ANTARCTIC METEORITE TEACHING

COLLECTION

Educational Meteorite Thin Sections

Originally prepared and written by

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Updated and revised by Kevin Righter, 2010

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Most of these meteorite samples were collected in Antarctica by National Science Foundation funded (NSF) expeditions led by Bill Cassidy as part of the Antarctic Search for Meteorites (ANSMET) program, that subsequently has continued under Ralph Harvey (see the attached summary papers by Lipschutz and Cassidy, 1990, and Harvey, 2003). Pieces of these meteorites are distributed for scientific research as part of the Planetary Materials Program of NASA. However, ten sets of educational thin sections were prepared and are available for distribution to university classes to help create interest in this branch of planetary science. A similar set of Educational Lunar Thin Sections is also available from:
Astromaterials Curation Division, Mail Code KT, NASA Johnson Center, Houston, TX 77058

The following draft report is authored by G. MacPherson, B. French and R. Clarke. Additional recommended references and resources are listed at the end of this document. Text was updated in 2010 by K. Righter.

Not all of the sections in the various sets are exactly the same as the ones discussed in this text. The student should make his/her own observations. The good student should QUESTION the interpretation!

CAUTION: Please do not use oil on these samples. And do not touch.

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GENERAL INTRODUCTION *(This introduction may be skipped and one may go directly to the samples.)*

Purpose. This set of meteorite thin sections will introduce students to the study of meteorites by making it possible for them to make their own direct examinations of typical meteorites under the microscope. The sections, and the accompanying descriptions, can teach several important lessons:

(1) the diversity of meteorite minerals, textures, origins, and histories;
(2) the similarities and differences between meteorites and terrestrial rocks;
(3) how the petrographic and mineralogical techniques used to determine the origin of terrestrial rocks can be applied to meteorites to yield similar genetic information about the early solar system.

This collection of samples will give students some appreciation of what meteorites are like and to introduce them to the ways in which meteorites give us information about the origin and early history of the solar system and about small asteroid-sized bodies as well as larger planets (Mars) in it.

The collection, and the accompanying descriptions, has been designed to be most effectively used in undergraduate and graduate-level Earth Science courses, in which the students have a background in mineralogy, petrology, and the use of the petrographic microscope. The sections themselves are best examined with a research-type polarizing microscope; ideally, the microscope used should have a capability for reflected light as well, so that the opaque phases (metal and sulfides) in the meteorites can be examined.

Meteorites and Moon Rocks. Until 1969, when the Apollo 11 astronauts returned samples from the Moon, meteorites were our only samples of extraterrestrial material and our only source of direct "hands-on" information about other bodies in the solar system. Long before the Apollo program, meteorites had provided extensive information about our planetary neighborhood.
At that time, it was generally accepted (and still is) that most meteorites have come from the Asteroid Belt between Mars and Jupiter. Chemical studies of meteorites had provided essential data for theories about the formation of the solar system and the origin of the Earth. The first precise measurement of the age of the Earth and the rest of the solar system, about 4.55 billion years (b.y.), was determined by studying meteorites in the 1950s; and this value has been changed little by more extensive studies since then.

Despite the important and extensive discoveries made by studying the lunar samples returned by the Apollo missions, meteorites remain important today, chiefly because they provide information about solar system processes that took place long ago and far away from the Earth-Moon system. In fact, meteorites and lunar samples complement each other in many ways. Meteorites record the earliest events in the solar system, when many small bodies (the ancestors of the present planets) were produced about 4.5 b.y. ago. (Such early records are not available on the Earth, whose rocks have been processed and recycled by eons of continuing geological activity.) Lunar samples, by contrast, are younger; they record the later events in the development of a single small differentiated body between about 4.5 and 3.2 b.y ago.

Current Meteorite Research. The post-Apollo period has been an exciting time for meteorite research as well, with major discoveries (all exciting, some unexpected) made in many areas:

- One group of meteorites, the carbonaceous chondrites, has long been known to have approximately the composition of the Sun. New chemical data from these meteorites continue to change our understanding about the chemical composition of the original solar system and the processes that went on when the solar system formed.

- Meteorites remain the standard for measuring the age of the solar system. The original age for the solar system, about 4.6 b.y., has been verified by more precise measurements on more meteorites. However, the new data are precise enough to show small age differences between different meteorites, adding new and intriguing complexities to our records of the solar system's birth.

- Some of the first solid matter to have formed in the solar system may have been retrieved from a few meteorites in the form of white inclusions composed of rare minerals made of calcium, aluminum, titanium, and other high-temperature elements.

- A few meteorites retain tantalizing traces of events before the formation of the solar system: anomalous patterns in certain chemical elements, tiny metal-rich grains, and even small particles of carbon and diamonds!

- The carbon-rich material in many meteorites is being actively studied because of its close relations to organic material in comets and interstellar dust and because it is a potential source of "biological building blocks," material for the development of life of Earth --and possibly elsewhere.

- The minerals and mineral compositions of all meteorites are providing detailed information about the physical and chemical conditions during the early solar system -- temperatures, pressures, cooling rates, and the composition and oxygen pressures in the gases that were present 4.5 b.y ago.

- Meteorites are now providing information about the history of small bodies (asteroids) in the solar system such as the formation and evolution of individual bodies, the results of collisions between them, and how their orbits change with time. Such changes eventually cause meteorites to move from the asteroid belt into orbits that intersect the earth - otherwise we could not collect them. Similar changes also work on larger objects, which have also collided with the Earth - producing major catastrophes - in the past.

- Meteorites in airless space are bombarded by all the matter and energy in the solar system - charged atoms from such (the solar wind and solar flares) and by even more energetic particles (cosmic rays) from outside the solar system. These particles produce permanent effects in meteorites, and meteorites therefore serve as "space probes" that record the behavior of the Sun and the space environment, not only in the present, but for billions of years into the past as well.

- meteorites from Mars and Earth's Moon are providing information about the origin and evolution of both of these bodies. Lunar meteorites (currently 62 in worldwide collections) are providing information from more random locations on the Moon's surface, as opposed to the specific sites where samples were collected by the Apollo and Luna missions. Martian meteorites (currently > 60 in worldwide collections) provide our only samples of the planet Mars and have thus yielded information about its origin as well as the solar system in general.

Meteorites on Ice. A major (and unexpected) boost to meteorite research came out of the Antarctic in 1969, when Japanese scientists discovered the polar ice cap collects and preserves large numbers of meteorites. As the ice flows slowly from the South Pole to the sea, meteorites that fall on it are concentrated together in special zones on "blue ice." In these zones, literally hundreds of different meteorites can be collected within a few square miles.

Since the late 1970s, an active US collecting program has discovered more than 17,000 new meteorites. Additionally, Japan, China, Italy, and Korea all have meteorite collection programs that together with the United States have recovered close to 50,000 meteorite samples. Within just a few decades, scientists have obtained from the Antarctic many more meteorites than have been collected by human beings in all previous centuries. It is now possible to carry out reliable abundance studies of different meteorites types and to see whether the meteorites that fall to Earth today are different from those that fell thousands of years ago. Furthermore, this huge bonanza of meteorites has contained many rare, unusual, and even unexpected types that have promoted special studies.

Probably the most surprising discovery from the Antarctic collections was the identification of meteorites that have come from the Moon! These non-Apollo lunar samples were blasted off the Moon by meteorite impacts and fell to Earth perhaps thousands of years ago. Other Antarctic samples may have an equally exotic source ---the planet Mars. Many unusual Antarctic meteorites ---which belong to a meteorite group that now includes about >60 specimens worldwide ---have provided data suggesting that they came from a large planet, probably from Mars. Thanks to the Antarctic discoveries, we now know that meteorites provide us with samples of more worlds than just the asteroid belt.

METEORITES AND THE EARLY SOLAR SYSTEM

Although the implications of meteorite research have expanded incredibly in the post-Apollo period, meteorites remain important in their traditional role ---providing direct information about the origin and early history of the solar system and of the worlds in it. This question, one of humanity's oldest speculations, has become more focused ---although by no means solved --in the last few decades by the merging of several separate lines of research ---theoretical studies and models, Earth-based observations of other stars, and the detailed information preserved in meteorites. There is, at the moment, far more agreement than ever before about the general nature of the process, but there is also a vast amount of exciting argument and debate about the details.

In the current view, what we now see as the Solar System began as a huge cloud (the solar nebula), made up of cold gas (mostly hydrogen) and tiny grains of interstellar dust. Similar clouds are commonly observed elsewhere in the universe; they usually fill the regions between stars. Under the influence of its own weak gravity, this diffuse cloud contracted and collapsed to form a dense, rapidly spinning disk. (In one version of this theory, the collapse was triggered by the shock wave from the nearby explosion of a star [a supernova]).

As the disk collapsed further, it became hotter. In the center, where the nebula was densest, temperatures finally reached thousands of degrees Celsius (˚C). At these temperatures, hydrogen atoms could fuse to form helium atoms, and the dense central core of the nebula began to shine with its own thermonuclear light, forming the Sun. Further out, where it was cooler, dust and ice particles collided to form larger particles, which in turn accumulated to form millions of small bodies (Planetesimals), ranging from a few kilometers to a few hundred kilometers in size. These small bodies continued to collide with each other, quickly building up the few larger planets and their moons.

The entire formation of the solar system, from the beginning of the collapse of the nebula to the formation of the planets, took a very short time, astronomically speaking ---perhaps as little as ~ 100 million years (Figure 1). The first few large objects to form quickly swept up almost all the available material and grew to be the planets we see today. All the planets, even the Earth, continue to sweep up the small amount of material remaining today; the larger pieces that the Earth sweeps up are called meteorites.

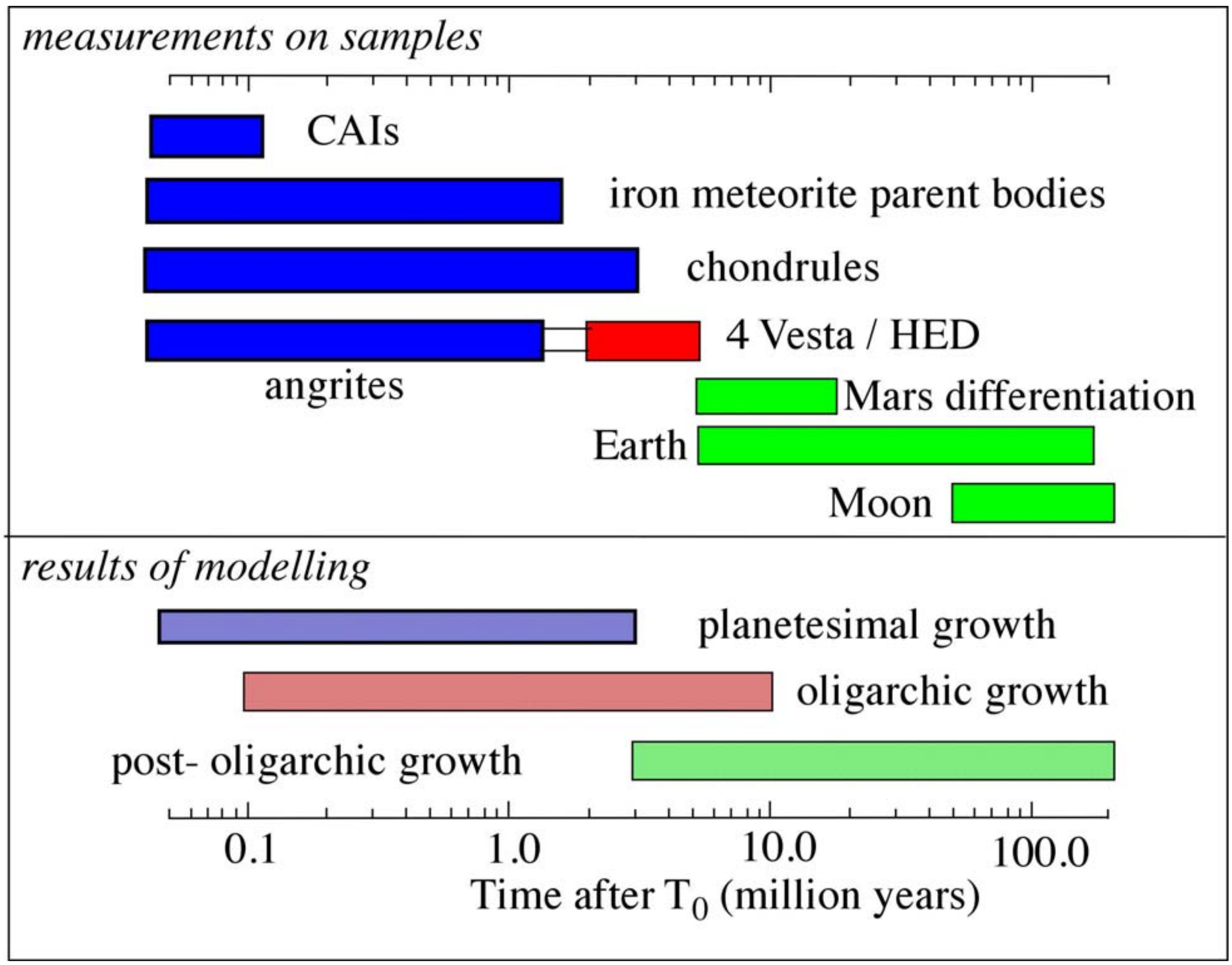

Figure 1: Summary of timescales of formation of various components in chondritic meteorites (CAIs and chondrules), asteroids (iron meteorite parent bodies, angrites, and 4 Vesta), and Earth, Moon, and Mars (from Righter and O'Brien, 2010). Also shown below are estimates of the duration of various stages in the growth in the early solar system, from planetesimal formation, planetary embryo (oligarchic)

formation, and then finally planet formation (post-oligarchic).

The survival of small meteorites to the present time is the result of a curious quirk in the original solar system. In the region between Mars and Jupiter, the planetesimals that formed were not swept up by either body, nor did they collect to form a small planet of their own. The reason for this is not clear, but it almost certainly involves the gravitational tug-of-war that exists between the Sun and Jupiter, the largest planets.

Whatever the reason, the planetesimals in this region survived. Today they are called asteroids, and they occur in the Asteroid Belt. Asteroids are small bodies, ranging in size from a few hundred kilometers to less than a kilometer in diameter. They are the direct descendants of the planetesimals that once saturated the solar system, and they preserve unaltered samples of what the planets were made from.

It is fortunate for scientists that the random chances of collisions and orbit changes in the asteroid belt shoot these bodies toward the Earth now and then to give us meteorites. Otherwise, we would have no samples of original Earth material. The long and active geological history of the Earth has recycled its original material through a wide range of geological activities: core formation, volcanism, mountain-building, crustal plate movements, oceanic and atmospheric processes, and the appearance and development of life. The original atoms of the Earth remain, but the rocks that now contain them are totally changed from what they were. We can no longer find any trace of what the earliest Earth was like on the Earth itself, and we depend on studying asteroids and their meteorites to understand the beginnings of our own world.

TYPES OF METEORITES

The first thing people have learned about meteorites is that they are very different. Meteorites include materials ranging from earth like volcanic rocks to chunks of cosmic armor-plate made out of nickel-iron alloys. If ---as we think ---meteorites come from the Asteroid Belt, then the asteroids themselves are very different and reflect complex and mysterious histories of their own.

Despite the complexity, three basic types of meteorites can be distinguished: (1) Stony meteorites are most similar to terrestrial rocks. They are made largely of silicate minerals; unlike terrestrial rocks, they also contain a small amount of metal. (2) Stony-iron meteorites contain approximately equal amounts of silicate minerals and metal. (3) Iron meteorites are composed mostly of different alloys of nickel-iron metal. Undifferentiated meteorites include the chondrites, whereas differentiated meteorites include achondrites, irons and stony-irons (Figure 2).

Stony meteorites are the most abundant type found in meteorites that are actually seen to fall and recovered (called falls). (Iron meteorites, because they are more distinctive and more resistant to weathering, are more abundant among older meteorite finds.)

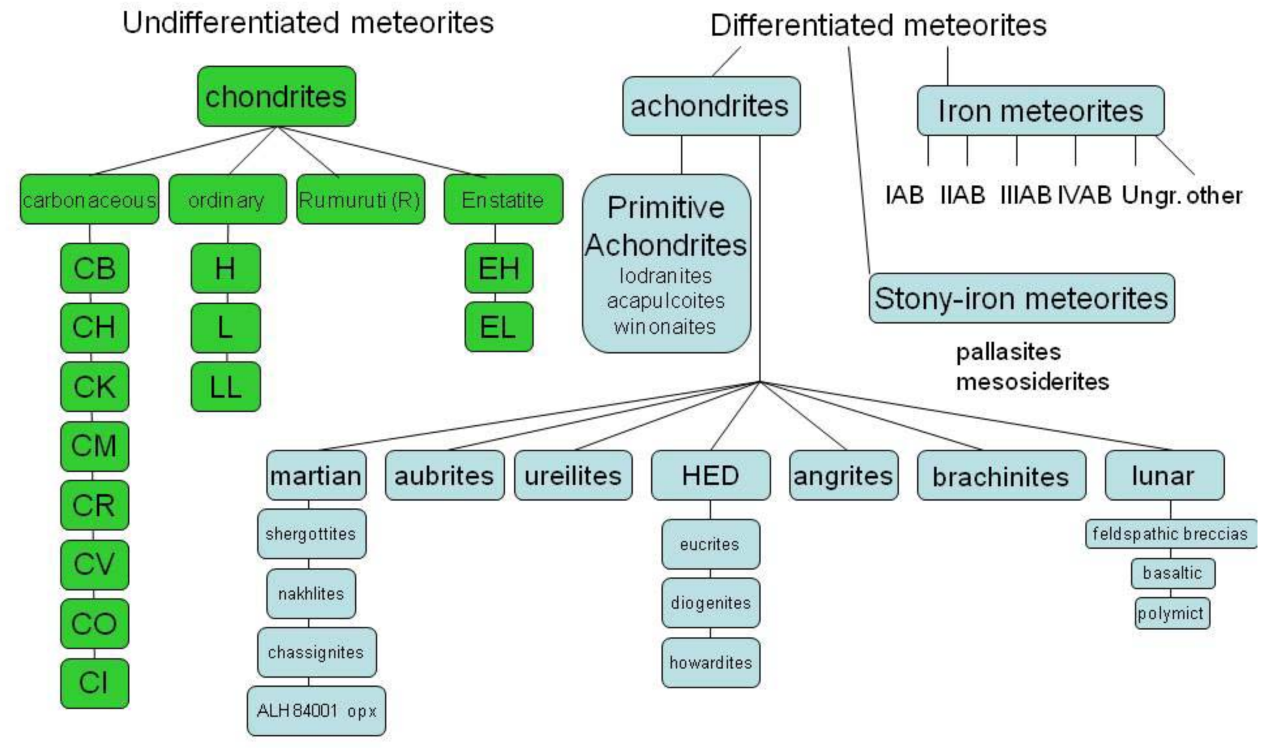

Figure 2: Classification of meteorites into undifferentiated (chondrites) and differentiated (achondrites, irons and stony-irons) illustrating the diversity of materials represented in the meteorite collections. Note: Stony meteorites include both chondrites and achondrites. Constructed from information in Weisberg et al. (2003).

Stony Meteorites: Crystalline. Among the stony meteorites, there is great diversity. One type of stony meteorites is crystalline and composed of interlocking crystals. Such meteorites, which are rare, are interpreted as rocks that have cooled and crystallized from a molten silicate melt. Similar igneous rocks have formed on the Earth by the cooling of erupted volcanic lava on the surface or by the slower cooling of masses of molten rock (magma) within the Earth. The discovery of such rocks among meteorites shows that heating, melting, and possibly volcanic eruptions took place on asteroids during the early years of the solar system.

Stony Meteorites: Breccias and Chondrites. The other and more abundant class of stony meteorites is fragmental, that is, they consist of small pieces of rock (fragments or clasts) in a finer-grained matrix. Similar terrestrial rocks are called breccias; they are formed by the breaking up and pulverizing of older rocks by some force and the subsequent reassembly of the pieces into newer and younger rocks.

In the most abundant type of stony meteorites, the fragments consist of small, round, beadlike objects ranging from a tenth of a mm. to a few mm. in size. These beads, called chondrules, are composed of varying amounts of crystals of different minerals, sometime accompanied by glass. Under the microscope, these chondrules show textures that indicate they cooled rapidly from drops of molten material. Chondrules, and their microscopic textures, are so distinctive (and so unlike anything observed in terrestrial rocks) that this group of meteorites is called chondrites.

(Stony meteorites which lack these beads --- such as the crystalline ones described above --- are called achondrites.)

Stony Meteorites: Histories and Implications. Chondrites are especially important meteorites. Their chemical composition is a close match for the chemical composition of the Sun (minus the volatile elements like hydrogen and helium, which make up most of the Sun). Chondrites are therefore regarded --- 'with considerable caution and debate --- as a chemical standard for the material that made up the original solar nebula from which other meteorites and the planets formed. One class of chondrites, the carbonaceous chondrites, contains significant amounts of both water and carbon and organic compounds. These rare meteorites have major implications for questions closer to home: the development of atmospheres and oceans on the early Earth, and the origin of life here and elsewhere.

The achondrites tell a different story. They do not have the primitive solar composition of chondrites. If they did start out with a primitive composition, they have undergone chemical modification (differentiation) by some mechanism. Many achondrites resemble terrestrial volcanic rocks, and it is suggested that such chemical differentiation took place in the same way it does in terrestrial rocks --- by the separation of newly-formed crystals from a cooling mass of molten magma.

Stony-irons and irons are less well known, for several reasons. For one thing, they are much less abundant than stony meteorites, and some rare types are represented by only one or two examples. For another, their high metal contents make them entirely different from terrestrial rocks, and our long experience in understanding Earth rocks is of little help.

An especially formidable problem with these meteorites is the extensive diversity in texture, mineral composition, and chemistry that exists, even within a single group such as iron meteorites. In the metallic parts, several different iron-nickel alloys may occur in a range of ways, from large crystals in metal-rich regions to smaller bits of metal dispersed among silicate minerals. Original melting and slow cooling explain some of the textures, but others suggest more exotic processes like remelting by later meteorite impacts.

Iron meteorites were originally thought to represent the core of an Earthlike planet that had occupied the Asteroid Belt. However, the remaining asteroids account for less than 1 percent of the mass of the Earth, and this fact has always been a problem with this theory. More recently, extensive laboratory experiments and analyses of the iron alloys in meteorites have shown that they cooled too quickly to have been buried deep in a large planet The asteroids from which iron meteorites have come could not have been more than a few hundred kilometers in size.

THE MINERALS OF METEORITES.

Like Earth rocks, meteorites are also made up of specific chemical compounds called minerals. Most of the minerals in meteorites are also found (sometimes commonly, sometimes rarely) in Earth rocks. A few rare minerals are unique to meteorites alone.

The most abundant minerals in stony meteorites are common in many terrestrial rocks as well.

They are silicates, minerals composed of the elements silicon and oxygen, with other metals (chiefly calcium, magnesium, aluminum, and iron). These minerals include olivine. pyroxene (several varieties), feldspar (or plagioclase). These minerals form at high temperatures (about 500-1200^{o}C), and they are common in terrestrial igneous rocks that have cooled from molten rock.

Irons and stony-iron meteorites are very different. They are composed of large amounts (from ~ 25-100 %) of nickel-iron metal (which is almost unknown in terrestrial rocks), and they contain corresponding less silicate minerals. The metal phase generally contains two (sometimes more) nickel-iron minerals; the most common ones are kamacite (low-Ni iron) and taenite (high-Ni iron). These metals usually occur with small amounts of other unusual minerals, especially troilite (FeS), schreibersite (Fe_3P) and graphite (C). Like the stony meteorites, the minerals in irons and stony-irons also indicate high temperatures and extensive melting. The iron-nickel alloys involved generally melt at temperatures between about 1000 and 1500 ºC.

An unusual group of rare but important minerals form small white fragments that have been found in a few carbonaceous chondrites. These minerals ---spinel. melilite. fassaite. perovskite, and others ---are made up of high-temperature (refractory) chemical elements such as calcium, titanium, and aluminum, and they form at very high temperatures, perhaps 1500-2000 ˚C. Because these inclusions indicate higher temperatures than any other meteorite material, it has been suggested that they were the first material to condense from the solar nebula itself.
Some meteorites retain evidence of temperatures at the lower end of the scale. Most meteorites contain virtually no water, but one group, the carbonaceous chondrites, contains significant amounts of water. This water occurs as a chemical component of the mineral serpentine, a silicate mineral (actually a group of related minerals) that forms at relatively low temperatures (about 300-600ºC) and which is a major component of carbonaceous chondrites. The presence of serpentine, together with other low- temperature minerals, indicates that these meteorites have undergone considerable low-temperature chemical reaction, apparently in the presence of water.

METEORITE TEXTURES AND PROCESSES.

Terrestrial Rocks and Meteorites. Studying thin sections of meteorites under the microscope to understand how they formed is a natural extension of terrestrial geology. Petrography, the study of thin sections of rocks under the microscope, has been an active part of Geology for more than a century. The importance of this field is based on the fact that the final solidification of a rock closes an episode in time, and the rock then preserves a record of what happened during that time. The overall texture of a rock, the composition of its minerals, the arrangements of the crystals, the relations of one mineral to another, all give information about what the rock is made of, how it formed, and what has happened to it since then.

By carefully studying a terrestrial rock in thin sections, geologists are able to answer many questions about its origin: How *did* it form? Was it originally molten? Did it form at high or low temperatures? Which minerals formed first, and which one came later? What forces acted on it while it was forming? Has it been heated after it formed? What other processes --- melting, deformation, shattering, hydration --- acted on it after formed? In short, by looking down a microscope, geologists can reconstruct the life history of a rock.

We can apply the same lessons that we have learned from examining terrestrial rocks to the study of meteorites. Just as a terrestrial rock is a piece of the Earth, a meteorite is a piece of an asteroid. From looking at meteorites, we can reconstruct the histories of different asteroids they came from, in the same way that geologists use terrestrial rocks to reconstruct the history of the Earth.

Studying meteorites and asteroids in this way is more complicated than studying the Earth. We do not know where any particular meteorite came from, and we have no field evidence to show how different meteorites are related to each other. At the same time, the search is exciting. By looking at meteorites, we are looking at the very beginning of the solar system. The events we decipher were critical to the formation of the Earth and other planets. And even in this beginning of things, there was tremendous diversity and complexity in what went on.

Most meteorites contain records of two kinds of processes: (1) internal processes, such as melting, recrystallization, and low-temperature alteration, that took place within a single asteroid, and (2) external processes, that acted on an asteroid from outside, usually through collisions with other asteroids.

Internal Processes: Melting, Metamorphism, and Hydrothermal Alteration. The original solar nebula, and the objects that formed from it, were hot, at least in the inner regions near the Sun where the asteroids and terrestrial planets formed. Temperatures probably reached *1000-1*500ºC, well above the melting point of most rocks and minerals. As a result, one of the earliest and most widespread processes during formation of the solar system was melting.

Nearly all meteorites show the effects of melting, cooling, and crystallization in one form or another. The chondrules that make up the majority of stony meteorites (chondrites) originated as small molten droplets, which may have been individual bodies in the original solar nebula itself. However, microscopic observations show that the chondrules were cool and solid before they were assembled into the meteorites in which they are now found.

Melting also affected larger volumes of meteorites. A few stony meteorites show textures of interlocking crystals like those observed in terrestrial volcanic rocks. Almost certainly, these meteorites (and perhaps the entire asteroids from which they came) were totally melted. Some pans of this original planetary melt cooled rapidly near the surface, perhaps as a lava flow. Other pans, deep within the melted asteroid, cooled more slowly, and the separation of newly- formed crystals from the cooling melt produced unusual cumulate textures like those seen in deep-seated terrestrial igneous rocks. Most iron meteorites also show textures indicating cooling from a melt, so large portions of iron-rich asteroids must also have been melted when the solar system formed.

One of the mysteries about the early years of the Solar System is the source of the heat needed to produce all the melting involved in the formation of asteroids and meteorites. Hot gases in the nebula could provide enough heat to melt small objects like chondrules, and such heat could have come from the gravitational energy of collapse of the nebula, or from the Sun in an early active phase.

Larger objects, like the early asteroidal bodies tens or hundreds of kilometers in size, could have been melted by a different mechanism --- the heat released by short-lived radioactive elements like ^{26}Al. Aluminum is a common element, and this atom, formed in the solar nebula, would have been incorporated into small solid objects in the early Solar System. It would then have changed (decayed) quickly to ^{26}Mg , perhaps releasing enough heat to melt even a body hundreds of kilometers across.

Later heating to lower temperatures (perhaps 600-1000˚C) also affected a number of meteorites after they formed and solidified. This heating did not produce temperatures high enough to cause melting, but it did produce recrystallization and metamorphism, processes which involve changes in textures and chemical composition (Figure 3). Microscopic observation is very useful in recognizing these altered meteorites. Earlier features, such as chondrules, are replaced by a mosaic of new crystals. The various grains of a single mineral, such as olivine, develop a uniform composition.

Chemical changes also occur during metamorphism. Certain volatile chemical elements (like carbon, hydrogen, and some metals) may be lost from the meteorite so that its composition changes. The complexity of heating in the early solar system is indicated by the fact that only some meteorite are altered by later heating, and they are altered in different degrees.

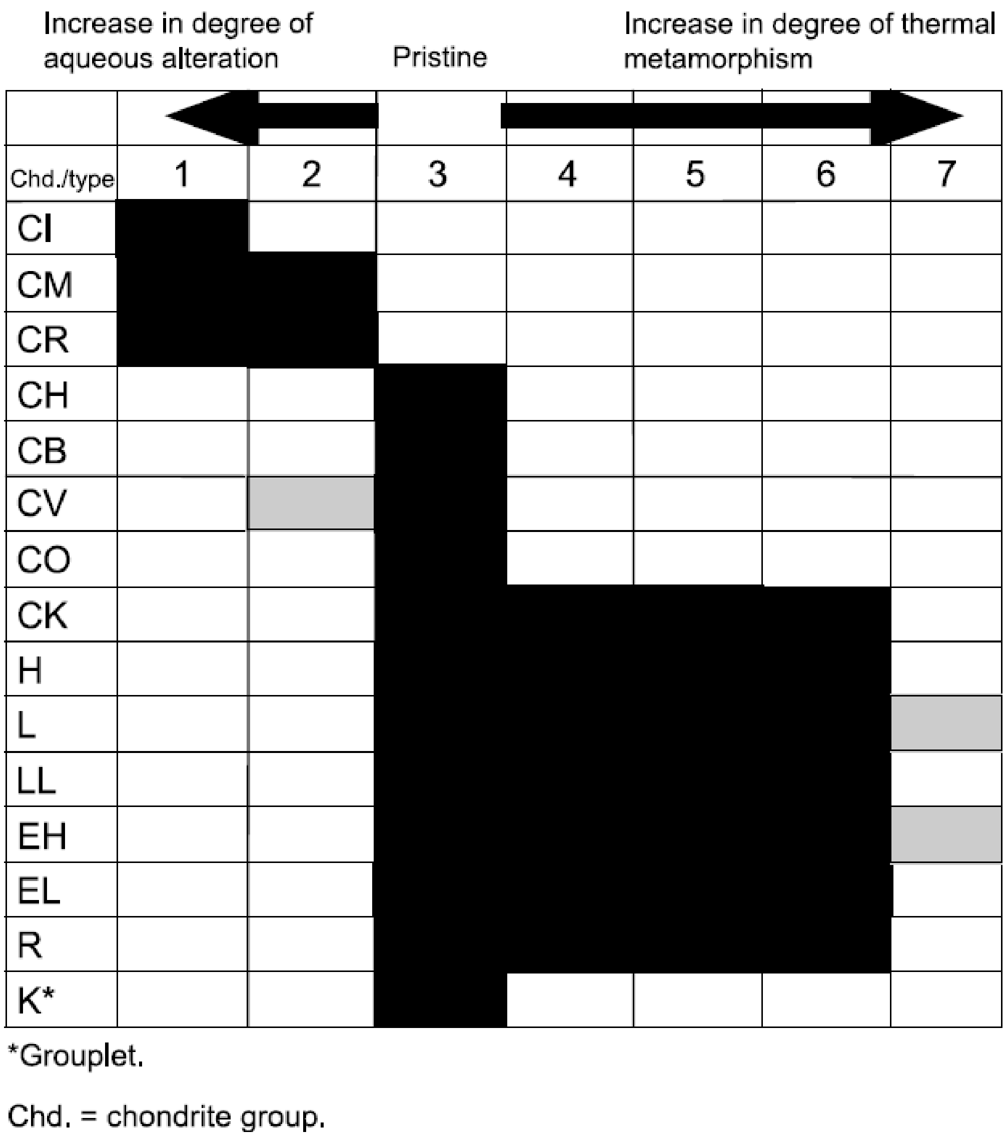

Figure 3: Petrologic classification of chondritic meteorites is base on the idea that some chondrites did not equilibrate and instead are compacted mixtures of matrix, chondrules, and inclusions that are pristine (Type 3). Transformation from type 3 occurs in two different ways – through thermal metamorphism or heating (Types 4, 5, 6, and 7), and through aqueous alteration (Type 2 and 1 with type 1 being the most severely altered. From Weisberg et al. (2003).

A few meteorites, notably the carbon-rich ones (carbonaceous chondrites), show a different kind of change hydrothermal alteration, in which the minerals in the meteorite react with water at even lower temperatures (perhaps $200\text{-}600^{o}C$). In these reactions, earlier-formed dry minerals, like olivine, react with water to form new water-bearing (hydrous) minerals like serpentine. Under the microscope, it appears clear that these hydrous minerals are late-comers; they frequently form veins that cut through the older minerals in the meteorite.

One of the more important chemical changes or variables is degree of oxidation. In a general sense, enstatite chondrites (EH and EL) are the most reduced with all iron being stable in the metal. Ordinary achondrites and some carbonaceous chondrites have Fe stable in both metal and silicates and sulfides. And the most oxidized samples are the CK, CM and CI chondrites that have all iron in the silicates and oxides and have no metal and little sulfide (Figure 4a). In a more absolute sense, meteorites have oxidation states ranging over 15 orders of magnitude from the most reduced enstatite meteorites (aubrite, EH and EL) to the most oxidized CK chondrites (Fig. 4b).

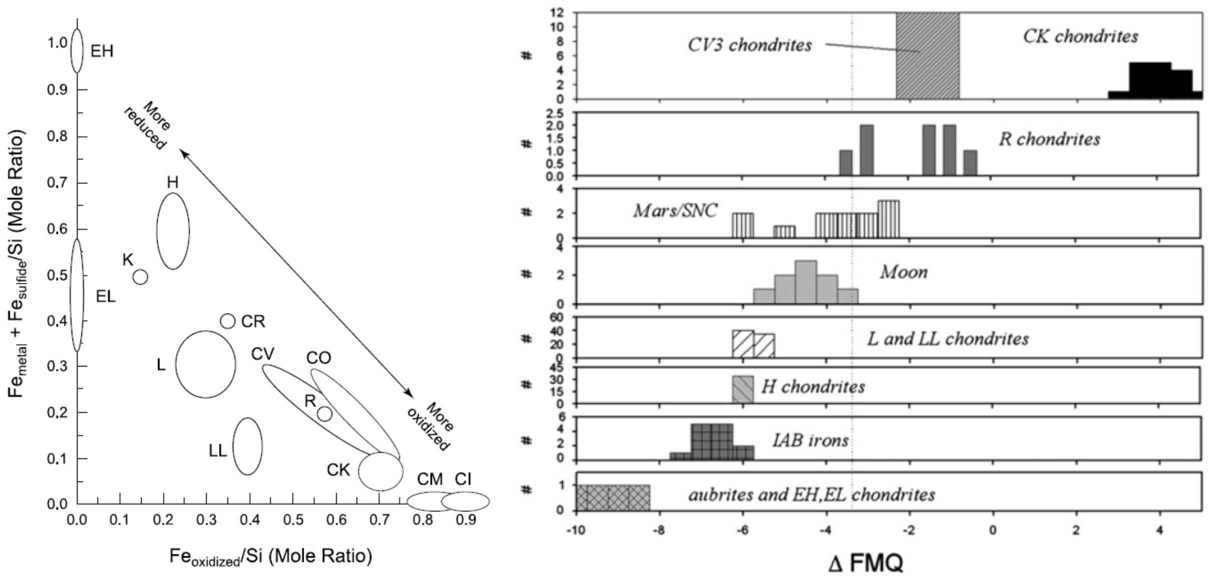

Figure 4: (left) Variation in oxidation state of iron observed in chondritic meteorite, as gauged by the amount of reduced Fe (in metal and sulfide) versus the amount of oxidized iron (in oxides and silicates). (right) Variation in oxygen fugacity (or pressure) in meteoritic materials, relative to the fayalite-quartz-magnetite FMQ oxygen buffer which is close to the oxygen fugacity of the Earth's upper mantle. The range for meteoritic materials is nearly 15 orders of magnitude (from Righter et al., 2006).

<u>External Processes</u>: Collisions and Shock Effects. The early solar system was a very crowded place. At first, it contained thousands, perhaps millions of small bodies, ranging in size from small fragments to small planets. Collisions were continuous as the few surviving objects grew into larger planets. On the Moon, the heavily cratered highland regions preserve a record of what this intense bombardment must have been like.

As the smaller objects were continually swept up to form planets, the collision rate dropped off. By about 3.9 billion years ago, about 700 million years after formation of the solar system, it had dropped to a tiny fraction of its original intensity. But such collisions still occur in the present asteroid belt and even rarely with the Earth itself.

The bodies of the Solar System ---planets, asteroids, small fragments, and bits of cosmic dust ---all move at high velocities relative to each other. Collisions at such high velocities ---especially between larger objects ---can be major catastrophes for the objects involved. At the point of collision, the immense kinetic energy of motion of the bodies is immediately converted into intense shock waves with pressures that reach hundreds of thousands to millions of atmospheres.

As these shock waves pass quickly through the colliding bodies, they produce intense changes. At lower pressures (a few thousand atmospheres) large volumes of rock are fractured, shattered, and crushed. At higher pressures (a few hundred thousand atmospheres) minerals are deformed in striking ways; some are even converted into a type of glass without melting. At the highest pressures (half a million atmospheres and above), rocks are melted and even vaporized.

The melting effects produced by high-intensity shock waves are often confused with the results of more normal melting within planetary bodies. This process, impact melting, can produce bodies of melt ranging from millimeters to kilometers in size, and the textures of these impact melts closely resemble those of chondrules and rocks produced by more normal processes. In studying meteorites, it is important ---and often difficult ---to distinguish between chondrules and melt rocks that have originated by normal melting at the beginning of the solar system and those which have been formed by the melting and shattering of rocks by later meteorite impacts.

An airless body, like an asteroid or the Moon, has no protection against collisions, and its surface is continually struck by both large and small objects. Each impact excavates a crater and deposits fragments of shattered and melted rock around it. As these impacts continue, they gradually build up a layer (regolith), composed of this broken and melted rubble, all over the surface of the asteroid.

By studying samples of the Moon's regolith (or "lunar soil," as it is generally called) obtained by the Apollo missions, we learned a great deal about how such layers are formed on the Moon and on asteroids. We now know that some meteorites, like the lunar samples we studied, are made up entirely of the surface regolith from some asteroid. These meteorites are a rock type called breccias and are made up entirely of fragments from other rocks (Figure 5). In fact, as the bombardment of the asteroid surface has continued with time, older breccias have been broken up and incorporated as fragments into younger ones.

Breccias
- 3.1. Monomict breccias
  - 3.1.1. Cataclastic rocks
  - 3.1.2. Metamorphic (recrystallized) cataclastic rocks
- 3.2. Dimict breccias
- 3.3. Polymict breccias
  - 3.3.1. Regolith (soil) breccias
  - 3.3.2. Fragmental breccias
  - 3.3.3. Crystalline melt breccias (impact melt breccias)
  - 3.3.4. Glassy melt breccias (impact glass)
  - 3.3.5. Granulitic breccias

Figure 5: breccia terminology (from Stoeffler, 1980) for monomict, dimict, and polymict breccias.

Every meteorite has had at least one impact ---the event that blasted the meteorite off the surface of the asteroid, perhaps tens or hundreds of millions of years ago, and sent it in the direction of Earth. In general, the shock-wave effects produced by this impact are not severe enough to be noticeable, and most meteorites appear under the microscope just as they appeared on the surface of their parent asteroid. However, some meteorites have been intensely shocked, and they show major changes (Figure 6).

Shock stage	Effects resulting from equilibrium peak shock pressure		Effects resulting from local P-T excursions	Shock pressure (GPa)	Post-shock temperature increase (°C)	Estimated minimum temp. increase (°C)
	Olivine	Plagioclase				
Unshocked S1	Sharp optical extinction, irregular fractures		None	<4–5	10–20	10
Very weakly shocked S2	Undulatory extinction, irregular fractures		None	5–10	20–50	20
Weakly shocked S3	Planar fractures, undulatory extinction, irregular fractures	Undulatory extinction	Opaque shock veins, incipient formation of melt pockets, sometimes interconnected	15–20	100–150	100
Moderately shocked S4	Mosaicism (weak), planar fractures	Undulatory extinction, partially isotropic, planar deformation features	Melt pockets interconnecting melt veins, opaque shock veins	30–35	250–350	300
Strongly shocked S5	Mosaicism (strong), planar fractures + planar deformation features	Maskelynite	Pervasive formation of melt pockets, veins and dikes; opaque shock veins	45–55	600–850	600
Very strongly shocked S6	Restricted to local regions in or near melt zones					
	Solid state recrystallization and straining, ringwoodite, melting	Shocked melted (normal glass)	As in stage S5	75–90	1500–1750	1500
Shock melted	Whole rock melting (impact melt rocks and melt breccias)					

Figure 6: Shock terminology (from Stoeffler et al., 1991) based on the crystallographic and textural changes in olivine and plagioclase,

METEORITES AND THEIR PARENT BODIES

A major goal of meteorite research is to use the features we see in them to determine the natures, histories, and relations of the different asteroids from which they came. This is a challenging goal. In trying to do the same thing for the Earth, we have only one planet from which literally millions of different rock samples have been obtained, and there is much that we still do not know about our own planet. In the case of asteroids, we have few samples and many worlds to decipher.

Nor is this a simple goal. Asteroids, and the meteorites which they have produced, record extensive and complex changes during both their formation and their subsequent history. The millions of asteroid-like bodies, generally less than a thousand kilometers in size, that formed in the early solar nebula, were apparently a bewildering variety of objects ---silicate materials, metals, volatile ices, and probably mixtures of all these components.

Even when these objects had formed, internal forces acted to change them further. Early .heating produced additional effects. Some objects may have melted completely, and the molten materials then separated into different components ---metal-rich, silicate-rich, possibly even water-rich.

Slow cooling of molten silicate bodies produced a variety of rock types: coarse-grained cumulate rocks inside, and fine-grained lavas on the surface. Even after the original objects had solidified, some were reheated. High-temperature reheating produced new textures and sometimes new minerals. Lower-temperature reheating in the presence of water (on an ice-rich body?) produced major changes, and new water-bearing minerals appeared.

Finally, the solid bodies were --- and continue to be --- affected by collisions with similar objects. These collisions often disrupted objects hundreds of kilometers across into smaller bodies. Less violent events left deep craters on their surfaces and gradually covered the original surface with a layer of rubble. This rubble layer, the regolith, consists of a mixture of broken and melted rock fragments. Some of the fragments are themselves pieces of older regolith.

The meteorites we see today are the results of a wide array of processes that are still not well understood: the original collapse of the Solar Nebula, heating of dust and gas as the Sun began to form; accretion of smaller objects into ever-larger ones, internal melting and heating, later episodes of heating and water-rich alteration, the gradual buildup of impact-produced rubble layers, and finally, the transfer of random samples of all these processes to Earth. To begin at the end of this history, and to reconstruct from small meteorites samples all that has gone before, is an exciting and challenging task. It seems miraculous that we can make any sense of it at all!!

SAMPLES

1. Ordinary Chondrite (Unequilibrated Type 3) (ALH A77011 ,39)

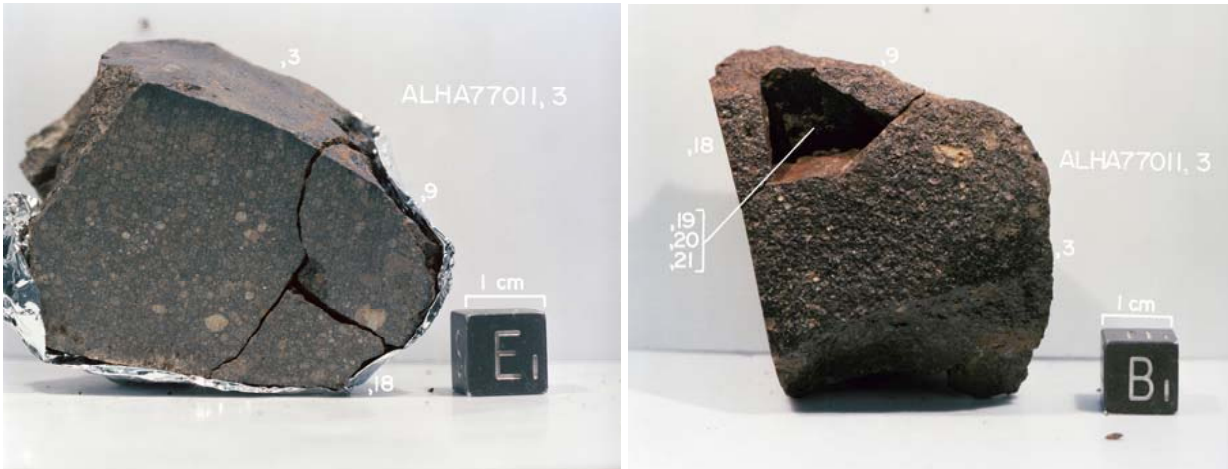

Figure 7: Laboratory photos of ALH A77011 illustrating the fusion crusted exterior (right; NASA photo S81-32616) and the chondrules, matrix and inclusions in the interior (left; NASA photo S81-32618).

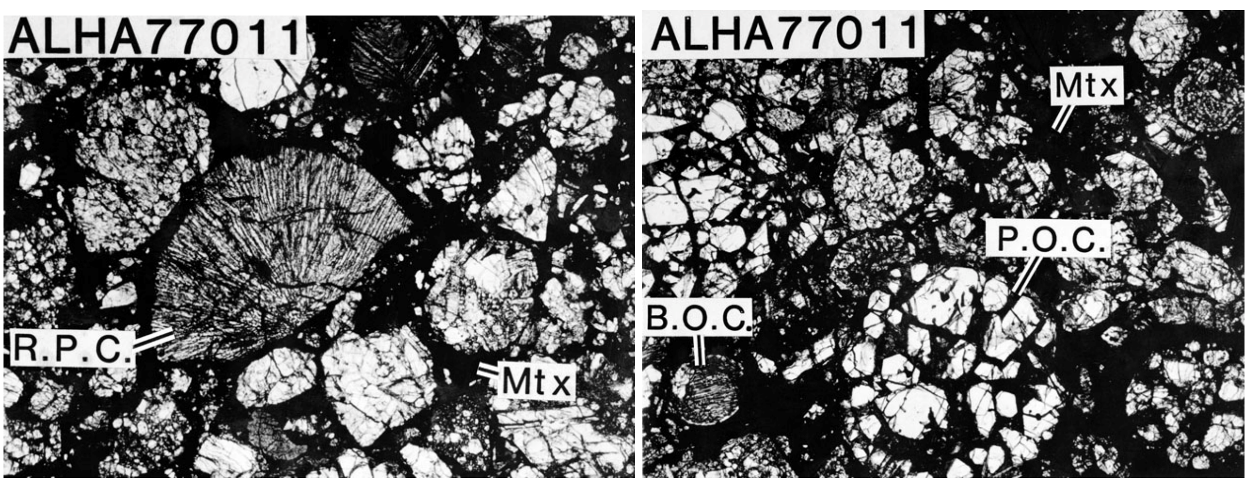

Figure 8: Petrographic thin section images of features in ALH A77011 including radial pyroxene chondrules (RPC), matrix (Mtx) on left (NASA photo S90-49400) and barred olivine chondrule (BOC) porphyritic olivine chondrule (POC) and matrix (Mtx) on right side (NASA photo S90-49401).

A. Introduction and General Appearance. The meteorite is fragmental and consists of numerous small pieces ranging from < 1 mm to 2 mm in size, contained in a black matrix. Fragments compose more than 80% of the rock, and the matrix less than 20%. The various kinds of fragments differ in shape and composition. Chondrules, small round to elliptical objects, are the most distinctive and give the name to this type of meteorite. They occur as entire rounded objects and also as broken pieces, indicating episodes of shattering after the chondrules formed. Other fragments are irregular and crystalline. Metal-rich fragments are dark, but their reflecting surfaces can be seen when light is reflected off the upper surface of the thin section. The fragmental nature and the wide range of fragment types suggest that the meteorite may have been part of a layer of broken-up fine rubble (a regolith) on the surface of an asteroid. Veins of orange color through the thin section are not part of the original meteorite; they are produced by terrestrial alteration ("rusting") of iron metal and other minerals.

B. Types of Different Fragments. Chondrules are abundant in this meteorite and are the most distinctive fragments. They form rounded bodies up to a few mm across. They contain several high-temperature minerals, olivine. Pyroxene, and Ni-Fe metal. and some contain uncrystallized glass. Individual chondrules probably formed by the cooling and solidification of droplets of molten silicate glass, either in the hot original solar nebula or possibly on the surface of an asteroid (where the melting and splattering were caused by meteorite impacts). The variety of textures reflects the different compositions and cooling histories (fast/slow) of individual chondrules. Barred chondrules consist of long thin parallel crystals (usually olivine) separated by glass. Porphyritic chondrules contain large stubby crystals, often with good crystal faces, in glass or a fine-grained matrix. Radial chondrules contain long, thin crystals (generally pyroxene) that radiate from a point in the center or near the edge of the chondrule. Other chondrule textures include microcrystalline (tiny crystals in an irregular or random arrangement), granular (larger crystals in an irregular or random arrangement), and herringbone (multiple zones of radiating crystals in the same chondrule).

Some chondrules may be rimmed. i.e., surrounded by a thin layer of different material that formed later (and often in a different way) than the interior of the chondrule. These rims consist of finely-crystalline material that is clearly different from the interiors suggesting a later -history of deposition and crystal growth onto the chondrule after its formation. The rims may have formed by deposition of new material while the chondrule was floating freely in the hot solar nebula. Other rims may have formed by recrystallizing during a later period, when the chondrule was buried in the hot surface layer of an asteroid. Such a process may have produced the distinctive mantled chondrules, in which the rim consists of one or more large crystals, which may be optically continuous with earlier-formed crystals in the interior of the chondrule.

Broken chondrules can be recognized by their sharp edges and only partly round shapes, but they contain the same crystal textures as complete chondrules. Their presence indicates period of shattering and breaking, probably as the result of meteorite impact, before the chondrules accumulated to make up this meteorite.

Other Fragments found in this sample are rounded or irregularly-shaped pieces of rock made up of the same minerals as chondrules. However, they do not show the distinctive crystallization textures of chondrules. These fragments may have formed by the slower cooling of larger bodies of melted rock, either in space or on the surface of an asteroid. The crystals, which are dominantly olivine and pyroxene, occur in a variety of textures; some fragments are made of crystals which are all about the same size. Others contain a mixture of larger and smaller crystals. Such fragments contain only a small amount «2%) of Ni-Fe metal, which is a low-Ni variety.

C. Matrix (Groundmass). The spaces between the fragments are filled with very fine material which appears indistinct under the microscope. Much of this material is probably small broken fragments, less than 0.01 mm in size, of chondrules, rock fragments, crystals and metal. The metal in these fine mixtures has altered to rust-like materials, which produce the distinctive orange color and make the textures difficult to see.

D. Origin and Interpretation. The fragments that make up this meteorite all formed at high temperatures from individual masses of molten silicate melt. Heat for the melting may have been provided by hot gas in the original solar nebula, by later volcanic eruptions, or by meteorite impacts on the surface of an asteroidal body. The chondrules formed as individual droplets of melt that cooled rapidly (quenched), often preserving glass between the rapidly-growing crystals. Other rock fragments may be pieces from larger bodies of melt like volcanic lavas.

After formation, many of the fragments were subjected to shattering and breakage, probably as a result of collisions between them or by meteorite bombardments on the surface of an asteroidal body. The mixture of broken and unbroken chondrules in this rock indicates that the breaking occurred elsewhere ---although perhaps nearby on the same asteroid. Subsequently, whole and broken chondrules along with other rock fragments were collected into the fragmental deposit represented by this meteorite. Subsequently, one or more meteorite impacts broke up the aggregate and hurled this piece of it toward Earth.

Meteorites, like terrestrial rocks, can be reheated by subsequent geological activity. When this reheating is intense, the minerals recrystallize and the original textures are lost. In some terrestrial metamorphic rocks, the rock is so thoroughly recrystallized that its original nature is uncertain. This chondrite, however, has undergone only a mild recrystallization that had changed the compositions of the minerals in the chondrules but has not been severe enough to modify the meteorite further. Note how well the textures of the original chondrules are preserved and how clearly the chondrules can be distinguished from the matrix.

2. Ordinary Chondrite (Equilibrated, high-Fe -Type H5) (ALH A81015 ,28)

A. Introduction and General Appearance. This sample is also a chondritic meteorite like #1. However, it has been intensely reheated after it formed. As a result, the original chondrule texture has been extensively recrystallized and is hard to recognize. Individual chondrules are still visible as round to elliptical areas, generally <1 mm across, that make up about 75% of the rock. The matrix, comprising about 25% of the rock, is light-colored and composed of small crystals generally <0.1 mm in size. The matrix is much more crystalline than in #1, and there is less dark material.

Figure 9: ALH A81015 ordinary chondrite as found in the field; 1 cm scale ticks are visible on lower edge of brown hand held number counter (NASA photo S82-27179). On right is a photo of the meteorite in the meteorite lab at NASA Johnson Space Center with a 1 cm scale cube at lower right (NASA photo S82-39967).

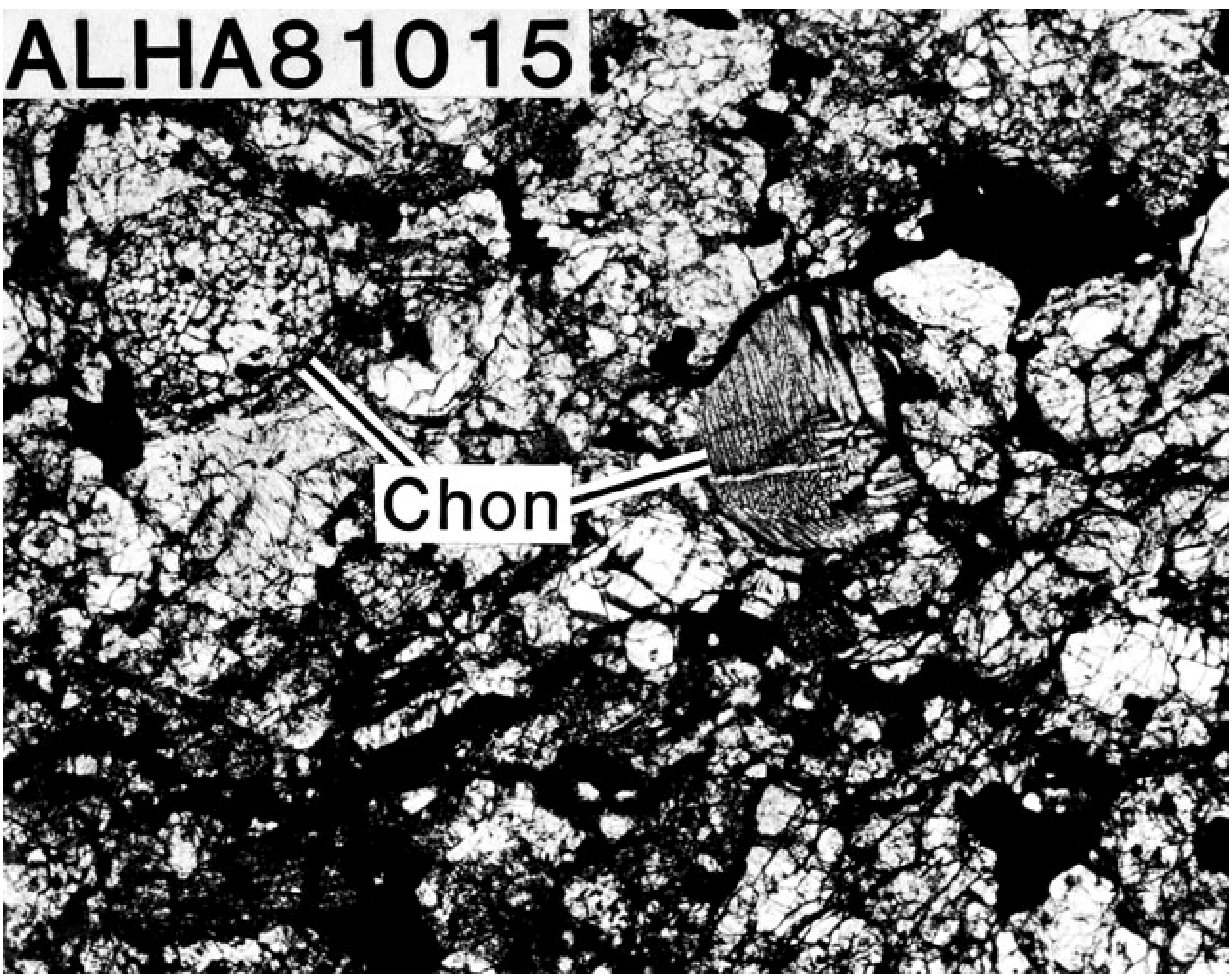

Figure 10: Petrographic thin section image of ALH A81015 illustrating the texture of a thermally metamorphosed chondrite with chondrules starting to have more diffuse boundaries compared to those in

the unequilibrated ordinary chondrite ALH A77011 of Sample 1 (NASA Photo S90-49391).

B. Types of Chondrules. Despite the recrystallization, the chondrule texture is still well preserved and individual chondrules can be easily recognized. However, the boundaries between chondrules and the recrystallized matrix are not as clear as in #1; the original boundaries have been blurred and overprinted by the recrystallization.

A wide range of different individual chondrules are still recognizable. Barred chondrules consist of long, narrow olivine crystals within the chondrules, oriented parallel to each other, and separated by areas of what was once uncrystallized (isotropic) glass. However, in this sample, the glass appears finely recrystallized (microcrystalline), probably as a result of the reheating of the meteorite after it formed. Porphyritic chondrules contain stubby, well-formed crystals of olivine, also in microcrystalline glass. Some of these chondrules are mantled with fine-grained irregular (anhedral) olivine crystals. Radial chondrules consist of thin crystals, usually pyroxene, in radial or subparallel arrangements. The radial patterns appear to originate from a point within the chondrule or along its edge.

In some places, the sample contains small areas composed only of one or more olivine crystals. Where multiple crystals are present, they are poorly-formed (subhedral) or irregular (anhedral). These areas may represent original granular chondrules which have been recrystallized. Alternatively, they may be fragments of original olivine crystals from another rock type.

C. Matrix (Groundmass). The matrix, consists chiefly of small olivine crystals, generally <0.1 mm, that fill the space between the chondrules. The texture of the crystals suggests that they have grown from a finer original matrix (perhaps like that in #1) as a result of subsequent heating. The matrix also contains Fe-Ni metal, about 5%. This is a larger amount of metal than in #1, indicating that this sample has a higher Fe content. (In fact, the Fe content of this sample is high enough to deserve a special category, "H" for high-iron.) *(NOTE: The difference in Fe content can be easily seen by holding the sections under a light and comparing the relative amounts of metal, which can be recognized by its high reflectivity.)*

The metal, and related minerals (such as sulfides) associated with it, have been terrestrially altered to orange material ("rust"), which forms narrow veins through the rock.

D. Origin and Interpretation. Like sample #1, this chondrite formed by accumulation of melted droplets and rock fragments. A relatively high amount of metal (in comparison to other chondrite meteorites) was mixed in with the fragments. The various fragments were then collected together, probably in the surface rubble layer (regolith) on the surface of an asteroid. After accumulation, the material was extensively heated throughout, so that all the original chondrules and matrix were recrystallized. The source of this reheating has not been clearly established. The material may have been buried in a layer of melted rock from a large meteorite impact. Or the asteroid itself may have somehow become hot enough to produce molten lavas by itself. (Some rock fragments formed in this way are seen in other meteorites.)

This reheating produced distinct changes in the meteorite. The original fine matrix recrystallized into small interlocking olivine crystals. The boundaries between chondrules and matrix became indistinct. Original isotropic glass in the chondrules was recrystallized. However, the chondritic texture was not completely destroyed, and the original character of the meteorites can still be recognized.

3. Carbonaceous Chondrite (Vigarano-type, CV3) (ALH 84028 ,58)

Figure 11: (left) Laboratory photo of ALH 84028 taken in the meteorite lab at NASA-JSC with a 1 cm scale cube at lower right (NASA photo S85-36788). (Right) photo of the surface of a slice through ALH 84028 showing the many chondrules and inclusions found within this meteorite, again with 1 cm scale cube at right (NASA photo S86-29985).

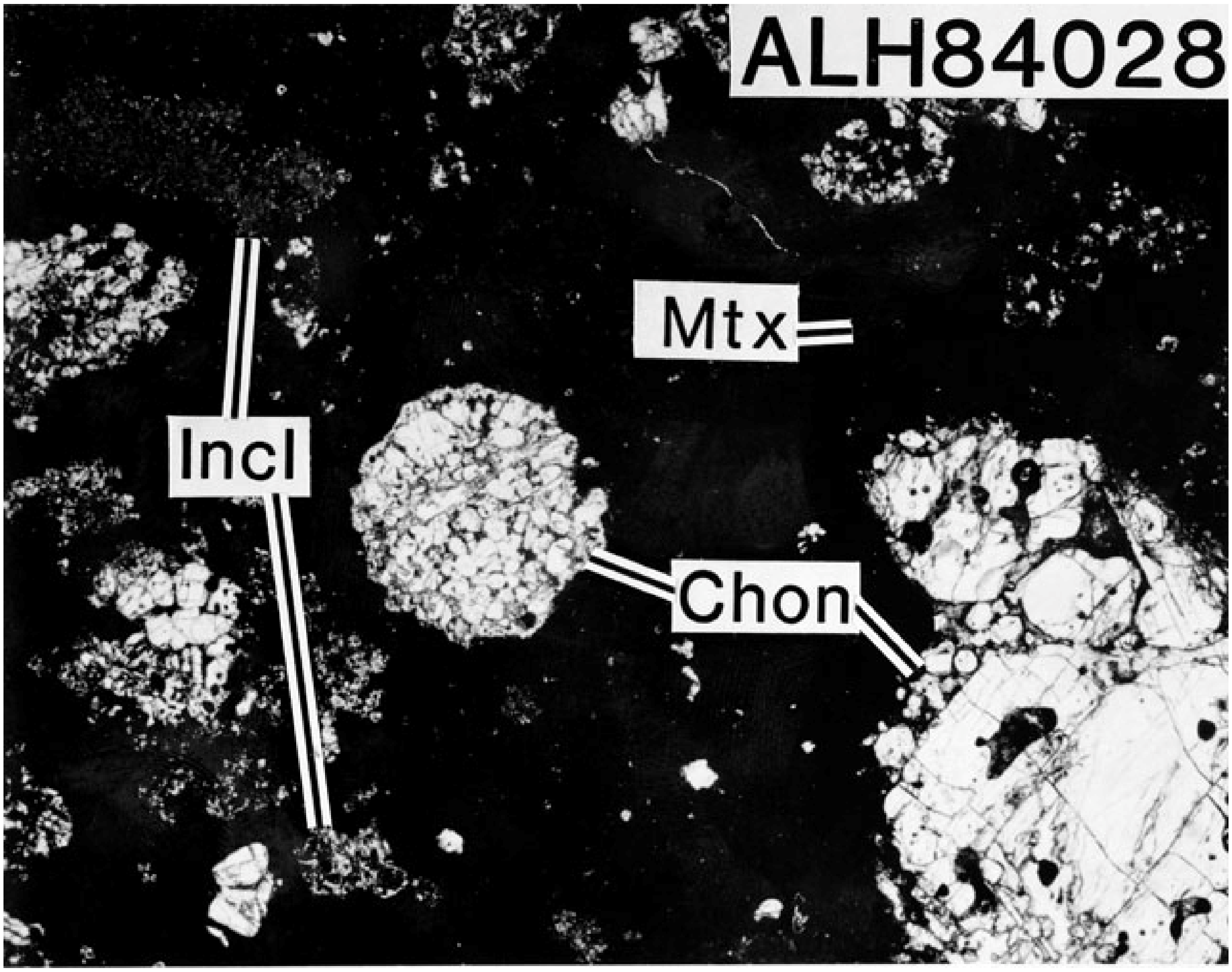

Figure 12: Petrographic thin section image of ALH 84028 showing the components in this carbonaceous chondrite: matrix (Mtx), chondrules (Chon), and calcium aluminum rich inclusions – CAIs (Incl). NASA photo S90-49397.

A. Introduction and General Appearance. This sample is a fragmental rock composed of rounded chondrules and irregular rock fragments in a dark-black, carbon-rich matrix. Chondrules and other fragments make up about 75% of the rock, and the matrix makes up about 25%. Contacts between fragments and matrix are sharp. There is little Ni-Fe metal visible.

Meteorites of this type are interesting for several reasons:

(1) Their chemical composition (except for gases like hydrogen and helium) is approximately the same as that of the Sun. For that reasons, carbonaceous meteorites (especially the most primitive or C 1 variety) have long been considered as a standard for the original solid material that formed the planets and asteroids. Most theories of the origin and evolution of planets have taken carbonaceous chondrite compositions as the initial step.

(2) They also contain significant amounts of carbon, which is present as complex organic material in the matrix. For this reason, the "c" in the meteorite classification stands for "carbonaceous." ("V" stands for Vigarano, the name of the first meteorite of this type to be recognized.) C3V meteorites contain about 0.2-0.4 wt.% carbon overall. More primitive meteorites, the C1 group, can contain 2-4 wt%. The carbon and the complex organic compounds

in these meteorites are important because they provide important ingredients ("building blocks") for developing life, and it has been argued that the essential components for life on Earth were brought in by the infall of carbonaceous meteorites.

(3) Many contain unusual inclusions made of minerals that form at very high temperatures. These inclusions may have been some of the first solid material to form from the hot solar nebula, and they record conditions during the very earliest periods of solar system formation. Several inclusions in this sample are described below.

B. Fragments: Chondrules. Fragments in this meteorite are generally less than 2 mm in size. They are divided about equally between rounded chondrules and irregular finely-crystalline rock fragments that are discussed below. As in other meteorites, the chondrules are composed of several different minerals: olivine is generally the most abundant, but pyroxene, Ni-Fe metal, and glass are also present.

The chondrules display a variety of textures that are also found in other (non-carbonaceous) meteorites. Barred chondrules contain long, thin parallel crystals of olivine separated by bands of glass, Porphyritic chondrules are made up of individual stubby crystals, set in a matrix of glass. Granular chondrules are made up of a mosaic of interlocking olivine crystals. Radial or fibrous chondrules, composed of very thin sheaves of radiating crystals, seem to be absent in this sample. This lack may reflect a real difference in this meteorite, or it may simply reflect the fact that this small section does not provide a fully representative sample of the meteorite.

The chondrules provide evidence that the whole meteorite has been reheated (metamorphosed) since it formed. For one thing, none the glass in the chondrules remains in its original glassy, noncrystalline (isotropic) state. It has all been recrystallized (devitrified) to tiny crystals to produce a microcrystalline texture. This texture develops when glass is reheated below its melting point for a long period of time, and the presence of this texture in this sample indicates that the whole meteorite has been subject to such a reheating event

Other textures in the chondrules may also reflect reheating and recrystallization. Some samples of this meteorite also show complex alteration of the chondrules themselves. One such complex fragment consists of an inner core, made of a typical barred chondrule, which is surrounded (mantled) by a complex rim that may have formed by reaction between the original chondrule and the surrounding matrix during recrystallization. From inside out, this rim consists of: (l) a zone composed of a single olivine crystal which is continuous with the olivine inside the chondrule; (2) a zone composed of small, multiple, well-shaped (euhedral) olivine crystals; (3) an indistinct outer rim of fine dark material, which grades into the matrix.

C. Fragments: Inclusions. Approximately half the fragments in this sample are not chondrules, but are irregular microcrystalline fragments, generally less than 2 mm in size. These fragments are irregular in shape and often have an amoeboid shape composed of embayments and protuberances. Some of the fragments appear to have been pressed or molded against chondrules, suggesting that the fragments were soft, presumably at a high temperature. Two types of inclusions can be recognized in this rock: (1) refractory inclusions composed of unusual high-temperature minerals; (2) olivine-rich inclusions composed mostly of olivine.

Refractory inclusions in this sample and in other carbonaceous meteorites have received much attention since they were recognized in the newly-fallen Allende meteorite in 1969. They contain an unusual suite of minerals ---chiefly silicates and oxides of such refractory chemical elements as Ca, Al, Ti, and Mg ---that apparently formed at high temperatures (1200-2000 ºC). These inclusions are believed to be the first material to have crystallized from the solar nebula 4.6 billion years ago, and they provide hard evidence to test our theories of how the solar nebula and meteorites formed. Some of these inclusions even preserve isotopic and other chemical characteristics apparently inherited from interstellar material that was incorporated into the nebula.

In this sample, the refractory inclusions are generally fine-grained or microcrystalline and consist of many small crystals generally 0.005-0.02 mm in size. These inclusions can often be recognized by the their uniform fine crystal size, by the presence of thin rims around them, and by the general absence of opaque minerals (e.g., Ni-Fe metal). The individual minerals in refractory inclusions are hard to identify, but such inclusions generally contain melilite, fassaite an Al,Ti-rich pyroxene), anorthite. and spinel. Fassaite can sometimes be recognized by its faint pale blue color, and spinel by its faint pink color and isotropic optical nature.

Olivine-rich inclusions, as the name implies, do not contain the unusual minerals found in refractory inclusions. Crystal sizes may be larger in these inclusions, up to 0.05 mm, and a mixture of large and small crystals may exist in the same inclusion. Other differences from refractory inclusions include the general absence of rims around them and the presence of significant Ni-Fe metal and other opaque minerals within them. *(NOTE: Although these tests are good general rules, they are not foolproof,' to be sure, each inclusion has to be studied and analyzed on its own.)*

D. Matrix, The matrix around the chondrules and inclusions consists of a small amount of mineral fragments, chiefly olivine and Ni~Fe metal, enclosed in a black featureless material. (Near the edges, where the section is thinner, the matrix material appears dark-brown to brown in color.) This matrix material is almost impossible to resolve under an ordinary microscope. When studied at higher magnification under an electron microscope, it can be resolved into a mixture of components: tiny crystals of olivine, Ni-Fe metal, Fe in sulfide and possible water- bearing minerals (serpentine), with a non-crystalline (amorphous) carbon-rich material. This carbon-rich material produces the distinctive black color of carbonaceous meteorites.

E. Origin and Interpretation. This meteorite has an early origin and a complex history. It was probably one of the first solid objects to form as the Solar System developed, and it has not been strongly altered by later processes. Early origin is suggested by several lines of evidence: the fact that its chemistry is like that of the Sun, and its content of high-temperature, early-formed refractory inclusions. In this meteorite and its components, we are, in fact, probably looking at the first stages in the formation of planets.

The meteorite was accumulated from a variety of early-formed, mm-sized and smaller fragments in the early Solar System. The refractory inclusions probably formed first, at the highest temperatures, probably as independent small objects floating in the solar nebula. The chondrules, and perhaps the olivine-rich inclusions represent a slightly later stage of solar system activity which probably overlapped the refractory inclusions, allowing both types of objects to be collected into a single meteorite. The presence of chondrules in these carbonaceous meteorites provides a tie with more common meteorite families and also indicates that the wide range of meteorite varieties formed more or less at the same time.

The carbon-rich matrix is important for several reasons. First, it is a relative low-temperature material, and its presence suggests that accumulation of this meteorite took place during a relatively cool stage of solar system formation. Second, it is important as a source of raw materials for the development of Life. Studies of other meteorites have shown that this material contains amino acids and other "building blocks" for Life.

When the high-temperature fragments and low-temperature matrix were collected together to form the meteorite, it probably existed either as a small object (a few km?) in space or as part of the surface layer (regolith) on a larger body. At some point, the whole meteorite was mildly reheated, as indicated by the recrystallization of glass and the formation of new rims around some of the chondrules. This alteration was not severe enough to change its original chemical composition or to convert the carbon into crystalline minerals like graphite or diamond.

4. Carbonaceous Chondrite (ALH 83100 ,140)

Figure 13: Carbonaceous chondrite ALH 83100 as found in the field in the Allan Hills (NASA photo jsc2009e041519). ALH 83100 as photographed in the meteorite lab at NASA Johnson Space Center, with a cm cube at lower right (NASA photo S84-32448).

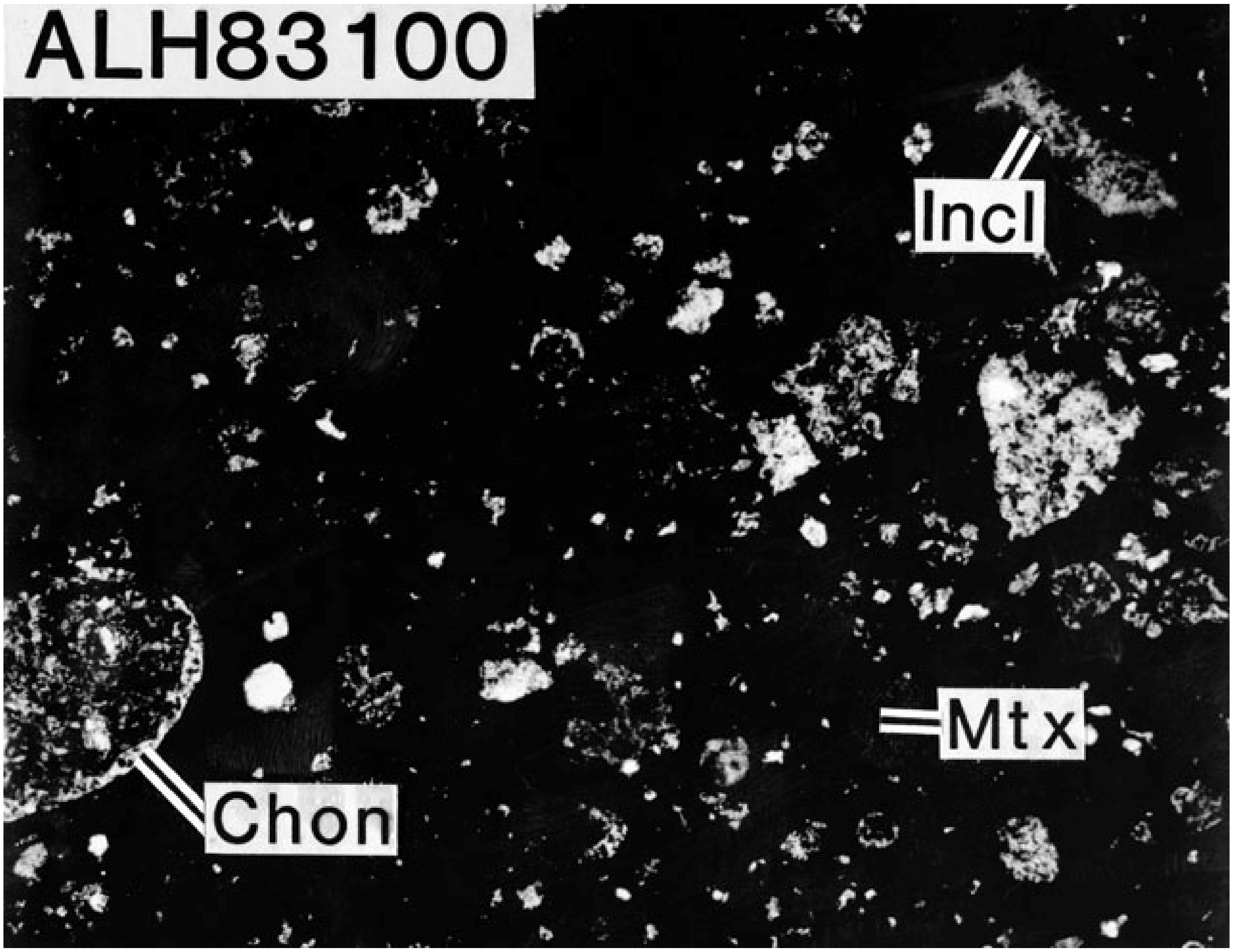

Figure 14: Petrographic thin section image of ALH 83100 showing the components in this carbonaceous chondrite: matrix (Mtx), chondrules (Chon), and calcium aluminum rich inclusions – CAIs (Incl). NASA photo S90-49398.

A. Introduction and General Appearance. sample consists of small (<1 mm) irregular fragments and single mineral crystals in a dark black, featureless, nearly opaque matrix. Where the matrix is thin (as at the edges of the section), it has a greenish color. In these areas, fragments compose about 75% of the rock and matrix is about 25%. In other areas, where the matrix is thick, it becomes opaque and hides the smaller fragments, so that percentages cannot be estimated. The sample contains virtually no Ni-Fe metal, as can be seen by the absence of any metallic reflections when light strikes the top of the section.

This meteorite, like #3, is also a carbonaceous chondrite. as indicated by the dark black color. However, it is different in many ways. It lacks chondrules, it has a higher content of carbon, and much of it is composed of a water-bearing mineral called serpentine. Unlike #3, most of the material in it originated at relatively low temperatures <500ºC). Its composition also suggests that it is a primitive meteorite, but there is much debate over whether the unusual minerals in it were primary condensates from the solar nebula at low temperatures or whether they resulted from the alteration of original olivine in a low-temperature, water-rich environment on the surface of an asteroidal body.

B. Fragments. Several different types of fragments can be distinguished by looking in areas of the section where the matrix is thin. Olivine crystals, < about 0.2 mm in size, are rare but more easily identified. They occur scattered through the matrix.

The most common fragments are rounded to slightly irregular chondrule-like object~; they are generally < 1 mm in size and resemble chondrules in their shape, but they contain no olivine or pyroxene. Instead, they consist of a green, fibrous mineral called serpentine. On Earth, this mineral often forms when olivine-bearing rocks are affected by hot water at temperatures < 500ºC. In the process, original olivine and pyroxene are transformed to serpentine. The presence of serpentine in these meteorites is an argument for the existence of hot water early in the origin of the solar system, probably as hot fluids circulating through a small asteroidal body.

Other fragments are small, irregular objects also composed of serpentine. These may have originally been small chondrules or fragments of broken chondrules, now replaced by serpentine.

C. Matrix. The matrix is black, nearly opaque, featureless, and carbon- rich. Meteorites of this type contain 2-4 wt. % carbon, virtually all of it in the matrix. The matrix is impossible to resolve with an ordinary microscope. In other meteorites of this type, the higher magnification possible with an electron microscope shows tiny fragments and interlocked crystals of serpentine and other minerals.

D. Origin and Interpretation. This meteorite formed as a carbonaceous object similar to #3. It differs in several important ways: fewer and smaller chondrules, conversion of all original chondrule minerals to serpentine, and a higher carbon content in the matrix.

These differences indicate that both accumulation and subsequent alteration of this CM2 meteorite were different than for #3, the CV3. The fragments and chondrules were smaller and the low-temperature material (e.g., serpentine) is more abundant. If the low-temperature material is original, then much of this meteorite was produced in cooler conditions that existed later in the history of the solar nebula. If the low-temperature material is secondary (formed from earlier olivine), then this meteorite was subjected to more intense alteration processes after it formed.

5. Enstatite Chondrite (Type E6) (ALH A81021 ,28)

Figure 15: (left) Image of ALH A81021 as found in blue ice in the Allan Hills region of Antarctica (1 cm ticks at lower edge of sample counter; NASA photo S82-27319). (right) Laboratory image of ALH A81021 in the meteorite laboratory at NASA-JSC with a cm scale bar at right edge (NASA photo S82-39971).

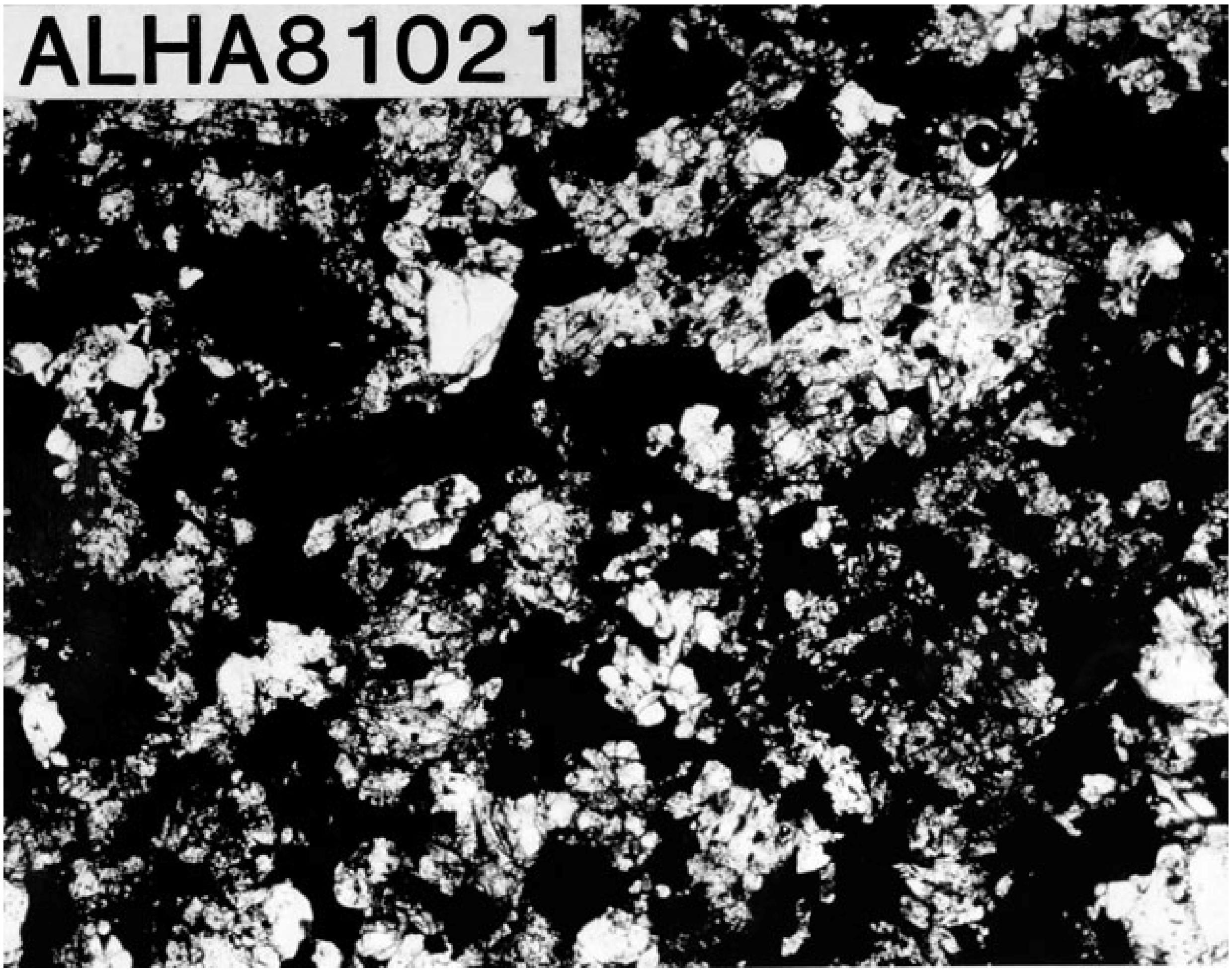

Figure 16: Petrographic thin section image of ALH A81021 enstatite chondrite showing a typical texture for a petrologic grade 6 chondrite, where there are no discernable chondrules or inclusions visible, and the texture is almost entirely recrystallized (NASA photo S90-49396).

A. Introduction and General Appearance, This sample, although identified as a chondrite, is very different from the typical chondrites such as sample #1. It is a highly recrystallized granular rock made up of interlocking grains of several minerals. Pyroxene (enstatite) and feldspar (plagioclase) are the most abundant minerals. Minor minerals include Ni-Fe metal and troilite (iron sulfide, or FeS).

The origin of this meteorite is not clear because any original textures have been almost completely destroyed by later heating and the resulting recrystallization of the minerals. The textures in this sample now resemble those produced by cooling and crystallization of a silicate melt to produce the kind of rocks (lavas) erupted from terrestrial volcanoes. Such melting and eruption also occurred on asteroidal bodies 4.6 billion years ago; and many meteorites are actually made up of such cooled primordial lavas. These meteorites form a separate group called achondrites because they lack the distinctive chondrule textures found in most stony meteorites.

It is not always possible to tell whether a given sample is achondritic (once molten) or a highly-recrystallized chondrite in which the original texture has been erased. The best way to identify a recrystallized chondrite is to find remnants of the original chondrule structure preserved among the recrystallized mineral grains. Some such remnants of circular or elliptical features are preserved in some samples of this meteorite, and their presence has made it possible to identify it as a chondrite, although one of the most highly recrystallized ones (6 on a scale of 1-6).

Another feature of this meteorite is its extreme chemical reduction. All the iron in the meteorite occurs as metal, and there is virtually no iron (as Fe^{2+}) in the pyroxene or olivine. The pyroxene is therefore the highly Mg-rich variety called enstatite. These conditions indicate that the enstatite chondrite meteorites, and the similar but chondrule-free enstatite achondrites, formed under unusual conditions involving much lower partial pressures of oxygen that was the case for other meteorites.

B. Minerals. Pyroxene (var. Enstatite) makes up most (70-75%) of the rock and occurs through the rock as irregular crystals ranging from about 0.05 mm to about 0.2 mm in size. The smaller crystals tend to be grouped into small patches through the rock. Feldspar (var. Plagioclase) makes up 10-15% of the rock, and is distributed with enstatite in crystals of about the same size. Unlike plagioclase in most terrestrial rocks, these crystals show no twinning, but they contain numerous tiny inclusions of both pyroxene and olivine. In reflected light, the plagioclase appears darker gray and less reflective than the associated enstatite. Finally, Ni-Fe metal and Troilite (FeS) form irregular compound opaque grains, as much as 0.5 mm across, which make up about 15-20% of the rock.

One very rare mineral that occurs in this meteorite is sinoite, an usual compound of silicon, nitrogen, and oxygen. It occurs as small crystals which have high relief and (under polarized light), very strong colors (high birefringence), Sinoite only forms under very reducing conditions, and its presence in the enstatite-bearing meteorites is additional evidence that these meteorites have had a very different history from most others.

C. Matrix. Unlike the other meteorites, there is no distinct matrix in this one. The whole meteorite shows only a texture of interlocking crystals, resulting from the intense recrystallization that has destroyed all the original textures.

As noted above, some of the sections of this meteorite contain a few badly altered remnants of original chondrules. In these areas, the chondrule rims remain outlined by original dark material or by differences in the textures of the crystals that have grown across them. Other possible chondrules may be the areas of fine-grained olivine.

D. Origin and Interpretation. This meteorite probably originated as a chondrite, by the accumulation of small droplets and other fragments together to produce a meteorite similar to #1 or #2. Some time after accumulation, the whole meteorite was strongly reheated, probably within an asteroidal body. The exact nature of this reheating and the source of the heat are not certain, but it occurred soon after formation.

This reheating produced extensive recrystallization that erased virtually all of the original chondrule texture and left a granular texture of pyroxene, feldspar, metal, troilite, and other minerals. The reheating environment was extremely reducing, and these conditions produced unusual chemical changes as well. The Ni-Fe metal, unlike metal in other meteorites, contains significant amounts of Si, and the unusual mineral sinoite formed in small amounts.

6. Enstatite Achondrite (Aubrite) (ALH 84007 ,45).

Figure 17: (left) Field image of aubrite ALH 84007 as discovered in Antarctica (NASA photo jsc2009e041626). (right) Laboratory image of ALH 84008, an aubrite sample that is part of a large pairing group that also includes ALH 84007, taken in the meteorite laboratory at NASA-JSC with a 1 cm cube for scale (NASA photo S86-33516).

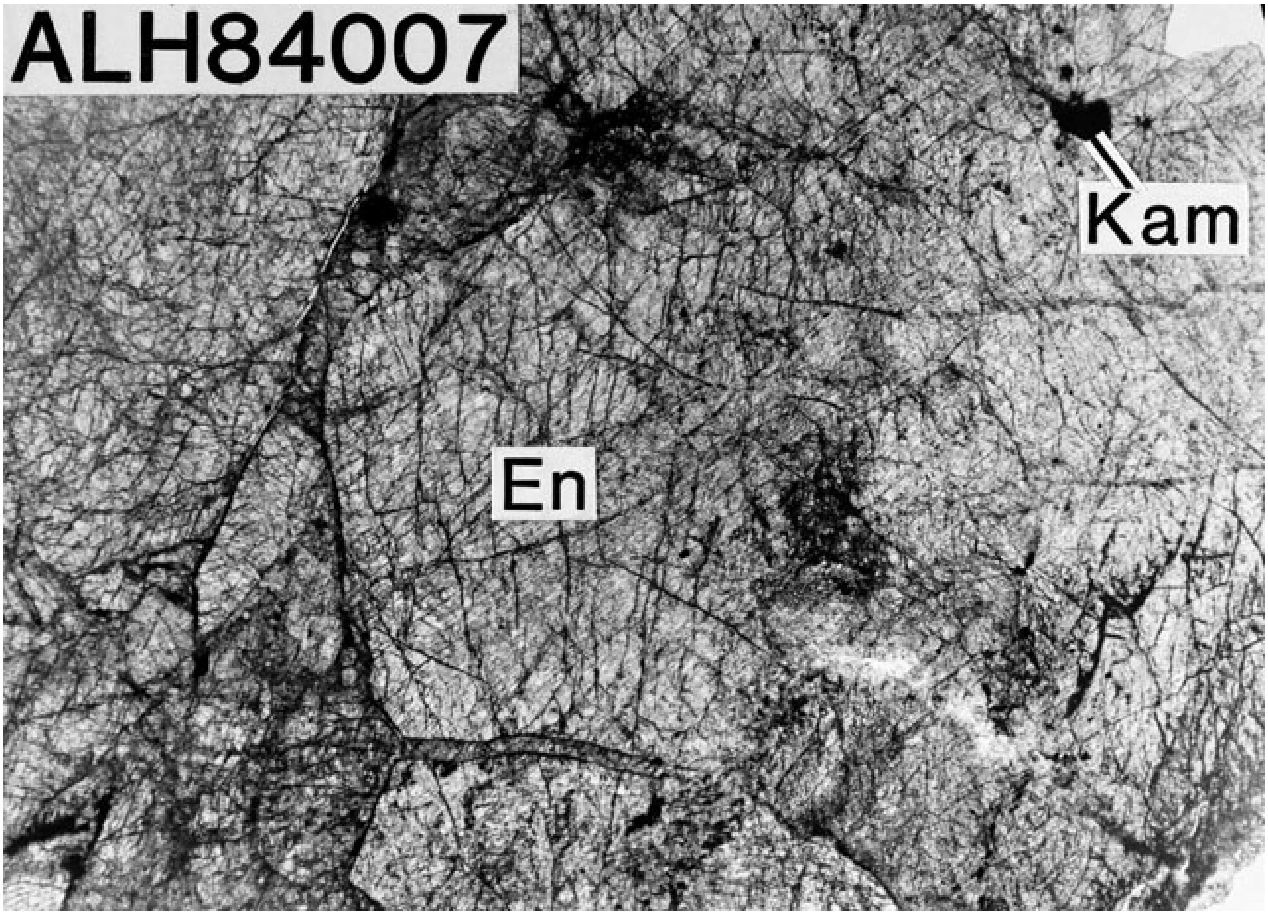

Figure 18: Petrographic thin section of aubrite ALH 84007, showing the very coarse grained enstatite (En) and small grains of enclosed kamacite metal (Kam). NASA photo S90-49395.

A. Introduction and General Appearance. This sample is a completely crystalline rock composed almost entirely of large intergrown crystals an Mg-rich pyroxene (var. enstatite), together with minor amounts of a second (Ca-Mg) clinopyroxene (var. endiopside). Minor minerals are olivine. Ni- Fe metal. troilite. and other sulfide minerals. The crystals, especially those of enstatite, have been strongly deformed. They are intensely fractured, and in places they have been pulverized (brecciated) into smaller fragments. These features were probably caused by intense shock waves generated when asteroid bodies collided together at high velocities (5-20 km/sec).

This meteorite is noteworthy for several reasons. It has no chondrules, and it lacks the typical chondritic texture of many meteorites. (Such meteorites are called achondrites.) Also, it is composed almost entirely of a single mineral (enstatite), and it therefore has an unusual chemical composition that is different from that of typical chondrites.

Meteorites like this indicate that the material in the early solar system went through a great deal of chemical processing and change ~ it was collected into solid objects. The original bulk composition of the solar nebula is thought to be represented by the more common chondritic meteorites, which show the distinctive chondrule texture and which have chemical compositions that are identical (except for gases) to that of the Sun. It is thought that the chondrite meteorites formed by the collection of small solid fragments in the original solar nebula.

However, the achondrite meteorites such as this one have very different compositions from chondrites and from the original solar nebula. This difference is indicated clearly by the fact that this meteorite is made up almost entirely of one mineral (enstatite), while chondrites are composed of many different minerals, including a great deal of olivine. The achondrite meteorites must therefore be made out of Solar System material that has been chemically processed (differentiated) to produce a different composition from the original batch of material from the solar nebula.

One method of chemical processing that may explain the unique characteristics of this meteorite is melting and crystallization. As a larger body of molten silicate rock cools and crystallizes, the first crystals to form have compositions that are different from the original bulk composition of the melt. If these early crystals can be separated from the melt, e.g., by settling in a gravitational field, they can collect together to form a rock whose chemistry and mineral composition is very different from the composition of the original melt.

This process, called magmatic differentiation, is often observed in terrestrial igneous rocks, especially those formed at depths of 5-20 km in the Earth's crust Under these conditions, this separation can produce rocks composed entirely of single minerals ---particularly olivine or enstatite. The same process may have occurred in the first large asteroids to be formed in the solar system. Although these bodies are small, at most a few hundred Ian in diameter, many of them may have been partly or completely melted when they first formed. Even though such bodies have only tiny gravitational fields, similar separation of single minerals could have occurred in them before they solidified. Such bodies would then be made up of regions of different chemical and mineral composition. Later impacts could excavate their interiors, bringing the different rocks to the surface or blasting them into space to become ---eventually ---meteorites striking the Earth.

B. Minerals. Virtually all the meteorite (85-90%) is made up of irregular (anhedral) crystals of the Mg-pyroxene enstatite. The crystals are much larger than enstatite crystals observed in other meteorites, especially in typical chondrites. In this sample, individual crystals are up to 4 mm in size, and crystals as large as 10 mm (about half an inch) have been observed in other meteorites of this type. The large crystal size is consistent with slow cooling, a situation which supports the idea that the material was part of the interior of a moderately sized body and not on the surface, where cooling would have been more rapid.

Other minerals make up only 10-15% of the rock. A second pyroxene mineral, with a Ca-Mg composition and called clinopyroxene or endiopside, forms 5-10% of the rock and occurs in two ways: (1) as isolated single crystals about a mm in size; (2) as planar crystals (lamellae) formed within larger enstatite crystals. This pyroxene can be best distinguished with polarized light; under these conditions, it shows more intense colors (higher birefringence) than the associated enstatite, and the lamellae within enstatite crystals can be easily distinguished.

Olivine occurs as rare isolated crystals < 1 mm; it also shows high colors under polarized light. Ni-Fe metal is rare in this meteorite; there is < 1 %, and it is barely visible when the section is examined under reflected light. Several unusual sulfide minerals occur as tiny isolated grains that also constitute < 1% of the rock.

C. Chemistry and Textures. Reducing conditions (low oxygen pressures). Like the Enstatite Chondrite in this set (sample #5), this meteorite also shows evidence that it formed under unusually reducing conditions. All the pyroxenes and olivine are highly Mg-rich and contain virtually no iron in the Fe^{2+} state. Some of the sulfide minerals are also unusual and form only under highly reducing conditions. It seems likely that the melting and separation involved in forming this meteorite took place under unusual reduced conditions that existed in the inside of a relatively large object.

Deformation by shock waves (meteorite impact). A key feature of this meteorite is the widespread deformation of its minerals after the rock had solidified. All the crystals are highly fractured. In some areas, small veins have developed that contain small broken pieces of crystals in a matrix of even finer powder. Similar zones often occur around and between larger crystals, suggesting a process by which the crystals were deformed and shattered (milled) together. Under polarized light, other unusual deformation features can be observed. Strain in the crystal is indicated by the irregular or patchy extinction of the colors in the crystal as the stage is rotated. In some larger crystals, which contain lamellae of clinopyroxene, the lamellae are often bent and deformed.

Such features indicate that the meteorite was strongly deformed after it had solidified. However, such features are not observed in most meteorites, and their presence in this one requires some special explanation. In terrestrial rocks, such features form during deformation by the intense stresses associated with mountain building. However, such processes do not develop on small asteroids, so the textures in this meteorite must have originated in some other way.

The most likely possibility is that the rock was deformed as the result of a collision between two asteroids. In the crowded asteroid belt, collisions between objects travelling as fast as several km/sec must occur fairly frequently. Collisions at these speeds can generate intense pressures (shock waves) with intensities that can range from 10,000 to 10 million atmospheres. These shock waves spread out from the collision point like ripples on a pond, and they penetrate both colliding objects and produce intense deformation (even melting) of their rocks. (The same process takes place during the impact of a large meteorite on the Earth, and the resulting meteorite crater also contains rocks that show similar evidence of intense deformation.) Such a collision would also serve to excavate deeply-buried material from the interior of the asteroid and bring it to the surface. The same collision, or a later one, would serve to blast the fragment off the asteroid and hurl it toward the Earth.

D. Origin and History. Unlike the chondritic meteorites, which preserve the earliest recorded processes of solar system formation, the achondrites record a series of later processes. (The term "later" is relative, since age measurements indicate that most of the achondrites were also formed by about 4.5-4.6 billion years ago, at essentially the same time as the chondrites.)

One reasonable interpretation suggests that a batch of original chondrite material eventually collected to form a relatively large asteroid, possibly a few hundred km in diameter. When it first formed, the asteroid was molten. As it cooled, crystals of enstatite formed and separated from the rest of the melt, collecting together to form a rock made up almost entirely of enstatite. (The same process may have produced other unusual rock types as well within this differentiated asteroid.) Because this material was inside the asteroid, cooling was slow, and the crystals had time to grow to an unusually large size.

During the cooling and crystallization, the partial pressure of oxygen was unusually low, producing highly reduced conditions. As a result the pyroxenes and olivine are Mg-rich and contain no oxidized iron, and small amounts of rare and unusual sulfide minerals formed.

After solidification, the rock was severely deformed, producing fracturing of the crystals, brecciated zones between crystals, and bending of lamellae within crystals. The most likely source for such deformation is the shock waves generated by a collision between this asteroid and another object. This collision probably excavated the asteroid deeply enough to bring this material to the surface. The same collision, or a later one, served to blast the meteorite into a trajectory towards Earth.

7. Ureilite (Olivine·Pigeonite Achondrite) (PCA 82506 ,41).

Figure 19: (left) PCA 82506 ureilite as found in blue ice in the Pecora Escarpment region of the Trans Antarctic Mtns (NASA photo jsc2009e041590). (right) Lab photograph of PCA 82506 in the meteorite laboratory at NASA-JSC with a cm cube for scale at lower right (NASA photo S83-45243).

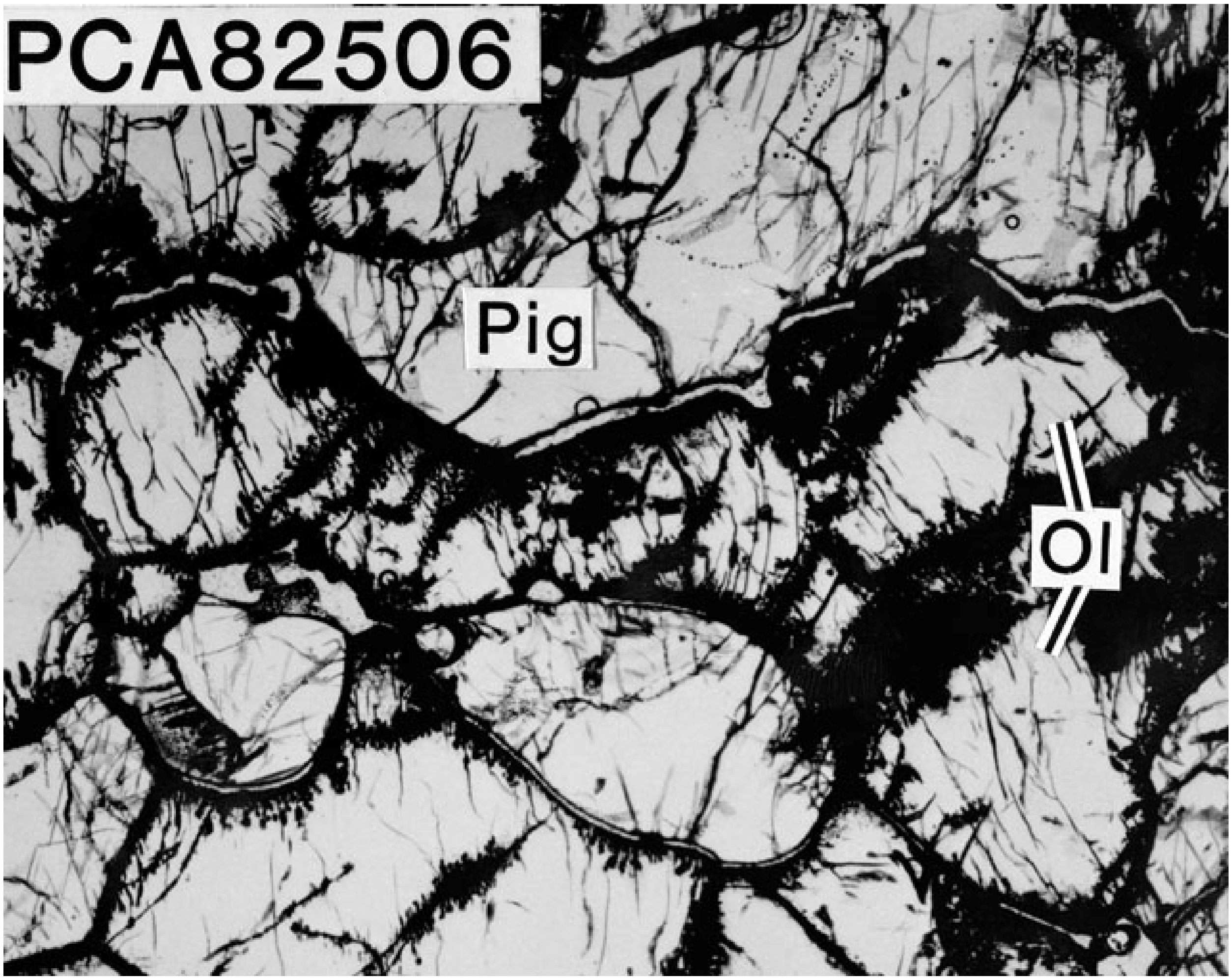

Figure 20: Petrographic thin section image of PCA 82506 showing the coarse grained pigeonite and olivine in a typical ureilite (NASA photo S90-49394).

A. Introduction and General Appearance. This sample is an achondrite meteorite that lacks the typical chondrule textures. It is a crystallized rock made up of crystals up to 5 mm in size. About three-quarters of the rock (75-80%) is made up of crystals of two minerals: olivine and a Ca-Mg pyroxene (var. pigeonite). The crystals are coarse, irregular (anhedral), and rounded in shape; a few form crude polygons. The crystal size and the occasional polygonal shape suggest formation during slow cooling. There is only a small amount of Ni-Fe metal; very little of it in large grains and most of it as small opaque inclusions in olivine. A black, indistinct matrix (about 20-25%) fills the spaces between the crystals and often penetrates into them, producing a kind of "sawtooth" texture along the boundary. This matrix is unusual and not typical of most meteorites.

The ureilites are a small group of unusual and poorly-understood meteorites. They seem to combine two processes seen in other meteorite types: chemical processing and alteration by the shock waves produced during meteorite impacts.

Their chemical composition differs from the composition of chondritic meteorites, which is assumed to be the same as that of the solar nebula, and this difference shows up strikingly in the fact that they are composed of only two minerals, olivine and pyroxene. As in the case of the enstatite achondrite meteorite (#7), this difference may also reflect the result of separation of minerals during cooling of the molten interior of an asteroid.

The effects of intense shock waves (produced by high-velocity collisions) on the meteorite after it solidified are shown by the deformation of the crystals and by the formation of the dark matrix between the crystals. The shock waves were apparently concentrated along grain boundaries, where they produced intense pulverization, melting, and the formation of high-pressure minerals such as diamond (the high-pressure form of carbon), which is found in this group of meteorites. (None have so far been identified in this particular specimen, however.)

B. Minerals. Olivine makes up about 35-40% of the rock. It occurs as irregular (anhedral) crystals as much as 5 mm across. Olivine can be distinguished from the other major mineral (the pyroxene mineral pigeonite) in several ways. Olivine crystals tend to have small black opaque inclusions (made of Ni-Fe metal or sulfide minerals), while the pyroxenes generally do not. Another way of distinguishing the two minerals is to look at the contact between the crystal and the matrix; the black matrix tends to penetrate olivine crystals extensively, producing a "sawtooth" texture along the boundary. The edges of pyroxene crystals are more regular and do not show this penetration. However, the best distinction between olivine and pyroxene is their different appearance under polarized light. Olivine can be recognized by its bright colors (high birefringence) relative to the relatively dull appearing pyroxene.

The olivine in this rock contains a significant amount of iron (about 21% of the fayalite component). This situation indicates that the rock did not form under extremely reducing conditions; in that case, the olivine would have been Mg-rich, and the available iron would have gone into the reduced metal phase).

Pyroxene (a Ca-Mg variety called pigeonite) makes up most of the remainder of the rock, about 35-40%. It occurs as irregular (anhedral) crystals as much as 3-5 mm in size, intergrown with olivine. The crystals tend to be larger and more irregular than the olivine crystals and may be 3-5 mm in size. Unlike the associated olivine crystals, they constrain virtually no inclusions of opaque minerals.

The pyroxene crystals show several different features which provide information about the crystal formation, growth, and subsequent deformation. Some crystals show a pattern of parallel fractures (cleavage) which can be seen as a series of straight parallel cracks within the crystal. Other crystals show a similar arrangement of parallel lines that are not fractures. These lines are the boundaries of other planar crystals (lamellae) of a different kind of pyroxene (with a different chemical composition) that formed (exsolved) within the crystals as the crystal cooled. Under polarized light, these lamellae can be distinguished by a different (and usually brighter) color than the rest of the crystal. And the whole crystals show alternating bands of different colors. In other crystals, a similar pattern is produced by the formation of multiple back-to-back crystals called twins; in these crystals, all the crystals are the same kind of pyroxene.

C. Matrix (Veins). Black, featureless material forms a matrix of small veins that fill the spaces between olivine and pyroxene crystals. The material often corrodes, replaces, and penetrates the olivine crystals, producing a "sawtooth" structure along the boundary. Against pyroxene crystals, the boundary is more regular.

Even under high microscope power, the material that makes up these black veins is hard to resolve and harder to identify. Much of it seems to be a mass of very fine grains 0.001 mm or less in size, which may be either tiny fragments or small crystals of olivine, pyroxene, or both. Additional components are probably finely divided Ni-Fe metal, carbon (which, with the metal, provides the black color, sulfides, and possibly melted glass. To determine exactly what the matrix is made of, even higher magnifications, such as those possible with an electron microscope, are needed.

The veins were probably produced in the rock by intense shock waves that passed through it as a result of a collision between this asteroid and some other object. Intense shock waves, possibly involving pressures of hundreds of thousands of atmospheres, can reverberate from the boundaries between crystals and produce shattering, deformation, and even local melting. This melted material can dissolve the margins of the crystals and can penetrate into them along cracks in the brief time before it cools and solidifies. Such penetration of melt is one explanation for the "sawtooth" texture along the edges of the olivine crystals.

Evidence that high pressures were present during vein formation is found in the minerals in the veins, some of which require high pressures to form. The carbon in this meteorite is particularly interesting. Most of it is an uncrystallized (amorphous) form similar to that found in the carbonaceous chondrites (#3 and #4).

D. Origin and History. Like other achondrite meteorites, this ureilite has a chemical composition that is different from that of chondritic meteorites and the Sun. Its material has somehow been processed (differentiated) during formation. As with the enstatite achondrite (#6) the separation probably occurred by the separation of minerals during crystallization of a body of melt within an asteroid. In this case, two minerals, olivine and pyroxene (pigeonite), collected together.

Two features of this meteorite suggest a slow cooling rate: the large size of the crystals and the development (exsolution) of crystals (lamellae) of a different pyroxene within the original pyroxene (pigeonite) crystals. This evidence for a slow cooling rate is consistent with formation inside an asteroid-sized object, where heat loss would be slower than from the surface.

However, unlike the enstatite achondrite, oxygen partial pressures were higher, and conditions were less reducing than when this meteorite formed. The condition is indicated by the significant amount of oxidized iron (Fe^{2+}) present in the olivine. It is concluded that this meteorite and the enstatite achondrite (#6) probably originated on different asteroid bodies, but the reasons for the differences in cooling environment between two different asteroids are not clear.

Subsequent to crystallization and solidification, the history of this meteorite, like that of #6, also involves deformation by the shock waves generated during the collision events. The deformation of this meteorite must have been more intense. Not only are the crystals fractured, but intense

deformation, probably accompanied by actual melting, was produced at the grain boundaries. The small zones of melt actually corroded and replaced the adjacent olivine crystals. As with #6, such a collision could have excavated this meteorite material from deep within the asteroid, and a similar collision (or the same one) could have propelled it to Earth.

8. Polymict eucrite (Feldspar-pigeonite-basaltic breccia) (ALH A78040 ,82).

Figure 21: Laboratory images of ALH A78040 in the meteorite lab at NASA-JSC. The left-hand image shows the fusion crusted exterior (NASA photo S79-33368). The right-hand image shows the interior with a prominent basaltic clast to the left of the vertical fracture (NASA photo S80-26737). Both images have a 1 cm cube for scale.

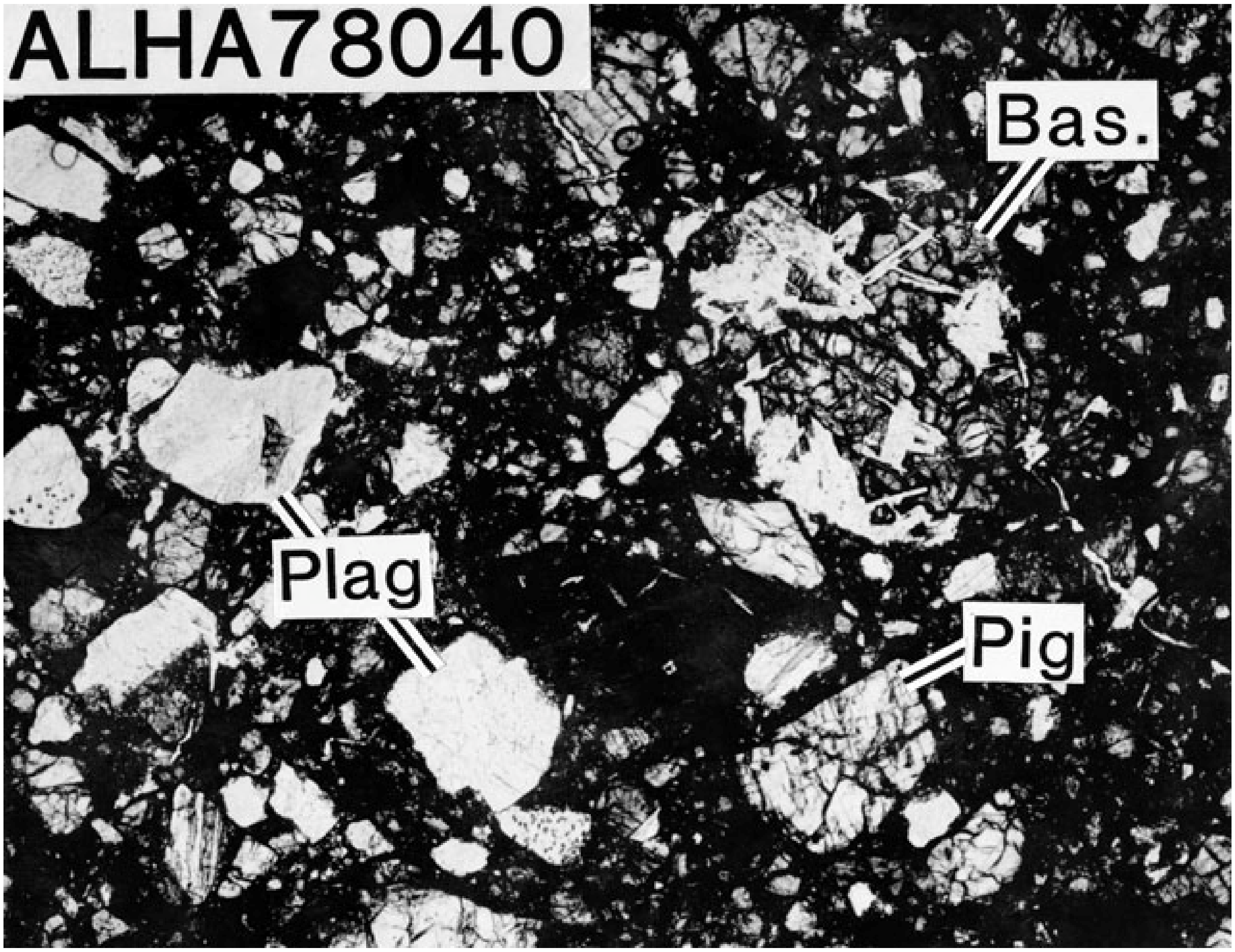

Figure 22: Petrographic thin section image of ALH A78040 polymict eucrite with a basaltic clast (Bas.), and plagioclase (Plag) and pigeonite (Pig) fragments in the brecciated matrix. NASA photo S90-49399.

A. Introduction This sample is a highly fragmental rock (Breccia). It consists of fragments of rock, set in a matrix of finely-pulverized fragments of similar rocks and minerals. The rocks that make up the individual fragments are different varieties of basalt, a volcanic rock composed mostly of pyroxene and feldspar (plagioclase). Basalts seem to be widespread in the solar system. In addition to occurring as meteorites, they are found on Earth as lavas erupted from volcanoes in places like Hawaii and Iceland. They also make up the dark areas (maria) on the surface of the Moon.) This basaltic meteorite is likely from the surface of asteroid 4 Vesta (see below).

The recognition that basalt lavas occur as fragments in meteorites (and sometimes make up whole meteorites; see #9), was a major step in understanding the early history of the solar system. This evidence indicated that, when the solar system formed about 4.6 billion years ago, many small asteroid bodies (or planetesimals) were hot enough to melt, to produce melted lava, and even to erupt that lava onto their surfaces. The existence of this melting made it possible to produce a wide range of meteorite compositions from what may have been a uniform batch of original solar nebula material. The separation of minerals from a cooling melt could produce rocks made up only of one or two minerals (such as meteorite #6 and #7), and the composition of such rocks would be very different from the original solar nebula starting material.

The source of the heat needed to produce the melting is not agreed on. It could have come from collisions during formation of the planetesimals themselves, from heating of the solar nebula by an early active Sun, or by the heat generated from the decay of original radioactive elements such as ^{26}Al. Regardless of the source, the meteorites show that melting must have occurred, and this melting goes a long way to explain the major differences in chemistry and mineral composition that we now see in meteorites, as in their parent asteroids as well.

In this sample the individual rock fragments are made up of several different varieties of basalt, and this sample is therefore called a polymict breccia. (If the fragments had all been of the same rock type ---which does occur in some meteorites ---it would be called a monomict breccia.) Individual fragments in this sample have a wide range of sizes, from about 5 mm in the larger pieces down to less than 0.010 mm in the smallest grains. The large fragments are angular and sharp-edged, indicating that they were broken off cleanly from the bedrock and were not altered by grinding or erosion. The boundary (contact) between the rock fragments and the matrix is clear and sharp, indicating that there has been no detectable heating, recrystallization, or other alteration since the fragments and matrix were assembled together.

This meteorite most probably was formed as part of the layer of fragmental rubble (regolith) that forms on the surface of as asteroid as the result of bombardment by smaller particles. When an asteroid is struck by a small object ---an event that probably occurs frequently in the Asteroid Belt ---the impact produces an impact crater, excavates material from deep within the asteroid, and scatters the excavated material across the surface of the asteroid. Because asteroids have very weak gravity, much of the excavated material is ejected into space and never returns. (Some of it goes off to Earth to make meteorites; some of the rest goes off to hit other asteroids.) However, much of the material comes back to the surface.

As time goes on, and impacts keep occurring, a thick layer of fragmental debris (called the regolith) can build up on the surface of the asteroid. Future impacts can then excavate pieces of the regolith, as well as pieces of the underlying bedrock, and throw both types of rock to Earth.

This process of regolith formation has been well-documented for the Moon, another airless body which also suffers continuing meteorite bombardment, and many of the returned lunar samples are regolith material. (In this sense, the Moon can be thought of as a large asteroid.)

On the moon, the regolith is from 1-20 m thick on the dark maria (or "seas") which are the youngest regions on the Moon. In the older lunar highlands, regolith thickness may be as much as several hundred meters. The thickness of regolith layers on asteroids is not known, but thicknesses of at least several meters have been suggested as reasonable.

B. Rock Fragments. The larger rock fragments, from 1-5 mm in size, are composed of multiple crystals and retain their original formation textures. Most of the fragments are basalt lavas. Their two most abundant minerals are pyroxene and feldspar (plagioclase), which are also the main ingredients of the basalt lavas found on both the Earth and Moon. The pyroxene forms angular or irregular (anhedral) crystals, which generally show a pale brownish color. The pyroxene is closely intergrown with feldspar (a Ca-rich variety called plagioclase). The feldspar is clear and transparent, and the crystals are often tabular or lath-shaped, with parallel sides. The textures of the pyroxene and plagioclase crystals in these rock fragments are typical of those formed when a melt (magma) of basalt composition erupts (lava), cools and crystallizes, usually at temperatures of 1200-1000 ºC, and these rocks closely resemble lavas collected from terrestrial volcanoes and from the Moon.

A variety of different rock fragments are present in this meteorite (hence the term polymict breccia). Different fragments can be distinguished (and given different names) on the basis of such features as grain size and the relative amounts of the two minerals, pyroxene and feldspar. Distinct fragments in this section include:

1. Pyroxene-Feldspar Rocks (Basalt lavas or eucrites). These are the most common fragments. They are made up of about equal amounts (about 50-50) of pyroxene and plagioclase. Their textures indicate that they formed from molten lavas that were cooled fairly rapidly and which may have been actually erupted onto the surfaces of newly-formed asteroids. Two varieties of basalt lavas are visible in this section. One is coarser-grained; it is made of crystals about 0.5-2 mm in size, and the feldspar laths are relatively thick. The other in finer-grained, with crystals <0.5 mm in size and relatively thin feldspar laths.

2. Pyroxene rock (diogenite), These fragments are composed almost entirely of pyroxene, which forms rounded to irregular crystals up to 0.5 mm in size. Feldspar is absent. The unusual mineral composition of the rock suggests formation by separation of pyroxene from slowly cooled melt within an asteroid. In this respect, this rock fragment is similar to meteorites #6 and #7, although the crystal size is smaller. Like the other two meteorites, the pyroxene crystals in this fragment also show evidence of deformation, probably from shock waves produced by impacts. The crystals show fracturing, and abnormal color effects (strained extinction) are seen under polarized light.

3. Breccia (earlier?). If meteorite impact is a continuing process on the surfaces of asteroids, then the fragmental rocks (breccias) formed by one impact can be broken up and redistributed by later impacts. Pieces of earlier breccias should therefore show up in later breccias, and such features have been frequently observed in samples of the fragmental layer (regolith) from the Moon. In this section, one fragment about 3 mm long shows the typical texture of a breccia. It consists of fragments of pyroxene and feldspar crystals < 1 mm in size in a dark matrix. The matrix consists of very small crystals, possibly mixed with glass. It probably represents a piece of an earlier regolith that was deformed by shock waves so intense that much of the original material melted.

C. Mineral Fragments and Matrix. The matrix between the larger fragments is made up of smaller fragments of pyroxene and feldspar crystals. Individual fragments range from the sizes of similar crystals in the rock fragments, about 0.5 mm, down to barely visible ones about 0.05 mm in size. Even at the smallest sizes, the fragments are sharp and the boundaries between fragments are clear, indicating little or no subsequent alteration. The wide size range (poor sorting) of the fragments indicate that the parent rocks have been extensively pulverized and that no process (such as wind or water erosion) has acted to separate the finer fragments from the coarser ones.

The compositions and properties of these small crystals are similar to the minerals found in the larger fragments, and it seems certain that they were produced by the crushing of these same rocks down to smaller sizes. Many of the crystal fragments show deformation effects (most typically the strained extinction of the colors under polarized light), indicating that impact-produced shock waves were involved in the pulverization that formed the matrix.

D. Origin and History. The origin and history of this meteorite must be considered in two parts:

(1) the formation of the individual fragments that make it up; (2) the later process by which the fragments were assembled into the present fragmental rock (breccia),

(1) The origin of the component fragments began when a newly-formed planetesimal body was partly or completely melted. As the object cooled, the composition of the melt changed as minerals separated, and the final result was a range of rock compositions that were very different from each other and from the original starting material. When the melt had cooled and solidified completely, the original planetesimal may have become, in fact, a composite object composed of different kinds of rocks produced from the same batch of original melt. For example, the deep interior of the body could have been composed of coarse-grained pyroxene-rich rocks produced by mineral separation and slow cooling. The shallower regions of the object, perhaps even the surface, may have been made of basalt lavas that cooled more quickly, before minerals had time to separate.

(2) As soon as the planetesimal was solid (perhaps even before it was completely solid), it began to be bombarded by other small objects in the same region of space. These collisions produced large and small impact craters on the surface, excavated bedrock material from different depths, and scattered much of the excavated material across the surface. As these impacts continued, a fragmental layer (regolith) built up from this ejected material. The layer consisted of broken rock fragments, pulverized rocks and minerals, and even a few pieces (breccias) of earlier-formed regolith.

Most of the complex history of this meteorite occurred very rapidly in the earliest history of the solar system, and this meteorite may have reached its final form by 4.5 billion years ago. A subsequent impact --- or perhaps a collision large enough to break up the whole planetesimal --- blasted this chunk of material out of the regolith and sent it into a trajectory that would eventually take it to Earth.

The basaltic clasts and mineral fragments in this sample, are thought to be derived from the asteroid 4 Vesta. Eucrites, diogenites (orthopyroxenites) and howardites (brecciated mixtures of eucrites and diogenites) (HED meteorites) are an excellent spectral match to 4 Vesta and similar S-type asteroids. In addition, the Hubble Space Telescope discovered a large crater on the polar region of Vesta – it may be the source of many HED meteorites (Drake, 2001). Thus these samples, many of which are only a few million years younger than the age of the solar system, hold information about the earliest differentiation events in the solar system (e.g., Drake, 2001).

Meteorites like this, which have accumulated on or close to the surface of their original planetesimals, have an additional importance as probes of the early history of the solar system --- they actually record the behavior of the Sun and of other objects in the universe. Because the planetesimals have no atmosphere, the rocks exposed at their surfaces are bombarded by all the radiations and highly energetic atomic particles that come out of the Sun and from other high-energy sources.

The more important of these particles are the low-energy hydrogen atoms (protons) in the solar wind, higher-energy atoms produced in eruptions of solar flares on the Sun, and very-high-energy atoms (cosmic rays) produced by poorly-understood processes far outside the solar system. When these atomic particles strike exposed rocks, they produce a variety of permanent effects: new radioactive elements, or microscopic tracks of damage within single crystals. Some of these effects are permanent and can be measured in terrestria1laboratories on meteorites, even after 4.5 billion years have passed.

Measurements made on newly-fallen meteorites and on returned lunar samples have made it possible to measure the past history of the Sun and cosmic rays over periods that range from decades (using meteorites) to hundreds of millions of years (using lunar samples). The same measurements, made on other meteorites (like this one) which originated in the surface layer of small planetesimals, provide information about the behavior of the Sun 4.5 billion years ago, when both the Sun and the solar system had just formed. Such meteorites are more than just pieces of the solar system's earliest rocks. They are probes into the life history of a star.

9. Shergottite (Pyroxene-Feldspar basalt, Shock-Deformed) (EET A79001 ,266}.

Figure 23: EET A79001 shergottite as found in the blue ice in the Elephant Moraine region of the Trans Antarctic Mountains (left; NASA photo S80-28838). EET A79001 in the meteorite laboratory at NASA-JSC, with a 1 cm cube for scale (NASA photo S80-37633).

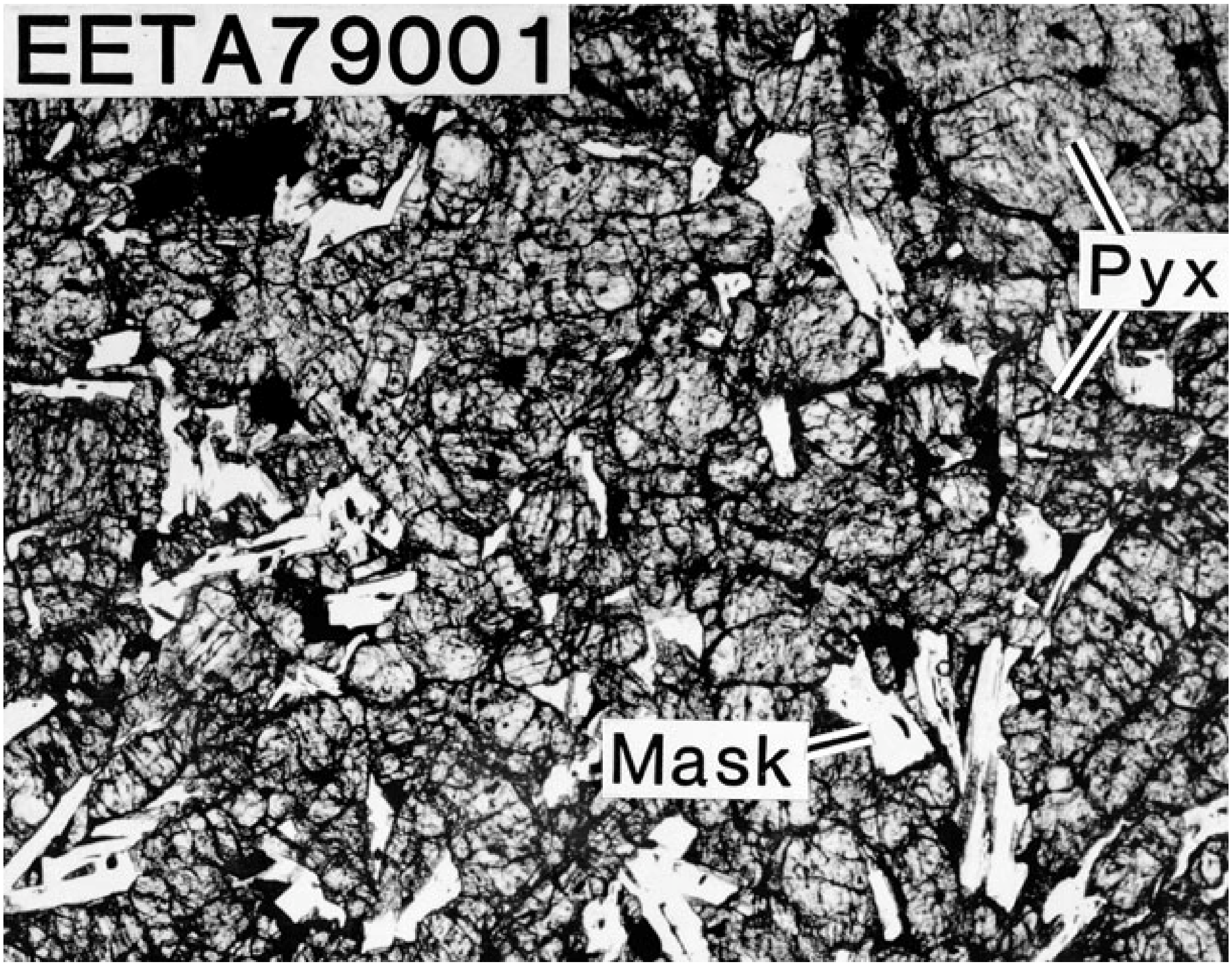

Figure 24: Petrographic thin section image of EET A79001 showing the basaltic texture and maskeleynite (Mask) and pyroxene (Pyx) in the groundmass. NASA photo S90-49402.

A. Introduction and General Appearance. This sample is a completely crystalline rock composed chiefly of interlocking crystals, about 1 mm in size, of pyroxene (var. pigeonite) and feldspar (plagioclase). A number of minerals are present in minor amounts: a second pyroxene (var. clinopyroxene or augite), olivine. and several opaque minerals. The minerals and their textures are typical for a basalt. a volcanic lava crystallized from a mass of molten silicate, and the rock closely resembles similar basalts collected from both the Earth and the Moon.

The rock is cut by a few very thin veins filled with dark featureless material which cut through individual crystals. Along some veins, opposite sides of a single crystal are offset, indicating that the opposite sides of the vein moved relative to each other. However, most veins do not show evidence of such motion.

The most striking feature of this rock is the nature of the feldspar (a Ca-rich variety called plagioclase). Instead of having an ordered crystal structure like the feldspar found in normal meteorites and terrestrial rocks, it has been converted to a glassy material called maskelynite.

This conversion is best seen with a polarized light microscope. Under cross-polarized light, normal feldspar shows colors (interference colors) that range from gray to dull yellow. In contrast, the feldspar material in this rock is completely glassy (isotropic) and shows no colors at all.

Careful examination of this meteorite shows that the glassy feldspar in it has not been produced by normal melting. In normal melting, a solid mineral is converted to a glass by heating; at a certain temperature (the melting point), the mineral turns into a liquid and begins to flow. As it flows, the texture of the original solid material is gradually destroyed. The formation of the glassy feldspar in this meteorite occurred by a totally different process. The original texture of the rock has not been destroyed. The feldspars retain their original shape, and there is no evidence of flow.

The feldspar (plagioclase) in this meteorite has, in fact, been converted from a crystal directly to a glass (maskelynite) without melting. Such a transformation requires a very unusual process, and it is in fact the result of intense shock waves, probably generated by high-velocity collisions, that passed through the rock. Similar maskelynite has been found in the highly-shocked rocks at terrestrial impact craters. It has also been produced in laboratory experiments in which high shock pressures have been generated. The shock pressures required to produce maskelynite are so high (400,000 to 600,000 atmospheres) that the presence of maskelynite is a unique indicator for shock and (in natural rocks) for meteorite impact.

This meteorite has other unusual features as well. It has little or no iron metal, a feature which indicates unusually high oxygen pressures and a high oxidizing environment when it formed. The iron in the rock occurs as oxidized $Fe^{2}+$ in the pyroxene and the opaque minerals. Even more curious is the age measured on the meteorite, which is not the usual 4.5-4.6 billion years obtained for almost all meteorites. The age of this meteorite is less than 2 billion years, implying that it came from an object that had remained hot and molten for more than 2 billion years after the solar system formed.

This meteorite is one of a small group of meteorites (originally less than a dozen, but now over 50) that show these common characteristics: an oxidizing environment, a relatively low formation age, (sometimes) the effects of intense alteration (metamorphism) by shock waves, and an three oxygen isotopic fingerprint that is distinct from that of the Earth and Moon and other achondrites. In addition, the noble gas contents and isotopic ratios are an exact match to those measured in the atmosphere of Mars by the Viking landers in 1976 and 1977. The meteorites in this group have different mineral and chemical compositions, and they are called shergottites, nakhlites. and chassignites (The names come from the three towns ---one in India, one in Egypt, and one in France ---where the first meteorite of each type was found). The group has therefore been called the SNC meteorites, although the addition of orthopyroxenite ALH 84001 in the mid 1990s has made this acronym obsolete. The are now generally called martian meteorites, and they have been the objects of intense study in the last few years.

The unusual chemistry and ---even more important ---the young ages of formation of these meteorites indicate that they could not have come from an asteroid. Even a large asteroid that was totally molten when it formed would have cooled rapidly ---in only a few million years ---that they could not have produced volcanic lavas less than 2 billion years old. The source of these meteorites must be a larger object, one that could have remained hot and active for a long period of time after it formed.

Mars is large enough to have produced young volcanic activity, and it shows volcanic features of approximately the right age. More significantly, the gases trapped in some of the SNC meteorites resemble the composition of martian atmosphere as analyzed by the Viking spacecraft in 1976. Furthermore, new theories about meteorite impact indicate that it is possible --assuming some unusual circumstances ---for a large meteorite to strike Mars and blast pieces of its surface through the atmosphere and away from the planet. Since 1979, several lunar meteorites, which had been similarly blasted off the Moon, have been found on the Antarctic icecap, and it now seems reasonable that the same process has operated on Mars as well.

The martian meteorites, including this one, have a special significance in our study of the Solar System. They do not record the earliest period of Solar System formation, nor do they tell us anything about the asteroid belt. Instead they are samples of the planet Mars, and give us detailed information about this planet that entirely complements data obtained from robotic exploration missions. Combining sample science with exploration missions such as Viking, Pathfinder, Mars Express, Mars Exploration Rovers and future missions provides valuable information about Mars allowing us to assess whether it has water sources, organic compounds, and other chemical ingredients necessary for the origin of life.

<u>B. Minerals. 1. Pyroxenes.</u> Several varieties of the mineral <u>pyroxene</u> make up about 80% of the rock. The mineral occurs as two distinct forms. Most of it is a low-Ca variety called <u>pigeonite</u>; a lesser amount is a higher-Ca variety called <u>clinopyroxene</u> or <u>augite</u>. About-5-10% of the pyroxene is present as large crystals (<u>phenocrysts</u>) 1-3 mm in size that are usually rounded and highly fractured. The remainder consists of smaller crystals generally 0.2-0.5 mm in size that forms rims around the larger crystals and constitute most of the matrix (<u>groundmass</u>) of the rock.

The larger pyroxene crystals (<u>phenocrysts</u>) are mostly <u>pigeonite</u> crystals 1-3 mm across. A smaller number are <u>augite</u> crystals 2-4 mm across. (Under polarized light, the augite crystals unusually show brighter and more intense colors than the pigeonite.) The large crystals usually occur as isolated individuals, but sometimes a group of them occur clumped together. A few of the large crystals show the development of multiple parallel crystals <u>(twinning)</u> within them; this texture is best seen as alternating bands of different color under polarized light. However, this texture is rare in the larger crystals. It is much more common in the smaller pyroxenes that make up the bulk of the rock.

In this section, the large pyroxene crystals appear colorless to faint pale brown, but some of them have a rim of darker brown. This color difference indicates that the rims of the crystals are <u>zoned.</u> i.e., the rims have a different chemical composition from the centers. Such <u>zoning</u> is usually produced when the crystal grows slowly, while the composition of the melt gradually changes. Normally, the centers of such zoned pyroxenes tend to be Mg-rich, while the more strongly colored rims are richer in Fe.

The presence of the large crystals, the tendency of some large crystals to clump together, and the chemical zoning observed suggest that the large crystals formed first and grew relatively slowly in a cooling melt. The smaller crystals formed later during a period of more rapid cooling. One interpretation of these textures is that the larger crystals formed in a body of melt below the surface, and that the smaller crystals formed when the mixture of melt and large crystals was erupted as a lava onto the surface of the asteroid, where it rapidly cooled and solidified.

The smaller pyroxene crystals that make up the matrix (groundmass) of the rock are generally elongate or tabular in shape. Some of them are rounded or irregular, and none of them show crystal faces. They are all <1 mm in size, and most of them are between 0.2-0.5 mm. Their texture is irregular. There is no indication that the long dimensions of the crystals are lined up parallel to each other. In some rocks, such an alignment (preferred orientation) occurs because the rock is only partly crystallized and the remaining liquid is still flowing.

Unlike the larger pyroxene crystals, the smaller crystals show the development of multiple parallel crystals (twinning) within single grains. This effect is best seen under polarized light, in which the small crystals display parallel bands of different colors. In these crystals, the texture may reflect the crystallization of a different pyroxene (var. clinopyroxene) within the host crystal during subsequent cooling after the crystal had formed.

2. Feldspar (Plagioclase). Feldspar (or rather the feldspar glass called maskelynite, makes up 10-15% of the rock. Feldspar appears as clear, transparent crystals, generally < 0.5 mm -in size, that fill the spaces between the more abundant pyroxene crystals. The crystals are often tabular or lath- shaped, with parallel sides, similar to the appearance of plagioclase feldspar found in terrestrial and lunar basalt lavas. The contacts between the feldspar and the adjacent pyroxene are sharp, and there is no indication of deformation along the grain boundaries. These textures suggest that pyroxene and plagioclase formed together at about the same time, as would be the case in a rapidly cooling lava.

The mineral that formed from the cooling lava was probably normal crystalline feldspar, just like that seen in other meteorites, terrestrial rocks, and lunar basalt lavas. However, the feldspar in this meteorite is no longer crystalline; it has been converted to a glassy (isotropic) material. (The transformation can be best seen under polarized light; the glassy material shows no colors whatever.) The transformation of the feldspar to a glass did not occur by normal melting; there is no evidence of fluid flow, and the original textures of the rock appear unaffected. Conversion of the original crystal to glass by intense shock waves is the most likely explanation, and this idea is consistent with current theories in which this meteorite was blasted off the surface of the planet Mars by a huge meteorite impact.

3. Olivine. Olivine, a common minor component of terrestrial and lunar basalts, occurs rarely in this rock as large rounded crystals 2-4 mm across. The large crystal size suggests that olivine formed early in the cooling of the melt, with the larger pyroxene crystals. (This association of olivine plus pyroxene is very common in terrestrial lavas as well.)

4. Opaque minerals. Metallic iron is rare or absent in this meteorite, an indication that it formed under unusually oxidizing conditions. At least two oxide minerals have been identified, and they form scattered grains about 0.1 mm in size: ilmenite, an Fe- Ti oxide, and chromite, an Mg-AI-Fe oxide. Because the minerals do not transmit light, it is difficult to learn much about them in a conventional microscope. For detailed studies of these minerals, a special reflected light microscope is necessary.

C. Thin dark veins. The rock, and the crystals in it, are cut by thin veins that are generally < 0.05 mm wide and composed of fine, featureless, dark material. Where some of the veins cut through single crystals, the parts of the crystals on the opposite sides of the veins have been offset, indicating that movement occurred along the vein. Most of the veins, however, show no such offsets.

The veins may have formed during the same shock-wave alteration that converted the feldspar into its present glassy condition. Similar veins are observed in other meteorites and in terrestrial rocks that have been subjected to shock waves. The fact that some of the veins become wider in the vicinity of grains of opaque minerals suggests that they contain material produced by the melting of opaque minerals by the shock waves. D. Origin and History. This meteorite shows two distinct phases of history: (1) formation from the cooling and crystallization of a silicate melt; (2) intense alteration (metamorphism) by shock waves, which convened the original feldspar (plagioclase) into a glassy phase.

The cooling and crystallization of the rock occurred at about 1-2 b.y. ago. Because the small planetesimals formed during formation of the solar system 4.6 b.y. ago would have been cold and solid by this time, the rock must have formed in a planet-sized body, possibly Mars. The cooling rate was apparently slower than would have been the case on the surface, indicating that the rock formed at some depth (a few km?) below the surface. Slow cooling is indicated by the presence of large pyroxene and olivine crystals (phenocrysts) and by the presence of chemical variations (zoning) within them. Such slow cooling would also have allowed time for the settling of denser pyroxene crystals, which could have played a role in producing the unusual pyroxene-rich composition of this rock.

The early period of slow cooling may have been followed by a short period of rapid cooling and crystallization, which produced the uniform texture present in most of the rock. Such rapid cooling could have been caused by the eruption of the rock, as a mixture of early-formed crystals and melt, onto the surface.

Sometime after the rock had cooled and solidified on (or close to) the surface, it was ejected by the impact of a large meteorite. The time of the impact is not well known, but detailed studies of the meteorite suggest that it occurred at least a few hundred million years ago. This impact produced distinct shock features in the rock, most notably the conversion of original feldspar crystals into a glassy material (maskelynite) with the same chemical composition. Additional shock effects may include the formation of thin black veins and the possible melting of the opaque minerals.

The force of the impact was sufficient to eject the rock fragment from the surface of its original body (likely Mars) and into space, perhaps as a part of a much larger fragment. After drifting in space for perhaps several hundred million years, a series of events ---collisions with other objects and gravitational "nudges" by Mars, Jupiter, or smaller asteroids ---sent the remaining small fragment into a trajectory to Earth, perhaps a few thousand years ago. It entered the atmosphere and survived to land on the Antarctic ice cap. It was buried and trapped in the ice and carried with it as the ice moved outward from the center of Antarctica toward the coasts. Eventually, as the ice melted down, it was brought to the surface again and collected by human beings in 1979.

10. Mesosiderite (Stony-Iron Meteorite) (RKP A79015 ,50).

Figure 25: The left-hand image is a photo of RKP A79015 as discovered in the blue ice of Reckling Peak region of Antarctica (NASA photo S80-28568). The right-hand image is a view of a cut surface through RKP A79015, showing the large metallic portions as well as the silicate-rich inclusions (NASA photo S81-29181).

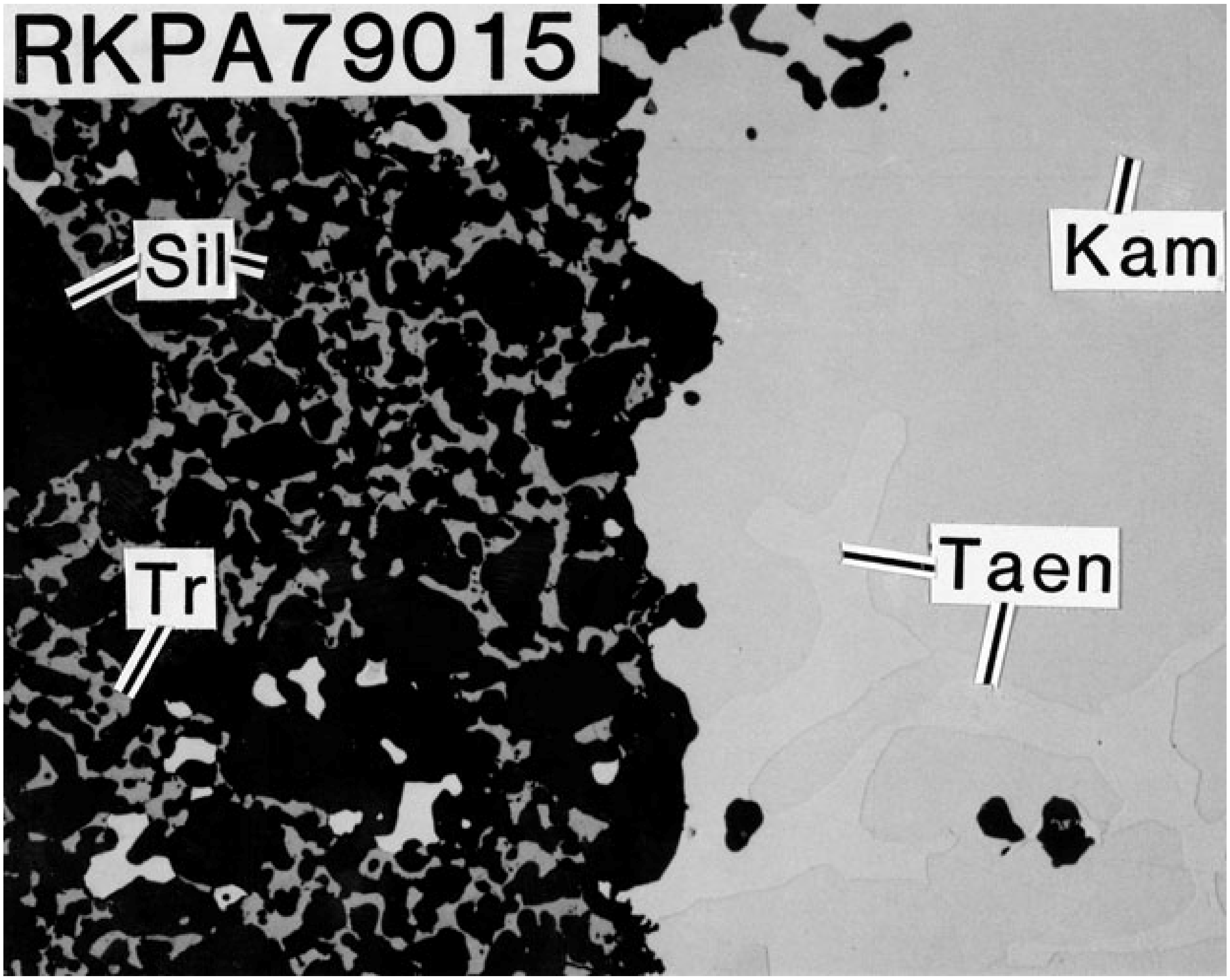

Figure 26: Reflected light image of a portion of the mesosiderite RKP A79015, showing silicates (Sil), troilite (Tr), kamacite (Kam), and taenite (Taen). NASA photo S90-49392.

A. Introduction and General Appearance. The meteorites that reach us from the Asteroid Belt are very different in chemistry and mineral composition, indicating that the many small bodies in the Asteroid Belt are also very different among themselves. The most common meteorites are the stony type, made up mostly of silicate minerals (pyroxene, olivine, feldspar) with only a small amount of Fe-Ni metal. However, less common meteorites are metal-rich and contain little or no silicates. These are the stony-irons, composed of a mixture of silicate minerals and metal, and the irons which are composed almost entirely of metal.

This meteorite is a type of stony-iron called a mesosiderite. It is composed largely (about 75%) of Fe-Ni metal. The metal contains isolated grains of silicate minerals (25%) that range from about 0.05-2 mm in size. The silicate grains are enclosed by the metal or by other minerals. In addition to metal, the specimen also contains a number of opaque minerals: troilite (FeS) and graphite (C).

The distribution of the silicate minerals through the metal is irregular and patchy. In some metal-rich areas, there is <5% silicates, and the metal crystals are large (1-2 nun or larger). In other areas 10-20 nun across, the silicate grains may make up as much as 50% of the meteorite, and the associated metal grains are much smaller are intimately intergrown.

The nature and origin of mesosiderites, and their relation to other meteorite types, are major unsolved problems in the study of meteorites. Mesosiderites are rare among meteorites, only a few examples are known, ant those few are all different. Mesosiderite meteorites have been referred to ---unkindly but accurately ---as "wastebaskets" because of the large number of different components that they contain. Some of them appear to be related to other fragmental silicate meteorites, such as the eucrites (see #8). Others appear to have no obvious relations to any meteorite type.

B. Silicate Minerals (Olivine). Virtually all of the silicate material is olivine, which occurs as isolated single grains with a wide range of sizes, generally 0.05-2 mm. The grains are generally rounded and irregular, but they frequently show sharp boundaries and angular corners, as though they had been broken. Many of the larger grains are apparently cracked and broken, and some of the cracks appear to have been filled with metal from the surrounding matrix. However, the olivines show no indication of the kind of crystal deformation produced by shock waves; under polarized light, the colors are uniform and the pattern of colors shows no strain.

Other textures suggest that the olivine has been partly melted or altered by the metal matrix. Some of the boundaries between olivine and metal appear corroded, as if the edges of the olivine had been dissolved. The olivine crystals themselves vary; some are clear, but others are rich in opaque inclusions, again suggesting alteration.

C. Metal (Fe-Ne minerals). Fe-Ni metal makes up the bulk of the meteorite (about 75%). In this metal, two different Fe-Ni minerals are present. Although both are composed chiefly of Fe, they have different crystals structures and different Ni contents. One, kamacite or alpha-iron, contains 2-5 wt.% Ni and occurs as large crystals, more or less equant in shape and ranging from 2 mm to more than 5 nun in size. In reflected light, it appears slightly tan-colored. The other mineral, taenite or gamma-iron, contains 5-10 wt.% Ni and forms smaller crystals; in reflected light, it appears silvery.

These crystals, which range from 0.05 to more than 5 mm in size, are much larger than the crystals formed in similar nickel-iron alloys produced on Earth. The large size of the metal crystals in meteorites is one of several lines of evidence that indicates that the meteorites cooled and crystallized slowly. By analyzing the distribution of Ni in the metal crystals, it has been able to calculate the actual cooling rates. Depending on the meteorite estimates of from 1-10 ºC per million years have been obtained.

D. Other Minerals. In addition to silicate minerals and metal, both iron and stony-iron meteorites contain small amounts of other minerals, usually compounds of Fe with P, S, or C. In this meteorite, these minerals make up a few percent of the rock. They occur as small crystals in dark patches, associated with the metal. The patches are often rounded (nodules) but are sometimes irregular. In this meteorite, the nodules and other dark areas contain small crystals of troilite *(FeS)* and schreibersite *(Fe_3P)*. Both are associated with even smaller crystals of graphite (C). To study these minerals in detail, a special microscope is needed, one providing reflected light.

E. Origin and History. The mesosiderites and other stony-iron meteorites are complex mixtures of materials, and many details of their origin are poorly known and extensively debated. Many of them show evidence of two fundamental processes that have been recognized in other meteorites: cooling from a melt, and mechanical mixing of different components from different sources.

It is generally accepted that at least part of the meteorite material, the metal, originated as a molten melt and cooled and crystallized slowly, probably within an early planetesimal body. However, the textures of the silicates in the metal, especially the sharp corners and edges, suggest that the olivine was brought into the meteorite as separate fragments and that it did not crystallize in a normal fashion from the melt.

These processes are to some extent contradictory. Slow cooling requires formation deep within a parent planetesimal body. Mechanical mixing indicates the effects of repeated meteorite impact on the surface. There is as yet no definite theory that combines these two processes in a satisfactory way.

One explanation is that a silicate-rich parent object, was heavily-bombardment by many different types of objects, including metal-rich ones. The bombardment was intense enough to melt large volumes of both the silicate target and the metal from the incoming projectiles, and the resulting melt cooled slowly at depth. This period of slow cooling made it possible for the metal crystals to grow to large sizes and for the denser silicates to separate, forming a variety of rocks enriched in minerals like olivine and pyroxene.

Subsequently, multiple impact events excavated the metal- rich and silicate-rich materials and mixed them together on the surface. Continuing impacts could pulverize and mix the rocks and could also remelt the metal in them, forming fragmental rocks (breccias), some of which could be composed of a mixture of unmelted pieces of silicate minerals (e.g., olivine) in a matrix of melted and rapidly-cooled metal. It has hard to tell, from this section, how much (if any) of the metal and silicate are remnants from the original slow cooling within a parent body and how much has been formed near the surface by the continued pulverizing and melting produced by continuing meteorite bombardments.

INTRODUCTION TO METAL METEORITES

The study of meteoritic metal employs reflected-light optical microscopy as one of its most useful and petrologically informative techniques. Highly polished sections, normally acid etched to reveal internal structural features, are examined using the microscope at magnifications of 25X or more depending upon the sophistication of the examination. Sections are normally much thicker than those used for transmitted light microscopy, and they may require mounting and leveling so that the specimen surface is perpendicular to the incident light.

Polished metal surfaces are easily scratched, sensitive to moisture in the air, and particularly sensitive to finger prints. Repolishing and etching is the remedy, but this requires an experienced person and proper facilities.

DEFINITIONS

Brief descriptions of several probably unfamiliar minerals and structural terms that will be used in this text are defined here.

Kamacite (low-Ni Ni-Fe, bcc, ferrite, α-iron): An alloy of Ni, Fe, and Co with Ni in the 5-7.8 wt.% range, Co from 0.3,-0.8 wt.%, and the remainder Fe. White in color but may turn slightly brown on etching. This is the most abundant metallic mineral in meteorites.

Taenite (high-Ni Ni-Fe, fcc, austenite, γ-iron): An alloy of Ni and Fe with Ni in the 20-40 wt. % range. Taenite contains some Co, but normally considerably lower levels than in kamacite. It is similar to kamacite in color but more pinkish or slightly cream colored.

Tetrataenite: A tetragonal ordered mineral with an ideal composition of FeNi and with observed compositions ranging from 48 to 56 wt. % Ni. It is cream colored like taenite in reflected light but in contrast is anisotropic and displays characteristic polarization colors under crossed polars.

Troilite: FeS, hexagonal. Yellow-brown to bronze in color fairly strongly birefringent under crossed polars depending on the plane of section.

Schreibersite: $(Fe,Ni)_3P$ tetragonal. Rhabdite is a common morphological term applied to small prismatic of plate-shaped schreibersites. A cream-white in color, more yellow than taenite.

Daubreelite: $FeCr_2S_4$, cubic. Gray in color.

Plessite: A structural term that applies to fine inter-growths of kamacite and taenite.

Cloudy taenite: Cloudy taenite is the dark etching, high Ni region of a taenite lamellae, normally observed with a thin rim of tetrataenite separating it from kamacite. It is an optically unresolvable two phase structure that forms at low temperatures, composed of islands of tetrataenite within a matrix of lower Ni metal.

Widmanstatten Pattern: A term for the characteristic structural feature, revealed upon acid etching, of those iron meteorites known as octahedrites. It forms by slow cooling and crystallographically controlled subsolidus growth of kamacite from parent taenite. This results in plates of kamacite forming parallel to octahedron faces within taenite.

Neumann bands: Plate-shaped twin lamellae formed by the stress of comparatively mild shock on kamacite. They range from 1-10 mm wide and are exceedingly long compared to their width. Abundance varies but is very high in some kamacite.

The descriptions given below emphasize features common to the particular type of meteorite the specimen represents. Iron meteorites are heterogeneous on a centimeter scale, so that all features mentioned will not necessarily be found in a particular section.

The structure observed in meteoritic metal develops by sub solidus growth upon very slow cooling in the meteorite parent body. The two most important factors in the primary process are the composition of the cooling metal and the rate at which it cools. Typical cooling rates are in the range of 1-100 ºC per million years, and the process takes place between 800 to º300. Secondary processes such as shock, reheating, atmospheric ablation, and maltreatment by man have significant effects on these structures.

10. Mesosiderite (RKP A79015).

Sample RKP A79015 is an unusually metal-rich mesosiderite. Mesosiderites are stony iron meteorites containing subequal amounts of metal plus troilite, the major opaque phases, and of silicates. The metal of the polished thin section of this specimen has been etched for microscopic examination.

Mesosiderites have a distinctive metallographic structure due to their very slow cooling rate, probably the slowest among the major meteorite groups. This results in an association of kamacite with tetrataenite and cloudy taenite. Cloudy taenite areas, the dark etching areas, are contained in borders of tetrataenite that separate it from kamacite. Troilite and schreibersite are also present.

The section of RKP A79015 has been prepared from a slice taken through a small individual from a meteorite shower, and therefore the effects of heat alteration are seen at edges where there has been heat penetration during atmospheric ablation.

Tetrataenite is unusually well developed in this association, forming much more extensive areas than are seen in other meteorites. The wide, clear rims bordering lamellae or cloudy taenite regions display optical anisotropy as a consequence *of* its tetragonal structure. This may be demonstrated using partially crossed polars. Areas away *from* the edge of the sample should be selected for this purpose, as the heating associated with ablation may disorder tetrataenite and transform it to cubic taenite.

11. Hexahedrite Iron (ALH A81013)

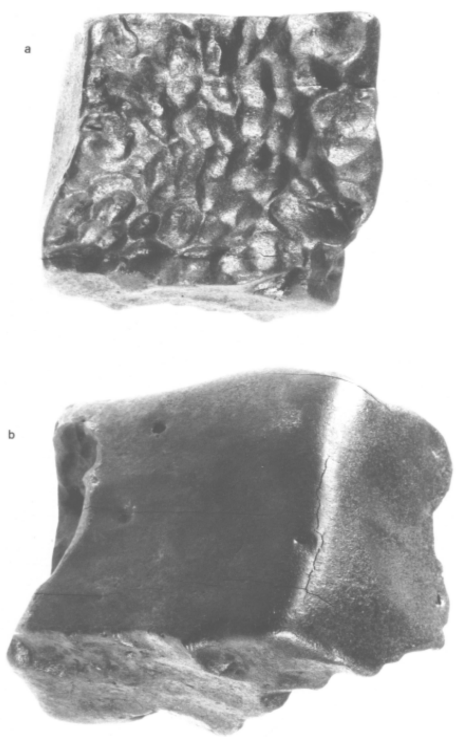

Figure 27: The left hand photo was taken when ALH A81013 was discovered in the Allan Hills region of Antarctica (NASA photo S82-27138). The right-hand photos were taken at the Smithsonian where the US Antarctic iron meteorites are housed (from Clarke, 1984).

Antarctic meteorite ALH A81013 is an example of the hexahedrite group of iron meteorites. This is the simplest class structurally, consisting of single crystal kamacite with minor and trace amounts of inclusions; It has a bulk composition typical for the hexahedrites of 5.5 wt. % Ni, 0.5 wt. % Co, and 0.2 wt. % P, the remainder consisting essentially of Fe with minor amounts of S, Cr, and C, and a number of trace elements, some of which have importance for chemical classification purposes.

The matrix kamacite is rich in Neumann bands that vary in density and clarity from place to place. It is also rich in micro-rhabdites that give a salt and pepper or matte appearance to the kamacite. Micro-rhabdites are tiny precipitates of schreibersite, below the resolution of normal optical examination. Occasional rhabdites large enough to be distinguished are seen, nonI1ally in areas comparatively free of the microrhabdite background. Occasional lamellar schreibersites may be seen.

Inclusions of bronze colored troilite in the ~ size range are sporadically distributed, the troilite showing twin lamellae under crossed polars. The troilite is normally associated with gray daubreelite, frequently as alternating lamellae, in this meteorite. These inclusions are bordered partially by schreibersite.

A layered fusion crust that developed during passage through the atmosphere is present at a few places on the exterior edges of the specimen, as is a terrestrial weathering crust of secondary iron oxides. The kamacite below the exterior surfaces generally shows metallographic transformation due to the steep thermal gradient associated with atmospheric entry.

12. Octahedrite Iron (GIBEON. Namibia. USNM #3187)

(Believe it or not, meteorites are named after the nearest post office.)

Figure 28: An etched surface of a slice through the Gibeon iron meteorite; 1 cm cube for scale.

The Gibeon meteorite is a fine octahedrite, a meteorite displaying a Widmanstätten pattern of kamacite lamellae separated by taenite lamellae and areas of plessite. Its chemical composition is 7.9 wt.% Ni, 0.4 wt.% Co, and 0.04 wt.% P. The higher Ni content than in the hexahedrite results in Gibeon being in the composition range for Widmanstätten pattern formation, and the very low P value indicates that schreibersite will be absent.

Kamacite lamellae 0.2 to 0.4 mm in width are a major feature of the structure and they may contain Neumann bands, frequently distorted due to shock. The kamacite lamellae are separated by grain boundaries which are partially occupied by thin lamellae of taenite (widths in the range of a few 0.01 mm).

Thin taenite lamellae are clear due to their high Ni content, and as they thicken they are likely to turn to dark etching taenite in the center due to somewhat lower Ni. Larger dark etching areas have lighter colored centers known as plessite regions. These plessite regions frequently have a triangular outline. Still larger plessite areas have a very thin rim of colorless taenite, followed by dark etching taenite, that enclose comparatively large areas of small kamacites and tiny taenites.

Sections may also include comparative large and complex troilite inclusions. These structures have been heated by shock and partially melted.

Additional references and resources

Books

McSween, H.Y., Jr. (1999) "Meteorites and Their Parent Planets (second edition)", Cambridge University Press, 310 pp.

Dodd, R.T. (1981) Meteorites- a petrologic-chemical synthesis. Cambridge University Press, 370 pp.

Wasson, J. T. (1985) Meteorites: Their Record of the Early Solar-System History. New York: W. H. Freeman & Co. 267 pp.

Grady, M.M. (2000) Catalogue of Meteorites, 5th Edition, Cambridge University Press. 696 pp.

Cassidy, W.A. (2003) Meteorites, Ice, and Antarctica: A Personal Account, Cambridge University Press., 364 pp.

Meteorites and the Early Solar System (1988) J.F. Kerridge and M.S. Matthews, eds., University of Arizona Press, 1269 pp.

Meteorites and the early solar system II (2006) D.S. Lauretta, H.Y. McSween, Jr., editors, with 88 collaborating authors ; University of Arizona Press, 2006, 943 pp.

Classification and other

Van Schmus, W. R. and Wood, J. A. (1967) A chemical-petrologic classification for the chondritic meteorites. Geochimica et Cosmochimica Acta 31, 747–765.

Grossman, J.N. and Brearley, A.J. (2005) The onset of metamorphism in ordinary and carbonaceous chondrites. Meteoritics and Planetary Science 40, 87-122.

Weisberg, M.K., McCoy, T.J., Krot, A.N., (2006) Systematics and evaluation of meteorite classification. In: Lauretta, D.S. Jr., McSween, H.Y. (Eds.), Meteorites and the Early Solar System II, University of Arizona Press, Tucson, 943 pp., p.19-52.

Righter, K. and O'Brien, D. (2010) Terrestrial planet formation. Proc. Nat Acad. Sci., in prep.

Righter K., Drake M. J. and Scott E. (2006) Compositional relationships between meteorites and terrestrial planets. In Meteorites and the Early Solar System II (D.S. Lauretta &. H.Y. McSween, eds.), 803-828, Univ. Arizona Press, Tucson, 943 pp.

Stöffler D., Knöll H.-D., Marvin U. B., Simonds C. H., and Warren P. H. (1980) Recommended classification and nomenclature of lunar highland rocks, In Proceedings of the conference on the lunar highland crust, edited by Papike J. J. and Merrill R. B. New York: Pergamon Press. pp. 51–70.

Stöffler D., Keil K., and Scott E. R. D. (1991) Shock metamorphism of ordinary chondrites. Geochimica et Cosmochimica Acta 55: 3845–3867.

Drake M. J. (2001) The eucrite/Vesta story. Meteoritics & Planetary Science 36:501-5 13.

Web Resources

ANSMET homepage	http://geology.cwru.edu/~ansmet/
Smithsonian Mineral Sciences	http://mineralsciences.si.edu/
NASA Johnson Space Center	http://curator.jsc.nasa.gov/antmet/index.cfm
Martian meteorites (JSC)	http://curator.jsc.nasa.gov/antmet/mmc/index.cfm
Lunar meteorites (JSC)	http://curator.jsc.nasa.gov/antmet/lmc/index.cfm