor match of S-asteroid spectra with laboratory spectra of ordinary chondrites has been attributed to alteration and space weathering of asteroid surfaces by a variety of processes (see Feierberg et al., 1982 and references therein). Another group of investigators suggests that many S-asteroids are partially differentiated (e.g., Gaffey et al., 1993). Since

study of acapulcoites and lodranites has resulted in a better understanding of the nature of the partly differentiated acapulcoite-lodranite parent body, this knowledge may also provide insight into the nature of S-asteroids and their parentage.

Gaffey et al. (1993) divided the spectrally diverse S-asteroids into seven subtypes, which they interpret as representing different types of meteoritic materials. They suggested that these subtypes could represent fragments of compositionally or petrologically distinct layers or units from a partially differentiated parent body. Our work suggests that fragmentation of a body like the acapulcoite-lodranite parent body could result in fragments even more diverse in mineralogical and bulk chemical composition than envisioned by Gaffey et al. (1993). If a collisional fragment from this body were dominantly composed of acapulcoite material, it would be spectrally indistinguishable from chondritic material. Further, documented compositional heterogeneity in the acapulcoites shows that this material could range from quite reduced (Fa_4 in ALH A81187/84190) to almost as oxidized as H chondrites (Fa_{12} in Acapulco). Fragments consisting of material similar to LEW 86220, which is an acapulcoite into which basaltic-Fe,Ni-FeS-rich melts intruded, could further add to the wide compositional range of fragments from one partly differentiated parent body. It is worth noting that Hiroi et al. (1993) concluded that S-type asteroid spectra could only be reproduced by linear combinations of laboratory reflectance spectra of six acapulcoites and lodranites and the Mundrabilla iron. The reddened spectra of the S-type asteroids results primarily from the iron component and these authors found it necessary to include 9–36% iron to produce a good fit. LEW 86220 is a sample of an acapulcoite host with a metal-enriched gabbroic lithology and thus, lends validity to such mixing models. Furthermore, considering the compositional diversity of lodranites, collisional fragments could range from essentially chondritic material and probably low in FeO (like Yamato 8002) to Lodran, which is metal-enriched, troilite- and plagioclase-depleted and oxidized (Fa_{13}). We, therefore, conclude that fragmentation of a single body like the acapulcoite-lodranite parent body could produce all of the subtypes of S-asteroids. Thus, asteroid families composed of all subtypes could result from breakup of one parent asteroid. Furthermore, individual fragments would probably contain multiple lithologies and the regolith would represent a mixture of these lithologies. Thus, reflectance spectra of the regolith may not be an accurate measure of the identity of a unique, underlying bedrock.

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