APPENDIX 1

Minerals in Meteorites

Minerals make up the hard parts of our world and the Solar System. They are the building blocks of all rocks and all meteorites. Approximately 4,000 minerals have been identified so far, and of these, ~280 are found in meteorites. In 1802 only three minerals had been identified in meteorites. But beginning in the 1960s when only 40–50 minerals were known in meteorites, the discovery rate greatly increased due to impressive new analytic tools and techniques. In addition, an increasing number of different meteorites with new minerals were being discovered.

What is a mineral? The International Mineralogical Association defines a mineral as a chemical element or chemical compound that is normally crystalline and that has been formed as a result of geological process. Earth has an enormously wide range of geologic processes that have allowed nearly all the naturally occurring chemical elements to participate in making minerals. A limited range of processes and some very unearthly processes formed the minerals of meteorites in the earliest history of our solar system.

The abundance of chemical elements in the early solar system follows a general pattern: the lighter elements are most abundant, and the heavier elements are least abundant. The minerals made from these elements follow roughly the same pattern; the most abundant minerals are composed of the lighter elements.

Table A.1 shows the 18 most abundant elements in the solar system. It seems amazing that the abundant minerals of meteorites are composed of only eight or so of these elements: oxygen (O), silicon (Si), magnesium (Mg), iron (Fe), aluminum (Al), calcium (Ca), sodium (Na) and potassium (K). A large number of minerals found in small or trace amounts are made of less abundant elements such sulfur (S), chromium (Cr), phosphorus (P), carbon (C), and titanium (Ti).

In meteorites, two or three dozen minerals can be identified with a hand lens or petrographic microscope. The rest are opaque or too small and don't yield to examination under transmitted light optical microscopes. They require sophisticated equipment and techniques to identify such as reflected light microscopy, x-ray diffraction, electron microprobe analysis, and electron microscopy.

The most abundant minerals in meteorites are pyroxene, olivine, plagioclase feldspar, kamacite and taenite (an iron-nickel mixture), and small amounts of troilite, schreibersite, and cohenite. The silicate

Table A.1. The 18 most abundant elements in our solar system. Those elements shown in **bold** have combined to make the abundant minerals found in meteorites and on Earth

Element Chemical	Elemental Symbol	Abundance, No. of Atoms[a]
Hydrogen	H	24,300,000,000
Helium	He	2,343,000,000
Oxygen	**O**	14,130,000
Carbon	C	7,079,000
Magnesium	**Mg**	1,020,000
Silicon	**Si**	1,000,000
Iron	**Fe**	838,000
Sulfur	S	444,900
Aluminum	**Al**	84,100
Calcium	**Ca**	62,870
Sodium	**Na**	57,510
Nickel	Ni	47,800
Chromium	Cr	12,860
Manganese	Mn	9,168
Phosphorus	**P**	**8,373**
Chlorine	Cl	5,237
Potassium	K	3,692
Titanium	Ti	2,422

[a]Abundance of each element is compared to one million atoms of silicon. For example, for every million atoms of silicon there are 3,692 atoms of potassium.

minerals—pyroxenes, olivines, and feldspars—dominate the stony meteorites. Metals—kamacite and taenite—along with small amounts of schreibersite and cohenite dominate iron meteorites.

The following list is a short guide to selected minerals found in meteorites.

Silicates

Albite $NaAlSi_3O_8$

Albite is the sodium end member of the plagioclase solid solution series. It is very rare in meteorites. Minor amounts in SNC meteorites.

Anorthite $CaAl_2Si_2O_8$

Anorthite is the calcium end member of the plagioclase solid solution series. It is a common accessory mineral in chondrites and achondrites. It is a major mineral in eucrites and an accessory mineral in angrites. Also found in refractory inclusions in C chondrites.

Augite $Mg(Fe,Ca)Si_2O_6$

A calcium-rich clinopyroxene found in some achondrites. Accessory amounts in eucrites and nakhlites and a major pyroxene in shergottites.

Bronzite $(Mg,Fe)SiO_3$

An orthopyroxene in the solid solution series between magnesium-rich enstatite and iron-rich ferrosilite.

Bytownite $(Na,Ca)Al_2Si_2O_8$

A calcium-rich member of the plagioclase series. Is often found in eucrites along with anorthite and in small amounts in angrites.

Clinoenstatite $MgSiO_3$

A meteoritic pyroxene mineral. It is the end member of the monoclinic pyroxene series $MgSiO_3$ $eSiO_3$. Clinoenstatite can be recognized under the microscope by its low birefringence and polysynthetic twinning. Common in ordinary chondrites.

Clinopyroxene $(Ca,Mg,Fe)SiO_3$

Pyroxene minerals that formed in the monoclinic crystal system including clinoenstatite, pigeonite, augite, diopside, and hedenbergite.

Coesite SiO_2

A very dense polymorph of quartz produced by high shock pressures on quartz sandstone material. The product of crater-forming meteorite impacts. Coesite was first found around Meteor Crater in Arizona in 1957.

Diopside $CaMgSi_2O_6$

A calcium-magnesium-rich clinopyroxene. An end member of a solid solution series with hedenbergite as the iron member. Also occurs in E chondrites, aubrites and mesosiderites. Also found in small quantities in refractory inclusions in CM chondrites as interstellar diamonds.

Enstatite $MgSiO_3$

Enstatite is the magnesium-rich end member of the enstatite-ferrosilite solid solution series of the orthopyroxenes. It is the major mineral in all ordinary, carbonaceous, and R chondrites as well as the basaltic achondrites.

Fayalite Fe_2SiO_4

The iron end member of the olivine solid solution series. Fayalite content is diagnostic for petrographic types of ordinary chondrites. It is a major mineral in all chondrites except E chondrites.

Feldspars $(K,Na,Ca)(Si,Al)_4O_8$

A group of minerals including plagioclase and orthoclase.

Feldspathoids

These silicates are chemically similar to feldspars. The primary chemical difference is the amount of SiO_2 (SiO_2 is called silica). Feldspathoids contain about two-thirds the silica as the feldspars. The common meteoritic feldspathoids are nepheline $(Na,K)AlSiO_4$ and sodalite $Na_4(Si_3Al_3)O_{12}Cl$. They are found in chondrules and refractory inclusions in CV chondrites.

Forsterite Mg_2SiO_4

The magnesium end member of the olivine solid solution series. See fayalite.

Glass

Common in many chondrites and achondrites. Because glass has no crystalline structure it is not considered a mineral. In meteorites, glass forms when molten silicate material cools rapidly and crystals have insufficient time to grow. Glass can crystallize if heated (but not to melting) and then slowly cooled. Minerals can turn into glass from high-pressure impact (see maskelynite).

Hypersthene $(Mg,Fe)SiO_3$

An orthopyroxene of the solid solution series enstatite to ferrosilite. It is more iron-rich than either enstatite or bronzite. Hypersthene is a major phase in diogenites appearing a light green or brown. It is also common in L-group ordinary chondrites.

Maskelynite $(Na,Ca)(Si,Al)_3O_8$

Has the composition of plagioclase and has been transformed into a glass by shock metamorphism. Most commonly found in shocked plagioclase-bearing shergottites and ordinary chondrites. Presence of maskelynite glass is diagnostic for shocked meteorites that suffered impact pressures of ~30 GPa or higher.

Mellilite $(Ca,Na)_2(Al,Mg)(Si,Al)_2O_7$

A complete solid solution series with compositions ranging between akermanite, $Ca_2MgSi_2O_7$, and gehlenite, $Ca_2Al(Si,Al)_2O_7$. Found in CAIs (calcium aluminum inclusions) in CV chondrites and in large chondrules of the Allende CV3 chondrite.

Olivine $(Mg,Fe)_2SiO_4$

A complete solid solution series of minerals ranging from magnesium-rich forsterite to iron-rich fayalite. The composition of olivine is usually expressed as the molecular percentage of fayalite (e.g., Fa_{20}); the remaining percentage of forsterite is assumed. Magnesium-rich olivines are much more common in meteorites than iron-rich olivines. Olivine is a major mineral in all chondrites, pallasites, and some achondrites, but is rare in E chondrites and aubrites. See fayalite and forsterite.

Orthoclase $KAlSi_3O_8$

Very rare in meteorites. Found in accessory amounts in eucrites and in nakhlites.

Orthopyroxene $(Mg,Fe)SiO_3$

Pyroxene minerals that formed in the orthorhombic crystal system including enstatite (also called orthoenstatite), ferrosilite, bronzite, and hypersthene. They are often referred to as low-calcium pyroxenes.

Phyllosilicates

This large class of hydroxyl-bearing and water-bearing minerals usually forms in stacked flat sheets. They comprise several groups and minerals including the serpentine group, smectite (clay) group, mica group and chlorite group. Of the four, the first two groups are most important to meteorites. They occur as a result of aqueous alteration of meteoritic minerals and are found most commonly in carbonaceous chondrites.

Pigeonite $(Fe,Mg,Ca)SiO_3$

A Ca-poor clinopyroxene with 5–15 mole% $CaSiO_3$. It is a major phase in eucrites and a cumulate mineral along with augite and orthopyroxene in shergottites. Iron-rich olivine is rimmed by pigeonite in nakhlites.

Plagioclase $(Na,Ca)(Si,Al)_3O_8$

A complete solid solution series of minerals ranging from anorthite (Ca-rich) to albite (Na-rich). See anorthite and albite.

Pyroxenes

A group of minerals including orthopyroxenes (e.g., enstatite) and clinopyroxenes (e.g., augite, diopside, and pigeonite). The composition of a pyroxene is more precisely stated in terms of three end members of the pyroxene composition system $CaSiO_3$–$MgSiO_3$–$FeSiO_3$. These end members correspond to the minerals wollastonite (Wo), enstatite (En), and ferrosilite (Fs) and are reported in terms of molecular percentages (e.g., $Wo_{42}En_{54}Fs_4$).

Quartz SiO_2
Extremely rare in meteorites. Found in small quantities in eucrites, other calcium-rich achondrites, and in the highly reduced E chondrites.

Ringwoodite $(Mg,Fe)_2SiO_4$
An olivine with a spinel structure. First found in shock veins in an ordinary chondrite in 1969. A high-pressure mineral in which magnesium-rich olivine is converted to ringwoodite at pressures of about 150 kbar or more. An indicator of impact shock in meteorites.

Serpentine $Mg_3Si_2O_5(OH)_4$
A group of hydrous minerals produced by the aqueous alteration of the magnesium silicates, olivine and pyroxene, in meteorites. Abundant in the matrices of CI and CM chondrites, usually fine-grained and mixed with organic matter.

Smectites
A group of clay minerals with complex compositions including montmorillonite and saponite. These have been found in CM chondrites and SNC (Martian) meteorites.

Stishovite SiO_2
A high-pressure extremely dense polymorph of quartz produced by meteorite impact into quartz-bearing rock. It is usually associated with coesite and forms at static pressures of over 100 kbar. Its occurrence is diagnostic for terrestrial impact craters.

Wollastonite $CaSiO_3$
End member in the pyroxene composition system $CaSiO_3$–$MgSiO_3$–$FeSiO_3$. Frequently the composition of a pyroxene is stated in terms of molecular percentages of these three end members: Wo (wollastonite), En (enstatite), and Fs (Ferrosilite).

Carbonates

Calcite $CaCO_3$
Rare in meteorites. Sometimes found along veins in CI chondrites. Often found associated with magnetite.

Hydroxides

Akaganeite β-FeO(OH,Cl)
This is a major corrosion product in the terrestrial weathering of FeNi in all meteorites. Akaganeite is the major carrier of chlorine indigenous to the environment, but not necessarily in meteorites. The low nickel iron, kamacite, is converted directly to akaganeite within the meteorite.

Goethite α-FeO(OH)
A major secondary mineral and the product of terrestrial weathering of FeNi in meteorites.

Oxides

Chromite $FeCr_2O_4$

Found in many meteorite groups. It is the dominant oxide in ordinary chondrites. Often found as small, black and opaque euhedral and subhedral grains in chondrules.

Ilmenite $FeTiO_3$

A black, opaque, slightly magnetic mineral; the principal ore of titanium. Occurs as a common accessory mineral in terrestrial igneous rocks, achondrites, lunar mare basalts and martian basalts.

Magnetite Fe_3O_4

Opaque, black, strongly magnetic iron oxide. Commonly found in the matrix of carbonaceous chondrites and in small amounts in ordinary chondrites and some achondrites. A common mineral in the fusion crusts of stony meteorites and forms a black coating on terrestrially weathered iron meteorites.

Perovskite $CaTiO_3$

A high temperature calcium-titanium oxide found in refractory inclusions (CAIs) in carbonaceous chondrites.

Spinel $MgAl_2O_4$

This oxide occurs in meteorites as small, usually opaque octahedrons. It is present in small amounts in chondrules, aggregates and refractory inclusions in CV chondrites.

Sulfides

Pentlandite $(Fe,Ni)_9S_8$

Resembles pyrrhotite in bronze color but is not magnetic until heated. Often associated with troilite inclusions in meteorites. Found in accessory amounts in the matrix and chondrules of CO, CV, CK, and CR chondrites

Pyrrhotite Fe1-xS

A magnetic iron sulfide found in meteorites that are deficient in iron with respect to sulfur. It is similar in appearance to troilite in meteorites and is an accessory mineral in CM chondrites.

Troilite FeS

A bronze-colored iron sulfide occurring as an accessory mineral in nearly all meteorites. It is found as nodules in iron meteorites and is often associated with graphite nodules. In chondritic meteorites it is usually found as small blebs or grains in both chondrules and matrix averaging about 6 wt.%. It differs from pyrrhotite by lacking an iron deficiency and is not magnetic.

Phosphides and Phosphates

Schreibersite $(FeNi)_3P$

An iron-nickel phosphide common as an accessory mineral in iron and stony-iron meteorites. Often oriented parallel to Neumann lines in kamacite plates. Silvery white when fresh and tarnished to bronze. Often found surrounding troilite nodules. A true extraterrestrial mineral not found on Earth except in meteorites.

Whitlockite $Ca_9MgH(PO_4)_7$

An important phosphate mineral in ordinary chondrites, R chondrites and CV chondrites. Also known as merrillite.

Carbides

Cohenite $(Fe,Ni)_3C$

Iron-nickel carbide found as an accessory mineral primarily in coarse octahedrite iron meteorites. Also found as a minor mineral in Type 3 ordinary chondrites. Oxidizes a bronze color and is often associated with schreibersite. It can be distinguished from schreibersite under a petrographic microscope.

Silicon Carbide SiC

Occurs as interstellar dust grains in the Murchison CM carbonaceous chondrite and other chondrites.

Native Elements and Metals

Awaruite Ni_3Fe

A nickel-rich iron similar to taenite found in minor amounts in CV chondrites and in small amounts in CK and R chondrites.

Copper Cu

Found widely in trace amounts in ordinary chondrites and iron meteorites. Trace amounts also found in some CV chondrites. It is usually found in tiny inclusions in FeNi and troilite.

Diamond C

A polymorph of graphite produced by shock pressures during impact either in space or on Earth. Found in some meteorites with graphite nodules and in the carbonaceous matrix in ureilites. Also found in CM chondrites as interstellar diamonds.

Graphite C

A common accessory mineral in iron meteorites, ordinary chondrites and ureilites. Occurs as nodules often associated with troilite. May be the site of diamond and lonsdaleite in IA irons and ureilites. Also found in CI and CM chondrites and some E chondrites.

Kamacite α-(Fe,Ni)

An alpha-phase (low temperature) iron-nickel metal alloy containing between 4 and 7.5 wt.% nickel. Kamacite is the principal metal in irons and stony-irons, an accessory metal in ordinary chondrites, and a minor metal in some achondrites.

Lonsdaleite C

A hexagonal polymorph of diamond. Occurs in ureilites and 1AB irons. Produced by shock metamorphism of graphite on the parent body. Lonsdaleite has been artifically produced in the laboratory.

Plessite (Fe,Ni)
A fine-grained intergrowth of kamacite and taenite commonly present in octahedrites and some chondrites.

Taenite γ-(Fe,Ni)
A gamma-phase (high temperature) iron-nickel alloy with variable nickel from 27 to 65 wt.% in iron meteorites. It occurs as thin lamellae bordering kamacite plates or as intergrowths with kamacite to form plessite.

Reference

Rubin, A.E. (1997). Mineralogy of meteorite groups. *Meteoritics and Planetary Science* 32, 231–247.

APPENDIX 2

Petrographic Types

Criteria	Petrographic Types 1	2	3	4	5	6
1. Homogeneity of olivine and pyroxene compositions	—	Mean deviation of pyroxene ≥5%		<5% mean deviation to uniform	Uniform ferromagnesian minerals	
2. Structural state of low-Ca pyroxene	—	Predominantly monoclinic crystals		Monoclinic cyrstals >20%	<20%	Orthorhombic crystals
3. Degree of development of secondary feldspar	—	Absent		<2μm grains	<50μm grains	>50μm
4. Igneous glass in chondrules	—	Clear and isotropic glass; variable abundance		Turbid if present	Absent	
5. Metallic minerals (maximum wt% Ni)	—	Taenite absent or very minor (Ni<200 mg/g)	Kamacite and taenite present (>20%)			
6. Sulfide minerals (average Ni content)	—	>5 mg/g	<0.5%			
7. Chondrule texture	No chondrules	Very sharply defined chondrules		Well-defined chondrules	Chondrules readily distinguished	Chondrules poorly defined
8. Matrix texture	All fine-grained, opaque	Much opaque matrix	Opaque matrix	Transparent microcrystalline matrix	Recrystallized matrix	
9. Bulk carbon (wt%)	3-5%	1.5-2.8%	0.1-1.1%	<0.2%		
10. Bulk water content (wt%)	18-22%	3-11%	<2%			

The 10 criteria for establishing a chondritic meteorite's petrographic type devised by R. van Schmus and J. Wood in 1967. Researchers today recognize 7 types.

APPENDIX 3

Useful Tests

Appendix 3.1

Testing for Nickel in Iron Meteorites

How often have you looked excitedly at a rock that you thought might be a meteorite? Perhaps you found a heavy, dark gray, brown or black rock covered with deep cavities. Most intriguing is that it's attracted to a magnet, at least a little. But a piece of vesicular basalt is heavy, often full of cavities, and it too is mildly attracted to a magnet. But does your rock contain nickel? All magnetic metal in meteorites is a mixture of iron and several percent nickel. If your rock contains nickel, it's probably a meteorite. Natural Earth rocks containing an iron-nickel mixture are exceedingly rare. But be aware that many manmade iron objects often contain nickel such as some nails and metal buttons on some blue jeans.

The standard test for nickel in meteorites goes back to O. C. Farrington in 1915. He used concentrated hydrochloric acid, concentrated nitric acid, concentrated ammonium hydroxide, litmus paper, and the nickel-testing chemical dimethylglyoxime (to do his test today would require protective gloves and glasses). The only ingredients here that are not dangerous are litmus paper and dimethylglyoxime. So let's modify Farrington's test with safety, availability, and cost in mind. Replace the strong acids with household vinegar and the strong ammonium hydroxide with household ammonia. The test still remains reasonably sensitive (especially if the vinegar is heated as described in method 2). Here's a list of the chemicals and equipment you'll need for two versions of this test.

Chemicals and Equipment

- Distilled white vinegar
- Household ammonia (preferably clear without soap or other cleaning agents)
- Isopropyl or ethyl alcohol (99%)
- Dimethylglyoxime
- Glass jars with tight lids (no metal)
- Three small plastic lids (e.g., water bottle lids) (for test method 1)
- White cotton swabs (for test method 1)
- Eyedropper

Buy the vinegar, ammonia, isopropyl alcohol (99%), and cotton swabs (e.g., Q-tips) from a local grocery store or super market. Dimethylglyoxime can be easily purchased from a scientific supply company. It's sold as a low hazard light tan to white powder. Order the less expensive "lab powder" grade instead of "reagent powder" grade. The price of 25 g of dimethylglyoxime is about $17 plus about $5 shipping. You'll have a lifetime supply if you buy 25 g. You can order dimethylglyoxime from several companies including *Wards Natural Science* (http://wardsci.com) and *Science Kit and Boreal Laboratories* (http://www.sciencekit.com).

Before testing, make a 1% solution of dimethylglyoxime and alcohol. In a glass jar dissolve 1 g of dimethylglyoxime in 100 g (127 ml) of alcohol at room temperature. In English units, that's 3 level teaspoons of dimethylglyoxime in 2 cup of alcohol. Shake well to dissolve the dimethylglyoxime. This may take several minutes. As long at the lid is tight this solution will last indefinitely.

Preparing Your Unknown Rock

For this test to work, your unknown rock must contain at least some elemental iron that attracts a magnet. Some of the metal must be exposed for a successful test even if you can't see it with the naked eye. Use a wire brush—preferably a wire wheel on a bench grinder or drill motor—to remove weathered or corroded surfaces. Or use sand paper or a grinding wheel to expose a clean surface on an out-of-the-way edge or corner. Don't use a metal file; it may contain nickel. By exposing a fresh surface, the acid in the vinegar can dissolve a small amount of the metal. If the iron contains nickel, both metals will dissolve in the vinegar and your test will be positive for nickel.

Running the Test—Method 1

1 Assemble the chemicals and equipment you will need (Figure A.1). Arrange the three small lids as shown in Figure A.2. Place a small amount of vinegar in the first lid, dimethylglyoxime solution in the second lid, and ammonia in the third lid. You need only enough liquid in the lids to thoroughly moisten cotton swabs. Use the lids to make sure your stock chemicals remain pure.

2 Dip a swab in the vinegar lid, rub your unknown object for 2 to 1 min, then set the swab aside. Don't let the moistened end touch anything. If possible, preheat your unknown object to body temperature or a little higher. The vinegar is much better at dissolving nickel at higher temperatures.

Figure A.1. Method 1 of the nickel test uses these chemicals, lids, and cotton swabs.

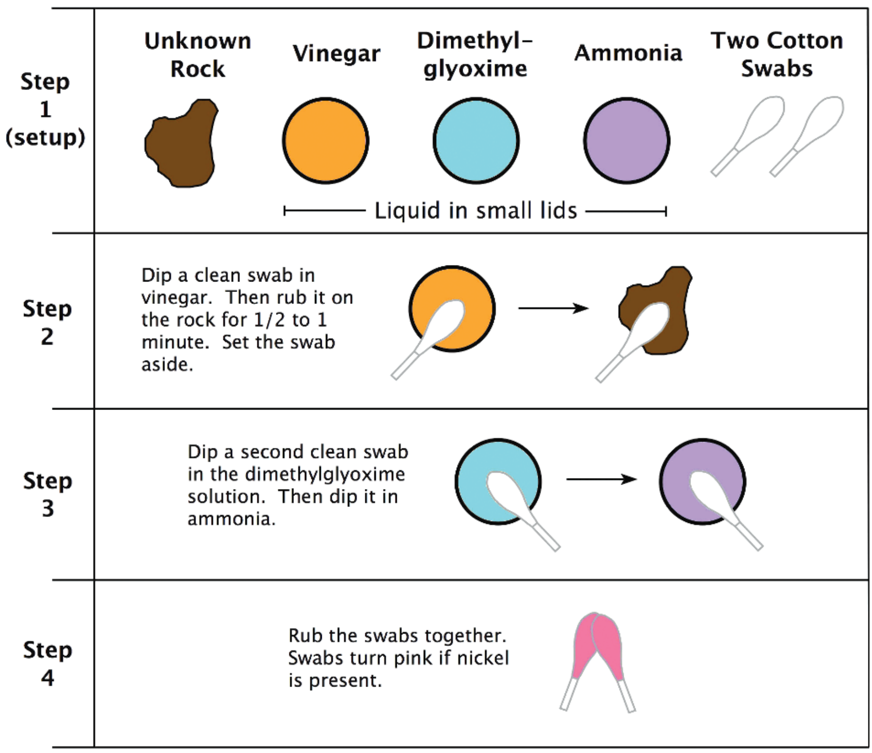

Figure A.2. How to do the nickel test – Method 1.

3 Dip a second swab in the dimethylglyoxime lid, then dip this swab in the ammonia lid.
4 Rub the swabs together. If nickel is present, the swabs will turn pink. If a pink color does not appear, repeat the test and rub longer in step 2. Even a weak pink color indicates nickel.
5 Clean up by rinsing out the lids with water and then drying them. To prevent rusting and alteration, rinse the rock or meteorite with water and dry, then immerse the rock in 99% alcohol for several minutes and dry. The alcohol helps remove water and vinegar from the cracks and pores of the rock.

Running the Test—Method 2

1 Place your unknown rock in a colorless glass jar or drinking glass and add enough vinegar to cover most or all of the rock (Figure A.3). Let stand for 5–10 min. Occasionally stir the vinegar (do not use metal to stir).
To speed up this test and increase its sensitivity, warm the vinegar first (without the rock) to about 100–120 °F. Place the vinegar-containing jar in a pool of hot water from the tap, or heat in a microwave oven briefly. Place the rock in the warmed vinegar and let stand for 2 or 3 min stirring occasionally.
2 Add ammonia until the smell of vinegar changes to the smell of ammonia (the acid is neutralized), or simply add an equal amount of ammonia to the vinegar. The solution may turn yellowish brown if a lot of iron dissolved in the vinegar. Ignore this color.
3 Add a few drops of the dimethylglyoxime solution. If nickel is present, the solution will turn a vivid pink. Even a weak pink color indicates nickel.
4 Clean up by discarding the solution, rinsing the glass with water, and then drying it. To prevent rusting and alteration, rinse the rock or meteorite with water and dry, then immerse the rock in 99% alcohol for several minutes and dry. The alcohol helps remove water and vinegar from the cracks and pores of the rock.

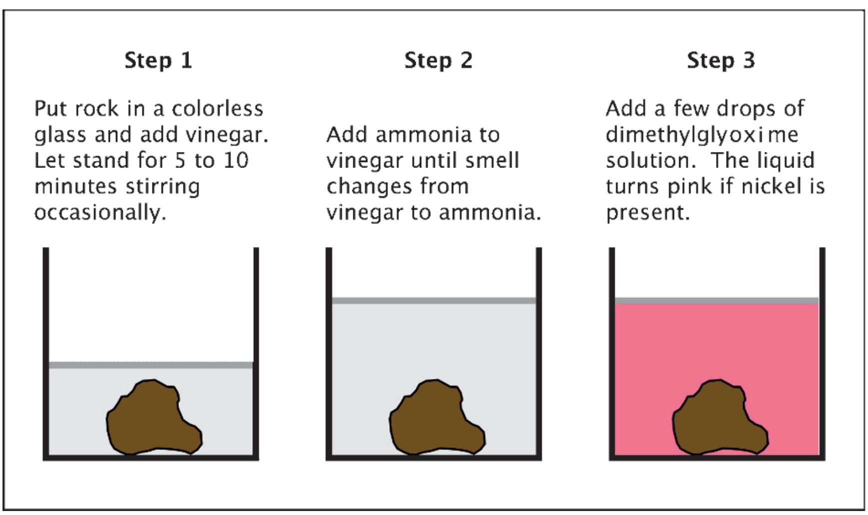

Figure A.3. How to do the nickel test – Method 2.

Appendix 3.2

Testing for Bulk Density

When we find a rock in the field we suspect is a meteorite, we immediately look for external characteristics which, if present, will indicate a true meteorite. We look for a black or dark brown fusion crust, regmaglypts or "thumb prints," and we test for magnetic attraction since most meteorites contain appreciable elemental iron. When we get it home we may slice the specimen to look for internal evidence of a meteorite. This is all well and good, but the rock may fail these tests. The fusion crust may have weathered away or been replaced by terrestrial oxides. This is what makes Gold Basin meteorites look like all the other stones in the desert pavement. Magnetic attraction works if the suspected meteorite contains elemental iron. Meteoritic iron always contains a few percent nickel, a sure sign of a meteorite.

Another useful test to distinguish some meteorites from terrestrial rocks is based on the measurement of bulk density. Most meteorites have bulk densities higher than common terrestrial rocks (Figure A.4). Thus, measuring the bulk density of a suspected meteorite can be an important step in its identification as a meteorite and in some cases what type of meteorite it is.

Using Archimedes' principle, you can easily measure bulk density with an electronic balance, water, a container to hold the water, a way to suspend a specimen, and a hand calculator. Figure A.5

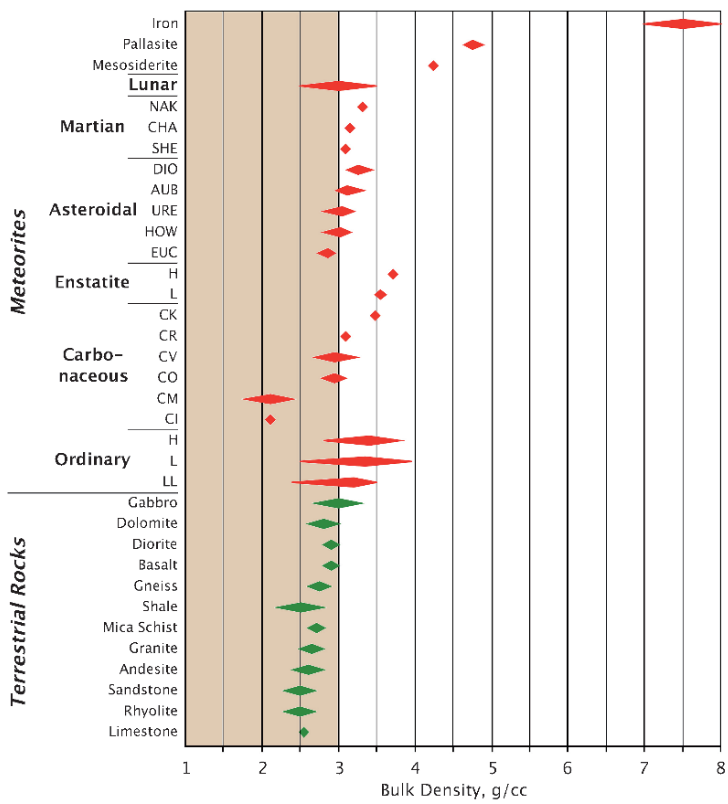

Figure A.4. Bulk density of meteorites and terrestrial rocks.

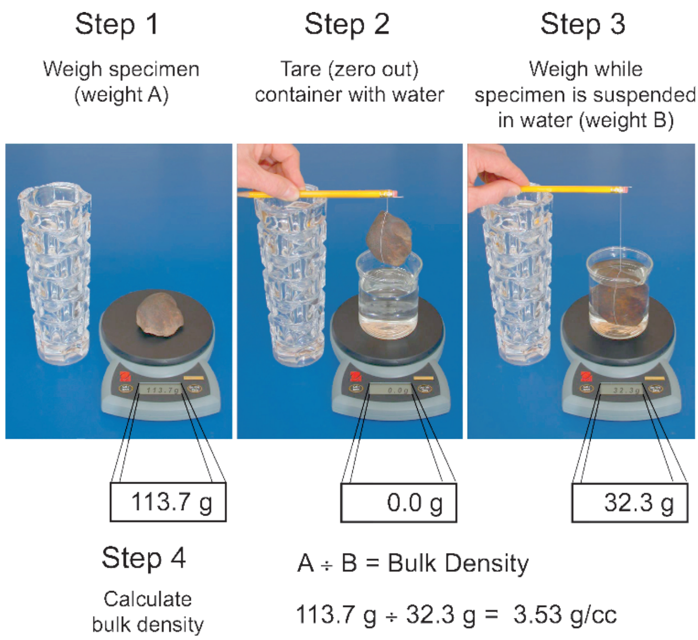

Figure A.5. How to measure bulk density using an electronic balance.

shows a step-by-step procedure for measuring bulk density. Beginning with Step 1, record the weight of the specimen using an electronic balance with an accuracy of 0.1 g. In Step 2, place a container with water on the electronic balance and tare (zero out) the balance. In Step 3, lower your specimen into the container of water using thin sewing thread tied to the specimen and to a wooden pencil. With the pencil resting on a solid support, lower the specimen into the water by rotating the pencil, similar to lowering a bucket into an old-fashioned water well with a hand crank. Make sure the specimen is completely submerged and not touching the sides or bottom of the container. Then record the weight on the balance. Finally in Step 4, calculate bulk density by dividing the weight of the specimen by the weight when the specimen is submerged.

In Step 3, the specimen may produce air bubbles while submerged. The bubbles come from air in tiny passageways in the specimen. Record the weight as soon as possible before water invades the specimen.

Figure A.5 shows an example of a specimen weighing 113.7 g and having a bulk density of 3.52 g/cc. Compare this bulk density with those of terrestrial rocks and meteorites given in Figure A.4. With a bulk density of 3.52 g/cc, the specimen is a candidate as an H or L ordinary chondrite or an L enstatite chondrite.

The vast majority of terrestrial rocks have bulk densities of 3.0 g/cc or less (the brown area of Figure A.4). Exceptions are a few rocks such as gabbro and peridotite and some terrestrial ores with bulk densities well above 3.0 g/cc. Most meteorites have bulk densities higher than 3.0 g/cc because of the elemental iron they contain. With time, meteorites lose bulk density due to weathering. Their iron and their minerals change to lower density minerals by oxidizing and hydrating. Eventually, highly weathered meteorites become indistinguishable from terrestrial rocks.

APPENDIX 4

Etching Iron Meteorites

Acquiring an iron meteorite for your collection is just the beginning of a lengthy process of preparation, display and storage. Etching a meteorite is as much an artistic endeavor as it is a carefully controlled scientific experiment. Witnessing the etching of an iron meteorite is a fascinating experience. It is comparable to watching a picture appear on a piece of black and white photographic print paper during chemical development. Etching is the final process that culminates in a lengthy and carefully executed preparation of the specimen. The internal structure of an iron meteorite is best revealed by cutting and polishing a slab, especially when we wish to study the Widmanstätten patterns in octahedrites and the Neumann lines in hexahedrites. Cutting an iron-nickel meteorite requires a great deal of time and effort, often progressing no more than about an inch per hour in the cutting phase alone. Compare this to cutting a stony meteorite (ordinary chondrite) at the rate of about 10 in./h. Once the specimen has been cut to size, it is often necessary to continue with the coarse grinding phase to eliminate any deep scratches that invariably appeared on the face of the meteorite after the initial grinding.

The cutting process begins with the selection of a suitable specimen. In this case, we selected a specimen cut from a large slab of the well-known fine octahedrite, Gibeon. The finished meteorite slab should be about 5 mm thick with the front and back sides flat and as parallel as possible. Using a smooth of piece of wood about 1 in. thick as the lower grinding table, attach silicon carbide grinding paper to the edge of the wood with staples. Grind the meteorite against the abrasive, utilizing in succession these three standard grades: (#220, #400, and #600). The first grade (#220) acts to reduce or eliminate any scratches on the face of the slab that might have been introduced during the cutting of the meteorite. Using the next two grades (#400 and #600) will produce a semi-polish that is more than adequate for etching purposes.

There have been a number of chemicals used by amateurs for the etching process. The most popular uses *nitol*, a concentrated nitric acid solution mixed with 99% ethanol. When mixing the ethanol/nitric acid solution great care should be taken to see that the nitric acid is always poured *into* the *alcohol* beaker, never the reverse. This prevents splattering of the acid as it is applied to the working solution. *(Working with concentrated nitric acid is dangerous and requires handling with extreme care.)* The chemistry is simple, requiring only 15 ml of concentrated nitric acid to be mixed with about 90 ml of 99% ethyl alcohol (ethanol).

This recipe makes 100 ml of etching solution, more than you would need for use with a single specimen. Unless you are etching many specimens at one time, you need to prepare only 1/10 of this amount. It is a good idea to wear latex gloves and protective goggles at this stage of the work. Often the specimen will be irregular in shape and does not lie flat on the work surface. It can be leveled by firmly applying a wad of clean modeling clay to back of the specimen. The slice should be placed in a shallow dish to catch the used nitol solution. Next, take a small flat paint brush approximately 10 mm wide and spread the nitol evenly over the surface with a sweeping motion. The constant motion of the brush over the surface will maintain an even flow of nitol. Within the first two minutes at this acid concentration the Widmanstätten figures will begin to appear. (Refer to the photographs in Figures A.4–A.6 to help judge the depth of the etch). As the etching proceeds, the low-nickel kamacite will slowly dissolve, leaving a bright nickel-rich taenite border. As you tilt the specimen look for the appearance of distinct kamacite plates which will appear alternately bright and dark depending upon your angle of view. When you have reached the point in your etching when the taenite looks silvery and the kamacite appears with a satin-like finish, feel free to remove the specimen from the nitol solution, and place it under slowly running tap water. At this point if you wish to darken the plates even further you can continue the etching for an additional 3 or 4 min, but usually no more.

Nitol has been used to etch iron meteorites for many years, but recently a new etchant has appeared on the scene that is much faster acting and seems to be replacing the nitol solution as the etchant of choice. This is the PC board etchant ferric chloride ($FeCl_3$) sold by Radio Shack electronics stores nationwide. Interestingly, it is not the ferric chloride that does the etching. Rather, it is the hydrochloric acid byproduct. The acid is stronger than the nitric acid etchant and it produces a deep etch in a shorter period of time, often in less than one minute, especially if the solution has been heated to about 100 °F. Just how permanent the results will be remains to be seen. Experiments with ferric chloride etchant, compared to a nitric acid/alcohol etch, have shown that the ferric chloride produces sharper Widmanstätten figures with substantially more contrast. Moreover, many of the kamacite plates show stronger Neumann lines than normal. PC board etchant is normally used by electronic industries to dissolve unprotected copper in circuit board design. It is available at most Radio Shack electronic stores (but not online) in 16 fl oz plastic bottles. Use full strength from the bottle.

Figure A.6. A prepared surface of a 46.7 g slab of Gibeon iron before etching.

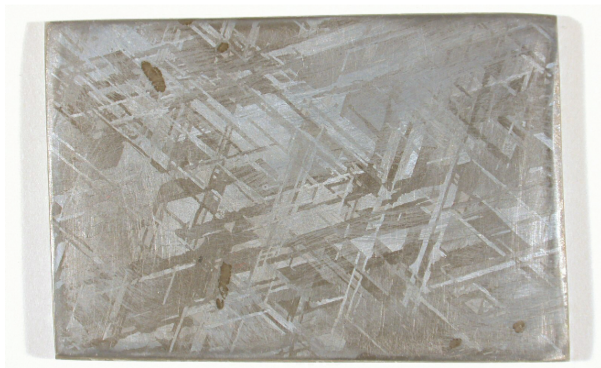

Figure A.7. A partially etched surface. The Widmanstätten figures emerge as the etchant preferentially dissolves kamacite faster than taenite.

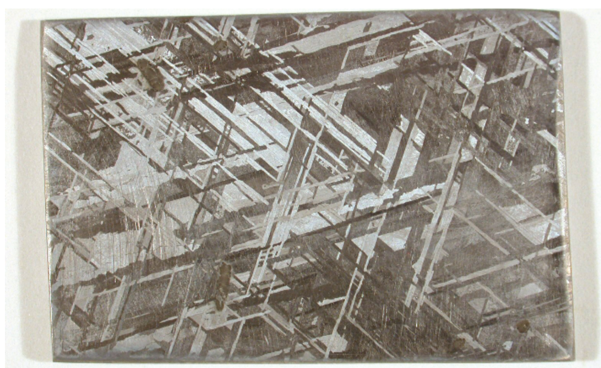

Figure A.8. The fully etched Gibeon iron. The pattern of the three sets of kamacite bands will look different when light shines from different directions.

APPENDIX 5

Unit Conversions

Length

1 in. = 2.54 cm
1 ft = 0.3048 m
1 mi = 1.609 km
1 mi = 5280 ft
1 cm = 0.3937 in.
1 m = 3.281 ft
1 km = 0.6215 mi
1 astronomical unit = 93,000,000 mi
1 astronomical unit = 150,000,000 km
1 light-year = 5.88 trillion mi
1 light-year = 9.46 trillion km
1 parsec = 3.26 light-years

Mass and Weight

1 kg = 2.2 lb (at sea level)
1 lb = 0.45 kg (at sea level)

Speed

1 mi/h = 1.609 km/h
1 km/h = 0.6215 mi/h

Pressure

1 Pa = 0.000145 lb/in.^{2}

1 GPa = 145,000 lb/in.^{2}

1 lb/in.^{2} = 6897 Pa

1 atm = 1.013 bar = 14.70 lb/in.^{2}

Volume

1 liter = 1000 cm^3

1 liter = 54.21 in.^{3}

1 liter = 1.057 qt

APPENDIX 6

Composition Percentages

Throughout this book we often express the amount of something as a percent of the total. The original measurements of these amounts were expressed in units of volume, weight, or moles, so the percentages are notated as vol.%, wt.%, or mole%. We report these various unit percentages as they are found in the scientific literature. They each have a specific technical meaning and a history of traditional use.

Volume percent (vol.%) refers to the volume of a constituent, such as chondrules, compared to the volume of all constituents. Point counts of thin sections give volume percents of constituents.

Weight percent (wt.%) refers to the weight (or mass) of a constituent, such as iron, compared to the weight of all constituents. In the days of wet chemistry, minerals and rocks were dissolved in strong acids and each element precipitated out as an oxide. Each precipitate was weighed and expressed as a percentage of the total weight of all precipitates (for example, SiO_2 49 wt.% or FeO 8.0 wt.%).

Mole percent (mole%) is a way to compare the number of different kinds of molecules (or atoms) in a mineral or rock. For example, the mineral olivine can be pure forsterite (Mg_2SiO_4), pure fayalite (Fe_2SiO_4), or any combination of the two (iron and magnesium are interchangeable). If we say that the olivine is 22 mole% fayalite (also written Fa_{22}), it means that for every 22 iron atoms there are 78 magnesium atoms (22 + 78 = 100).

See Figure A.9 for a comparison of the calculated differences of composition percentages for an imaginary meteorite made up of olivine and iron.

Figure A.9. Equivalent percentages by volume, weight, and mole for an imaginary meteorite composed of 70 wt.% olivine (forsterite) and 30 wt.% iron metal.

APPENDIX 7

Equipment, Storage, and Display

Meteorite collectors can benefit from a number of useful items to enhance the study, storage and display of their collections. Figure A.10 shows a number of items for a "home lab," and Figures A.11 and A.12 show a variety of items for storage and display.

Selected "home lab" items in Figure A.10:

A – Small powerful magnets. Rare earth magnets are recommended.
B – Hand lenses. 7× to 14× are best.
C – Electronic balance. Suggested minimum capacity 200 g, accuracy of 0.1 g. Preferred over beam balance because of small size and ability to "zero out" (tare) any additional weight.
D – Mechanical beam balance. Suggested capacity several hundred grams, accuracy of 0.1 g.
E – Binocular microscope. Best to have two or more magnifications or zoom magnification between 10× and 100×.
F – Thin sections and thin section boxes (see Chap. 11).
G – Petrographic microscope (see Chap. 11).

Other useful items not shown are those needed for the nickel test (Appendix 3) and for etching iron meteorites (Appendix 4).

Examples of storage and display boxes in Figure A.11:

H, I, J – Riker boxes come in various sizes with a glass window and padding. Ideal for slabs and small, uncut meteorites. Similar boxes with plastic windows are available.

K, L, M – Membrane boxes of various sizes hold specimens suspended between two thin highly elastic and tough transparent polyurethane membranes.

N – Small cardboard boxes of various sizes come with padding and opaque lids.

Specimen holders in Figure A.12:

O thru S – A sampling of various elegant brass or brass-colored specimen holders useful for creating beautiful displays of slabs and uncut meteorites.

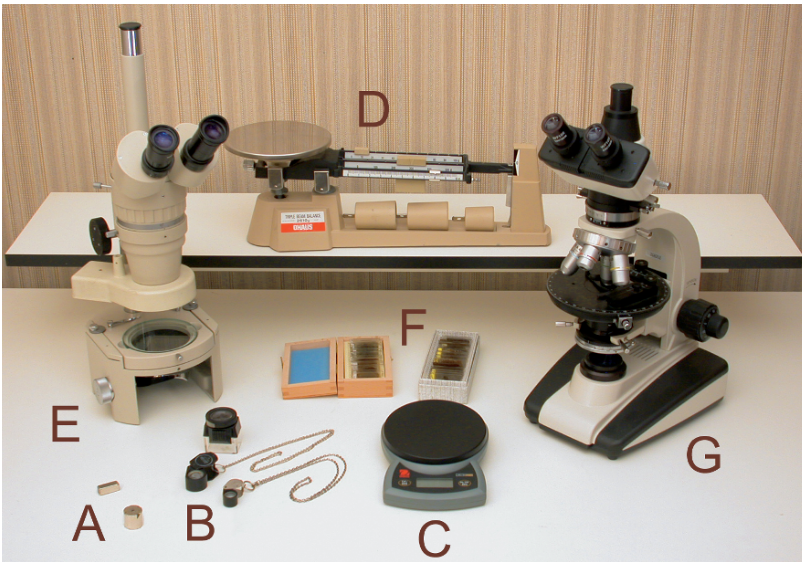

Figure A.10. A selection of useful items for a meteorite "home lab."

Figure A.11. Examples of boxes useful for storing and displaying meteorites.

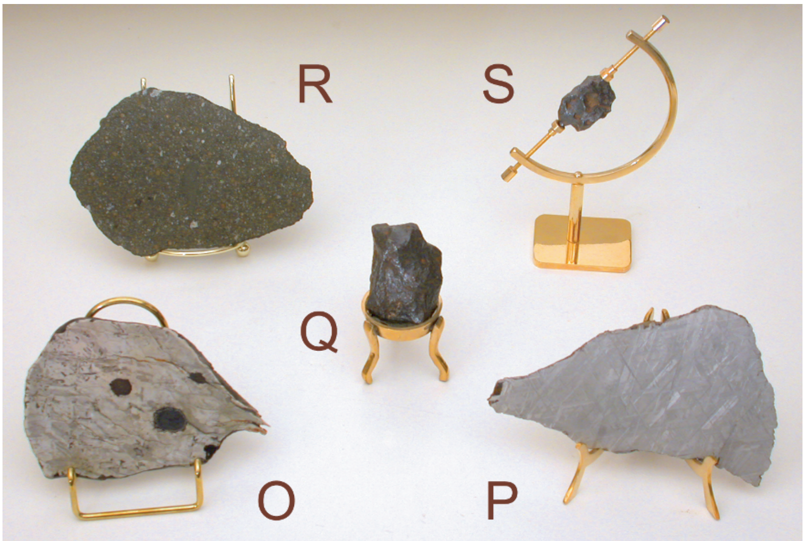

Figure A.12. Examples of elegant specimen holders for displaying slabs and uncut meteorites.

Useful Web Sites

www.jensenmeteorites.com/supplies.htm
www.membranebox.com
www.meteoritelabels.com/main.html
www.meteoritemarket.com
www.migacorp.com/meteorite_display.htm

Glossary

1 Ceres
1 Ceres is the largest known asteroid; and the first discovered in 1801.

Ablation
The removal and loss of meteoritic material by heating and vaporization as the meteoroid passes through Earth's atmosphere.

Acapulcoite
A primitive achondrite in which only partial melting and differentiation has taken place on the parent body. It has chondritic composition with some chondritic textures surviving.

Accretion
The gradual accumulation of material through the collision of particles within the Solar Nebula, or the process of interplanetary dust particles sticking together to form larger bodies.

Achondrite
A class of stony meteorites formed by igneous processes. A meteorite whose parent body has gone through melting and differentiation. These meteorites have crystallized from a magma. Achondrites include all stony meteorite types except ordinary, carbonaceous, and enstatite chondrites.

Albedo
The percentage of incoming incident light reflecting off the surface of a planetary body.

Amor asteroid
An asteroid whose perihelion distance lies just outside Earth's orbit or between 1.017 and 1.3 AU from the Sun.

Angrite
An achondritic meteorite composed of calcium, aluminum, and titanium-rich pyroxene. Accessory minerals include calcium-rich olivine and anorthite.

Anhedral
An individual mineral crystal usually of igneous origin that has failed to develop bounding crystal faces expressing its internal crystal structure.

Aphelion
In an elliptical orbit around the Sun, it is the point in the orbit where a planet is furthest from the Sun.

Apollo asteroid
A class of near-Earth asteroids defined as having a mean distance from the Sun greater than 1.0 AU and a perihelion of less than 1.017 AU. Apollo asteroids are Earth-crossers and candidate meteorite producers.

Asteroid belt
A region between the orbits of Mars and Jupiter, between 2.2 and 4.0 AU from the Sun where the Main Belt Asteroids are located.

Asteroid
A rocky or metallic orbiting body of subplanetary size showing no cometary activity; usually but not necessarily confined to the main asteroid belt.

Astronomical Unit (AU)
Mean distance between Earth and Sun; 1.496×10^8 km.

Ataxite
An iron meteorite composed of almost pure taenite with a nickel content greater than 16 wt% and showing no macroscopic structure.

Aten asteroids
An asteroid defined as having an aphelion distance of greater than 1 AU and a semi-major axis of less than 1 AU.

Aubrite
A stony meteorite formed by igneous processes containing enstatite as its primary mineral. It is also called an enstatite achondrite.

Basalt
A common fine-grained, mafic volcanic igneous rock usually erupted onto the Earth's surface from a vent or fissure. The mineral content is primarily plagioclase and pyroxene.

Basaltic achondrites
Achondrites are members of the HED class of meteorites. They have textures and compositions similar to terrestrial basalts and are believed to originate on the asteroid 4 Vesta.

Bolide
A very large meteor which is sometimes accompanied by loud sonic booms.

Brachinite
A rare primitive achondrite composed almost entirely of equigranular olivine.

Breccia
A rock made up of angular clasts of previous generations of rock cemented together by fine grained matrix material. A breccia is a common textural feature of stony meteorites.

CAI
Highly refractory inclusion rich in calcium, aluminum, and titanium. They are thought to be among the first minerals to condense out of the solar nebula. They are commonly found in C chondrites, especially CM2 and CV3 chondrites.

CB carbonaceous chondrite
A group of carbonaceous chondrites named for the type specimen, Bencubbin.

CH carbonaceous chondrite
A group of carbonaceous chondrites. The type specimen is ALH 85085.

Chassignite
A meteorite from Mars, one of the SNC group. It is similar to terrestrial dunite and made mostly of olivine.

Chondrite
A primitive stony meteorite containing chondrules. Chondrites are primitive aggregates of these chondrules.

Chondrule
Chondrules are small spherical or subspherical rock masses usually less than 1 mm in diameter which formed from molten or partly molten droplets while in space.

CI carbonaceous chondrite
A group of carbonaceous chondrites named for the type specimen, Ivuna.

CM carbonaceous chondrite
A group of carbonaceous chondrites named for the type specimen, Mighei.

CO carbonaceous chondrite
A group of carbonaceous chondrites named for the type specimen, Ornans.

Cohenite
An accessory mineral found in iron meteorites; an iron-nickel carbide. $(Fe,Ni,Co)_3C$.

Coma
The glowing part of a cometary body surrounding the nucleus and caused by radiation from the Sun.

Comet
A body that orbits the Sun and is primarily composed of frozen water, ammonia, methane and carbon dioxide along with countless pieces of rock and dust. A tail forms when it approaches the Sun from its suspected origin at the outer edge of the Solar System.

Commensurate orbit
Asteroid orbits whose periods are simple multiples or fractions of Jupiter's orbital period.

Cosmic dust or interplanetary dust particles (IDPs)
A general term for microscopic particles produced by comets as they loose their volatiles and trapped dust; iron particles may be produced by the tails of comets or by collision between asteroidal bodies; or dust shed by massive red giant stars.

CR carbonaceous chondrite
A group of carbonaceous chondrites named for the type specimen, Renazzo.

Cumulate
An igneous rock made up of relatively large crystals that settle out of a magma by gravity and accumulate on the floor of a magma chamber.

CV carbonaceous chondrite
A group of carbonaceous chondrites named for the type specimen, Vigarano.

Differentiation
A process in which a homogenous planetary body melts and gravitationally separates into layers of different density and composition. The body often separates into a core, mantle and crust.

Diogenite
An achondritic meteorite composed of magnesium-rich orthopyroxene cumulate. Diogenites may represent the upper mantle or lower crust of the asteroid 4 Vesta. It is related to howardites and eucrites that make up the HED series of achondritic meteorites.

Distribution ellipse
An elliptical area usually covering several square miles over which meteorites of a multiple fall tend to scatter. The more massive meteorites are distributed on the far end of the ellipse. See *strewn field*.

E chondrites
Enstatite chondrites; a highly reduced chondritic meteorite composed of the magnesium-rich orthopyroxene, enstatite, and iron-nickel metal.

Ecliptic
The plane of the Solar System defined as a projection of the Earth's orbit against the sky. It is the apparent yearly path of the Sun. Solar System objects are measured with respect to the ecliptic as a reference plane.

Entry velocity
A meteoroid's velocity at the beginning of the visible trail of a fireball. The initial velocity of a meteoroid at the top of the Earth's atmosphere.

Eucrite
The most common achondritic meteorite type. It is igneous in origin and is similar in composition and texture to terrestrial basalts. Possibly represents a lava flow on the surface of asteroid 4 Vesta.

Euhedral
Mineral crystals fully bounded by well-formed typical crystal faces.

Fall
A meteorite which is seen to fall and later recovered.

Fayalite
An iron -rich olivine (Fe_2SiO_4); the iron end-member of olivine.

Feldspar
A general term for aluminum silicate minerals with various amounts of sodium, calcium, and potassium.

Find
A meteorite that was not seen to fall but found at some later date. For example, many finds from Antarctica are 10,000 to 700,000 years old.

Forsterite
A magnesium-rich olivine (Mg_2SiO_4); the magnesium end member of olivine.

Fractional crystallization
A process in which, at specific temperatures, minerals crystallize out of a magma so that there are no longer reactions between the crystals and the original liquid, thereby changing the composition of the magma.

Fusion crust
A dark glassy coating that forms on stony meteorites as they ablate in the atmosphere; usually made of glass and iron oxide.

Gardening
Reworking and mixing of a regolith surface by impact from meteorites and asteroids.

Gegenschein
A faint, diffuse glowing region situated on the ecliptic plane opposite the Sun produced by sunlight reflecting off interplanetary dust particles.

Genomict breccia
A brecciated meteorite in which the individual clasts are compositionally of the same group but have differing petrographic characteristics.

Glass
A solid material that has no crystal structure. Glasses are formed during very rapid cooling of a melt in which there is no time for the constituent atoms to arrange themselves into an orderly atomic lattice.

Graphite
A lustrous soft form of carbon usually forming thin layers; often found as nodular inclusions in iron meteorites.

H-chondrite
A group of chondritic stony meteorites belonging to the ordinary chondrite clan. They have the highest total iron of the ordinary chondrites.

HED
Howardites-Eucrites-Diogenites, related basaltic meteorites believed to originate on the asteroid 4 Vesta.

Hexahedrite
An iron meteorite containing less than 5% nickel; usually occurs as nearly pure kamacite with Neumann lines running across the crystal faces.

Howardite
A brecciated achondrite composed of eucrite and diogenite fragments. Thought to be the soil of an asteroid parent body.

Hypersthene chondrites
An obsolete term for meteorites now referred to as L-chondrites.

Hypersthene
A magnesium-rich orthopyroxene $(Mg,Fe)SiO_3$; a common pyroxene in chondritic meteorites.

Individual
A single meteorite individual which has not been fragmented off a larger meteoroid having reached Earth intact.

Interplanetary dust particles
Micron-sized dust particles usually of chondritic composition that are ubiquitous along the Solar System plane and are thought to originate from comets and/or debris from asteroid fragments.

Interstellar grains
Submicron-sized solid grains thought to be ejected by red giant stars. The main constituents are carbon(diamonds) silicon carbide and graphite.

L chondrites
A group within the ordinary chondrite clan containing metal and combined iron in amounts intermediate between the H and LL chondrites.

Lherzolitic
Ultra mafic plutonic igneous rocks composed primarily of olivine and orthopyroxene. They are frequently found with orthopyroxene and clinopyroxene as xenoliths in alkali basaltic rock.

LL chondrites
A group within the ordinary chondrite clan that contains the lowest amounts of metal and combined iron.

Lodranite
A primitive achondrite. Like acapulcoites, they have suffered partial melting in their past history.

Mafic minerals
Silicate minerals that are rich in magnesium and/or iron. These ferromagnesium minerals form mafic igneous rock.

Magma
Molten rock containing dissolved gases and mineral crystals. Through fractional crystallization processes, minerals crystallize out of the magma and interlock to form igneous rock.

Mare basalt
Basalt that forms the maria, the great basins on the Moon. Mare basaltic meteorites are the rarest lunar meteorites.

Matrix
Fine-grained material between inclusions, chondrules and chondrites. This material usually has a similar composition as the chondrules themselves, primarily magnesium-rich olivine and pyroxene.

Mesosiderite
A class of stony-iron meteorites consisting of a mixture of iron/nickel metal and broken rock fragments of magnesium-rich silicate minerals. The rock fragments are similar in composition to eucrites and diogenites of the HED series.

Mesostasis
The last material to solidify from a melt. It is usually found as interstitial fine-grained material or glass between crystalline minerals in an igneous rock.

Metachondrite
A metamorphosed chondrite derived from a chondritic precursor.

Monomict breccia
A brecciated monomict chondrite is composed of angular fragments and matrix all of like composition.

Mosaicism
A characteristic of a mineral crystal seen microscopically under crossed polarizers in which extinction is not uniform but checkered into a mosaic pattern due to small irregularities within the crystal. This occurs when the crystal has been distorted by shock metamorphism. Mosaicism is an indicator of shock effects produced by an impacting body.

Nakhlite
A meteorite from Mars, one of the SNC group. It is composed of the clinopyroxene augite and olivine.

NEA
Near Earth Asteroid. Asteroids whose orbits bring them close to Earth's orbit.

Neumann bands
A network of lines (twinning planes) in an iron-nickel alloy often seen after light chemical etching. Due to mild shock.

Octahedrite
An iron meteorite of intermediate nickel content composed of low nickel kamacite bounded by high nickel taenite arranged in plates on the faces of an octahedrite. Acid etching reveals the Widmanstätten structure.

Olivine bronzite chondrites
This is an obsolete term for meteorites now referred to as H-chondrites, with the "H" standing for high iron. Total elemental iron is between 15 and 19 wt% for the H group.

Paired meteorites
Meteorites that have fallen simultaneously some distance from each other but that are found through analysis to be fragments of the same mass and therefore considered the same meteorite.

Parent body
An astronomical body of subplanetary to planetary size that fragments by collision to produce meteorites.

Parsec
A unit of distance commonly used by astronomers. The distance of an object that would have a stellar parallax of one arc second. 1 parsec = 3.26 light years.

Penetration hole
A hole made by a meteorite that impacts Earth but does not explode.

Perihelion
A position on an elliptical orbit where a celestial body is closest to the Sun.

Pallasite
A class of stony-iron meteorite containing approximately equal amounts of metal and olivine; the metal makes up a continuous network with isolated grains of olivine.

Petrologic type
A scale used to denote the texture of chondritic meteorites; denotes increasing metamorphism in chondrites.

Planetesimal
Small bodies up to a few hundred miles in diameter that formed from the first solid grains to condense out of the solar nebula; planetesimals accreted to each other to form the planets of the solar system.

Plessite
A fine-grained mixture of kamacite and taenite formed late in the diffusion process at low temperatures; usually found filling spaces between the Widmanstätten figures in octahedrite meteorites.

Plutonic rock
Any deep-seated massive body of igneous rock formed beneath the Earth's surface by the consolidation of magma.

Poikilitic texture
A rock texture in which small euhedral mineral grains are scattered without a common orientation within larger typically anhedral grains of different composition. For chondritic meteorites, poikilitic texture is often seen with small olivine grains enclosed in orthopyroxene (see text).

Polymict breccia
A rock made of angular fragments from other rocks of different compositions.

Polymorph
A mineral that has several crystal forms; i.e. graphite is the amorphous form, while diamond is the crystal form, both being polymorphs of carbon.

Porosity
A percentage of the bulk volume of a rock occupied by pore space.

Radiant point
A point in the sky in a specific constellation from which meteors of a meteor shower seem to diverge; an illusion of perspective.

Refractory elements
The first minerals to condense out of a cooling gas at relatively high temperatures; elements that have high vaporization temperatures.

Regmaglypts
Thumbprint-like deep pits or cavities on the exterior of some meteorites produced by the uneven flow of air during the meteorite's passage through Earth's atmosphere. The well-defined polygonal depressions on the surface of these meteorites are ablation features produced during the melting phase of the meteorite's atmospheric passage.

Regolith breccia
A chondritic brecciated meteorite made of consolidated lithified regolith material. Such meteorites have dark/light texture and represent material from beneath the surface as well as on the surface of its parent body.

Retardation point
The point in a meteoroid's path through Earth's atmosphere where its cosmic velocity has dropped to zero and the meteoroid falls freely by Earth's gravity alone.

Rumuruti (R) chondrites
A small clan of meteorites similar to ordinary chondrites but much more oxidized; little if any metal exists, the metal being incorporated into the minerals.

Secondary characteristics
Characteristics resulting from thermal metamorphism, partial melting and aqueous alteration reducing the parent body's primary characteristics to secondary characteristics. They define the physical and chemical history of the meteorite's parent body after its origin but before breakup.

Shergottite
A meteorite from Mars, one of the SNC group. Shergottites are basaltic, with pyroxene, plagioclase and maskelynite as major components.

Siderolite
A meteorite composed of iron and stone, a stony-iron meteorite.

Siderophile elements
The geochemical class of elements with an affinity for the metallic phase rather than the silicate or sulfur phases. Fe, Ni, Co, Cu, Pt (platinum group of metals).

SNC meteorites
An acronym for shergottites, nakhlites, and chassignites. All three are rare achondrite meteorites with young isotopic ages (~1.3 billion years) and are thought to have originated on Mars.

Space weathering
Changes in the spectral properties of surface minerals on asteroidal bodies due to impacts by solar wind particles and micrometeorites. Space weathering may disguise the true spectral characteristics of an asteroid.

Sporadic meteors
An unpredictable, isolated meteor not associated with a periodic meteor shower.

Stony-iron meteorites
A class of meteorite that contain both silicate minerals and iron-nickel metal in approximately equal proportions. Examples: pallasites; mesosiderites.

Terminal velocity
The velocity of a freely falling meteoroid due to Earth's gravity after its cosmic velocity has been reduced to between 320 and 640 km/h. This often marks the end of the visible trail of a fireball.

Tertiary characteristics
Characteristics produced by fragmentation of a meteorite's parent body, shock metamorphism, atmospheric ablation, impact and terrestrial weathering.

Thermal metamorphism
Changes in the chemical and physical characteristics due to internal heating of the parent body, probably by the decay of aluminum-26. Melting temperatures are not reached so that all changes are in the solid state. This is responsible for the various petrographic types of ordinary and carbonaceous chondrites.

Thin section
A slice of rock or mineral that has been ground to a thickness of 0.03 mm and mounted as a slide in a petrographic microscope.

Ultramafic rock
An igneous rock composed of more than 90% mafic minerals.

Ureilite
A rare type of achondrite meteorite consisting of pyroxene grains and olivine set in a carbon rich matrix.

Vitrification
The conversion of a glass to a crystalline texture while in the solid state.

Volatile elements
These are elements that are the last to condense out of a cooling gas. Volatile elements condense from a gas or evaporate from a solid at low temperatures relative to refractory elements. Volatiles are the first materials to be lost when a meteorite is heated.

Widmanstätten structures
An intergrowth of low nickel kamacite and high nickel taenite that mutually grow on the crystal faces of octahedrite meteorites.

Winonaite
A rare class of primitive achondrites that have been partially melted and differentiated. They are associated with IAB irons.

Xenolith
A foreign inclusion in an igneous rock that is not chemically related to the host rock.

Zodiacal light
Light from the Sun that is scattered by interplanetary dust particles along the ecliptic plane and between Earth and the Sun.

Meteorite Index

Italics indicate illustrations

General Index

Italics indicate illustrations