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Invited review

Acapulcoite-lodranite meteorites: Ultramafic asteroidal partial melt residues

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ABSTRACT

Acapulcoites (most ancient Hf-W ages are 4,563.1 ± 0.8 Ma), lodranites (most ancient Hf-W ages are 4,562.6 ± 0.9 Ma) and rocks transitional between them are ancient residues of different degrees of partial melting of a chondritic source lithology (e.g., as indicated by the occurrence of relict chondrules in 9 acapulcoites), although the precise chondrite type is unknown. Acapulcoites are relatively fine- grained (∼150–230 μm) rocks with equigranular, achondritic textures and consist of olivine, orthopyroxene, Ca-rich clinopyroxene, plagioclase, metallic Fe,Ni, troilite, chromite and phosphates. Lodranites are coarser grained (540–700 μm), with similar equigranular, recrystallized textures, mineral compositions and contents, although some are significantly depleted in eutectic Fe,Ni-FeS and plagioclase- clinopyroxene partial melts. The acapulcoite-lodranite clan is most readily distinguished from other groups of primitive achondrites (e.g., winoanites/IAB irons) by oxygen isotopic compositions, although more than 50% of meteorites classified as acapulcoites currently lack supporting oxygen isotopic data. The heat source for melting of acapulcoites-lodranites was internal to the parent body, most likely ^{26}Al, although some authors suggest it was shock melting. Acapulcoites experienced lower temperatures of ∼980–1170 °C and lower degrees of partial melting (∼1–4 vol.%) and lodranites higher temperatures of ∼1150–1200 °C and higher degrees (∼5 ≥ 10 vol.%) of partial melting. Hand-specimen and thin section observations indicate movement of Fe,Ni-FeS, basaltic, and phosphate melts in veins over micrometer to centimeter distances. Mineralogical, chemical and isotopic properties, Cosmic Ray Exposure (CRE) ages which cluster around 4–6 Ma and the occurrence of some meteorites consisting of both acapulcoite and lodranite material, indicate that these meteorites come from one parent body and were most likely ejected in one impact event. Whereas the precise parent asteroid of these meteorites is unknown, there is general agreement that it was an S-type object. There is nearly total agreement that the acapulcoite-lodranite parent body was <∼100 km in radius and, based on the precise Pb–Pb age for Acapulco of 4555.9 ± 0.6 Ma, combined with the Hf/W and U/Pb records and cooling rates deduced from mineralogical and other investigations, that the parent body was fragmented during its cooling which the U/Pb system dates at precisely 4556 ± 1 Ma. Hf-W chronometry suggests that the parent body of the acapulcoites-lodranites and, in fact, the parent bodies of all "primitive achondrites" accreted slightly later than those of the differentiated achondrites and, thus, had lower contents of ^{26}Al, the heat producing radionuclide largely responsible for heating of both primitive and differentiated achondrites. Thus, the acapulcoite-lodranite parent body never experienced the high degrees of melting responsible for the formation of the differentiated meteorites, but arrested its melting history at relatively low degrees of ∼15 vol.%.

Contents

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1. Introduction

The transformation from primitive nebular aggregates to differentiated, layered worlds is the most fundamental process in the evolution of the rocky bodies in the inner Solar System. The melting, melt migration and differentiation into core, mantle and crust established the heat engines of planets and segregated elements essential for life (C, H, O, N, P, S) near the surface. Although meteorites at the extremes of this process, including chondrites, basalts and irons, are well-known from the meteoritic record, meteorites that record the intermediate chemical and physical processes of asteroid differentiation have only been widely recognized in the last few decades. Bild and Wasson (1976) suggested that Lodran, the type meteorite of the lodranites, resulted from partial differentiation. These authors were hampered, however, by the lack of associated meteorites for comparison. Since that time, the recovery of large numbers of meteorites, first from Antarctica and then from the hot deserts of the world, has established the acapulcoites and lodranites as the largest and best-studied example of the partial differentiation of an asteroid. In this work, we review the properties of the acapulcoite-lodranite clan, including a comprehensive review of individual members, and the insights they provide into the process of asteroid differentiation and partial melting.

Acapulcoites are relatively fine-grained (~150–230 μm) rocks with an equigranular, achondritic texture (Fig. 1a,b) and consist of olivine (~Fa_{4-14}), orthopyroxene (~Fs_{5-13}), Ca-rich clinopyroxene (~$Fs_{3-8}Wo_{43-46}$), plagioclase (~An_{2-31}), metallic Fe,Ni as inclusions in silicates and in the meteorite matrix (Herrin et al., 2005), troilite, chromite and phosphates (e.g., McCoy et al., 1996, 1997a; Mittlefehldt et al., 1996; Mittlefehldt, 2005) (Table 3). Lodranites are coarser grained (540–700 μm) (Fig. 1e,f), with similar equigranular, recrystallized textures, mineral compositions and contents, although some are significantly depleted in cogenetic FeS-Fe,Ni and plagioclase- clinopyroxene partial melts (e.g., McCoy et al., 1993b, 1997a, 1997b). Transitional acapulcoites-lodranites (e.g., Floss, 2000a) generally have grain sizes between those of acapulcoites and lodranites (Figs. 1c,d).

Mineralogical, chemical and isotopic properties, Cosmic Ray Exposure (CRE) ages as well as the occurrence of at least three meteorites (LEW 86220, McCoy et al., 1997b; Fig. 2f; FRO 93001 and pairs, Folco et al., 2006; NWA 5782, Bunch et al., 2010) consisting of both acapulcoite and lodranite material, indicate that these meteorites come from one parent body (e.g., Mayeda and Clayton, 1980; McCoy et al., 1992a, 1992b, 1996, 1997a, 1997b; Nagahara, 1992; Bogard et al., 1993; Zipfel and Palme, 1993a, 1993b; Kim and Marti, 1994a, 1994b; Weigel et al., 1995, 1996, 1999; Clayton and Mayeda, 1996; Terribilini et al., 2000; Patzer et al., 2004; Eugster and Lorenzetti, 2005; Greenwood et al., 2012, 2017). Their compositional properties, including density (Macke et al., 2011), are grossly chondritic (e.g., as indicated by their mineralogy and Mg-normalized lithophile element contents; e.g., Rubin, 2007), whereas the texture is recrystallized (achondritic). This has prompted the designation of "primitive achondrites" for these and other similar meteorites such as the winonaites (Prinz et al., 1983). It has been pointed out that, on the basis of Fe/Mg vs. Fe/Mn contents, all primitive achondrites including the acapulcoites-lodranites are clearly separated from differentiated achondrites. This is because the primitive achondrites are residues of partial melting, whereas the differentiated achondrites are melts or cumulate products of melts (Goodrich and Delaney, 2000). The compositions and mineralogies of acapulcoites-lodranites are akin to ordinary chondrites (OCs), but they are different from known OCs (e.g., McCoy et al., 1996, 1997a). The occurrence of relict chondrules (e.g., Rubin, 2006, 2007; Schrader et al., 2017) in 9 acapulcoites (see below) (but not in the more highly recrystallized lodranites) is further strong evidence that the parent lithology of this meteorite clan was chondritic (Fig. 3).

Systematic compositional and textural differences (e.g., in the degree of recrystallization, resulting in larger grain sizes in lodranites than in acapulcoites), as well as the occurrence of meteorites with properties transitional between them (e.g., Floss, 2000a) (Fig. 1c and d), indicate that they are the residues of variable degrees of partial melting in a moderately reducing environment (Benedix and Lauretta, 2006; Benedix et al., 2009). The heat source was internal to the parent body, most likely ^{26}Al, although Kallemeyn and Wasson (1985), Takeda et al. (1994b), Rubin et al. (2002) and Rubin (2006, 2007) suggested it was shock melting. The acapulcoites experienced lower (~1–4 vol.%) and the lodranites higher degrees (~5 ≥ 10 vol.%) of partial melting (e.g., McCoy et al., 1997b). During partial melting, minor loss or enrichment of volatiles as well as migration of FeS-Fe,Ni cotectic partial melts and phosphate melts formed at or above ~980 °C (Kullerud, 1963; Kubaschewsky, 1982) took place in acapulcoites (Fig. 2a–c) and in some transitional acapulcoites-lodranites (Fig. 2d). Furthermore, plagioclase-clinopyroxene (basaltic) melts formed at ~1150–1200 °C (e.g., Jurewicz et al., 1995) in lodranites (Miyamoto and Takeda, 1994; McCoy et al., 1997b) (Fig. 2e).

2. Properties of individual acapulcoites, lodranites, and transitional acapulcoites/lodranites (A/L)

The total number of individual acapulcoites, lodranites and transitional acapulcoites/lodranites (A/L) is 138, of which 62 are acapulcoites, 61 lodranites, and 15 A/L (Table 1), but only two,

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