# PRIMITIVE ENSTATITE ACHONDRITES

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**Abstract:** Conclusions drawn from the breadth of analytical data on primitive achondrites and enstatite chondrites paired with results of research performed by the authors have led the authors to propose the establishing of a new group of meteorites: primitive enstatite achondrites. The group is defined as the residual remaining after the partial melting of their protolith, which, in the case of primitive enstatite achondrites, is the parent body of enstatite chondrites. In this article are characterized textural features and characteristics of their mineral, chemical, and isotopic composition. The most important of these defining features are the presence of relic chondrules and/or triple junctions of crystal faces, as well as characteristic atomic and molar ratios of main elements: Si, Al, Fe, Mg, Mn and Ca, and particularly the molar ratios Fe/Mn and Fe/Mg. Another important characteristic is the isotopic composition of entrained noble gases, especially ratios of the heaviest of the isotopes and oxygen isotopes, whose values should be close to that typical for enstatite chondrites.

It seems likely that the first meteorite to be classified as primitive enstatite achondrite will be the Zakłodzie enstatite achondrite.

**Key words:** Acapulcoite, lodranite, winonaite, brachinite, ureilite, metachondrite, primitive achondrite, enstatite chondrite, primitive enstatite achondrite.

The first criterion for dividing meteorites into "chondrites" and "achondrites" was the presence or lack of chondrules within a given meteorite. In accordance with that idea, amphoterites, in which chondrules are hardly visible, were formerly counted among achondrites. They are now deemed LL6 chondrites. Later, attention was paid to the fact that the texture of chondrites resembles terrestrial sedimentary rocks and the texture of achondrites is similar to that of terrestrial igneous rocks. However, when chemical compositions were taken into account, it was noticed that some achondrites had chemical compositions that were similar to those of chondrites, and some even exhibited relic chondrules. Assuming that achondrites originated as the product of melted chondritic material and the crystallization of the resulting magma, it was concluded that the achondrites of chondritic chemical composition were apparently so poorly melted that differentiation, which would change the chemical composition of the magma, could not occur.

So the achondrites were called primitive to emphasize that they are poorly developed (Prinz et al., 1983).

When at the end of 19th century Aristides Brezina of the Naturhistorisches Museum in Vienna introduced the term "achondrites" for stony meteorites without chondrules, there were known only three achondrites and one stony-iron meteorite, which today are counted among primitive achondrites. Moreover these three achondrites were ureilites, as to which some doubts exist if there are reasons good enough to count them among primitive achondrites (Hutchison, 2006). From other side the undisputable today primitive achondrite Lodran, which fell in 1868 on territory of present Pakistan, was, until quite recently, counted among a special subgroup of stony-iron meteorites – the lodranites. The question of primitive achondrites could appear only after 1976, when near the town of Acapulco, Mexico, a 1.9 kg stone was seen to fall (Palme et al., 1981).

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## Acapulcoites and lodranites

It was recently discovered that, despite minor primarily structural differences, acapulcoites and lodranites are of the same origin and should belong to one group. They differ mainly in that acapulcoites are texturally fine grained, equigranular rocks (grain size 150–230 µm) (Fig. 1), with chondritic olivine, pyroxene, plagioclase, metal and troilite contents. Lodranites are coarser rocks (grain size 540–700 µm) (Fig. 2) composed of olivine and pyroxene, with lower than chondritic contents of troilite and plagioclase. Acapulcoites and lodranites have similar oxygen isotopic compositions and they form one cluster on a diagram of
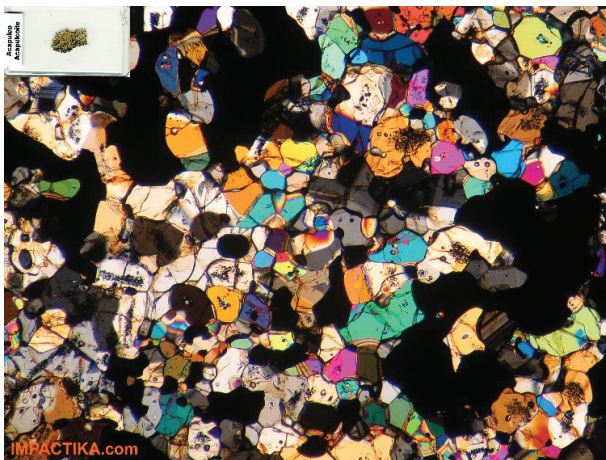


**Fig. 1.** A thin section of the type acapulcoite Acapulco with irregular, colorful grains of olivine, often with irregular fractures, but without visible traces of cleavage. Among translucent minerals (silicates) polysyntetically twinned plagioclase crystals can be found having gray interference colors. Black irregular grains are most probably FeNi metal and sulfides, mainly FeS (troilite). The rock shows finegrained, equigranular texture. Cross-polarized light. Field of view is about 3 mm wide. Photo courtesy of John Kashuba
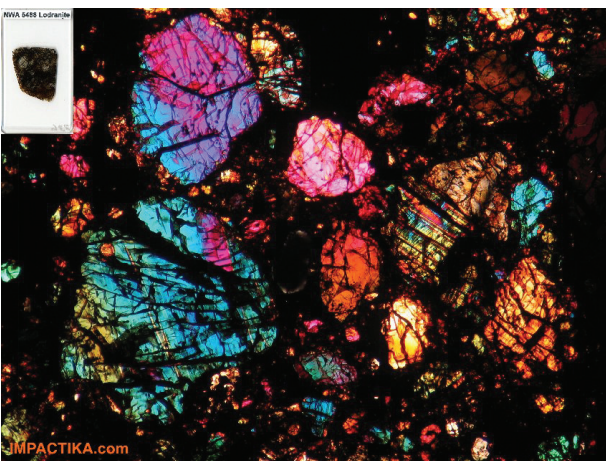


**Fig. 2.** A thin section of the NWA 5488 lodranite. Colorful olivine grains can be seen with many fractures, apparently larger than these in acapulcoites. Opaque minerals are surely FeNi metal, sulfides and limonite (the meteorite is rather heavy weathered). Cross-polarized light. Field of view is about 3 mm wide. Photo courtesy of John Kashuba
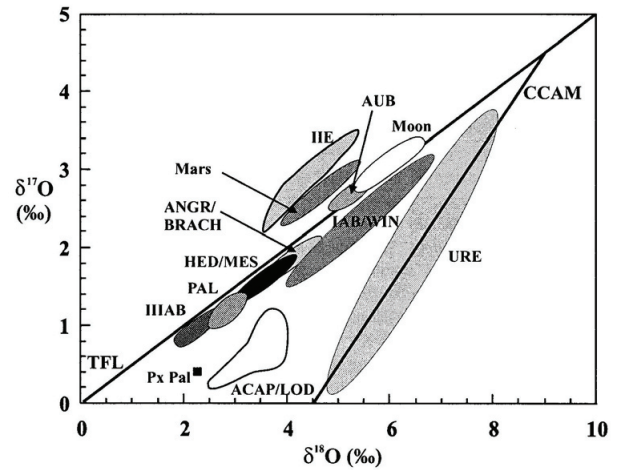


**Fig. 3.** Oxygen isotopic ratios of achondrites (after Clayton and Mayeda (1996); Hutchison, 2006)

relevant oxygen isotopes (Fig. 3) (Hutchison, 2006). Relic chondrules were subsequently found in a number of other acapulcoites, further confirming their close connection with a chondritic precursor (McCoy et al., 1996). Often, veins are visible, filled with metal and sulfide. Metal occurs as interstitial grains, too: as does plagioclase, when present. According to Hutchison (2006), acapulcoites resemble H chondrites in their plagioclase contents, metal, troilite and phosphate. However, Rubin (2007) suggests that carbonaceous chondrites of Renazzo type (CR) are a more probable progenitor of acapulcoites and lodranites.

Acapulcoites probably formed during the partial melting and recrystallization of a chondritic precursor above 950°C, but below the silicate solidus. Their texture formed possibly during slow cooling at high temperature, then rapid cooling through 500°C and finally slow cooling at low temperature. Lodranites were more strongly heated, sometimes even above the silicate solidus (about 1150°C), which caused the fractionation of basaltic melt. Their cooling went similarly as in the case of acapulcoites (Weissberg et al., 2006).

Now (April 2011), 47 acapulcoites are known, with nearly half of them found in Antarctica and nearly half on Sahara and Omani deserts. The great majority of them have been found in the past ten years. We now know of 29 lodranites and, similarly, most have been found in Antarctica and the Sahara Desert. At present, no lodranites have been found in Oman. The tight relationships between acapulcoites and lodranites has been additionally confirmed with finds of nine more stones in Antarctica and the Sahara, which are texturally and mineralogically intermediate between acapulcoites and lodranites (Meteoritical Bulletin Database, April 2011).
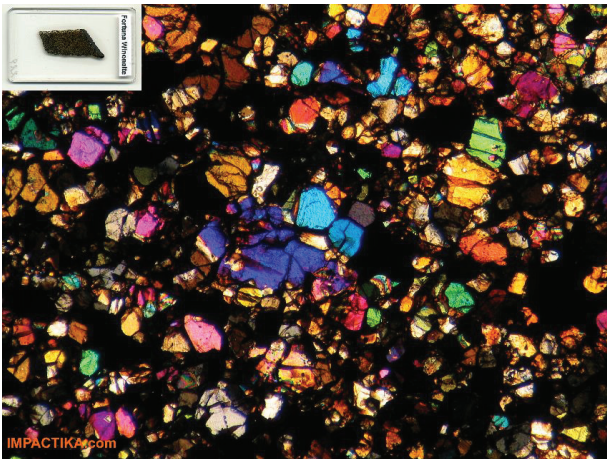
**Fig. 4.** A thin section of the Fortuna winonaite. Colorful grains of olivine can be seen together with gray pyroxene and possibly tiny grains of plagioclase. Opaque minerals are FeNi metal and troilite. Cross-polarized light. Field of view is about 3 mm wide. Photo courtesy of John Kashuba

### Winonaites and IAB iron meteorites clan

Like acapulcoites and lodranites, winonaites generally have chondritic mineral and chemical composition as well as recrystallized, achondritic texture. These are fine-to-medium-grained rocks, mostly equigranular, and in some of them (Pontlyfni and Mount Morris) features resembling relic chondrules can be found. Their mineral composition is intermediate between the compositions of E chondrites and H chondrites. Veins of metallic nickel-iron and troilite are common. They may represent first partial melts from a chondritic precursor. Texturally, winonaites are similar to acapulcoites, but contain coarser grains and abundant cross-cutting metal-sulfide veins (Fig. 4) (Benedix et al., 1998). Today, 20 winonaites are known, most of which were found in the Sahara or Antarctica. The only witnessed fall of a winonaite (Pontlyfni) was recorded in Wales, in 1931 (Grady, 2000).

Silicate inclusions occur in about half of known irons of IAB clan, and are composed of variable amount of Ca-poor and Ca-rich pyroxene, olivine, plagioclase, troilite, graphite, phosphate and metallic FeNi as well as minor amounts of daubreelite and chromite. Their mineral composition resembles that of winonaites, and oxygen isotopic composition in silicates of IAB clan of iron meteorites is similar to that of winonaites too. These similarities have brought researchers to conclude that silicate inclusions in IAB iron meteorites and winonaites originated from the same or from very similar parent bodies (Benedix et al., 2000).

### Brachinites

Brachinites are olivine-rich, medium-to-coarse-grained (0.1–2.7 mm), equigranular achondrites composed mainly of olivine (74–98%) grains of which meet in triple junctions, with minor amounts of augite (4–15%), plagioclase and Ca-poor pyroxene (0–10%), chromite (0.5–2%), iron sulphides (3–7%), phosphates, and Fe-Ni metal (Fig. 5). Lithophile element content in the Brachina meteorite is similar to the ranges seen in chondrites, suggesting that these elements were not fractionated, so brachinites are considered primitive achondrites (Nehru et al., 1996). However, in other brachinites, some depletion of Al, Ca, Rb, K, and Na is observed (Mittlefehldt & Lindstrom, 1998). The content of siderophile elements varies among brachinites. Textural and chemical differences among brachinites suggest that they could not all originate via the same processes or from the same parent body (Mittlefehldt et al., 2003). There are now 18 brachinites known, half of which were found on Sahara, five (including the very first, Brachina) in Australia and four in Antarctica. There is no witnessed fall among them (Meteoritical Bulletin Database, April 2011).

The origin of brachinites is still a subject of controversy. They may represent recrystallized chondritic material, residues from partial melting, or magmatic cumulates (Warren & Kallemeyn, 1989; Nehru et al., 1996). Mittlefehldt presented evidence that brachinites are magmatic cumulates from a differentiated asteroid and should be considered achondrites rather than primitive achondrites (Mittlefehldt et al., 2003).

### Ureilites

Ureilites are the largest group of primitive achondrites with 273 known as of April 2011, including six witnessed falls, the last being the spectacular fall of Almahata Sitta (Fig. 6) (Jenniskens et al., 2009). As
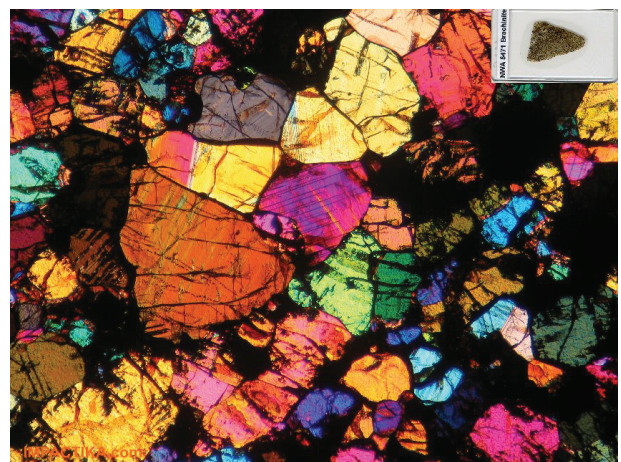


**Fig. 5.** A thin slice of possible brachinite NWA 5471 (not classified yet officially). Fractured, colorful olivine crystals can be seen. Cross-polarized light. Field of view is about 3 mm wide. Photo courtesy of John Kashuba

**Fig. 6.** A 0.29 g slice of the Almahata Sitta ureilite. Photo courtesy of Andrzej S. Pilski

would be expected, Antarctic and Saharan finds comprise the majority of known ureilites. Most of them are monomictic breccias (Meteoritical Bulletin Database, April 2011). Their textures, mineralogy and lithophile element chemistries suggest that they are highly fractionated rocks from an achondrite parent body. However, their oxygen isotopic compositions do not follow a mass-dependent fractionation trend characteristic of planetary differentiation; rather, they plot along the carbonaceous chondrite line, suggesting a possible relationship to the CV chondrites. Despite that, the assertion that ureilites are *primitive* achondrites is still very much debated (Goodrich, 1992).

Ureilites are olivine-pyroxene rocks with interstitial carbon in the form of graphite and diamonds, with additional Fe-Ni metal, sulfides and minor silicates. There are three major types of ureilites: (1) olivine-pigeonite, (2) olivine-orthopyroxene, (3) polymict (Weisberg et al., 2006). With the exception of polymict ureilites and a few other rare exceptions, ureilites are devoid of feldspar. The ureilites that have not been heavily modified by shock display elongated
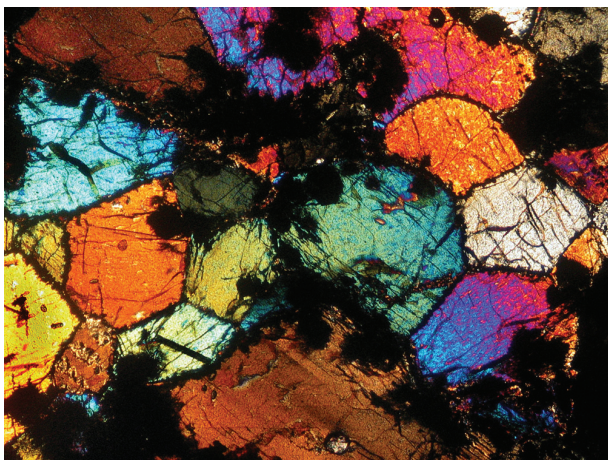
olivine and pyroxene grains about 1 mm in size that form triple junctions at 120° and have curved intergranular boundaries (Fig. 7). The mineral fabric of some ureilites suggests the settling and compaction of crystals.

The presence of interstitial carbon raises difficulties in understanding ureilite petrogenesis. The carbon contains trapped noble gases in abundances similar to those of primitive chondrites. If ureilites formed during high temperature igneous processes, one would expect these gases to have been driven off. A better explanation for the retention of these noble gases in carbon would be late-stage injection (Weisberg et al., 2006). Another question pertains to ureilites' diamonds, and whether they are shock formed or they formed from chemical vapor deposition in early solar nebula. A well-known characteristic of ureilites is that the olivine in contact with graphite has been reduced with regards to iron. It is visible in olivine grains with reduced rims that are composed of Fe-poor olivine with tiny blebs of Ni-poor metal (Weisberg et al., 2006).

The polymict ureilites are polymict breccias containing monomict ureilite fragments, feldspar-bearing lithic clasts, isolated mineral fragments, fragments of chondrules and chondrites, and dark chondritic inclusions (Fig. 8) (Ikeda & Prinz, 2000; Ikeda et al., 2000).

Because of their textural, mineralogical, and chemical similarity to terrestrial ultramafic rocks, ureilites are thought to be products of magmatic differentiation. The olivine-augite-orthopyroxene ureilites resemble magmatic cumulates (Goodrich et al. 1987, 2001). The olivine-pigeonite ureilites have been interpreted to be partial melt residues. The missing basaltic



**Fig. 7.** Typical ureilite (NWA 3140) with anhedral crystals, triple junctions, and opaque material surrounding and within grains. Some minor poikilitic texture is evident. Crossed-polarized light. Field of wiew is 3.2 mm wide. Photo courtesy of John Kashuba
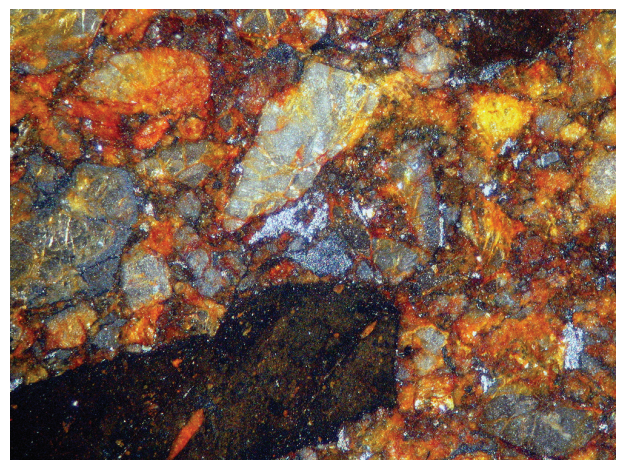


**Fig. 8.** Mixed mineral grains, dark clasts, and metal. DaG 319 polymict ureilite. Thin section in reflected light. Field of wiew is 3 mm wide. Photo courtesy of John Kashuba

component has been explained as being lost through explosive volcanism on ureilite parent bodies (Warren & Kallemeyn, 1992). Observed differences in oxygen isotopic compositions of ureilites may suggest that ureilites formed via the melting of chondritic material in a number of isolated magma chambers and not from a common magma source (Takeda, 1987). Recently, ureilites have been interpreted to be mantle rocks from a partially melted asteroid (Goodrich et al., 2004).

### Metachondrites

During the meeting of the Meteoritical Society in 2005, A. J. Irving and T. E. Bunch with colleagues (Irving et al., 2005) suggested that metamorphic rocks, formed as the result of the recrystallization of chondrites so extensive that chondrules are no longer discernible, should be called metachondrites. They distinguished five metachondrite groups by correlating ratios of oxygen isotopes with definite chondrite groups. Some meteorites, counted among primitive achondrites, fitted well to those groups, and those authors stated clearly that they were of opinion, that the term "metachondrites" should replace term "primitive achondrites". However, in the classification of meteorites on internet site of the Northern Arizona Meteorite Laboratory run by T. E. Bunch and J. H. Wittke, metachondrites and primitive achondrites form two independent groups.

## DISCUSSION

### Primitive achondrite criteria

It is generally accepted that primitive achondrites are residues left after the partial melting of chondrites. This melting occurred at temperatures too low for large-scale melting; differentiation of the magma was not possible. Temperatures were high enough only for the metamorphosing of chondritic rock to such an extent that only weak textural traces of the rocks' original structure remained. But the chemical and isotopic composition of the rock was left generally unchanged. Primitive achondrites are residue resulting from melting processes in which some textural features and the chemical and isotopic composition of their chondritic protoliths were preserved.

One of the indicators of the primitive nature of achondrites is their so called "planetary distribution" of noble gas contents. The content of heavier noble gases in chondrites is very similar to their content in the terrestrial atmosphere. It is a peculiarity hard to explain, as it is widely accepted that chondrites formed in the solar nebula, where the distribution of noble gas contents should fit their distribution in the solar atmosphere. However, the solar distribution of noble gases is observed in regolith breccias only, which are thought to come from surfaces of asteroids that were exposed to solar wind (Hutchison, 2006). Maybe the planetary distribution could be an indicator that chondrites formed not directly from the solar nebula, but perhaps in some processes that occurred on young asteroids and planetismals. Regardless, the planetary distribution is characteristic of all chondrites and it is accepted that its appearance in some achondrites is an indication that they formed as the result of metamorphism rather than in igneous processes including differentiation, an observation that is in some cases supported by their chondritic chemical compositions (Busemann et al., 2000). The contents of noble gases typical for carbonaceous and ordinary chondrites is expressed in ratios $^{36}Ar/^{132}Xe = 74$ i $^{36}Ar/^{84}Kr = 89$, which is represented with the letter Q (Wieler et al., 1992).

Another indicator of the primitive nature of achondrites, including ureilites, is the ratio Mn/Mg $< 9.0 \cdot 10^{-3}$ atomic (Goodrich & Delaney, 2000). In chondrites the ratio is within the range $3.9–9.0 \cdot 10^{-3}$, whereas in differentiated achondrites the ratio exceeds $9.0 \cdot 10^{-3}$.

One final indication that some achondrites should be deemed primitive is that some have oxygen isotopic ratios similar to chondritic ones. This criterion would suggest too, that aubrites should be included into primitive achondrites as they have the same oxygen isotopic ratios as enstatite chondrites (Hutchison, 2006). However, the textures of aubrites show that they formed from the crystallization of magma rather than by recrystallization. On the other hand one can distinguish a number of enstatite achondrites texturally resembling lodranites – that may deserve to be called primitive enstatite achondrites.

A textural criterion of a primitive achondrite is the presence of triple junctions of crystals at 120°, denoting crystal growth as the result of recrystallization rather than by crystallization from magma. An additional criterion is the presence of relic chondrules.

A summary of characteristics of primitive achondrites is shown in the Tab. 1.

### Primitive enstatite achondrites

Previously, scientists succeeded in matching some primitive achondrites like the acapulcoite-lodranite group and winonaites with parent chondritic rocks

**Table 1.** Properties of primitive achondrites (compiled using data from www4.nau.edu/meteorite/Meteorite/Book-PrimitiveAchond.html)

| | acapulcoites and lodranites | winonaites and silicates of a IAB | ureilites | brachinites |
|---|---|---|---|---|
| Texture | ACA fine-grained LOD coarse-grained | fine- and medium-grained | coarse-grained | equigranular |
| Olivine/pyroxene | $\leq 1$ | $<1$ | $>1$ | $>>1$ |
| oliwine | $Fa_{3-14}$ | $Fa_{1-8}$ | $Fa_{2-26}$ | $Fa_{30-35}$ |
| FeO/MnO in olivine | 24-30 | 18 | 17–22 | 50–60 |
| Low Ca-pyroxene | $Fs_{1-9}$ | $Fs_{1-9}$ | $Fs_{13-25}$ | <0.5 vol. % |
| FeO/MnO in pyroxene | 13–17 | 15 | – | 40 |
| Ca-pyroxene | $Fs_{46-50}Wo_{43-46}$ | $Fs_{2-4}Wo_{44-45}$ | $Fs_{13-32}Wo_{2-16}$ | $Fs_{10-13}Wo_{38-47}$ (up to 5% $TiO_2$ and 12% $Al_2O_3$) |
| plagioclase | $An_{12-31}$ | $An_{11-22}$ | rarely or absent | $An_{22-39}$ |
| silica | absent | absent | absent | absent |
| kamacite | <5 vol. % | <5 vol. % | <5 vol. % | absent |
| taenite | <5 vol. % | <5 vol. % | – | <0.5 vol. % |
| troilite | <5 vol. % | <5 vol. % | <0.5 vol. % | <5 vol. % |
| other minerals | phosphate, spinel, graphite | daubreelite, schreibersite, graphite | augite, graphite | oxides |

which could be considered their likely protoliths. These precursors are the parent bodies of H chondrites or CR carbonaceous chondrites and an intermediate between H and E chondrites, respectively. One can clearly see lack of primitive achondrites which could result from the metamorphism of a protolith of E chondrite composition. There are a few enstatite meteorites that are difficlut to place in the existing classification scheme that certainly are not enstatite chondrites, and that are, according to some authors, impact melts (Burbine at al., 2000; Keil and Bischoff, 2008). The authors would like to suggest the determination of a new meteorite group: the primitive enstatite achondrites. They would include the enstatite meteorite Zakłodzie into that group, as well as the enstatite meteorites Happy Canyon, Ilafegh 009, QUE 94204 and Yamato 8404 (Pilski, 2004; Przylibski et al., 2005; Karwowski et al., 2007).

The proposal to define a new group of primitive enstatite achondrites, analogous with existing groups of primitive achondrites, is certainly not yet well substantiated. In order to justify it, ample discussion would be necessary. Characteristic textural features, proportions of minerals, chemical and isotopic compositions – all of these criteria would need to be determined. Some suggestions can be drawn from the discussion above, which should be supplemented by

a short mineral-chemical-isotopic description of the protolith: the parent body of enstatite chondrites.

Like other primitive achondrites, the primitive enstatite achondrites should display characteristic textural features like the presence of relic chondrules and triple junctions, testifying to a metamorphic origin. The higher the grade of metamorphism, the fewer relic chondrules would be seen, and the more likely it would be for triple junctions to appear.

Among the definitive compositional criteria, the Mn/Mg ratio should be mentioned. From data for enstatite chondrites listed in Tab. 2 it can be calculated, that for enstatite chondrites the ratio should range from $5.0 \cdot 10^{-3}$ to $9.0 \cdot 10^{-3}$. Primitive enstatite achondrites should fall within the aforementioned range.

Isotopic ratios of noble gases may be diagnostic as well. Using the data listed in Tab. 3 it is possible to determine that ratios of noble gas isotopes in enstatite chondrites differ considerably from their values in ordinary and carbonaceous chondrites. Their mean values are $^{36}Ar/^{132}Xe = 196$ and $^{36}Ar/^{84}Kr = 182$, so it would appear that the same should be true for primitive enstatite achondrites. However, the above values are the means when taking into consideration all types of enstatite chondrites. When we analyze the changes in concentrations of heavy noble gases isotopes among petrologic types of enstatite chondrites, it becomes ap-

**Table 2.** Average element abundance for the enstatite chondrites (Lodders and Fegley, 1998, vide McSween & Huss, 2010; Hutchison (2006); Koblitz, 2010)

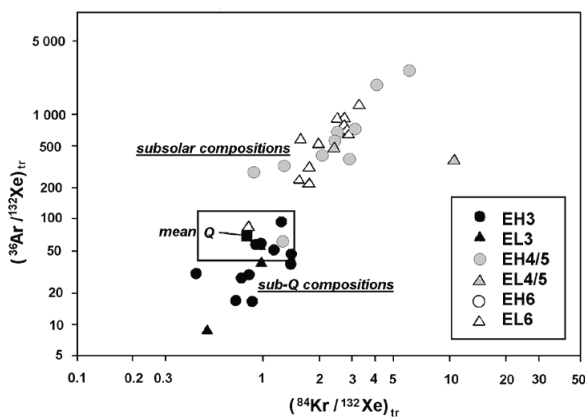| Element | Lodders & Fegley (1998) | | Hutchison (2006) | | Koblitz (2010) | | | |
|---|---|---|---|---|---|---|---|---|
| | EL | EH | EL | EH | EL | EH | EC | |
| | mean | mean | mean | mean | mean | mean | mean | range |
| Li (µg/g) | 0.7 | 1.9 | n.d. | n.d. | 0.82 | 1.55 | 1.18 | 0.52–2.28 |
| Be (ng/g) | n.d. | 21 | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| B (µg/g) | n.d. | 1 | n.d. | n.d. | 0.49 | 0.95 | 0.72 | 0.43–1.19 |
| C (mg/g) | 4.3 | 3.9 | 3.6 | 4.0 | 4.3 | 3.6 | 3.9 | 1–8.4 |
| N (µg/g) | 240 | 420 | n.d. | n.d. | 523 | 300 | 412 | 300–530 |
| O (mg/g) | 310 | 280 | 310 | 280 | n.d. | n.d. | n.d. | n.d. |
| F (µg/g) | 140 | 155 | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Na (mg/g) | 5.77 | 6.88 | 5.80 | 6.80 | 5.38 | 5.95 | 5.67 | 0.04–10.79 |
| Mg (mg/g) | 138 | 107 | 141 | 106 | 136.6 | 117.7 | 127.2 | 99–187 |
| Al (mg/g) | 10.0 | 8.2 | 10.5 | 8.1 | 10.7 | 8.9 | 9.8 | 3.9–17.4 |
| Si (mg/g) | 188 | 166 | 186 | 167 | 189 | 167 | 178 | 144–222 |
| P (µg/g) | 1250 | 2130 | 1170 | 2000 | 1110 | 1370 | 1240 | 70–2620 |
| S (mg/g) | 31 | 56 | 33 | 58 | 23.2 | 49.6 | 36.4 | 0.2–66.1 |
| Cl (µg/g) | 230 | 570 | n.d. | n.d. | 163 | 431 | 297 | 7.5–994 |
| K (µg/g) | 700 | 840 | 740 | 800 | 673 | 750 | 711 | 4–1740 |
| Ca (mg/g) | 10.2 | 8.5 | 10.1 | 8.5 | 9.1 | 7.9 | 8.5 | 0.4–16.7 |
| Sc (µg/g) | 7.7 | 6.1 | n.d. | n.d. | 6.9 | 5.7 | 6.3 | 0.1–28.1 |
| Ti (µg/g) | 550 | 460 | 580 | 450 | 493 | 495 | 494 | 20–1080 |
| V (µg/g) | 64 | 56 | n.d. | n.d. | 47 | 50 | 48.7 | 0.2–100.0 |
| Cr (µg/g) | 3030 | 3300 | 3050 | 3150 | 2786 | 2740 | 2763 | 10–10790 |
| Mn (µg/g) | 1580 | 2120 | 1630 | 2200 | 1561 | 1906 | 1734 | 30–5080 |
| Fe (mg/g) | 248 | 305 | 220 | 290 | 290 | 332 | 311 | 75–921 |
| Co (µg/g) | 720 | 870 | 670 | 840 | 1197 | 953 | 1075 | 11.7–3920 |
| Ni (mg/g) | 14.7 | 18.4 | 13.0 | 17.5 | 24.3 | 20.4 | 22.4 | 0.9–82 |
| Cu (µg/g) | 120 | 215 | n.d. | n.d. | 189 | 238 | 213 | 73–921 |
| Zn (µg/g) | 18 | 290 | n.d. | n.d. | 78.3 | 272 | 176 | 2.9–820 |
| Ga (µg/g) | 11 | 16.7 | n.d. | n.d. | 35.3 | 21.6 | 28.47 | 7–73 |
| Ge (µg/g) | 30 | 38 | n.d. | n.d. | 107 | 84 | 94 | 13.7–202 |
| As (µg/g) | 2.2 | 3.5 | n.d. | n.d. | 5.4 | 4.8 | 5.1 | 0.3–16.7 |
| Se (µg/g) | 15 | 25 | n.d. | n.d. | 13.4 | 26.6 | 20.0 | 5.3–82 |
| Br (µg/g) | 0.8 | 2.7 | n.d. | n.d. | 1.3 | 2.2 | 1.7 | 0.1–6.3 |
| Rb (µg/g) | 2.3 | 3.1 | n.d. | n.d. | 2.1 | 2.6 | 2.3 | 0.7–7.5 |
| Sr (µg/g) | 9.4 | 7.0 | n.d. | n.d. | 57 | 6.9 | 31.9 | 6–107 |
| Y (µg/g) | n.d. | 1.2 | n.d. | n.d. | n.d. | 1.330 | n.d. | n.d. |
| Zr (µg/g) | 7.2 | 6.6 | n.d. | n.d. | 30.2 | 5.9 | 18.1 | 3.8–53 |
| Mo (µg/g) | n.d. | n.d. | n.d. | n.d. | 3.6 | 4.0 | 3.8 | 1.1–4.8 |
| Ru (ng/g) | 770 | 930 | n.d. | n.d. | 2642 | 1663 | 2152 | 457–7400 |
| Rh (ng/g) | n.d. | n.d. | n.d. | n.d. | 641 | 547 | 594 | 92–880 |
| Pd (ng/g) | 730 | 820 | n.d. | n.d. | 3613 | 2171 | 2892 | 389–5510 |
| Ag (ng/g) | 85 | 280 | n.d. | n.d. | 105 | 229 | 167 | 12–386 |
| Cd (ng/g) | 35 | 705 | n.d. | n.d. | 280 | 373 | 327 | 1–1150 |
| In (ng/g) | 4 | 85 | n.d. | n.d. | 5.6 | 68.3 | 36.9 | 0.2–131 |
| Sn (ng/g) | 1360 | n.d. | n.d. | n.d. | 0.5 | 2.1 | 1.3 | 0.5–3.3 |
| Sb (ng/g) | 90 | 190 | n.d. | n.d. | 312 | 279 | 295 | 58–1040 |
| Te (ng/g) | 930 | 2400 | n.d. | n.d. | 564 | 2082 | 1323 | 90–3460 |
| I (ng/g) | 80 | 210 | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Cs (ng/g) | 125 | 210 | n.d. | n.d. | 171 | 178 | 175 | 35–338 |
| Ba (µg/g) | 2.8 | 2.4 | n.d. | n.d. | 18.0 | 2.7 | 10.4 | 1.3–32 |
| La (ng/g) | 196 | 240 | n.d. | n.d. | 260 | 259 | 260 | 73–3700 |
| Ce (ng/g) | 580 | 650 | n.d. | n.d. | 5262 | 762 | 3012 | 139–10000 |
| Pr (ng/g) | 70 | 100 | n.d. | n.d. | 62 | 140 | 101 | 47–680 |
| Nd (ng/g) | 370 | 440 | n.d. | n.d. | 3270 | 559 | 1914 | 224–6000 |
| Sm (ng/g) | 149 | 140 | n.d. | n.d. | 182 | 152 | 167 | 57–2260 |
| Eu (ng/g) | 54 | 52 | n.d. | n.d. | 92 | 55 | 74 | 25–638 |
| Gd (ng/g) | 196 | 210 | n.d. | n.d. | 236 | 248 | 242 | 106–1310 |
| Tb (ng/g) | 32 | 34 | n.d. | n.d. | 288 | 45 | 166 | 18–544 |
| Dy (ng/g) | 245 | 230 | n.d. | n.d. | 291 | 284 | 287 | 29–1300 |
| Ho (ng/g) | 51 | 50 | n.d. | n.d. | 51 | 68 | 59 | 26–259 |
| Er (ng/g) | 160 | 160 | n.d. | n.d. | 196 | 178 | 187 | 97–324 |
| Tm (ng/g) | 23 | 24 | n.d. | n.d. | 23 | 33 | 28 | 12–148 |
| Yb (ng/g) | 157 | 154 | n.d. | n.d. | 225 | 181 | 203 | 73–1990 |
| Lu (ng/g) | 25 | 25 | n.d. | n.d. | 116 | 26 | 71 | 11–300 |
| Hf (ng/g) | 210 | 140 | n.d. | n.d. | 658 | 140 | 399 | 96–1670 |
| W (ng/g) | 140 | 140 | n.d. | n.d. | 694 | 544 | 619 | 320–793 |
| Re (ng/g) | 57 | 55 | n.d. | n.d. | 197 | 79 | 138 | 24–392 |
| Os (ng/g) | 670 | 660 | n.d. | n.d. | 1478 | 788 | 1133 | 277–3590 |
| Ir (ng/g) | 560 | 570 | 525 | 565 | 928 | 679 | 803 | 1–3190 |
| Pt (µg/g) | 1.25 | 1.29 | n.d. | n.d. | 4.84 | 2.75 | 3.80 | 0.59–9.60 |
| Au (ng/g) | 240 | 330 | 225 | 330 | 432 | 421 | 427 | 9–2570 |
| Hg (ng/g) | n.d. | 60 | n.d. | n.d. | 930 | 465 | 698 | 260–1600 |
| Tl (ng/g) | 7 | 100 | n.d. | n.d. | 38 | 68 | 53 | 1–240 |
| Pb (ng/g) | 240 | 1500 | n.d. | n.d. | 225 | 1853 | 1039 | 85–2319 |
| Bi (ng/g) | 13 | 90 | n.d. | n.d. | 29 | 74 | 51 | 1–280 |
| Th (ng/g) | 38 | 30 | n.d. | n.d. | 238 | 34 | 136 | 23–450 |
| U (ng/g) | 7.0 | 9.2 | n.d. | n.d. | 60 | 9 | 34 | 4–110 |

n.d. – no data

**Table 3.** Noble gas concentrations and $^{129}Xe/^{132}Xe$ ratios in the enstatite chondrites calculated by authors on the data published by Patzer & Schulz (2001)

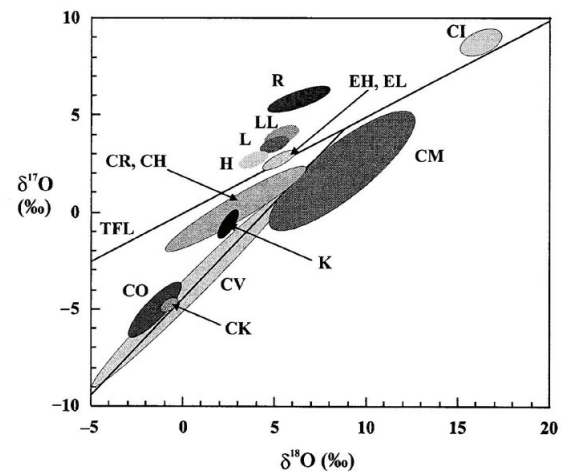| isotope | EL | | EH | | EC | |
|---|---|---|---|---|---|---|
| | mean | range | mean | range | mean | range |
| $^3He^*$ | 31.1 | 0.79–90.9 | 28.4 | 0.06–153 | 29.8 | 0.06–153 |
| $^4He^*$ | 3932 | 167–77950 | 16462 | 185–274000 | 10196 | 167–274000 |
| $^{20}Ne^*$ | 109 | 1–1560 | 75 | 0.58–1220 | 92 | 0.58–1560 |
| $^{21}Ne^*$ | 6.3 | 0.31–17.2 | 5.1 | 0.02–16.5 | 5.6 | 0.02–17.2 |
| $^{22}Ne^*$ | 15.1 | 0.41–124 | 11.1 | 0.08–108 | 13.1 | 0.08–124 |
| $^{36}Ar^*$ | 62 | 2.45–387 | 36 | 0.81–143 | 49 | 0.81–387 |
| $^{38}Ar^*$ | 12.3 | 0.83–74.3 | 7.4 | 0.32–27.2 | 9.8 | 0.32–74.3 |
| $^{40}Ar^*$ | 4243 | 1183–7900 | 4711 | 1340–11215 | 4477 | 1183–11215 |
| $^{84}Kr^\$$ | 2414 | 178–10940 | 2970 | 92.3–25700 | 2692 | 92.3–25700 |
| $^{132}Xe^\$$ | 1498 | 147–6730 | 3505 | 75–34600 | 2502 | 75–34600 |
| $^{129}Xe/^{132}Xe$ | 2.9 | 1.11–6.61 | 2.1 | 1.02–5.19 | 2.5 | 1.02–6.61 |
| number of meteorites | 25 | | 29 | | 54 | |

$^*$ in $10^{-8}$ ccSTP/g
$^\$$ in $10^{-12}$ ccSTP/g

parent that these concentrations differ between petrologic types (Patzer and Schultz, 2002; Patzer et al., 2002). As the most probable for primitive enstatite achondrites we should assume the values characteristic for enstatite chondrites type 3 as the most primitive. According to this statement we should adopt the Q ratio. So primitive enstatite achondrites should have $^{36}Ar/^{132}Xe$ and $^{36}Ar/^{84}Kr$ ratios close to the Q value; this is visible in the diagram in Fig. 9. Also, oxygen isotope ratios should be similar to those typical for enstatite chondrites: $\delta^{18}O$ 4–6‰, $\delta^{17}O$ 2–3‰, shown in Fig. 10. It should be noted, too, that the oxygen isotope ratios in enstatite chondrites follow the terrestrial fractionation line (TFL) (Hutchison, 2006).

To complement extrapolated characteristics of the mineral, chemical and isotopic compositions of the primitive enstatite achondrites' protolith (the parent body of enstatite chondrites), data on enstatite chondrites collected from the MetBase database (Koblitz, 2010) was thoroughly analyzed in addition to data from recent general reviews (Hutchison, 2006; McSween & Huss, 2010) whose authors offer a synthetic approach. Result of these analyses can be seen in tables 2 to 7 and figures 10 to 13.

The most important characteristic of mineral composition in enstatite chondrites is the presence of sulfides of primarily lithophile metals: namely Mn, Mg, Ca and K (Hutchison, 2006). The presence of



**Fig. 9.** Relative content of heavy noble gases in the enstatite chondrites and suggested primitive enstatite achondrites. The frame in the middle contains values for ordinary and carbonaceous chondrites (after Patzer et al., 2002)



**Fig. 10.** Oxygen three-isotope plot, 13 chondrite groups and Kakangari triplet (Hutchison, 2006)

**Table 4.** Light noble gas isotopes concentrations and selected ratios of these isotopes in enstatite chondrites (Koblitz, 2010)

| isotope | EL | EH | EC | range |
|---|---|---|---|---|
| $^3$He$^*$ | 33.5 | 24.7 | 29.1 | 0.61–153 |
| $^4$He$^*$ | 3568 | 12999 | 8284 | 134–328900 |
| $^{20}$Ne$^*$ | 75.9 | 77.5 | 76.7 | 0.71–2243 |
| $^{21}$Ne$^*$ | 6.9 | 4.5 | 5.7 | 0.12–15.5 |
| $^{22}$Ne$^*$ | 13.2 | 14.3 | 13.8 | 0.31–492 |
| $^{36}$Ar$^*$ | 60.0 | 95.9 | 78.0 | 0.75–1903 |
| $^{38}$Ar$^*$ | 11.9 | 15.6 | 13.8 | 0.38–363 |
| $^{40}$Ar$^*$ | 4412 | 5349 | 4880 | 9–38000 |
| $^4$He/$^3$He | 107 | 526 | 316 | 4.19–4454 |
| $^3$He/$^{21}$Ne | 4.9 | 5.5 | 5.2 | 0.33–26.45 |
| $^4$He/$^{21}$Ne | 520 | 2875 | 1698 | 21.3–29577 |
| $^3$He/$^{38}$Ar | 2.8 | 1.6 | 2.2 | 0.04–75.3 |
| $^{20}$Ne/$^{22}$Ne | 5.8 | 5.4 | 5.6 | 0.71–12.6 |
| $^{22}$Ne/$^{21}$Ne | 1.9 | 3.2 | 2.6 | 0.14–44.2 |
| $^{36}$Ar/$^{38}$Ar | 5.0 | 6.2 | 5.6 | 0.7–5.6 |
| number of meteorites | 42 | 100 | 142 | |

$^*$ in $10^{-8}$ ccSTP/g

**Table 5.** Mean bulk composition of the enstatite chondrites (Wasson and Kallemeyn, 1988, vide Hutchison, 2006; Koblitz, 2010)

| Element | Wasson & Kallemeyn (1988), vide Hutchison (2006) | | Koblitz (2010) | |
|---|---|---|---|---|
| | EL | EH | EL | EH |
| | wt% | | | |
| Si | 18.6 | 16.7 | 18.15 | 16.68 |
| Ti | 0.058 | 0.045 | 0.06 | 0.04 |
| Al | 1.05 | 0.81 | 1.05 | 1.01 |
| Cr | 0.305 | 0.315 | 0.30 | 0.24 |
| Fe | 22.0 | 29.0 | 19.89 | 21.71 |
| Mn | 0.163 | 0.220 | 0.19 | 0.17 |
| Mg | 14.1 | 10.6 | 13.13 | 11.17 |
| Ca | 1.01 | 0.85 | 0.75 | 0.59 |
| Na | 0.580 | 0.680 | 0.54 | 0.63 |
| K | 0.074 | 0.080 | 0.07 | 0.07 |
| P | 0.117 | 0.200 | 0.12 | 0.13 |
| Ni | 1.30 | 1.75 | 1.56 | 1.69 |
| Co | 0.067 | 0.084 | 0.9 | 0.8 |
| S | 3.3 | 5.8 | 2.92$^*$ | 4.89$^*$ |
| $H_2O^+$ | – | – | 1.16 | 1.82 |
| $H_2O^-$ | – | – | 0.15 | 0.68 |
| C | 0.36 | 0.40 | 0.4 | 0.36 |
| O | 31.0 | 28.0 | n.d. | n.d. |
| | | | | |
| Fe$^0$/Fe$^{tot}$ | 0.74 | 0.65 | 0.37 | 0.65 |
| | ppb | | | |
| Ir | 525 | 565 | n.d. | n.d. |
| Au | 225 | 330 | n.d. | n.d. |
| | | | | |
| number of analysed meteorites | n.d. | n.d. | 21 | 23 |

$^*$ S calculated only from the composition of troilite

n.d. – no data

**Table 6.** Volatile-free mean compositions and selected atomic ratios of the enstatite chondrites (Wasson and Kallemeyn, 1988, vide Hutchison, 2006)

| Element | EL | EH |
|---|---|---|
| | wt% | |
| Si | 31.3 | 27.2 |
| Ti | 0.09 | 0.08 |
| Al | 1.76 | 1.32 |
| Cr | 0.52 | 0.51 |
| Fe | 37.0 | 47.3 |
| Mn | 0.27 | 0.36 |
| Mg | 23.7 | 17.3 |
| Ca | 1.70 | 1.39 |
| Na | 0.97 | 1.10 |
| K | 0.13 | 0.13 |
| P | 0.20 | 0.33 |
| Ni | 2.18 | 2.86 |
| Co | 0.12 | 0.14 |
| | atomic ratio | |
| Mg/Si | 0.871 | 0.731 |
| Al/Si(x$10^4$) | 585 | 505 |
| Ca/Si(x$10^4$) | 380 | 358 |
| Fe/Si(x$10^4$) | 5934 | 8730 |
| Ca/Al | 0.65 | 0.71 |

ferroan alabandite [$\delta$-(Fe,Mn)S] is distinctive EL chondrites and niningerite [(Mg,Fe$^{2+}$,Mn)S] is representative of EH chondrites. Other rare minerals characteristic of the strongly reducing conditions of the environment in which they formed in, may also be found. These are: keilite [(Fe,Mg)S], djerfisherite [K$_6$(Fe,Cu,Ni)$_{25}$S$_{26}$Cl], oldhamite [CaS], daubréelite [Fe$^{2+}$Cr$_2$S$_4$], and schreibersite [(Fe,Ni)$_3$P], as well as si-

noite [Si$_2$N$_2$O], osbornite [TiN], and nierite [Si$_3$N$_4$]. Presolar grains of diamond and SiC may also be found in enstatite chondrites (Hutchison, 2006; McSween & Huss, 2010; Zhang et al., 1995). Chemical compositions of enstatite chondrites are characterized by a depletion of lithophile elements relative to other chondrite groups that supports the idea that they formed in strongly reducing conditions. In EL chondrites the content of Si in kamacite is <2 wt% and in EH chondrites is about 3 wt% (Hutchison, 2006).

In tables 2, 5, 6, and 7, data concerning of chemical composition of the enstatite chondrites are compiled. The data represent bulk compositions of both EH and EL chondrites, as well as compositional data for all known enstatite chondrites. They contain information about major and trace elements including rare earth elements. Based on that data, one can determine whether or not the chemical composition of an examined non-chondritic enstatite meteorite resembles the composition of an enstatite chondrite so that it might be regarded a primitive enstatite achondrite. The most useful information for determining the relationship between enstatite chondrites and achondrites would be the concentrations of elements characterized by narrow range of their contents in enstatite chondrites: namely Mg, Al, Si, Ca and Fe as major elements, W, Pt, Sn, Cs, Ga, Ge, Rb, Zr, Mo and Rh among trace elements, and Ho, Er and Tm among rare earth elements. The characteristic ranges of the concentrations of these elements in enstatite chondrites are shown in table 6 and in figures 11 and 12. The molar ratios Fe/

**Table 7.** Average abundance of Y, Sc and rare earth elements for the enstatite chondrites (McSween & Huss, 2010; Koblitz, 2010)

| Group of metal | Element | McSween & Huss (2010) | | Koblitz (2010) | | | |
|---|---|---|---|---|---|---|---|
| | | EL | EH | EL | EH | EC | |
| | | mean | mean | mean | mean | mean | range |
| LREE | La (ng/g) | 196 | 240 | 260 | 259 | 260 | 73–3700 |
| | Ce (ng/g) | 580 | 650 | 2103 | 762 | 1433 | 139–10000 |
| | Pr (ng/g) | 70 | 100 | 62 | 140 | 101 | 47–680 |
| | Nd (ng/g) | 370 | 440 | 1632 | 559 | 559 | 224–6000 |
| | Sm (ng/g) | 149 | 140 | 182 | 152 | 167 | 57–2260 |
| HREE | Eu (ng/g) | 54 | 52 | 92 | 55 | 74 | 25–638 |
| | Gd (ng/g) | 196 | 210 | 236 | 248 | 242 | 106–1310 |
| | Tb (ng/g) | 32 | 34 | 288 | 45 | 166 | 18–544 |
| | Dy (ng/g) | 245 | 230 | 291 | 284 | 287 | 29–1300 |
| | Ho (ng/g) | 51 | 50 | 51 | 68 | 59 | 26–259 |
| | Er (ng/g) | 160 | 160 | 196 | 178 | 187 | 97–324 |
| | Tm (ng/g) | 23 | 24 | 23 | 33 | 28 | 12–148 |
| | Yb (ng/g) | 157 | 154 | 225 | 181 | 203 | 73–1990 |
| | Lu (ng/g) | 25 | 25 | 116 | 26 | 71 | 11–300 |
| | Y (µg/g) | n.d. | 1.2 | n.d. | 1.330 | n.d. | n.d. |
| | Sc (µg/g) | 7.7 | 6.1 | 6.844 | 5.690 | 6.267 | 0.13–28.10 |

n.d. – no data
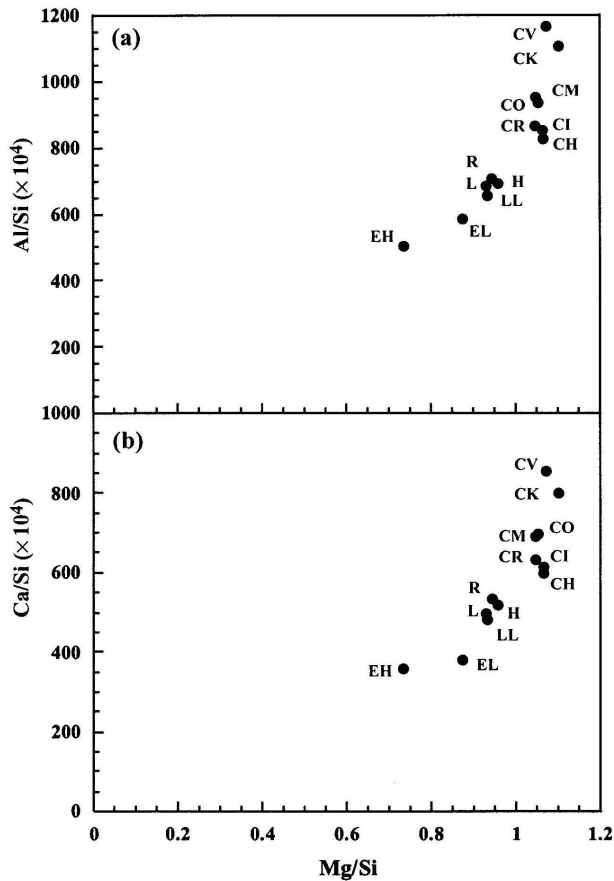
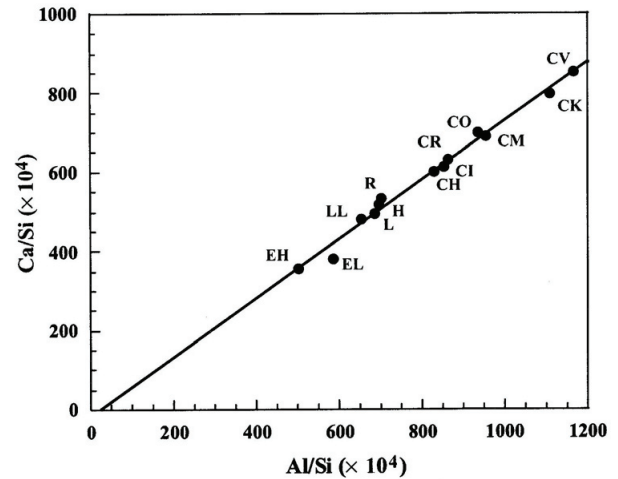Fig. 11. Al/Si and Ca/Si versus Mg/Si in 13 chondrite groups (Hutchison, 2006). The ratios are atomic



Fig. 12. Al/Si versus Ca/Si in 13 chondrite groups (Hutchison, 2006). The ratios are atomic

due. In the latter case (metamorphosed restite with crystallized residual melt) or in the case when its composition differs only slightly from that of the protolith (the parent body of enstatite chondrites) the enstatite meteorite should be called a primitive enstatite achondrite.

Tables 3 and 4 contain information concerning the isotopic compositions of noble gases in enstatite chondrites. The tables list the mean values of specific isotopes as well as the ranges and ratios of concentrations of selected isotopes. Isotopic compositions of noble gases in primitive enstatite achondrites should not differ largely from the listed composition in enstatite chondrites. Similarly, the oxygen isotopic compositions expressed in the form of ratios $\delta^{18}O$ and $\delta^{17}O$ should be typical for enstatite chondrites and for the terrestrial fractionation line (TFL) (Fig. 10).

Mn and Fe/Mg, shown in figure 13, reveal the chemical evolution of a rock from a chondritic protolith to a melt that during its fractional crystallization produces cumulates and melts depleted with Mg (and enriched with $SiO_2$); if not, it will form a metamorphosed resi-

## CONCLUSIONS

At present it is possible to single out a new group of meteorites – primitive enstatite achondrites. Though no meteorite has been classified officially to this group until now, examinations of other primitive achondrites and enstatite chondrites make it possible to propose standardized criteria that can be met by primitive enstatite achondrites.

Primitive enstatite achondrites represent the residual material following partial melting of a protolith, the parent body of enstatite chondrites. However, the temperature reached during that process was too low to facilitate the complete melting of the rock. For the same reason, differentiation of the magma was not possible. Thus, primitive enstatite achondrites are weakly metamorphosed residues (restites with crystallized residual melt) with traces of chondritic textures

in the form of relic chondrules. In the slightly more metamorphosed primitive enstatite achondrites, distinctive triple junctions of adjoining mineral grains 120° angles can be observed. The melting process that created these primitive achondrites was relatively quick, so the parent enstatite chondrite material is only slightly metamorphosed compared to higher petrologic types of E chondrites, which were subjected to regional metamorphism for very long periods of time on their parent body.

The most important characteristic of the mineral composition of primitive enstatite achondrites is presence of sulfides of lithophile metals. In these meteorites one can find ferroan alabandite, niningerite, keilite, oldhamite, daubréelite, sinoite, schreibersite, osbornite, and other sulfides as well. These minerals are characteristic of strongly reducing conditions.
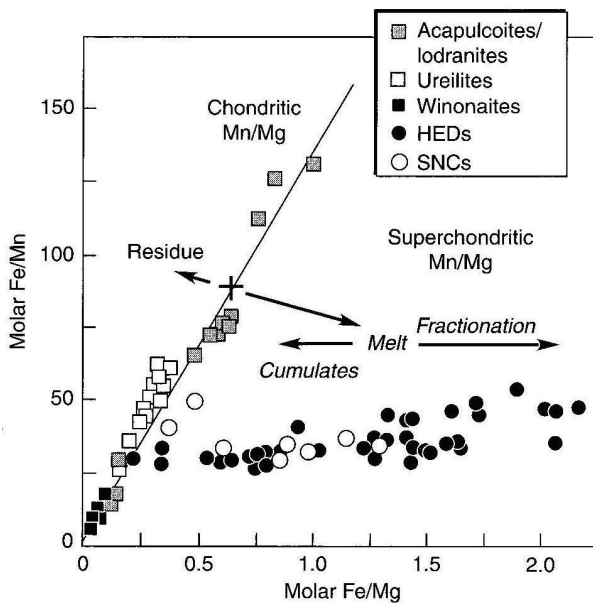
Fig. 13. Diagram used to distinguish achondrites that crystallized from melts and primitive achondrites that represent the solid residue once melt has been extracted (McSween & Huss, 2010)

The chemical and isotopic compositions of primitive enstatite achondrites should be similar to those of enstatite chondrites. Of special importance would be similarity in oxygen isotopic compositions and of isotopic compositions of heavy noble gases. The chemical composition of primitive enstatite achondrites should reflect visible characteristics of enstatite chondrites in atomic and molar ratios of main elements: Si, Al, Fe, Mg, Mn, and Ca. Especially the molar ratios of Fe/Mn and Fe/Mg allow the incorporation of an enstatite achondrite into the group of primitive enstatite achondrites – if their values are located within the field of chondrites or what might be determined to be unfractionated melt residue (see: Fig. 13).

The first enstatite meteorite to be included into the group of primitive enstatite achondrite, should be the Zakłodzie enstatite achondrite (Przylibski T. A. et al., 2005). Detailed examinations of this meteorite and of other similar enstatite meteorites that are possible candidates for the primitive enstatite achondrites group, both classified and waiting for classification, are currently being conducted by the authors.

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