- **Meteorites:**
  - How are meteorites found?
  - Main types
  - Where do they come from?
  - Meteorites as time capsules

The main points: Meteorites

- Each year the Earth sweeps up ~80,000 tons of extraterrestrial matter, from microscopic dust particles to large rocks
- Some are identifiable pieces of the Moon, Mars; most are pieces of asteroids
- Meteorites were broken off their parent bodies 10's to 100's of million years ago (recently compared to age of Solar System)
- Oldest meteorites (chondrites) contain bits of interstellar dust, organic molecules and amino acids (building blocks of life), tiny spherules left over from the very early Solar System
- Direct insight into pre-solar system matter, solar system formation

What are meteorites?

- **Chunks of rock or iron-nickel that fall to Earth from space**
- **Pieces of asteroids, comets, Moon, Mars, interstellar dust**
  - **Can weigh from < 1 ounce to a few tons (!)**
- **"The Poor Man's Space Probe"**
  - **From parts of the Solar System astronauts may never explore**
- **Usually named after the place where they fall**
  - **Examples: Prairie Dog Creek (US), Zagora (Morocco), Campo del Cielo (Argentina), Mundrabilla (Australia)**

Meteor showers

- **Time exposure image, tracking stellar motion**
- **Stars stay still, meteorites make trails**

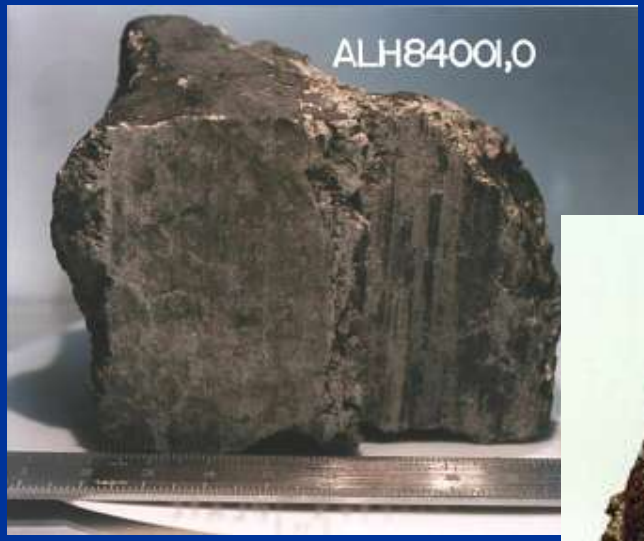
Table 12.1 Major Annual Meteor Showers

Shower Name	*Approximate Date*	*Associated Comet*
Quadrantids	January 3	?
Lyrids	April 22	Thatcher
Eta Aquarids	May 5	Halley
Delta Aquarids	July 28	?
Perseids	August 12	Swift-Tuttle
Orionids	October 22	Halley
Taurids	November 3	Encke
Leonids	November 17	Tempel-Tuttle
Geminids	December 14	Phaeton
Ursids	December 23	Tuttle

Rocks Falling from the Sky

- **meteor – a flash of light caused by a particle which enters Earth's atmosphere.**
  - **most of these particles are the size of a pea or smaller**
  - **they completely burn up in Earth's atmosphere**
- **meteorite – a rock which is large enough to have survived its fall to Earth**
- **How can you tell that you have a meteorite?**
  - **they have a higher metal content than terrestrial rocks**
  - **they contain Iridium and other isotopes not found in terrestrial rocks**

What do meteorites look like?



Mars meteorite

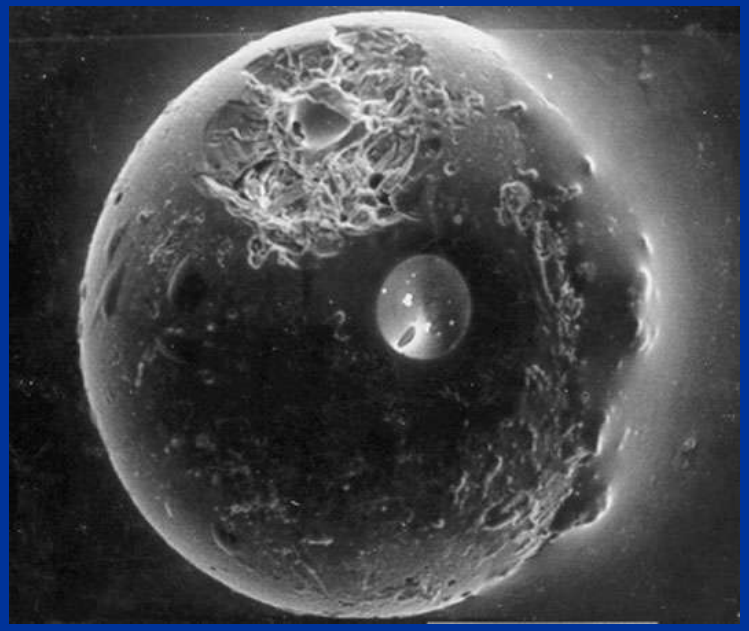
Allen Hills (Moon)

Variety of meteorite "falls"

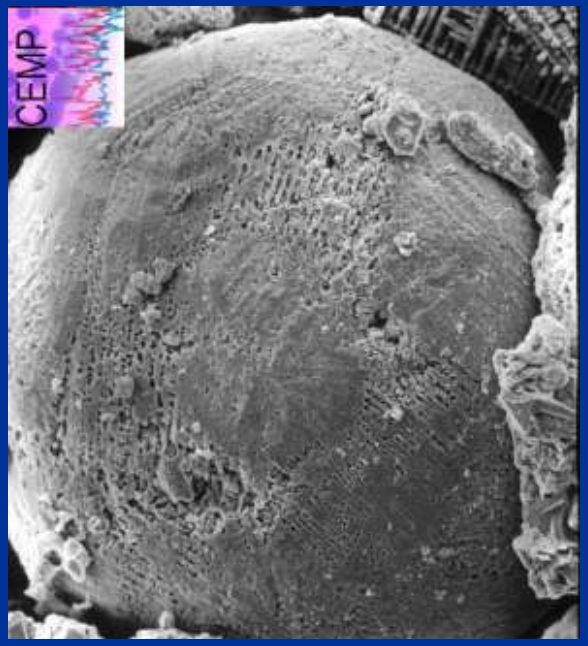
- **Tiny pieces of cosmic dust**
  - **Collected by special airplanes, in clay under the oceans, or in Antarctic ice**
- **Find single small chunks of rock**
  - **Sometimes at random, sometimes by following trajectory of a "fireball" or meteor trail**
- **A several-ton meteorite breaks up during descent, falls as separate pieces**
  - **Biggest pieces can make large craters if they hit land**

Small particles: spherules

- Tiny droplets from space
- Formed by melting and re-solidification after impacts



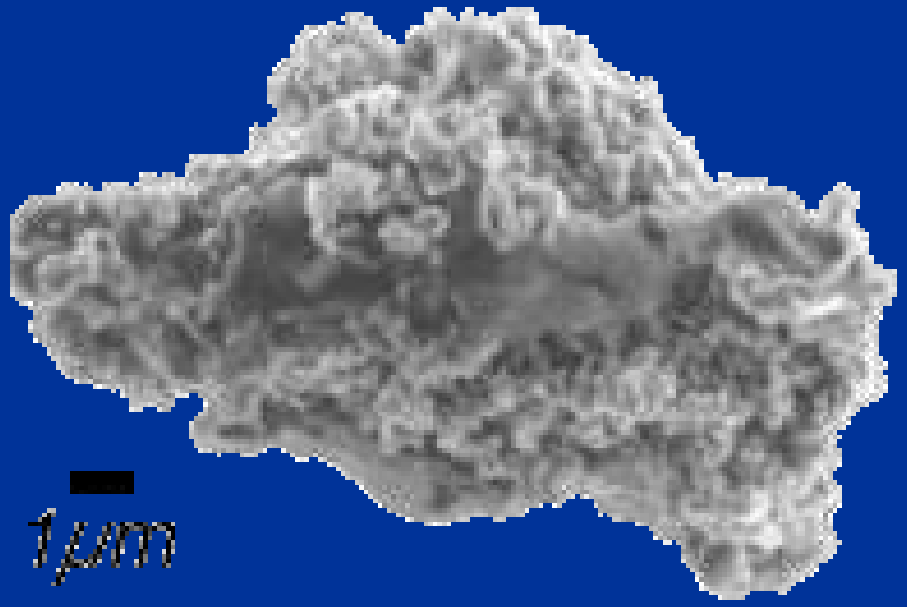
Spherule from Moon
Collected by Apollo 11 astronauts

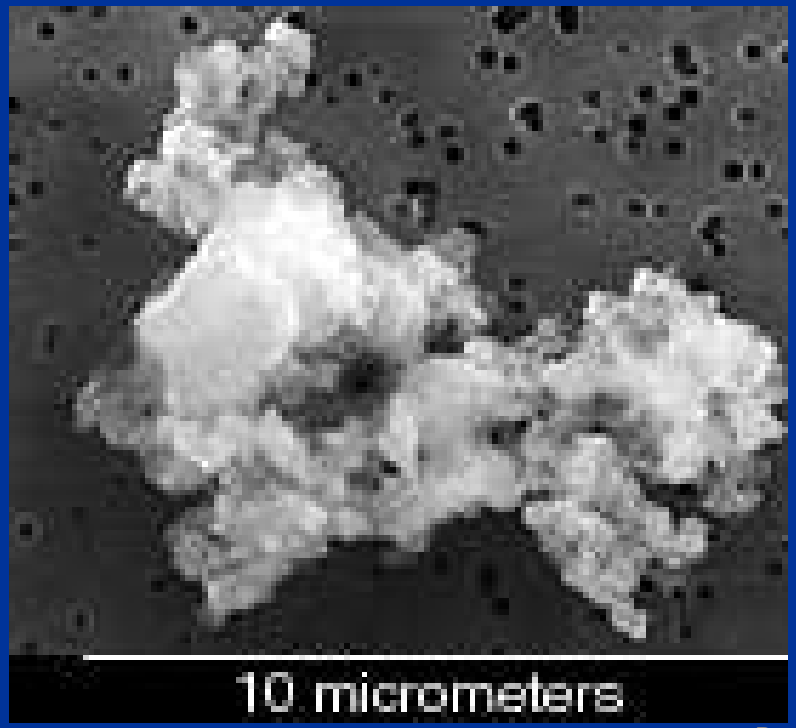


Spherule
from bottom of the Indian Ocean

Small particles: cosmic dust

- **Sometimes from comets, sometimes left over from the cosmic dust cloud from which the Solar System formed**





Single small chunks of rock

Iron-nickel meteorite
A few inches across

Allende Carbonaceous chondrite

Several-ton boulders

Hoba Meteorite, Namibia

Worldwide frequency of meteorites as function of size

Impact Frequencies		
size	frequency	destruction area
Pea	10/hr	
Walnut	1/hr	
Grapefruit	1/10 hrs	
Basketball	1/mo	
50 meters	1/century	New York City
1 kilometer asteroid	1/100,000 yrs	Virginia
2 kilometer asteroid	1/500,000 yrs	France
10 kilometer asteroid	1/100,000,000 yrs	worldwide?

Tonguska meteorite in Siberia caused widespread devastation

- **Fortunately it hit in an unpopulated area!**

How meteorites are found

- Random “finds” lying on ground
- Fragments around meteor craters
- Follow glowing trail of meteor or fireball
- Systematic searches in Antarctica
- Special high-flying airplanes (for dust)

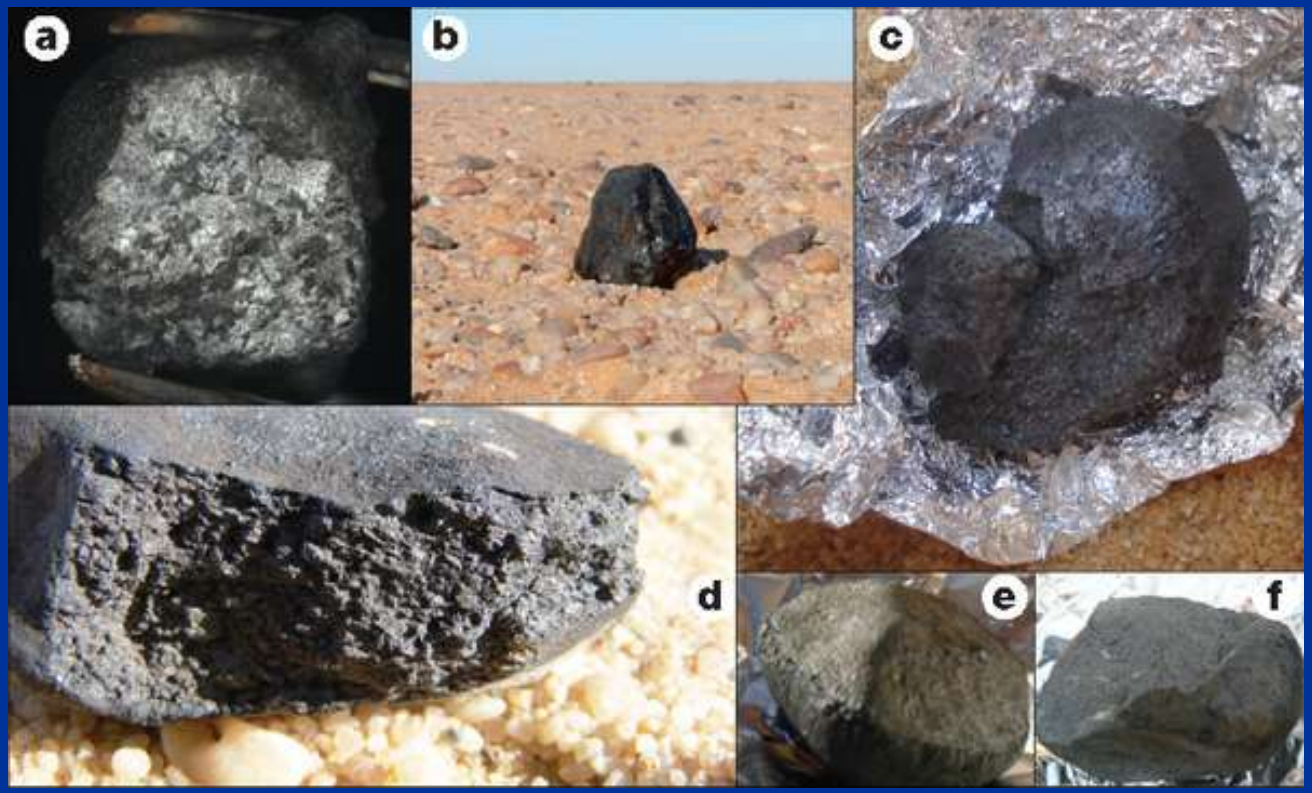
Random "finds"

- **Rare: a big meteorite in desert of Oman**
- **Pretty rare: random "finds" of smaller chunks**

Fragments around meteor craters

- **Very large meteorites vaporize when they hit ground, form big craters**
- **Sometimes small pieces are found around crater**

Macroscopic features of the Almahata Sitta meteorite.



P Jenniskens *et al. Nature* **458**, 485-488 (2009)

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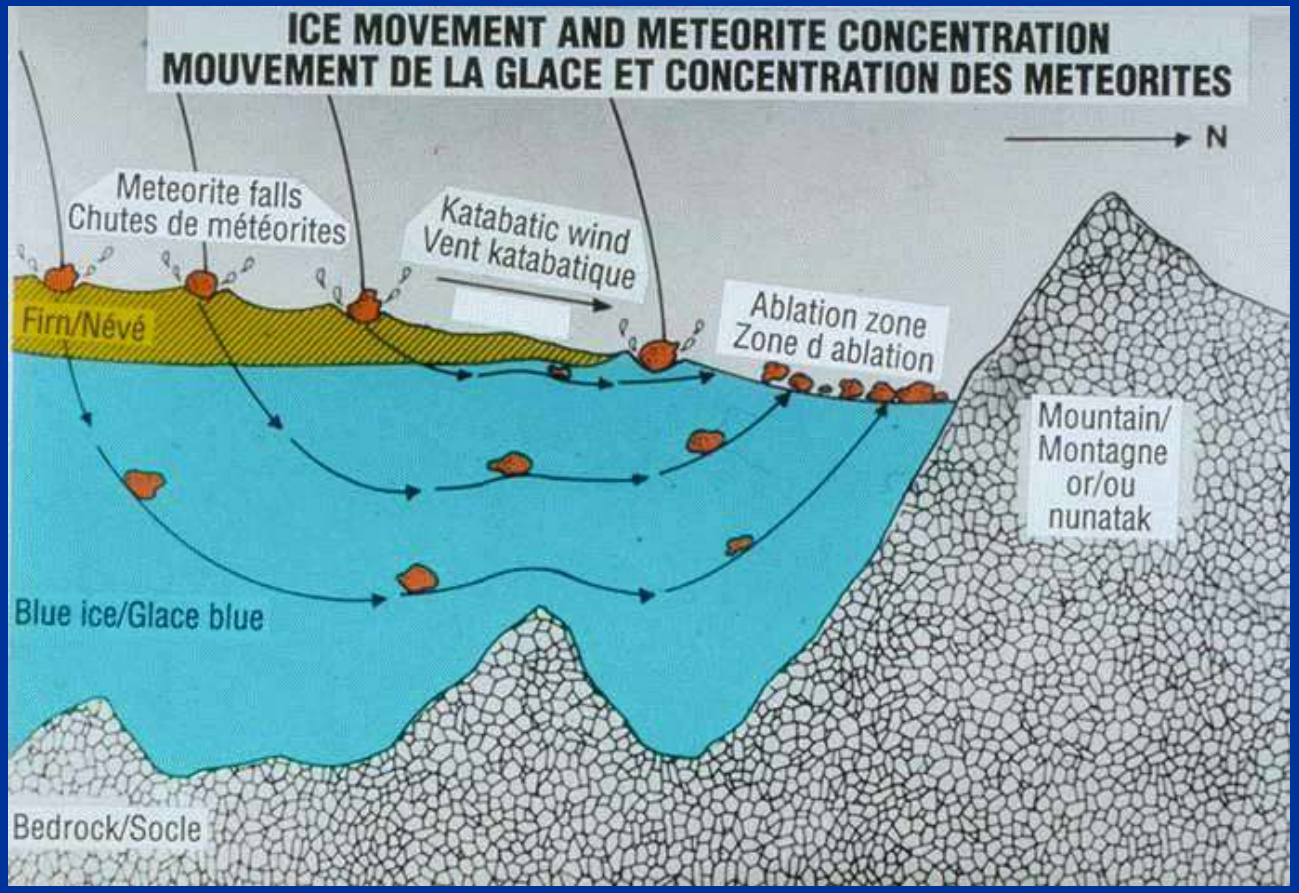
Systematic searches in Antarctica

Systematic searches in Antarctica

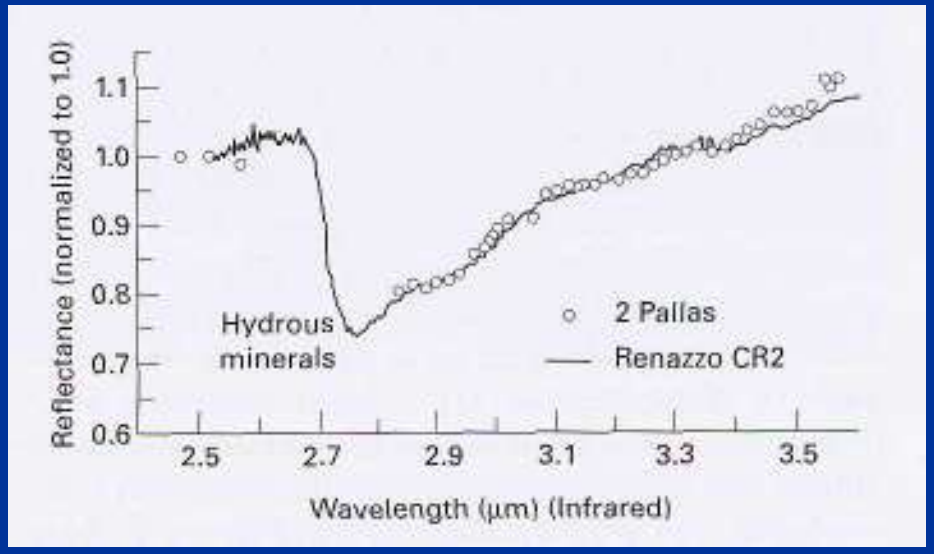


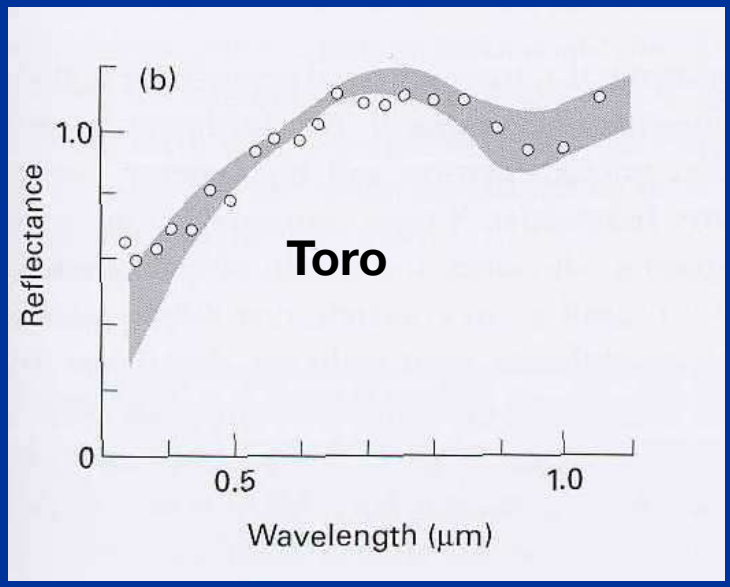
Searching for rare meteorites amidst thousands of Earth-rocks

Victory!

Where do meteorites come from, and how do we know?

- **Spectra: reflection of sunlight as function of wavelength of light**
- **Spectra of some meteorites and asteroids can be identical**
- **Implies asteroid was parent body**

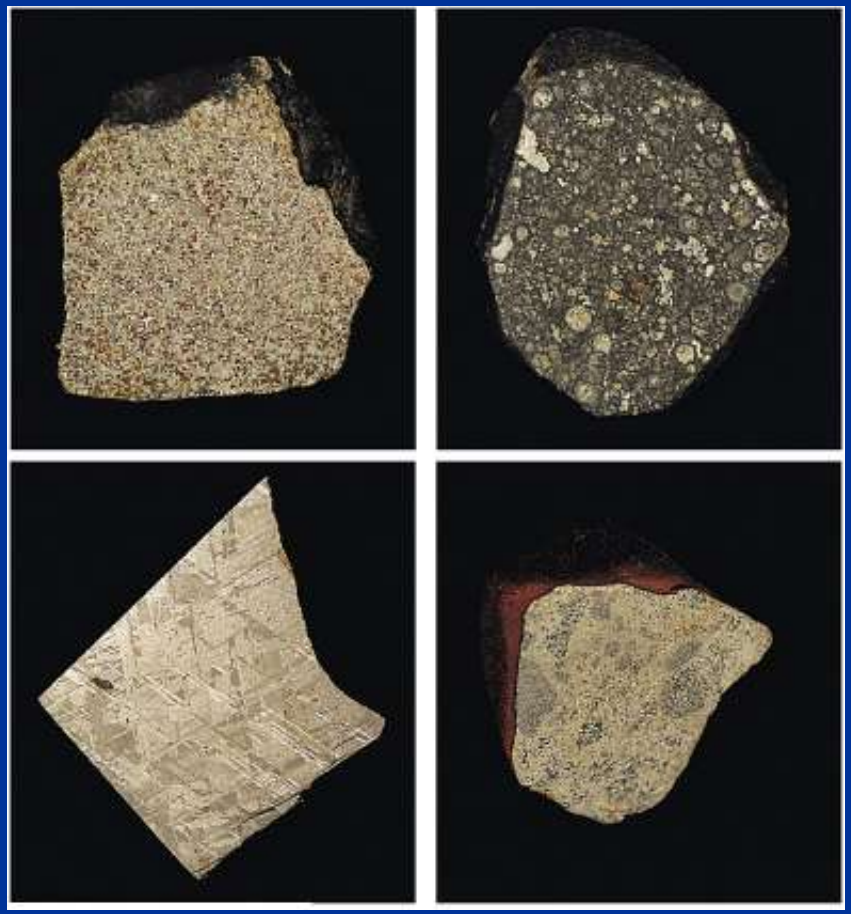




Primitive vs. processed meteorites

Based on composition, meteorites fall into two basic categories:

- primitive
  - **about 4.6 billion years old**
  - **accreted in the Solar nebula**
- processed
  - **younger than 4.6 billion years**
  - **matter has differentiated**
  - **fragments of a larger object which processed the original Solar nebula material**



Origin of Meteorites

- **Primitive meteorites condensed and accreted directly from the Solar nebula.**
  - **the stony ones formed closer than 3 AU from the Sun**
  - **the Carbon-rich ones formed beyond 3 AU from the Sun, where it was cold enough for Carbon compounds to condense**

- **Processed meteorites come from large objects in the inner Solar System.**
  - **the metallic ones are fragments of the cores of asteroids which were shattered in collisions**
  - **the rocky ones were chipped off the surfaces of asteroids, Mars, and the Moon by impacts**

Main types of meteorites

- **Chondrites**
  - **Carbonaceous**
  - **Non-carbonaceous**
- **Achondrites**
- **Iron**
- **Stony-Iron**

Chondrites

- **Rocky, inhomogeneous, contain round "chondrules"**

Microscope image

Carbonaceous Chondrites contain complex organic molecules

- **Amino acids, fatty acids, other so-called "building blocks of life"**
- **Did building blocks of life come to Earth from space?**
- **Did life itself come to Earth from space?**

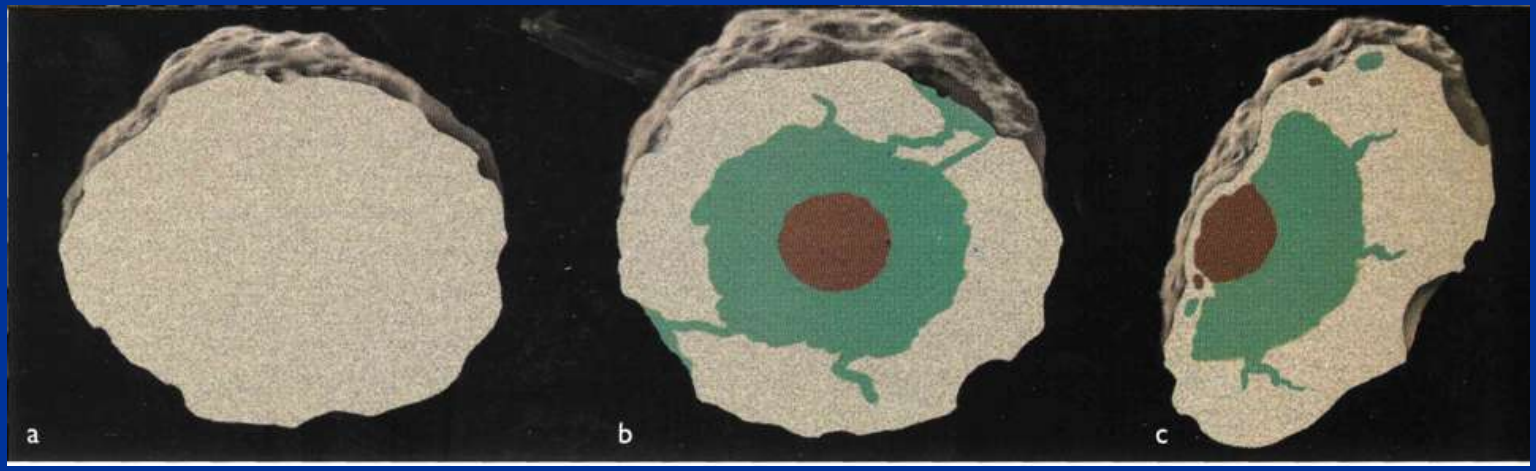
Carbonaceous Chondrites: Insights into Planet Formation?

- **The oldest meteorites; quite rare**
- **Chondrules (round): primitive chunks of early Solar System**

Iron meteorites

- **Made of iron and nickel**
- **Pits made during atmospheric entry (hot!)**

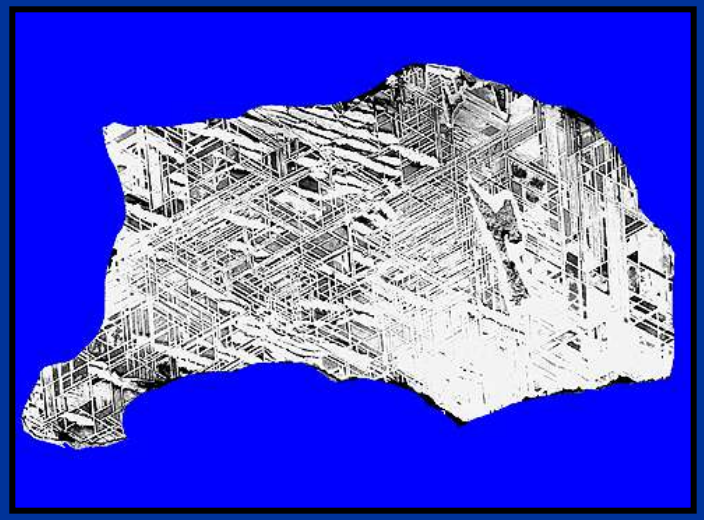
Iron meteorites: from core of differentiated asteroids



The making of future meteorites!

Crystalization pattern of the iron is unique

- **Characteristic of very slow cooling of iron within an asteroid core**
- **Due to diffusion of nickel atoms into solid iron as core cools**
- **Says original asteroid must have been large enough to be differentiated**



Stony-Iron meteorites - the prettiest

- **Crystals of olivene (a rock mineral) embedded in iron**
- **From boundary between core and mantle of large asteroids?**

Achondrites: from Mars and Moon

- **From Mars:**
  - **Tiny inclusions have same elements and isotope ratios as Martian atmosphere (measured by spacecraft on Mars)**
- **From the Moon:**
  - **Astronauts brought back rocks from several regions on the Moon**
  - **Some achondrites match these rock types exactly**