Meteorite Minerals[1]

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Abstract—"The Meteorite Minerals Catalog" is the first edition in Russia prepared in the 21st century. It includes all the minerals found in meteorites, approved by the Committee on New Minerals and MMA Mineral Names approved before January 1, 2017, and mineral phases. The Russian and English names, chemical compositions, and meteorites or meteorite groups characterized by the considered minerals are given for all minerals and mineral phases. Notably, the first descriptions of all minerals and phases and references to publications are also given in the Catalog. Minerals whose origin is associated with specific processes are also presented. These include pre-solar meteorite minerals, refractory and ultra-refractory solar condensates, impact minerals of meteorites and products of the terrestrial weathering of meteorites.

Keywords: catalog, minerals, pre-solar grains, refractory condensates, impact minerals, terrestrial weathering minerals

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INTRODUCTION

Meteorites are one of the only types of material that reaches Earth in a natural way (literally fall from the sky). They have attracted attention for a long time owing to their uniqueness, starting with their unique mineral composition. Meteorites contain both common terrestrial minerals, which obviously reflect the general laws of the formation of terrestrial and extraterrestrial matter of the Solar System, and unique minerals that are unknown on Earth or were described for the first time in meteorites and occur in the biosphere only in extreme settings. This also shows the peculiar and unique settings of meteorite formation. The great progress in studying meteorites using modern methods, especially through the Soviet and American meteorite programs, in the second half of the 20th century has facilitated an understanding of these objects as products of diverse and complex processes proceeding during the formation of the solid component of the protoplanetary nebula and on numerous bodies, named "parent bodies". The mineralogy of different types and classes of meteorites, the discovery of unique mineral association formed under peculiar critical conditions, in combination with chemical and isotope data, demonstrate the wide diversity of meteorites and problems in their correlation with terrestrial objects. This opens up a new world of phenomena and events which predated not only Earth's formation but likely the formation of the entire Solar system. Undoubtedly, deciphering these phenomena and events must be based on data on the mineral composition of meteorites, the diversity of their mineral associations, and composition variations of the minerals.

Lists of meteorite minerals have been published repeatedly both for all meteorites (Mason, 1962; Mason, 1967; Yudin and Kolomensky, 1987; Rubin, 1997a, 1997b; Petaev, 1988; Ulyanov, 1998) and for individual meteorite classes (Ramdohr, 1963; 1973;. Buchwald, 1977; Petaeva and Skripnik, 1983).

However, the volume of new, frequently unexpected data, which provides insight into previously unknown properties of meteorite matter, has increased at such a rapid rate that all published summaries become out of date. Therefore it is expedient to return again to the problem of meteorite mineralogy, at least to supplement lists of known minerals. This paper is an attempt to catch up with progress in this field, although by the time of publishing it also will be out-of-date.

This catalog was compiled using previously published lists of meteorite minerals. However, in most cases, we based the catalog on first descriptions of minerals.

The catalog includes three main sections:

Section 1 "Classification of Meteorites" includes brief descriptions of the main meteorite groups: stony, stony-iron, and iron.

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Section 2 "Minerals and Mineral Phases—Distribution by Mineral Classes" is represented by Supplementary Table S1, which demonstrates minerals grouped by classes, their varieties, and mineral phases. The first column shows the main composition and structural group, if determined, and geochemically significant varieties of minerals. The second column includes meteorites and meteorite groups, which usually contain the considered minerals. In most cases, mineral names are accompanied by a reference which reports the type locality and reliable description of the mineral. The exception is minerals which have terrestrial analogs known since the early works on meteorite study (since the 18th century). Supplementary Table S1 yields the intra-tabular numbering of sections, which is used in the alphabetical list of all minerals presented in the Supplement.

Section 3 "Peculiar Groups of Meteorite Minerals" presents mineral groups that are ascribed to definite chemical groups, but have a peculiar origin. Four mineral groups are distinguished in this section: 3.1 Presolar meteorite minerals, 3.2 Ultra-refractory solar condensates, 3.3 Shock-induced minerals in meteorites, 3.4 Terrestrial weathering minerals.

As mentioned above, the Section 2 in the Supplement is followed by an alphabetic list of minerals approved by the International Mineralogical Association. Names and chemical composition are given. This list includes minerals that are known in meteorites but have not been found in terrestrial rocks. The number of each mineral corresponds to that in the Supplementary Table S1. For instance, number 2.1 Awaruite implies that information on this mineral can be found in the section 2.1 of Supplementary Table S1.

The supplement also includes a list of mineral phases which have accurately determined composition but were not identified as minerals for one reason or another. This is usually related to the poorly determined structural characteristics of the material. Each phase has a definite entry in Supplementary Table S1.

The alphabetical list of minerals in the Supplement is followed by a complete list of literature for all sections of the catalog.

Terminology:

Since the catalog is intended for professional readers, well-known abbreviations used in the scientific literature, including references, are not deciphered. The abbreviations of mineral structural groups also are not deciphered.

It is reasonable to explain some terms used primarily only in the meteorite literature:

—**CAI** means "Calcium-Aluminum-rich Inclusion," ascribed to inclusions enriched in calcium and aluminum, or white inclusions;

—**AOA** means "Amoeboid Olivine Aggregate";

—**Fremdling** (from German, meaning strange or foreign) includes very rare small objects which are enriched in the refractory siderophile elements and occur in Ca–Al-rich inclusions (CAI) in CV carbonaceous chondrites.

Chemical compositions are given in weight percent. Exceptions are specially noted, for instance, albite <10 mol % $CaAl_2Si_2O_8$.

The presence of trace elements in minerals is shown by the element symbol in parentheses, after the mineral name, for instance, violarite-(Co).

List of mineral synonyms:

Bloedite = Astrakhanite

Wustite = Iozite

Cosmochlor = ureyite,

Sphene = titanite

Chalcosine = chalcocite,

Khogarite = kokharite.

1. METEORITE CLASSIFICATION

At present, the total world collection includes approximately 30000 meteorites. Most of them are fragments of asteroids. Cometary material is supplied to Earth as small dust-like micron sized particles. Fragments of large planetary bodies such as the Moon and Mars also fall to Earth.

This catalog does not consider Lunar and Martian meteorites, because they are formed through deep differentiation in the interiors of sufficiently large cosmic bodies and therefore, sharply differ from asteroidal matter. The material of lunar and Martian meteorites significantly expands our knowledge of the composition and processes of formation of their parent bodies and should be considered in combination with data on these bodies obtained by other methods. Correspondingly, minerals of these meteorites should be included in other catalogs: Catalogs of Minerals of the Moon and Mars.

Table 1 lists the present-day classification of meteorites. The table and further description are based mainly on data from (Dodd, 1981; Brearley and Jones, 1998; Mittlefehldt et al., 1998; Krot et al., 2003). Isotope composition is of highest significance for meteorite classification, in particular, oxygen isotope data on stony meteorites (Clayton and Mayeda, 1996; 1999).

Below we report the brief characteristics of meteorite groups. Detailed descriptions of the chemical and mineral compositions of the meteorite groups, their petrographic features, isotope composition, the degree of aqueous and impact reworking, and other parameters can be found in the papers cited above and references therein, as well as in publications from Meteoritics & Planetary Science, Geochimica et Cosmochimica Acta, American Mineralogist, Meteoritika, and others.

Chondrites

Chondrites represent the earliest, most primitive material of the Solar System. They are formed by condensation from a solar gas in different parts of the Solar nebula under various physicochemical parameters, which determine the specifics and diversity of their formation.

The class of carbonaceous (C) chondrites includes 8 groups:

CI chondrites (Ivuna type) are the most primitive meteorites, the composition of which is close to that of the solar photosphere. These meteorites are the most hydrated among all chondrites. CI chondrites consist mainly of fine-grained matrix made up of layer silicates with admixture of magnetite, sulfides, sulfates, and carbonates, and scarce grains of olivine and pyroxene.

CM chondrites (Mighei type) are characterized by a high abundance of matrix (~70 vol %) consisting of layer silicates, tochilinite, sulfates, carbonates, and magnetite with high content (~30 vol %) of relatively small chondrules ~300 μm across of different types. CAI and AOA are common.

CO chondrites (Ornans type). This group is characterized by a relatively low abundance of matrix (~30–45 vol %) and a high content (~35 vol %) of small chondrules (~150 μm across), as well as CAI and AOA. Minerals of chondrules and CAIs are commonly subjected to secondary alterations with formation of nepheline, sodalite, olivine, andradite, hedenbergite, and ilmenite, while layer silicates are absent.

CR chondrites (Renazzo type). The CR chondrites have high content of large magnesian chondrules rich in Fe,Ni-metal, high Cr_2O_3 content (about 0.5%) in olivine chondrules, high content of Fe,Ni-metals with a positive Ni/Co correlation, contain rare CAI and AOA, and numerous strongly hydrated clasts usually termed dark inclusions.

CH chondrites (ALH85085 type) have high content of Fe,Ni-metal (about 20 vol %) with positive Ni/Co correlation, small chondrules and CAI about 20 μm, with a predominance of cryptocrystalline chondrules, high Cr_2O_3 (about 0.5%) in the olivine chondrules, absence of matrix, and the presence of strongly hydrated crystalline dark clasts.

CB chondrites (Bencubbin type). This group of carbonaceous chondrites is highly enriched in Fe,Ni-metal (60–70 vol %) with positive Ni/Co correlation; chondrules are high-Mg (Fa and Fs = 4) with cryptocrystalline and skeletal olivine texture. Meteorites of this group are subdivided into CB_a and CB_b subgroups, which differ in the content and composition of metal, CAI content, and chondrule size.

CV chondrites (Vigarano type). The CV chondrites are characterized by the high abundance of CAI and AOA widely varying from a millimeter to a centimeter in size; millimeter-sized chondrules mainly have porphyritic texture and magnesian composition, and contain unique nodules of salite—hedenbergite±andradite composition. Based on the difference in the metal/magnetite modal ratio and the Ni content in metal and sulfides, the CV chondrites are subdivided into two subgroups: oxidized CV_{Ox} and reduced CV_R. These subgroups of CV chondrites differ significantly in mineralogy. The chondrules of CV_R chondrites show no visible aqueous alteration. The chondrules of CV_{Ox} chondrites are characterized by diverse water-fluid alterations of varying degrees, expressed in the replacement of primary minerals by layer silicates, magnetite, Ni-rich sulfides, etc.

CK *chondrites* (Karoonda type) are practically completely devoid of Fe,Ni-metal, have a high abundance of matrix, contain rare CAI and AOA, large (0.7–1 mm) porphyritic chondrules, high-Fa olivine ($Fa_{29–33}$), high NiO content in olivines (up to 0.7 wt %), high magnetite content, high Ni content in sulfides, and the wide variations of plagioclase composition.

The **class of ordinary (O) chondrites** includes **H, L, and LL groups** of **chondrites**. In general, O chondrites are characterized by a high content of chondrules of mainly non-porphyritic texture, and rarity of Al-rich chondrules, as well as CAI and AOA, and wide variations of metamorphic grade, which affects the composition of the major minerals: olivine, pyroxene, and plagioclase. The H, L, and LL chondrite groups differ in the content of metallic iron (on average, 8.4, 4.1, 2.0 vol %) and Fe_{met}/Fe_{tot} ratio (on average, 0.6, 0.3, 0.1), as well as in the average diameter of chondrules

Table 1. Classification of meteorites

Stony meteorites	
Chondrites	Achondrites
Carbonaceous CI-CM	Primitive
CO CV CK	Acapulcoite
CR–CH-CB	Winonaite
Ordinary H	Lodranite
L	Differentiated
LL	Eucrites
Enstatite EH	Howardite
EL	Diogenite
Rumuruti type R	Angrite
Kakangari type K	Aubrites
	Brachinites
	Ureilites

Stony-iron meteorites	
Mesosiderites	Pallasite

Iron meteorites	
Structural groups	Chemical groups
Hexahedrite	IAB, IC, IIAB, IIC, IID, IIE,
Octahedrite	IIIAB, IIICD, IIIE, IIIF,
Ataxite	IVA, IVB

(0.3, 0.7, 0.9 mm) and the Co content in kamacite (H, L, and LL up to 0.51, 0.95, 37 wt %, respectively).

The *class of enstatite (E) chondrites* has a unique mineralogical composition. These chondrites contain sulfides of lithophile elements (osbornite, alabandite, niningerite, keilite), nitrides (osbornite, sinoite), and phosphor-silicide (perryite), high silica content in kamacite, which indicates the extremely reducing conditions of formation. The silicate component is mainly represented by cryptocrystalline and porphyritic chondrules of essentially enstatite composition at the extremely low abundance of matrix. Based on chemistry and mineralogy, class E chondrites are subdivided into two groups: EH and EL. The typomorphic EH sulfides are niningerite and keilite, while EL chondrites contain alabandite. The EH group is enriched in sulfides, contains alkali sulfides, and has higher Si content in kamacite (up to 4.9%) compared to EL chondrites (up to 1.2%), and some other features.

Group K chondrites (Kakangari type) includes only two meteorites, Kakangari and Lewis Cliff 87232 and in terms of some parameters is similar to meteorites of other classes and groups. In particular, the K chondrites resemble C chondrites in terms of the high matrix abundance (70−77 vol %), and H chondrites in terms of content of metallic phase (6−9 vol %), and occupy an intermediate position between H and E chondrites in terms of the average composition of olivine and enstatite, etc.

Group R chondrites (Rumuruti type) are characterized by a moderately high content of matrix (about 50 vol %), high NiO content in olivines, and nearly complete absence of metal, which indicates their highly oxidized state, as well as by the extreme rarity of CAI. The majority of R chondrites are brecciated and enriched in solar wind gases, which identifies these rocks as regolith breccia.

Achondrites

Achondrites are rocks formed through remelting and differentiation of chondrite matter in planetary bodies. Mineralogically, the achondrites sharply differ from chondrites in the absence of CAI and AOA, ultra-refractory solar condensates, nitrides, and some other specific minerals. Based on degree of melting and further evolution, achondrites are subdivided into two main categories: **primitive** and **differentiated**.

The primitive achondrites are compositionally close to chondrites, but have metamorphic or magmatic texture. These are acapulcoite, lodranites, and winonaites.

The acapulcoites and lodranites are close to chondrites in their mineralogy, in the first approximation, but differ in the composition of minerals, their grain size, and proportions. Some acapulcoites contain the relicts of chondrules. These two similar achondrite groups differ mainly in the grain size of constituent minerals: acapulcoite is fine-grained (150−230 μm), while lodranites are coarse-grained rocks (540−700 μm). Based on the exposure age, these achondrite groups could have been ejected from a single parent body during a single shock event.

Winonaites in general are close to chondrites in chemistry and mineralogy, but significantly differ from them in texture. These are mainly equigranular fine to medium-grained rocks, and are transitional in mineral composition between E and H chondrites. The winonaites contain metal-troilite veinlets and, in some cases, relicts of chondrules. The mineral and oxygen isotope composition indicate a genetic link between winonaites and silicate inclusions in type IAB and likely type IIICD iron meteorites.

Differentiated achondrites are the products of large-scale partial melting in the interior of parent bodies and subsequent differentiation of the material. They include angrites, aubrites, brachinites, ureilites, and achondrites of the HED group (abbreviation of howardites, eucrites, and diogenites).

Angrites are medium to coarse-grained (up to 2−3 mm) magmatic rocks, which have basaltic composition but contain peculiar minerals (for instance, accessory kirschsteinite and high-Al clinopyroxene). These are the lowest alkali basalts in the Solar System.

Aubrites (enstatite achondrites) are strongly reduced enstatite pyroxenites. They contain 75−95 vol % Fe-free enstatite. Almost all aubrites are represented by fragmentary or, more rarely, relict breccias. Judging from the mineral composition and oxygen isotopy, the aubrites are related to E chondrites but were derived from different parent bodies.

Brachinites are dunite wehrlites. These are medium to coarse-grained rocks containing up to 74−98 vol % olivine (Fo_{65-70}).

Ureilites are carbon-bearing ultrabasic rocks consisting mainly of olivine and pyroxene, mainly pigeonite. Olivine is enriched in Ca and Cr, while pigeonite is enriched in Cr. Carbon (up to 5 wt %) in ureilites is mainly represented by graphite, as well as chaoite, diamond, and lonsdaleite, and is involved in cogenite present in silicates. Ureilites are subdivided into three types based on petrography and mineralogy.

Characteristics of the HED *Group achondrites* (howardites, eucrites, diogenites) indicate a genetic affinity of meteorites of this group. Among these characteristics are the identical oxygen isotope composition, similar Fe/Mn ratio of pyroxenes, the presence of breccias containing fragments of the rocks of this group, and some others. Such characteristics suggest that the meteorites were ejected from a single parent body, likely Asteroid 4 Vesta.

Diogenites are coarse-grained, frequently brecciated and defragmented (>5 cm) cumulate orthopyroxenites. According to the existing model, the dio-

genites represent the deepest sampled horizon of the parent body of HED group achondrites.

Eucrites were localized higher to the surface of the parent body. These are pyroxene—plagioclase basalts and are subdivided into three subgroups: noncumulate (basaltic) eucrites, cumulate eucrites, and polymict eucrites. The non-cumulate eucrites were initially formed as rapidly cooling, later metamorphosed lava flows. These weakly brecciated metamorphosed basalts are most abundant among eucrites. The cumulate eucrites are coarse-grained, frequently unbrecciated gabbros. The polymict eucrites are polymictic breccias made up mainly of eucrite, but containing up to 10 vol % diogenite.

Howardites are lithified regolith of a parent body. These are polymict breccias consisting mainly of eucrite and diogenite, with numerous brecciated fragments and impact-melt rocks. The fine-grained matrix has a high content of implanted solar wind gases.

Stony-Iron Meteorites

The stony-irons are differentiated meteorites. They include mesosiderites and pallasites.

Mesosiderites are breccias consisting of almost equal amounts of silicates and Fe,Ni metal. The silicate part consists of rock fragments of basalts, gabbroids, and pyroxenites, with subordinate dunites and scarce anorthosites, and large grains of orthopyroxene, olivine, and plagioclase. The magmatic rocks and minerals are compositionally close to those of the HED group achondrites. In terms of orthopyroxene abundance, the mesosiderites are subdivided into three classes. The metal is represented by grains from a millimeter to sub-millimeter in size. Compositionally, it is close to that of type IIIAB iron meteorites.

Pallasites consist of approximately equal amounts of silicates, Fe,Ni metal, and troilite. Based on the composition of silicate phases and metal and oxygen isotope composition, the pallasites are subdivided into three groups: (1) main group, (2) Eagle Station subgroup (4 meteorites), (3) pyroxene pallasite subgroup (2 meteorites). The silicate component of the main group is mainly represented by olivine ($Fo_{88\pm1}$) with trace orthopyroxene. The Fe,Ni metal is close in composition to the metal of the IIIAB iron meteorites. The Eagle Station subgroup is mineralogically similar to the pallasites of the main group, but olivine is higher in Fe and Ca. The metal of this subgroup is close to that of IIF group iron meteorites. The pyroxene pallasite subgroup contains 55−63 vol % olivine, 30−43 vol % metal, and 1−3 vol % pyroxene. Unlike other pallasite groups, these rocks contain millimeter-sized pyroxene grains. The metal of this group has variable composition.

Iron Meteorites

Iron meteorites are the products of deep differentiation in the interior of a parent body. They consist mainly of kamacite and taenite, with troilite and schreibersite as common accessories.

There are structural and chemical classifications of iron meteorites.

The structural classification is based on the presence of two polymorphic phases of Ni,Fe metal: kamacite (α-Ni,Fe, Ni < 6%) and taenite (γ-Ni,Fe, Ni > 25%). Their abundance is determined by the Ni content. In the majority of iron meteorites, the Ni content accounts for 6−16%, while kamacite occurs as lamellae oriented parallel to the octahedral planes in taenite, thus forming a specific pattern called widmanstatten. Meteorites with such patterns are usually named octahedrites (denoted as O) and are subdivided into types by thickness of the kamacite lamellae (rods), which shows a negative correlation with the Ni content (type of octahedrites—width of lammelae): very coarse structured, Ogg >3.3; coarse-structured, Og 1.3−3.3; medium-structured, Om 0.5−1.3; fine-structured, Of 0.2-0.5; very fine structured, Off - <0.2; plessite, Opl <0.2. Meteorites with Ni <6% consist practically completely of kamacite, are devoid of widmanstatten pattern, and termed hexahedrites (denoted H). Meteorites with high Ni content and also devoid of widmanstatten pattern are termed ataxites (designated D).

The chemical classification is based on the relative content of some siderophile elements in the metal. In log M—log Ni diagrams, where M is Ge, Ga, or Ir, about 85% of them fall in one of 13 fields, with alphanumeric designations of chemical groups which include no less than five meteorites. The chemical groups do not always correspond to the structural groups.

Some groups of iron meteorites (IAB, IIICD, IIE, IVA) contain silicate inclusions of diverse composition. Inclusions in IAB and, to lesser extent, in IIICD groups in terms of oxygen and mineral composition are close to winonaites and could have been ejected from a single asteroid. Inclusions in group IIE meteorites are characterized by a diversity of structural types from chondrite to gabbro, but in terms of oxygen isotope composition they are similar to H chondrites, which may indicate a genetic linkage. Silicate inclusions in group IV A iron meteorites have chondrite mineralogy.

Most of the classes contain meteorites which cannot be ascribed to a certain group. These account for about 15% of iron meteorites. These meteorites are designated as unusual, unique, or anomalous.

2. MINERALS AND MINERAL PHASES: DISTRIBUTION BY MINERAL CLASSES

This section is made as the Supplementary S1 Table.

Table 2. Pre-solar minerals of meteorites

Nanodiamond—C	Magneli phases Ti_nO_{2n-1}
Graphite—C	Chromium oxides—Cr_2O_3
Grain of metal $Os_{79}Mo_{10}Ru_9Fe_2$	Iron oxide (wustite-?)—FeO
Kamacite—Fe,Ni	SiO_2-phase
Cohenite—$(FeNi)_3C$	Hibonite—$Ca(Al,Ti)_{12}O_{19}$
Silica carbide—SiC	Spinel—$MgAl_2O_4$
Titanium carbide—TiC	Magnetite—Fe_3O_4
Carbides of weakly volatile metals—(Zr,Mo,Ti,Ru)C	Chromite—$FeCrO_4$
Silica nitrides—α-Si_3N_4	Magnesiochromite—$MgCrO_4$
Aluminum nitride—AlN	Spinel—magnesiochromite solid solution—$MgAlCrO_4$
Corundum—Al_2O_3	Silicates: magnesian and ferroan
Rutile—TiO_2	Olivines and pyroxenes, amorphous silicate phases
Tistarite—Ti_2O_3	
Oxide Ti—Ti_3O_5	

3. PECULIAR GROUPS OF METEORITE MINERALS

3.1. Pre-solar minerals of meteorites

Pre-solar (interstellar) grains represent isotopically anomalous inclusions in a fine-grained matrix of primitive (disequilibrium) chondrites. The grains are identified as pre-solar on the basis of anomalous rare gas isotope composition (Ne, Kr, Xe), C, N, O, Al, Si and others) with respect to Solar System material, indicating that the elements were formed in the interior of stars of different classes (Zinner, 1998; 2003; Nittler, 2003).

Grains of pre-solar minerals, nanodiamond and silicon carbide SiC, were found in 1987 in the residuals from the chemical decomposition of meteorite material (Bernatowicz et al., 1987; Lewis et al., 1987). Later, grains of pre-solar oxides and silicates were found in primitive meteorites (Nagashima et al., 2004; Nguyen and Zinner, 2004). At present, pre-solar mineral grains have been found in primitive meteorites of almost all chondrite classes. The finding of pre-solar grains of diverse minerals in situ is common. In some cases, the pre-solar grains represented by TiC, carbides of hardly volatile metals, TiO_2, and kamacite occur within pre-solar spherical graphite grains (Bernatowicz et al., 1991, 1996, 1999; Croat, 2007).

The sizes of pre-solar gains vary widely, usually within $0.1-1 \mu m$ (Nittler, 2003; Ott, 2007; Ebata et al., 2007). Nanodiamond grains have minimal sizes. The largest pre-solar grain 30 μm in size is made of silica carbide and was found in the Murchison meteorite (Zinner et al., 2010). This grain was named Bonanza after the prospecting term for a rich mineral find.

Below, we report a fairly comprehensive list of presolar minerals and mineral phases of meteorites, which is and continuously supplemented (Table 2). Information on the occurrence of these minerals and phases is given in Supplementary Table S1.

3.2. Ultra-refractory solar condensates

Condensation was the leading process during formation of the solid component of the Solar System from a hot solar gas. The composition of forming solid particles was mainly controlled by the condensation temperatures of nebular gas components. The early condensates are so-called Ca- and Al-rich inclusions usually termed CAI, the abbreviation of their English name. These inclusions are most abundant in the CV3 chondrites, but also occur in some other types of chondrites. The major minerals of common CAIs are spinel, melilite, gibeonite, perovskite, and Al–Ti-rich clinopyroxene previously termed fassaite. However, some CAIs contain minerals and associations with condensation temperatures much higher than typical of the common CAI minerals. These ultra-refractory minerals are enriched in weakly volatile Zr, Hf, Sc, Y, Ti, and HREE. All minerals and mineral phases ascribed to the ultra-refractory solar condensates are oxides. The early formation of these minerals is consistent with their predominant presence in the inner parts of CAIs.

Table 3 below presents a list of minerals and mineral phases of this type. Information on the occurrence of these minerals and phases in meteorites is given in Supplementary Table S1.

3.3. Shock-induced minerals in meteorites

Collision of solid bodies in outer space is one of the most important processes of transformation of solar system material. A meteoroid is a cosmic body, which becomes a meteorite when reaches Earth. It is formed through shock events such as the ejection of fragments from a parent body during impact or through destruction of smaller bodies.

One of the most significant results of shock events is the formation of new high-pressure mineral phases (Table 4). Such phases are mainly present in shock-

Table 3. Minerals of ultra-refractory solar condensates

Allendeite—$(Sc,Ti,Ca)_4Zr_3O_{12}$	Tazheranite—$(Zr,Sc,Ti,Ca)O_{1.75}$
Anosovite—$(Ti^{4+},Ti^{3+},Mg, Sc,Al)_3O_5$	Thorianite—$(Th,U)O_2$,
Varkite—$Ca_2Sc_6Al_6O_{20}$	Thortveitite—$Sc_2Si_2O_7$
Davisite—$Ca(Sc,Ti,Mg)((Al,Si)_2O_6)$	Zirconolite—$(Ca,Fe,Y)ZrTi_2O_7$
Kangite $(Sc,Ti,Al,Zr,Mg,Ca, \square)_2O_3$	Eringaite—$Ca_3(Sc,Y,Ti)_2Si_3O_{12}$
Lakargiite—$CaZrO_3$	Mineral phase—$((Sc_{0.66}Ti^{4+}_{0.41}Ca_{0.39}Y_{0.52})_2(Zr,Hf)_3)_5O_9$
Panguite—$(Ti^{4+},Sc,Al,Mg,Zr,Ca)_{1.8}O_3$	Mineral phase—$Sc_2(Zr,Ti)_2O_7$
Perovskite Zr,Y,Sc —$CaTiO_3$	Mineral phase—$(Y,Ca,Sc)(Zr,Ti^{3+})_3O_7$
Zr-bearing pyrochlore Th,U,Ti-$(Ca,TR,Th)_{1.8}(Nb,Ti,Zr)_2O_7$	

Table 4. Shock-induced minerals in meteorites

Diamond—C	Mineral with olivine structure and pyroxene composition—$Na_{0.06}Mg_{0.71}Fe_{0.20}Al_{0.11}Si_{0.94}O_3$
Lonsdaleite—C	
Chaoite—C	Maskleynite is the plagioclase glass, is alternatively interpreted as diaplectic or melt glass
Coesite—SiO_2	
Stishovite—SiO_2	Lingunite is a plagioclase polymorph with hollandite type structure $(Na,Ca)AlSi_3O_8$
Ringwoodite (spinel)—γ-$(Mg,Fe)_2SiO_4$	
Wadsleyite—(spinel) β-$(Mg,Fe)_2SiO_4$	Xieite—($FeCr_2O_4$ with $CaTi_2O_4$-type structure)
Fe_2SiO_4-spinel Fe_2SiO_4	$FeCr_2O_4$ with $CaFe_2O_4$-type structure
Majorite—pyrope solid solution	Tuite—γ-$Ca_3(PO_4)_2$
Akimotoite—($MgSiO_3$-ilmenite)	
$MgSiO_3$-perovskite	
Jadeite—$Na(Al,Fe^{3+})Si_2O_6$	
Magnesiowustite—$(Mg,Fe)O$	

induced melt veinlets in L6 S6 chondrites. At the same time, high-density carbon phases are quite evenly distributed in host samples.

Below, we report a list of shock-induced pre-solar minerals and phases in meteorites. This list is sufficiently comprehensive and continuously supplemented. Information on the occurrence of these minerals and phases in meteorites is given in Supplementary Table S1.

3.4. Terrestrial weathering minerals

When a meteorite falls to Earth, it enters conditions that are sharply different from those of its parent body and inevitably lead to its transformations. There are several main groups of mineral formation processes related to meteorites falling to Earth:

Oxidation and decomposition of meteorite minerals during formation of fusion crust as the meteorite passes through the Earth's atmosphere. The major minerals of the fusion crust are magnetite and wustite (Yudin and Kolomensky, 1987).

Transformation of meteorite minerals under terrestrial conditions owing to the oxidation, hydration, and input of components from terrestrial rocks. The actual transformation of the meteorite material depends significantly on the type of meteorite, conditions of the landing site, and its terrestrial age. For instance, the Cl-bearing oxides, akaganeite and hibbingite, are typical of Antarctic L6 chondrites, but extremely rare in such meteorites from hot deserts. On the other hand, L6 chondrites from hot deserts contain Mg sulfates and carbonates, which are nearly absent in samples from Antarctica (Lee and Bland, 2004).

Evaporation and redeposition of material, interacting with components of Earth's atmosphere. These processes are responsible for the formation of sulfates (epsomite, starkeyite, jarosite) and some other minerals of Antarctic meteorites (Marvin and Motylewski, 1980). A similar mechanism explains the formation of veinlets in CI chondrites stored in museum collections (Gounelle and Zolensky, 2001).

Deep reworking of fossil meteorites. A study of the Brunflo H4-5 chondrite (Nyström and Wickman, 1991) found in Ordovician sediments (460—470 Ma) showed a cardinal change of mineral composition, including, for instance, the formation of arsenides and sulfoarsenides.

It should be noted that a mineral could be formed under terrestrial conditions and also on parent bodies of

Table 5. Terrestrial weathering minerals

Akaganeite—β-FeO(OH,Cl)	Nesquehonite—Mg(HCO$_3$)(OH) $\cdot$ 2H$_2$O
Arypite—Ni$_3$(PO$_4$)$_2$ $\cdot$ 8H$_2$O	Nickeline—NiAs
Baričite—(Mg,Fe^{2+})$_3$(PO$_2$)$_2$ $\cdot$ 8H$_2$O	Orcelite—Ni$_{5-x}$As$_2$
Vaterite—CaCO$_3$,	*Pecoraite—Ni$_3$Si$_2$O$_5$(OH)$_4$
Galena—PbS	Portlandite—Ca(OH)$_2$
Gerdsorfite—NiAsS	Rammelsbergite—(Ni,Co)As$_2$
Hydromagnesite—Mg$_5$(CO$_3$)$_4$(OH)$_2$ $\cdot$ 4H$_2$O	*Reevesite—Ni$_6$Fe$_2$(CO$_3$)(OH)$_{14}$ $\cdot$ 4H$_2$O
*Droninoite—Ni$_3$Fe^{3+}Cl(OH)$_8$ $\cdot$ 2H$_2$O	Safflorite—(Co,Ni)As$_2$
*Cassidyite—Ca$_2$(Ni,Mg)(PO$_4$)$_2$ $\cdot$ 2H$_2$,O	Starkeyite—MgSO$_4$ $\cdot$ 4H$_2$O
Cobaltite—CoAsS	Trevorite—NiFe$_2$O$_4$
Covellite—CuS	Francolite—Ca$_5$(PO$_4$,CO$_3$)F
Collinsite—Ca$_2$(Mg,Fe)(PO$_4$)$_2$ $\cdot$ 2H$_2$O	Chalcocite—Cu$_2$S
Lepidocrocite—γ-FeO(OH).	Hibbingite—γ-Fe$_2^{2+}$(OH)$_3$Cl
Lipsocombite—(Fe,Mn)Fe$_2^{3+}$(PO$_4$)$_2$(OH)	*Chukanovite—Fe$_2$(CO$_3$)(OH)$_2$
Magnesioferrite—MgFe$_2$O$_4$	Schwertmannite—Fe$_{16}^{3+}$O$_{16}$(OH)$_{12}$(SO$_4$)$_2$
Maucherite—Ni$_{11}$As$_8$	

Table 6. Minerals representing the alteration products of meteorites under terrestrial and extraterrestrial conditions

Awaruite—Ni$_2$Fe-Ni$_3$Fe	Hematite—α-Fe$_2$O$_3$
Apatite—Ca$_5$(PO$_4$)$_3$(F,OH,CL)	Goethite—α-FeOOH
Barite—Ba(SO$_4$)	Gypsum—CaSO$_4$ $\cdot$ 2H$_2$O
Bassanite—CaSO$_4$ $\cdot$ 0.5H$_2$O	Dioxide Ti—TiO$_2$
Bloedite (Astrakhanite)—Na$_2$Mg(SO$_4$)$_2$ $\cdot$ 4H$_2$O	Dolomite—CaMgCO$_3$
Bornite—Cu$_5$FeS$_{4.3}$	Isocubaniye—CuFe$_2$S$_3$,
Bunsenite—NiO	Illite—
Vivianite—Fe$_3$(PO$_3$)$_2$ $\cdot$ 8H$_2$O	Ni-pyrite (bravoite)—(Fe,Ni)S$_2$
Wustite—FeO	Calcite—CaCO$_3$
Quartz—SiO$_2$	Sulfur—S
Quartz—SiO$_2$	Siderite—FeCO$_3$,
Copiapite—Fe^{2+}Fe$_4^{3+}$(SO$_4$)$_6$(OH)$_2$ $\cdot$ 20H$_2$O	Sulfide Cu—Cu$_4$FeS$_4$
Maghemite—γ-Fe$_2$O$_3$	Sulfide Cu—Cu$_5$S$_3$
Magneite—FeFe$_2$O$_4$	Sphalerite—ZnS
Copper—Cu	Chalcopyrite—CuFeS$_2$
Melanterite—FeSO$_4$ $\cdot$ 7H$_2$O	Heazlewoodite—Ni$_3$S$_2$
Nickel—Ni.	Honessite—(Ni,Fe)$_8$SO$_4$(OH)$_{16}$ $\cdot$ 4H$_2$O
Opal—SiO$_2$ $\cdot$ nH$_2$O	Schöllhornite—Na$_{0.3}$CrS$_2$ $\cdot$ H$_2$O
Pentlandite—(Fe,Ni)$_9$S$_8$	Epsomite—MgSO$_4$ $\cdot$ 7H$_2$O
Pyrite—FeS$_2$	Eskolaite—Cr$_2$O$_3$
Pseudobrookite—Fe^{2+}Ti$_2$O$_5$	Jarosite—KFe$_3$(SO$_4$)$_2$ $\cdot$ (OH)$_6$

some meteorites, for instance, during oxidation and hydration of matter on carbonaceous chondrite bodies.

A list of terrestrial weathering minerals is shown below and includes both minerals that were not found in unaltered meteorites (Table 5) and minerals that could be formed both through terrestrial weathering and reworking on the parent body (Table 6), for instance, owing to the impact events in outer space or through coalescence of materials of different composition within a single body.

Data on the occurrence of these minerals and phases in meteorites are given in Supplementary Table S1.

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