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Meteorite classification and the definition of new chondrite classes as a result of successful meteorite search in hot and cold deserts

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Abstract

Meteorites are classified in order to sort these extraterrestrial rocks into broadly similar types of objects to enable a better understanding of the origin of these rocks and their relationships. Considering their origin and evolution, meteorites are broadly subdivided into two main divisions "differentiated" and "undifferentiated" meteorites. Successful meteorite searches in hot and cold deserts have drastically increased the number of meteorite finds. More than 20 000 meteorite fragments have been recovered mainly by Japanese and American expeditions from Antarctica. The number of collected meteorites from hot deserts is estimated to be about 7000–8000 including several 10 000 of fragments. Many rare samples are among the new meteorite finds leading to the definition of new meteorite classes and groups. These are R chondrites, CK, CR, and CH chondrites, acapulcoites, winonaites, lodranites, brachinites, angrites, and Lunar meteorites.

Keywords: Meteorite classification; Desert meteorites; Chondrites; Differentiated meteorites; Undifferentiated meteorites

1. Introduction

Among the hundreds of tons of extraterrestrial materials that arrive on the Earth's surface every day less than 1% is large enough to be recovered for classification and detailed investigations in science laboratories. The material that reaches the Earth's surface as meteorites includes small pieces from asteroids as well as rocks from the Moon and probably from Mars. Cometary solids are also abundant among the tiny dust particles acquired by the Earth.

Fragments of foreign planetesimals and planets travel through space as *meteoroids*, enter the Earth's atmosphere, and the pieces surviving the processes of frictional heating, surface melting, and evaporation in the atmosphere arrive at the surface as *meteorites*.

A historical overview about meteorite research is given in detail by Dodd (1981). Some important aspects can be summarized as follows. Meteorites have been scientifically investigated for more than 200 years (e.g., Chladni, 1794). Old meteorite classification schemes were mainly based on the petrography of the rocks. One of the earliest schemes was the Rose–Tschermak–Brezina-classification (Brezina, 1904). This system considered macroscopic and microscopic petrographic features as well as the metal abundances of meteorites. Prior (1916) published a mineralogical classification dividing chondrites into three major groups on the basis of the iron content of orthopyroxene (enstatite, bronzite, hypersthene). Today, the Van Schmus and Wood chemical-petrologic classification for chondritic meteorites is in general use to describe the degree of metamorphic modification (Van Schmus and Wood, 1967). In the last 50 years, chemical, structural, and isotopic (oxygen) aspects were included in classification schemes (e.g., Urey and Craig, 1953, Wiik, 1956; Mason, 1962; Ahrens, 1964; Von Michaelis et al., 1969; Wasson, 1974; Buchwald, 1975; Clayton et al., 1976, 1991; Clayton and Mayeda, 1983, 1984, 1996, 1999; Wasson and Kallemeyn, 1988; Kallemeyn et al., 1991, 1994, 1996).

The aim of this paper is to summarize the new meteorite classes that have been defined and established as the result of successful meteorite searches in the last 25 years in hot and cold deserts, to include these new classes in an actual classification scheme, and to briefly describe the new chondritic groups. The paper will not focus on unique samples (e.g., Acfer 094; Bischoff and Geiger, 1994) or small grouplets of meteorites (B chondrite grouplet, K-grouplet; e.g., Weisberg et al., 1996, 1998). General information on such meteorite samples are given by Meibom and Clark (1999).

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Table 1
Meteorite falls and finds

Class	Falls		Old finds[a]		All finds[b]	
	n	%	*n*	%	*n*	%
C-chondrites	36	3.6	32	1.9	521	2.5
O-chondrites	737	73.5	785	46.0	13 183	62.3
E-chondrites	14	1.4	11	0.6	186	0.9
R-chondrites	1	0.1	—	—	16	0.1
Others	1	0.1	4	0.2	2	< 0.01
Total chondrites	789	78.7	832	48.7	13 918	65.8
Achondrites	77	7.7	63	3.7	525	2.5
Unclass. stones	72	7.2	65	3.8	5781	27.3
Total stones	938	93.5	960	56.2	20 224	95.6
Total irons	48	4.8	683	40.1	815	3.9
Total stony-irons	12	1.2	63	3.7	104	0.5
Unknown types	5	0.5	—	—	7	0.03
Total meteorites	1003		1706		21 150	

[a]Greatly excludes finds from Antarctica and hot deserts; based on data of Graham et al. (1985) including only about 200 Antarctic samples.
[b]Based on data of Grady (1999). All data are uncorrected for pairing.

2. Number of meteorites and modern search expeditions

In 1985, less than 1000 meteorite falls and 1706 authenticated meteorite finds (referred to as "old finds" in Table 1) were listed in the Catalogue of Meteorites (Graham et al., 1985). Most of these objects were subdivided into several distinct meteorite classes, others were described as grouplets (e.g., Carlisle Lakes-type meteorites, metamorphosed carbonaceous chondrites) or unique samples (e.g., Winona, Kakangari, Lodran, Angra dos Reis). Meteorite searches in hot and cold deserts have led to an enormous increase in the number of meteorites, as well as to an increase in the number of distinct meteorite classes.

After 15 meteorites were found before 1970 in Antarctica, systematic searches for extraterrestrial samples, mainly by Japanese and American expeditions, started in 1973. Up to the present, more than 20 000 meteorite fragments have been recovered (number uncorrected for pairing; Figs. 1 and 2). Especially on so-called blue ice fields meteorite search is very successful. Based on the ice movement, meteorites that fell on a huge ice area are transported through and by the ice and are concentrated in distinct ablation zones near mountain chains (Fig. 2). Because liquid water is very rare in Antarctica, meteorites survive for a very long time. In addition, very small samples can be collected due to the lack of vegetation. In Antarctica, all individual fragments are given a separate number due to the impossibility of knowing which fragments derived from the same original fall.

For the many thousand meteorite fragments recently collected in hot deserts, particularly the Sahara, the situation is somewhat different. The meteorites have much shorter terrestrial ages, since severe weathering under the climatic conditions (rain and atmospheric water, strong temperature changes, wind erosion, etc.) causes a more rapid breakdown of the meteorites than in Antarctica. The meteorites are not transported over tens of kilometers. Therefore, fragments lying close to each other receive the same collection name and number and several thousand of new meteorite numbers have been approved by the Nomenclature Committee of the Meteoritical Society. In North Africa most meteorites have been recovered by private meteorite hunters from large, flat, and almost featureless desert areas (Regs), which are typically covered with cm-sized rounded rocks (pebbles) and a small amount of sand. All these sediments are light-coloured, yellow to grey (Figs. 3–5; compare Bischoff and Geiger, 1995).

Fig. 1. Successful meteorite search in Antarctica. Photograph provided by L. Schultz, Max-Planck-Institut für Chemie (Mainz).

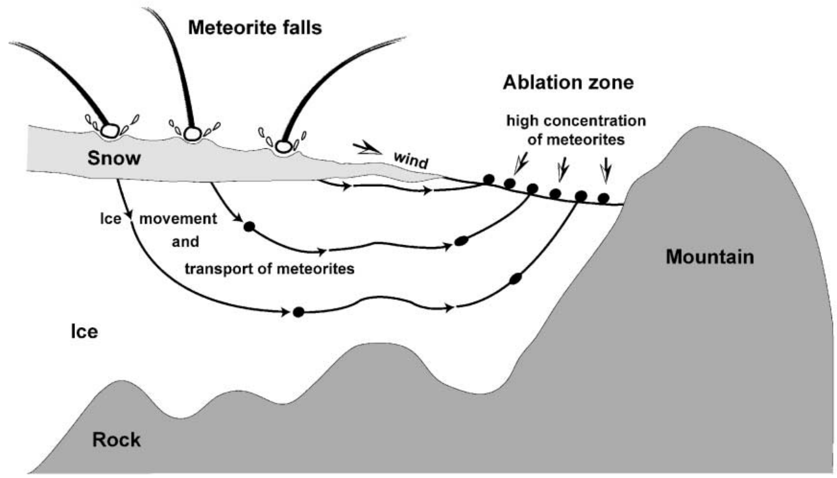

Fig. 2. Meteorite transport and accumulation in Antarctica. Figure redrawn after drawing of L. Schultz, Max-Planck-Institute für Chemie (Mainz).

Fig. 3. Meteorite find in the Ilafegh region of Algeria. The Ilafegh 007 H5 chondrite weighing 615 g was found in October 1989.

At present, the number of collected meteorites from the main meteorite search fields in hot deserts can only be roughly estimated to be 7000–8000 (numbers uncorrected for pairing) including several 10 000 of fragments. About 450 samples are known from Algeria, mainly from the Acfer and Tanezrouft areas.

One group of meteorite hunters does not publish their find locations: More than 2000 "Sahara xxxxx"-samples exist as indicated by the Web-sites of the finders. Small pieces of about 1000 Sahara xxxxx-objects are located in the meteorite collection of the Institut für Planetologie (Münster). Unfortunately, only a small number of these samples has been classified yet.

From Libya about 1300 samples are known mainly from the fields of Dar al Gani (~840), Hammadah al Hamra (~290), and Daraj (~145). More and more samples are coming from Morocco and Western Sahara (main names: Lahmada xxx; Northwest Africa (NWAxxx)). Recently, several hundred samples were collected from different areas within Oman (Dhofar xxx, Jiddat al Harasis xxx, Sayh al Uhaymir xxx). Far more than 2500 meteorite fragments have been recovered in Australian deserts (Koeberl et al., 1992), most of which have not been classified yet. From North America the finding of about 200 samples is known, mainly from the Roosevelt County area, but also from deserts in California, Nevada, Arizona, and Mexico.

3. Classification of meteorites

The main aim of meteorite classification is to sort these extraterrestrial rocks into broadly similar types of objects in order to better understand their origins and relationships. An old classification system is simply distinguishing between stony, stony-iron, and iron meteorites. Such a classification focuses on the modal abundance of metal and does not contain any information on the formation process of the rocks. Especially within the group of stony meteorites considerable diversity exists. This group includes primitive, unequilibrated chondrites as well as differentiated rocks from asteroids as well as stones from significantly larger parent bodies (Lunar and Martian meteorites).

Fig. 4. Meteorite find in the Acfer area of Algeria. A total number of 28 pieces of the H chondrite Acfer 273 with a total weight of 2.11 kg were found in October 1991.

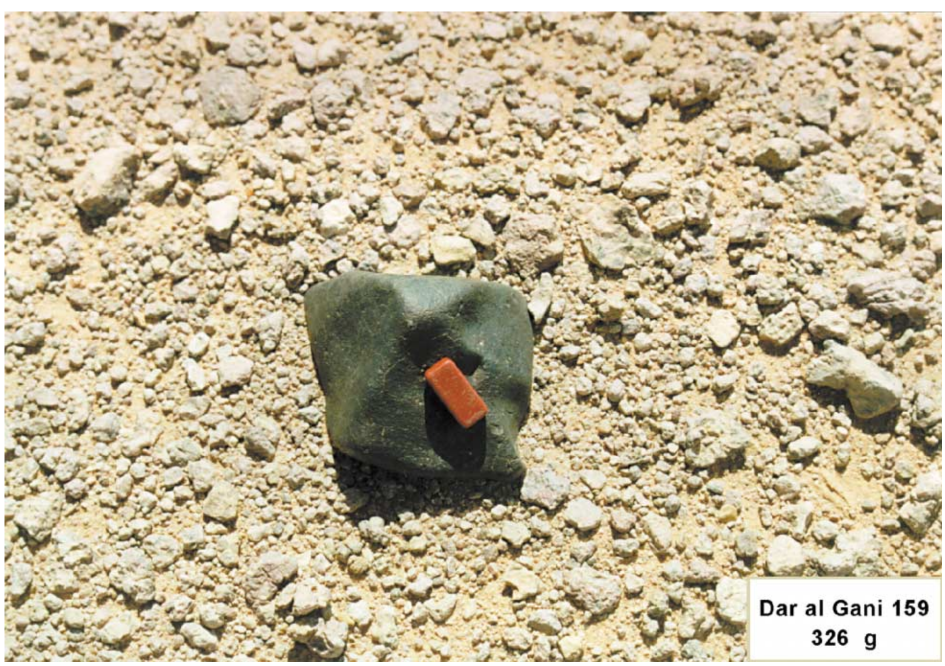

Fig. 5. Meteorite find in the Dar al Gani region in Libya. The single fragment of Dar al Gani 159 weighing 329 g was found in April 1996.

Considering their origin and evolution, meteorites are much better broadly subdivided into the two main divisions "differentiated" and "undifferentiated" (Fig. 6). All the chondritic rocks would belong to the undifferentiated meteorites, whereas the differentiated meteorites include the (metal-poor) achondrites as well as the stony-iron and iron meteorites. Note that the distinction between differentiated and undifferentiated meteorites does not rule out that the accreted starting materials of the parent bodies were similar. It only indicates that the evolution of the body was different.

Considering that five similar meteorites are commonly accepted to be necessary to define a new meteorite class (as done for the CI chondrites) the finding of several ten thousand new samples has resulted in establishing new meteorite classes.

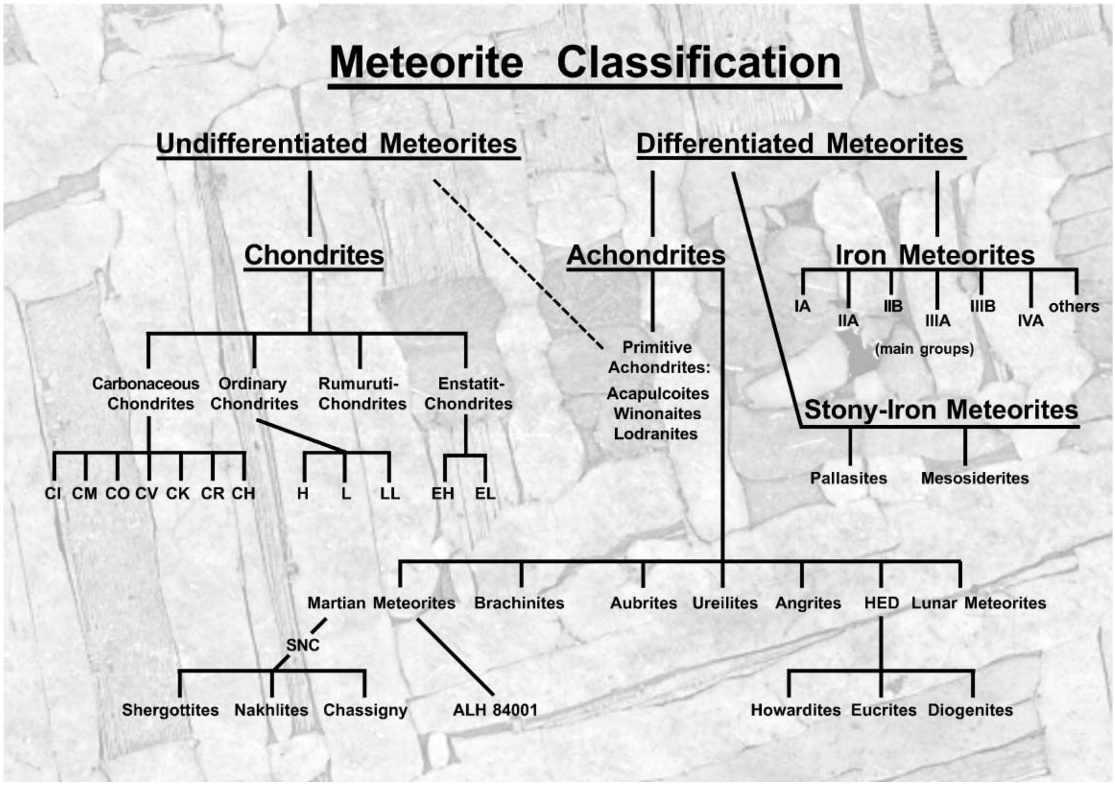

Fig. 6. Classification of meteorites. Division of meteorites into differentiated and undifferentiated rocks. Unique and ungrouped meteorites omitted.

Mainly based on mineralogy and mineral chemistry, actually, four distinct chondritic classes with 12 groups are well defined: (a) carbonaceous chondrites (with the groups: CI, CM, CO, CV, CK, CR, CH), (b) ordinary chondrites (with the groups: H, L, LL), (c) enstatite chondrites (with the groups: EH, EL), and (d) Rumuruti chondrites (R chondrites).

Considering the differentiated meteorites besides the diverse groups of iron meteorites and the two classes of stony-irons (pallasites and mesosiderites) the following main achondrite groups are defined: HED-meteorites (Howardites, Eucrites, Diogenites), aubrites, ureilites, brachinites, and angrites. Furthermore, the Martian SNC (Shergottites, Nakhlites, Chassigny) and the Lunar meteorites have to be included in the achondrite group.

Since desert meteorites were collected, among the undifferentiated chondrites the new class of the Rumuruti (R) chondrites was defined and the carbonaceous chondrites gained three more groups (CR, CH, and CK chondrites). These new undifferentiated meteorite classes will be briefly characterized in the next section. Also, among the achondrites new meteorite classes were defined in recent years (angrites, brachinites, and the primitive achondrite classes of acapulcoites, winonaites, and lodranites).

To be complete, certainly, the most spectacular discovery among the cold and hot desert meteorites was the recognition of the Lunar meteorites. In addition, the number of Martian meteorites has been significantly increased based on successful meteorite search.

4. Brief characterization of new chondrite classes

4.1. R chondrites

Since 1994, the R chondrites have been recognized as a new well-established chondrite group different from carbonaceous, ordinary, and enstatite chondrites (e.g., Schulze et al., 1994; Bischoff et al., 1994, Rubin and Kallemeyn, 1994; Kallemeyn et al., 1996). This group is named after the Rumuruti meteorite, the first, and so far the only, R chondrite fall (Schulze and Otto, 1993; Schulze et al., 1994). The first R chondrite, Carlisle Lakes, was found in Australia in 1977 (Binns and Pooley, 1979), meanwhile the number of R chondrites has increased to about 20.

Most R chondrites are regolith breccias showing the typical light/dark structure and having solar-wind-implanted rare gases (Weber and Schultz, 1995). These meteorites contain unequilibrated, type 3 fragments and clasts metamorphosed to various degrees and should be considered as R3-5 or R3-6 breccias (e.g., Bischoff et al., 1994; Schulze et al., 1994; Kallemeyn et al., 1996; Bischoff, 2000; Fig. 7). Carlisle Lakes is an unbrecciated meteorite of petrologic subtype 3.8. Hammadah al Hamra 119 (Weber

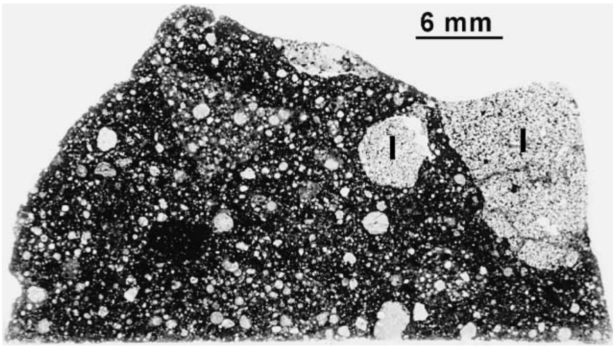

Fig. 7. Photograph of a thin section of the Dar al Gani 013 R chondrite breccia. Various clasts of different lithologies are embedded in a fine-grained matrix. The light fragments (I) on the right-hand side are impact melts (Jäckel et al., 1996).

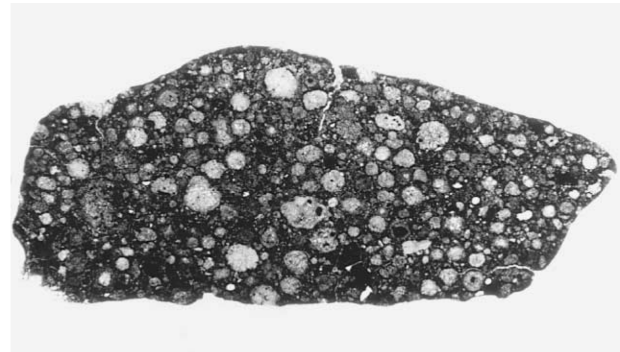

Fig. 8. Transmitted light photomicrograph of a thin section from Acfer 187, a paired sample of the Acfer 059/El Djouf 001 CR chondrite. CR chondrites contain abundant chondrules and chondrule fragments. Width of photograph: ∼4.5 cm. See also Bischoff et al. (1993a).

et al., 1997) and the small sample of Sahara 98248 show no obvious brecciation (R4; Grossman, 1999).

Rumuruti chondrites are rich in modal olivine (> 70 vol%). Pyroxenes and plagioclase both have an abundance of roughly 10 vol%. Only traces of metals occur. Nickel is mainly present in sulfides (∼7 vol%) or as NiO in olivines. Olivine in equilibrated R chondrites or metamorphosed fragments has Fa-contents of 38–41 mol%. Rumuruti chondrites show the highest $\Delta^{17}O$ values among the chondritic meteorites (e.g., Bischoff et al., 1994; Schulze et al., 1994). Unequilibrated lithologies in R chondrites have been recently characterized in detail by Bischoff (2000).

4.2. CR chondrites

Since about 1993 a certain group of chondrites (e.g., Renazzo, Al Rais, Elephant Moraine 87770, MacAlpine Hills 87320, Yamato 790112, 791498, 793495, and Acfer 059-El Djouf 001) has defined the CR group (e.g., Weisberg et al., 1991, 1993; Bischoff et al., 1993a; Kallemeyn et al., 1994). Mineralogical and chemical characteristics indicate a relationship to the CH chondrites. The CR carbonaceous chondrites consist of mm-sized chondrules (approximately 40–60 vol%), dark inclusions, and rare refractory inclusions embedded in a fine-grained, phyllosilicate-rich matrix (Bischoff et al., 1993a; Fig. 8). Metal is quite abundant (approximately 5–10 vol%). Most silicates are reduced: olivine and low-Ca pyroxene have low FeO-contents (Fa_{0-4} and Fs_{0-5}, respectively).

Refractory and common lithophile element abundance is close (within 5%) to the CI abundance. The refractory siderophile elements are chondritic, while the common siderophiles (Fe, Co, Ni) are about 5–15% and the volatile siderophile and chalcophile elements are substantially depleted relative to CI (Bischoff et al., 1993a; Kallemeyn et al., 1994).

The oxygen isotopic composition of CR chondrites is similar to that of CM chondrites (Clayton and Mayeda, 1999). The oxygen data are also indistinguishable from those obtained for CH chondrites, forming a linear trend with a slope of 0.59 (Clayton and Mayeda, 1999).

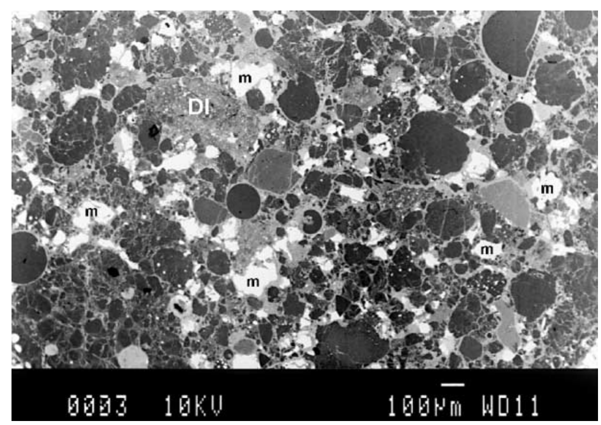

Fig. 9. Typical area of CH chondrite Acfer 182 showing abundant fragments, dark inclusions (DI), metal (m, white), and tiny chondrules. BSE photomicrograph; compare Bischoff et al. (1993b).

4.3. CH chondrites

The major components of CH chondrites include fine-grained, phyllosilicate-rich matrix, abundant mineral and polymineralic silicate fragments and aggregates, chondrule fragments, small chondrules, abundant metal, and fine-grained, dark inclusions. Chondrules in CH chondrites are smaller than in other chondrite groups, but variable in size (ALH85085: ∼20 µm; Acfer 182: ∼90 µm; LEW85332: ∼170 µm (Scott, 1988, Bischoff et al., 1993b, and Rubin and Kallemeyn, 1990, respectively); Fig. 9).

Other mineralogical characteristics include (1) low FeO contents in olivine and pyroxene and correspondingly high metal abundance, (2) high Cr content in olivine, (3) fine-grained, dark inclusions, and (4) abundant grossite in Ca, Al-rich inclusions (Weber and Bischoff, 1994). Bischoff

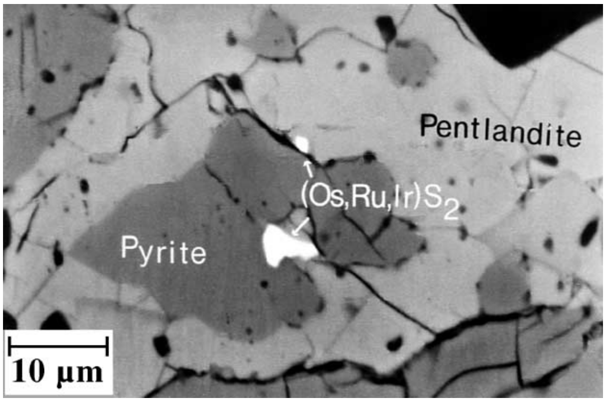

Fig. 10. The occurrence of PGE-bearing minerals is a characteristic feature of all CK chondrites. ((Os,Ru,Ir)S_2)-particles were found in Karoonda. See also Geiger and Bischoff (1995). Photograph provided by T. Geiger.

et al. (1993b) pointed out that a mineralogical and chemical relationship to the CR chondrites exists.

Major chemical signatures include enrichment of Fe and other non-volatile metals and strong depletion of volatile and moderately volatile elements relative to CI chondrites (e.g., Bischoff et al., 1993b). The oxygen isotopic compositions of CH chondrites are basically indistinguishable from those of CR chondrites (Clayton and Mayeda, 1999).

4.4. CK chondrites

Before 1990, meteorites like Karoonda, Mulga (West), and several others from Antarctica were described as C4-6 chondrites, and several authors pointed out that these meteorites should belong to a new and independent group of carbonaceous chondrites (e.g., Kallemeyn, 1988; Geiger and Bischoff, 1990). In 1991, Kallemeyn et al. suggested that these rocks should be described as CK chondrites. Based on chemical analyses, these authors summarized that the elemental abundance patterns in CK chondrites are basically similar to those in CO and CV chondrites. The refractory lithophile elements are about $1.2 \times$CI, while the most volatile elements are depleted by 10–20% relative to CV chondrites (Kallemeyn et al., 1991). The oxygen isotopic compositions of CK chondrites almost exactly match those of CO chondrites (Clayton and Mayeda, 1999).

The CK chondrites are highly oxidized meteorites, having very low metal contents and abundant magnetite. The main petrographic characteristics (Geiger and Bischoff, 1991) include (1) presence of equilibrated olivines with mean Fa-contents between 28 and 33 mol%, 0.5 wt% NiO, and < 0.1 wt% CaO, (2) occurrence of two different pyroxenes (low-Ca pyroxene: Fs_{24-28}; Ca pyroxene: Fs_{8-12}), and (3) presence of many different opaque minerals including rare phases like Pt-group element-bearing sulfides, tellurides, and arsenides (Geiger and Bischoff, 1995; Fig. 10). Some unequilibrated CK3 chondrites were recovered recently (e.g., Geiger et al., 1993).

5. Conclusions and outlook

Based on thousands of new meteorite finds during modern meteorite searches in deserts, our knowledge about early solar system processes and the formation and evolution of planetesimals has been fundamentally enlarged. Rocks from previously unsampled parent bodies were recovered. The number of meteorite classes has been significantly increased. Certainly, new meteorite classes will continue to be established. Considering five independent meteorites as the minimum number of samples necessary to define a new group, only a few additional meteorites will be necessary to establish the K chondrites (Kakangari, LEW87232, Lea Co. 002; Weisberg et al., 1996) and B chondrites (Bencubbin, Weatherford, GRO95551; Weisberg et al., 1998).

It will be very interesting to follow how long meteorite hunters will be able to recover new samples from various locations in hot deserts. Some hunters report already that it will be more and more difficult to detect meteorites in distinct areas, because these areas were prospected by many different companies.

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