Wed. Sept. 06, 2017
Reading:

- For today: Wood Ch. 6 & 8
  (Asteroids & Meteorites, Solar Nebula)

- For this Friday:
  Rozel et al. 2017 "Continental crust formation on early Earth controlled by intrusive magmatism." Nature 545: 332-335
  (links to electronic verson on class web site)

- For next Friday Grossman 1972 "Condensation in the primitive solar nebula"
  Geochimica et Cosmochimica Acta 36: 597-619
  (links to electronic verson on class web site)

- Homework due Friday

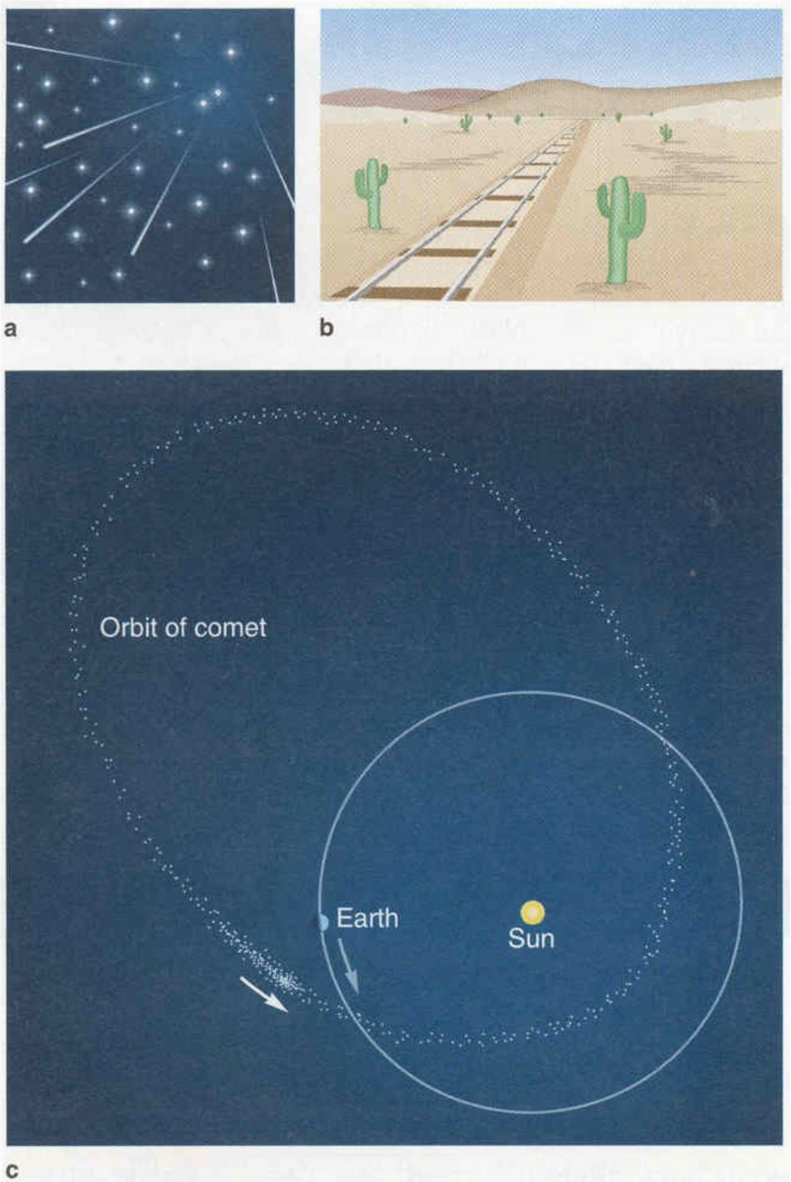
Meteors vs. Meteorites

- Meteor is seen as streak in sky
- Meteorite is a rock on the ground
- Meteoroid is a rock in space

- Meteor showers (related to comet orbits) rarely produce meteorites
  - Apparently most comet debris is small and doesn't survive reentry

- Meteorites can be "finds" or "falls"
  - For a fall – descent actually observed and sometimes orbit computed
  - "Finds" were heavily biased towards most recognizable (so unusual) meteorites – but discovery of Antarctic meteorites has produced a large "unbiased" sample
  - Most measured meteorite orbits have aphelion in asteroid belt

Meteor Showers and Comets



- Meteor showers caused by large amount of small debris spread out along comet orbits
- Almost none makes it to the ground – no meteorites
- Occur each year as earth passes through orbit of comet
- Appears to come from “radiant point” in sky

- Leonids: Mid November

From the Astro 1050 text Horizons, by Seeds

Meteorites as samples of asteroids

- Meteorites (which survived) are not associated with comets
- They seem to come from the asteroid belt

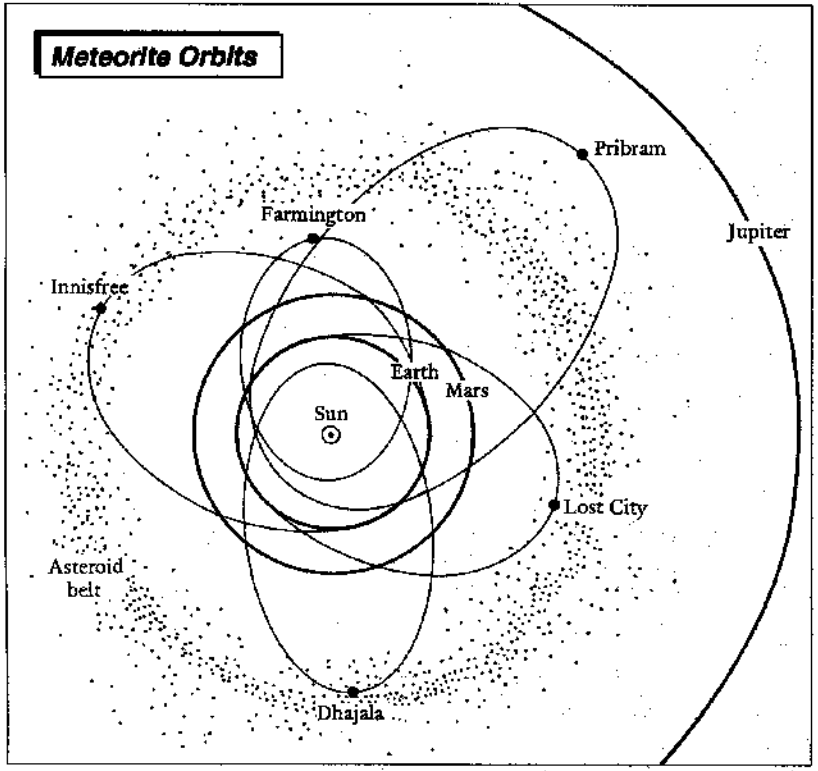


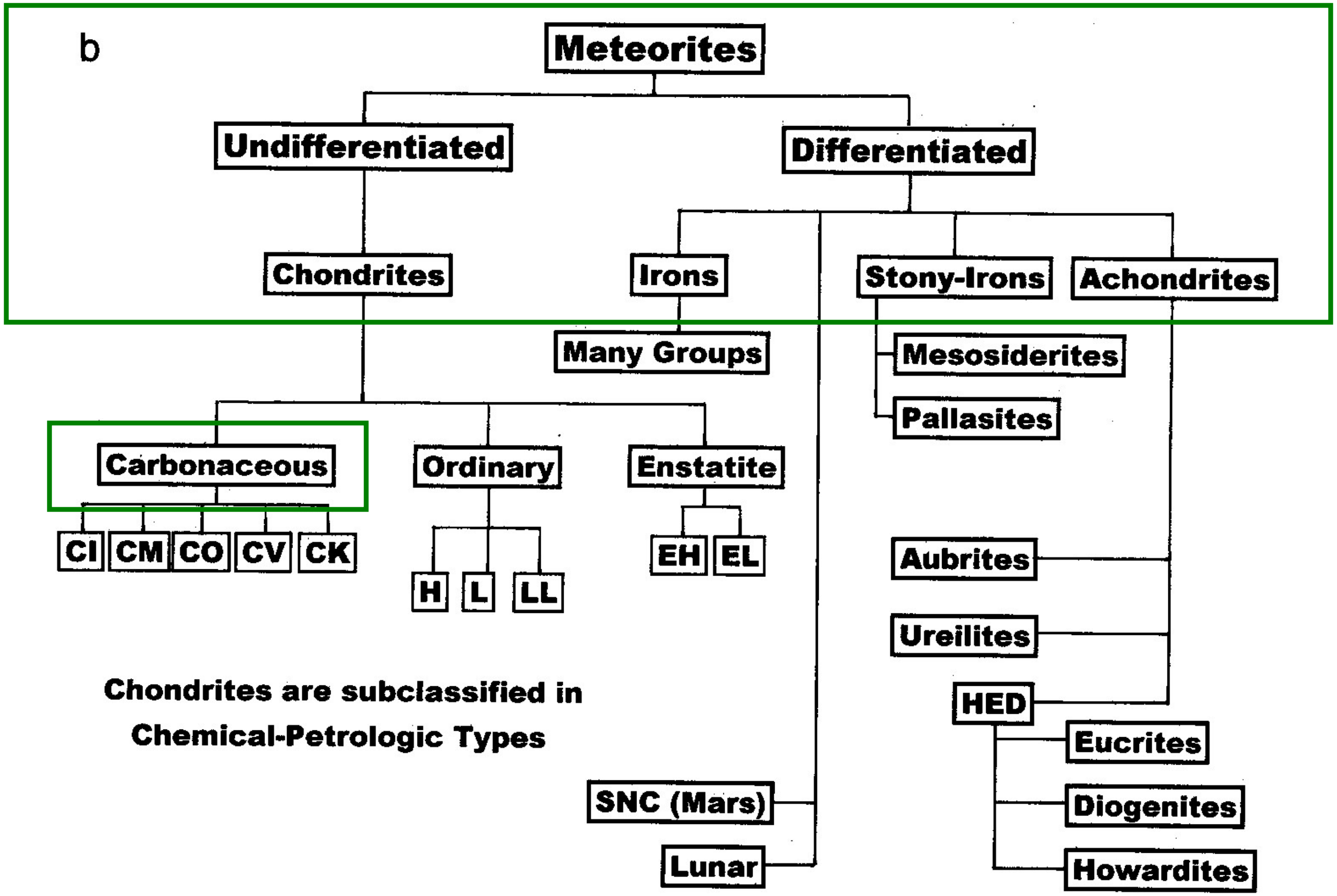
Figure 3.2: The calculated orbits of recovered meteorites provide information on the sources of these objects. Five recovered ordinary chondrites had highly elliptical orbits. All of these had aphelia, the approximate locations of which are illustrated by small dots in this figure, within or near the asteroid belt between Mars and Jupiter. This suggests that chondrites may be fragments of asteroids. The orbits are drawn to scale, but their orientations are chosen for clarity of illustration.

Common Classification of Meteorites

- Simplest classification is
  - Stones   Stony-Irons   Irons
  - But there are two very different types of stones
    - Stones that look like "ordinary" igneous rocks
    - Stones that are strange assemblages of very primitive components
- Better classification based on how "altered" they are – then with subdivisions based on details of composition

Types of Meteorites

- Many fine divisions, we'll only care about the main ones



Future Topics

- Further overview of Asteroids, Meteorites
- More details on Equilibrium Condensation Model

- Complications in the above simple picture
  - Details of meteorite composition/processing
  - Unusual exoplanets
  - Subtle composition effects in major planets
  - Theoretical models

New Material
Posted in Lecture 3 PDF on website.
(Will continue with this on Friday and Monday)

Equilibrium Condensation Model

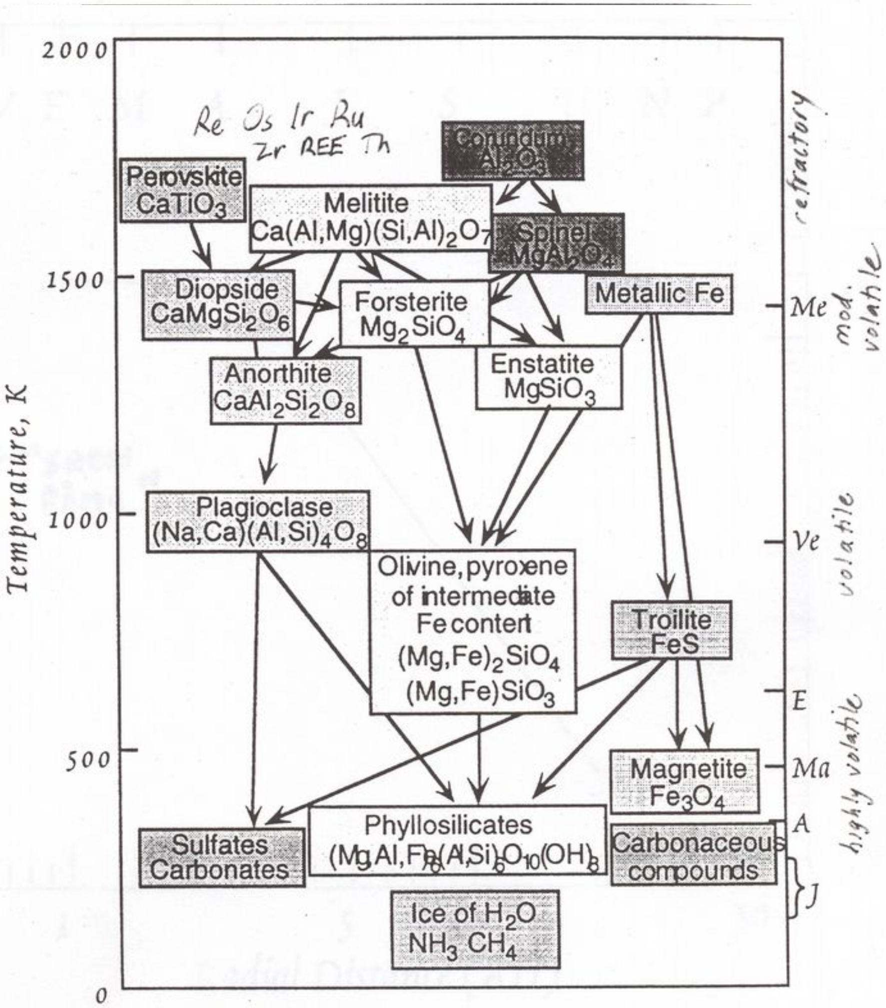


Figure 10.33. Simplified mineralogical condensation sequence.

- Will cover details in papers next week
- Basic idea:
  - Start with solar composition material
  - Calculate equilibrium abundance of compounds as gas cools
  - Calculate which are solid
  - Solid material preserved, gaseous material lost

Asteroid Composition

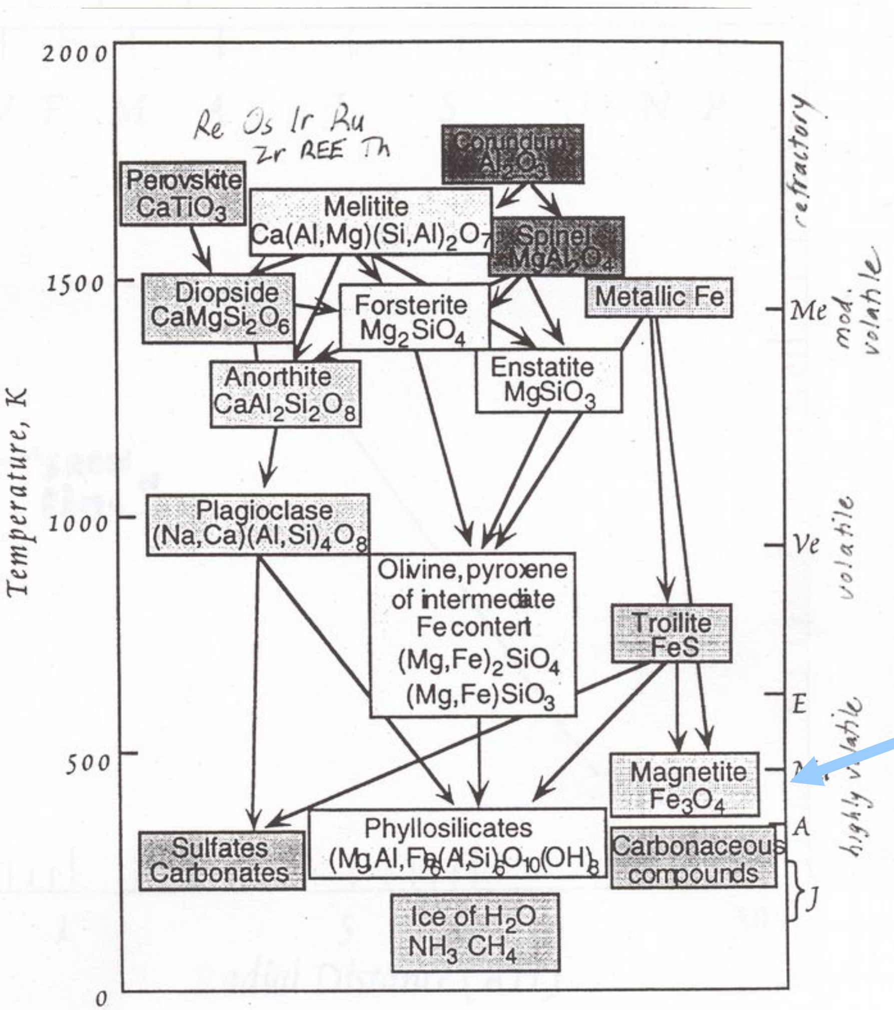


Figure 10.33. Simplified mineralogical condensation sequence.

- If unaltered expect:
  - Hydrated silicates
  - Carbonaceous compounds
  - Sulfates
  - Carbonates

Asteroids

Types of asteroids observed

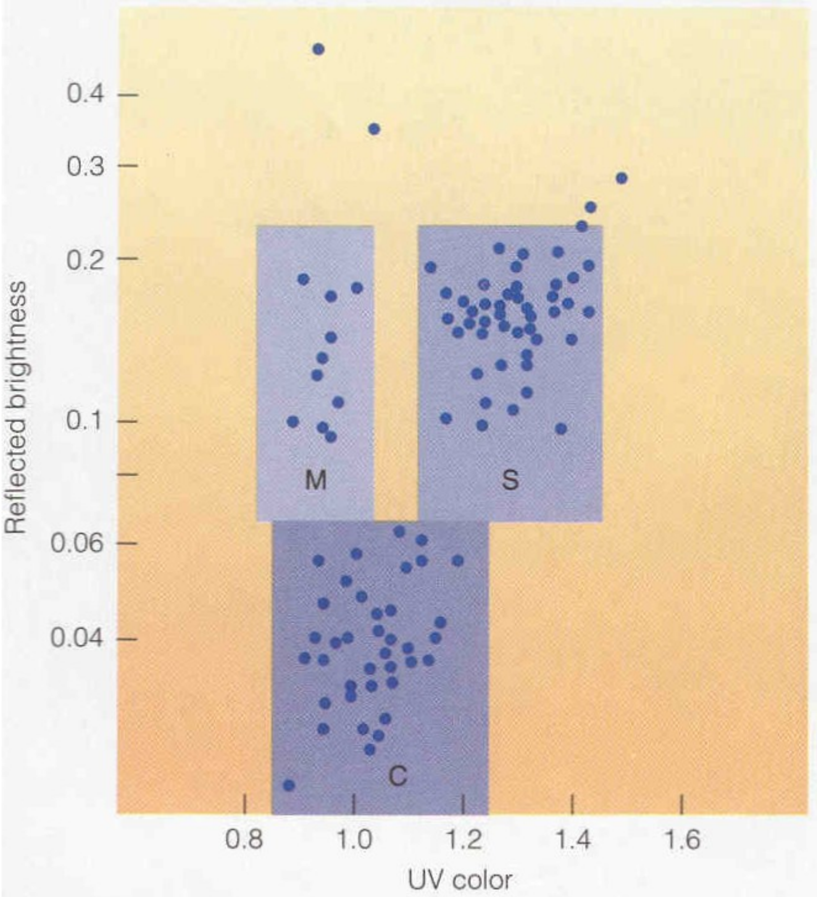


Figure 19-6
The three principal types of asteroids. In a diagram of albedo versus color (ultraviolet minus visual), the most reflective asteroids lie near the top, and the reddest at the right. The S types, which are believed to resemble chondrites, are clearly redder than the M types, which seem to be metallic. The darkest asteroids, the C types, are believed to be similar to carbonaceous chondrites. *(Diagram adapted from a figure by B. Zellner)*

- Simple classification by albedo and color
- Three main types
  - C (carbonaceous chondrites)
  - S (~~stones~~ ordinary chondrites)
  - M (metals?)
- Finer classification by spectra

From Horizons, by Seeds

Location of different types of asteroids

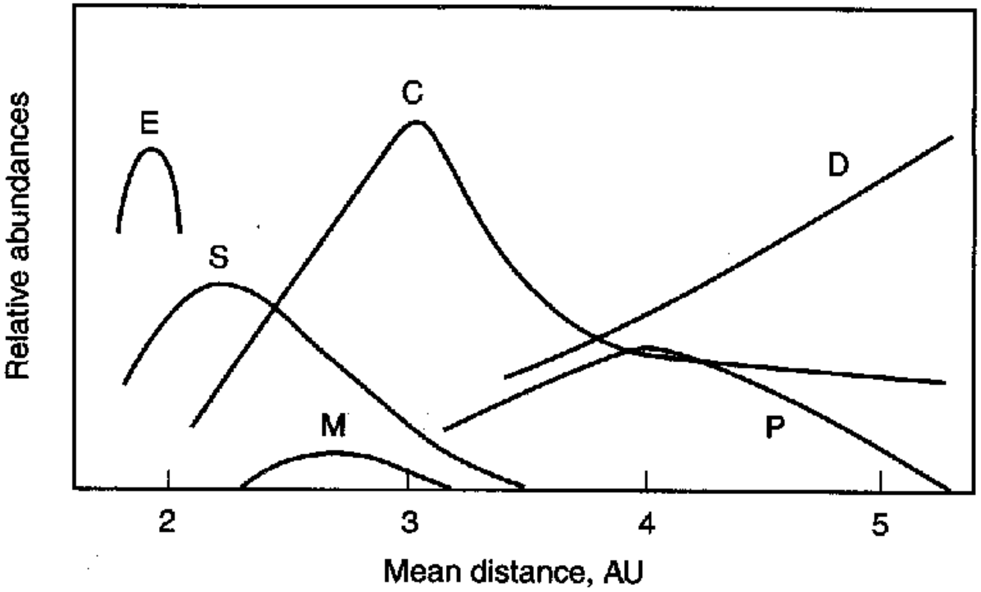
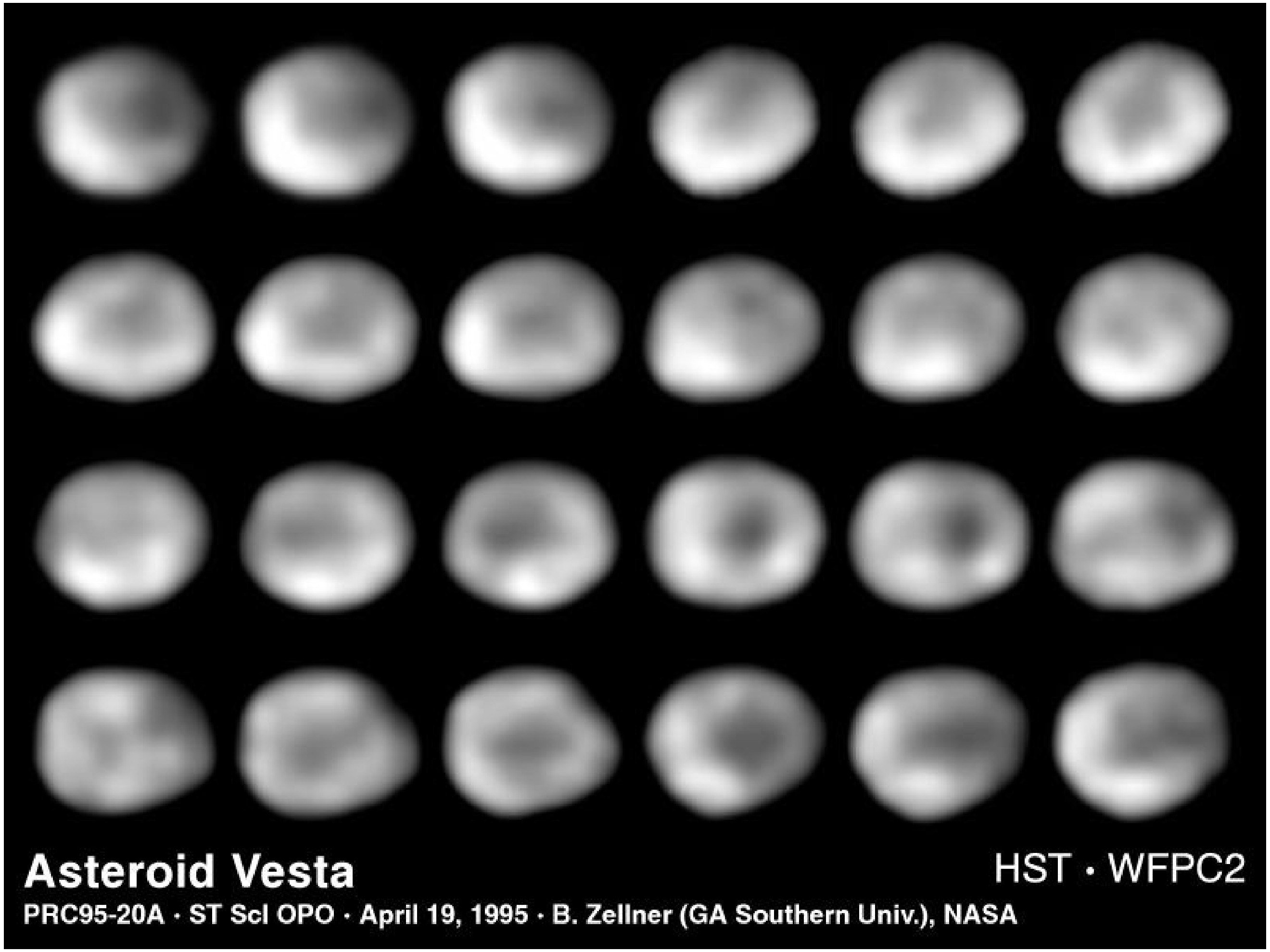


Figure 6.7 The uneven distribution of various spectral classes of asteroids in the asteroid belt. E asteroids may be the source of enstatite chondrites (Table 6.1); S asteroids, ordinary chondrites and/or stony-iron meteorites; M asteroids, iron meteorites; and C asteroids, carbonaceous chondrites. D and P asteroids are dark, carbon-rich objects that may not be represented in meteorite collections. (Abstracted with permission from J. Gradie and E. Tedesco, "Compositional Structure of the Asteroid Belt," *Science* 216, 1982, 1405–1407. Copyright 1982 American Association for the Advancement of Science)

Are Asteroids Primitive?

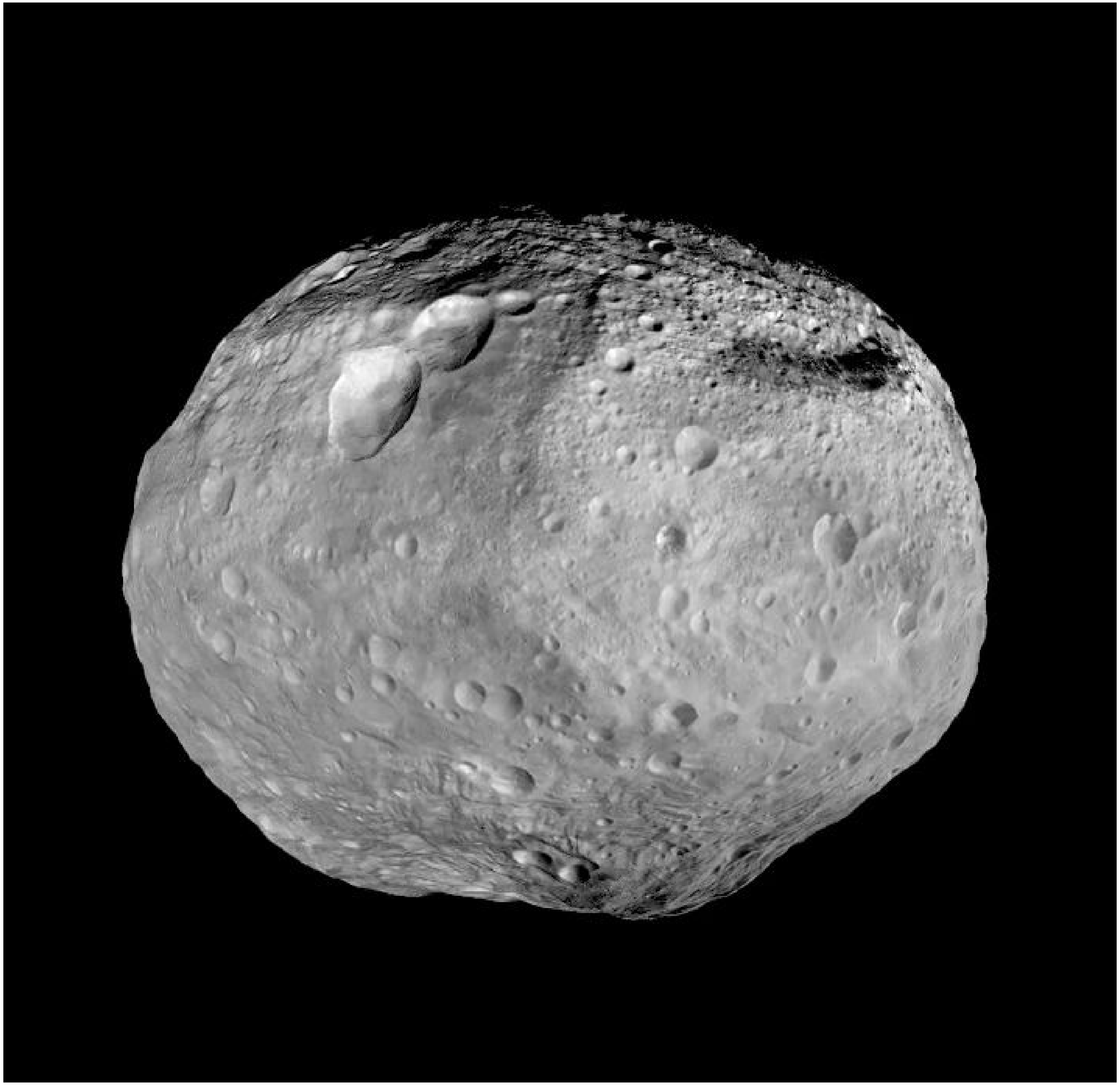
- Ida (56 km diam.) and its moon Dactyl (1.5 km diam.)
  - Colors have been “stretched” to show subtle differences
- Imaged by Galileo on its way out to Jupiter
- Presence of craters indicates great age
  - Absolute age requires knowledge of cratering rate – uncertain
  - Not spherical – gravity too weak to pull it into a sphere

Are all asteroids “primitive”?



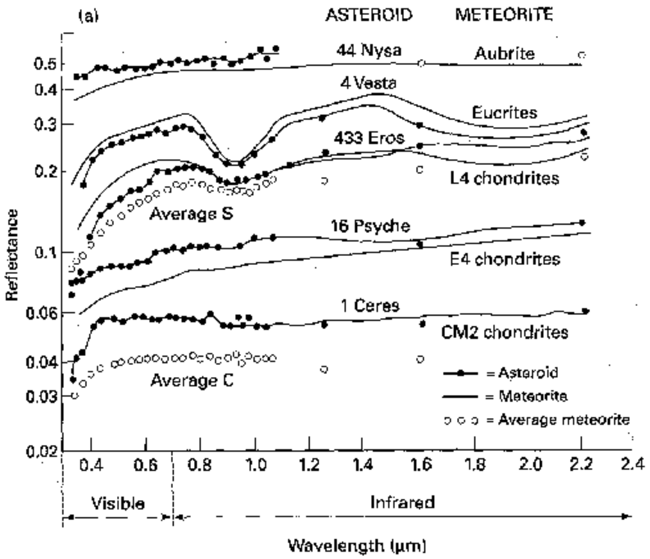
- Vesta spectrum seems to indicate “basalt” like surface
- Seems identical to certain meteorites recovered on earth

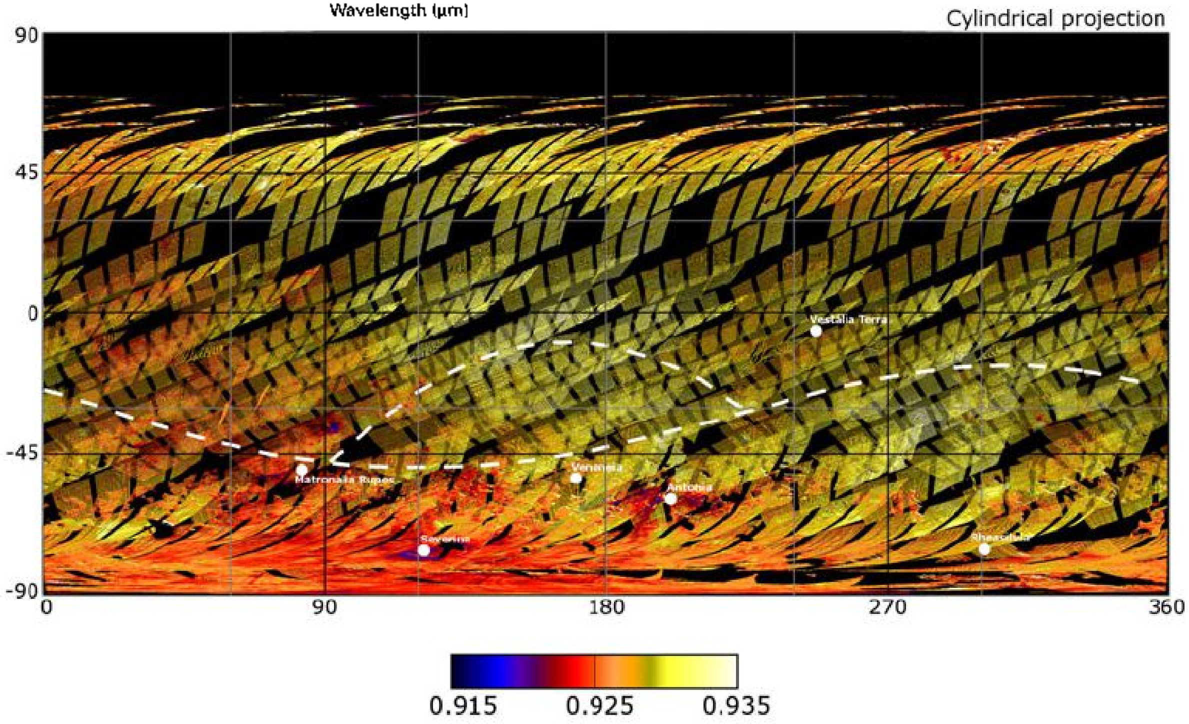
Dawn Mission: Vesta then Ceres



- Dawn spacecraft orbited has ion propulsion system
- OrbitedVesta Aug. 2011 till May 2012
- Arrives to orbit Ceres Feb. 2015

Dawn results just appearing:





- Example: Mapping pyroxene 0.9-μm band to study composition

From Ammannito et al. 2013

Asteroid spectra

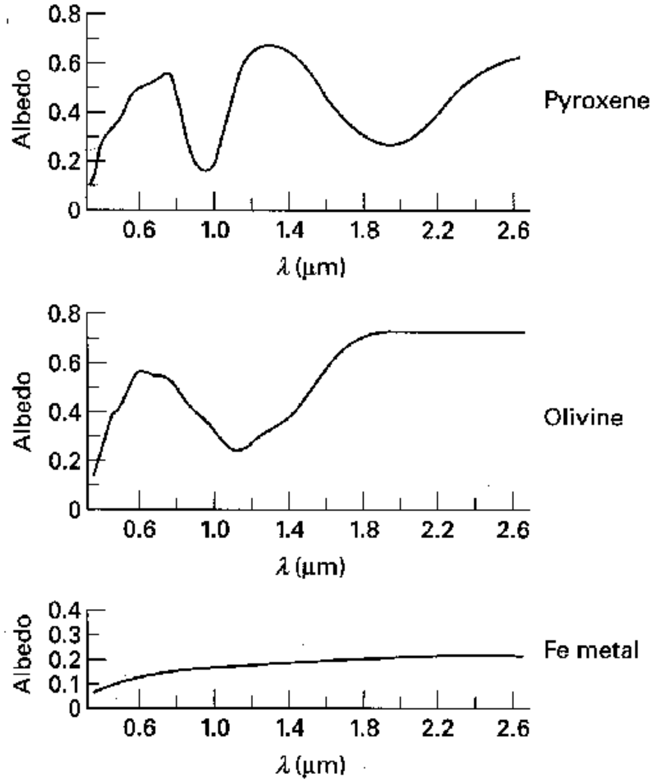
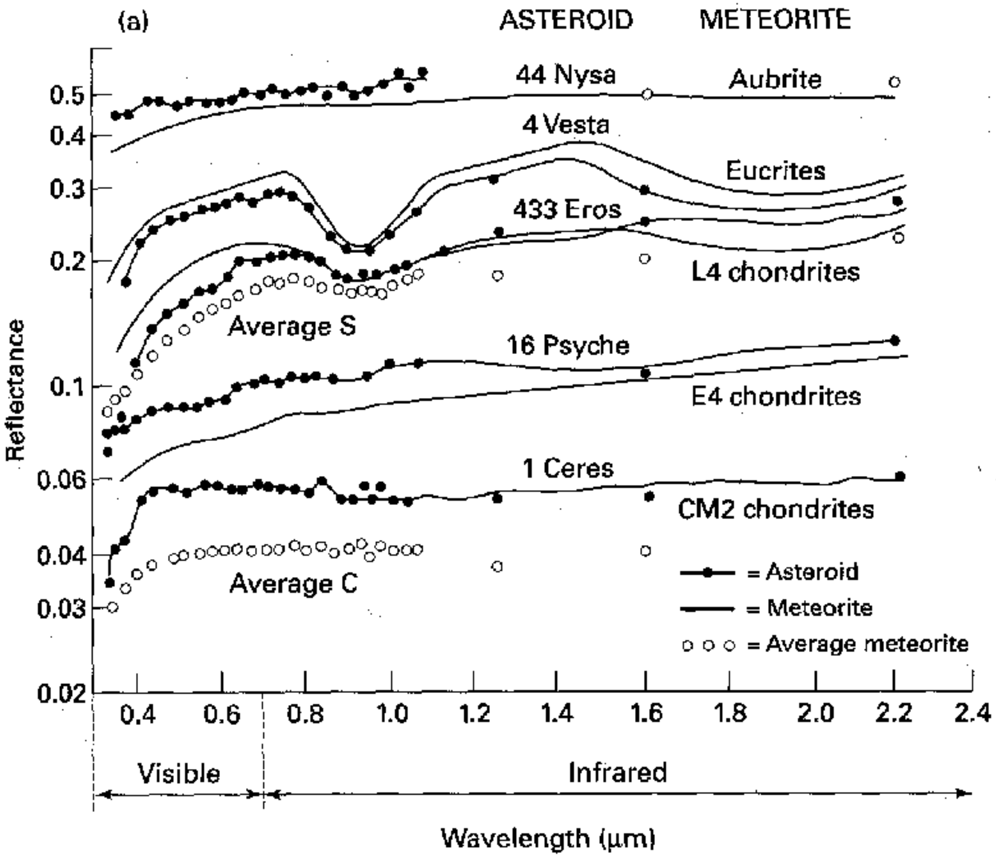


Fig. 11.7. Reflectance spectra of the three most common silicate minerals found in ordinary chondritic meteorites: olivine, pyroxene, and metallic iron. Note that pyroxene has a double valley in its absorption spectrum while olivine has only a single absorption feature. Both spectra are in the near infrared. Iron is characterized by a relatively flat curve with no absorption features.



Types of Meteorites

Whole-rock samples of common meteorite types (approximate longest dimension, in cm). Top left: Whitman, H5 (6 cm); top right: Allende; C3V (8 cm)—note 1 cm chondrule in center; center left: Springwater pallasite (18 cm); center right: Sioux Co. eucrite (8 cm); bottom left: Sanderson IIIB medium octahedrite (13 cm)—note large FeS inclusions. (All Arizona State University) Bottom right: nearly complete fusion crust, the Noblesville H chondrite, which fell on August 31, 1991. (NASA Johnson Space Center)

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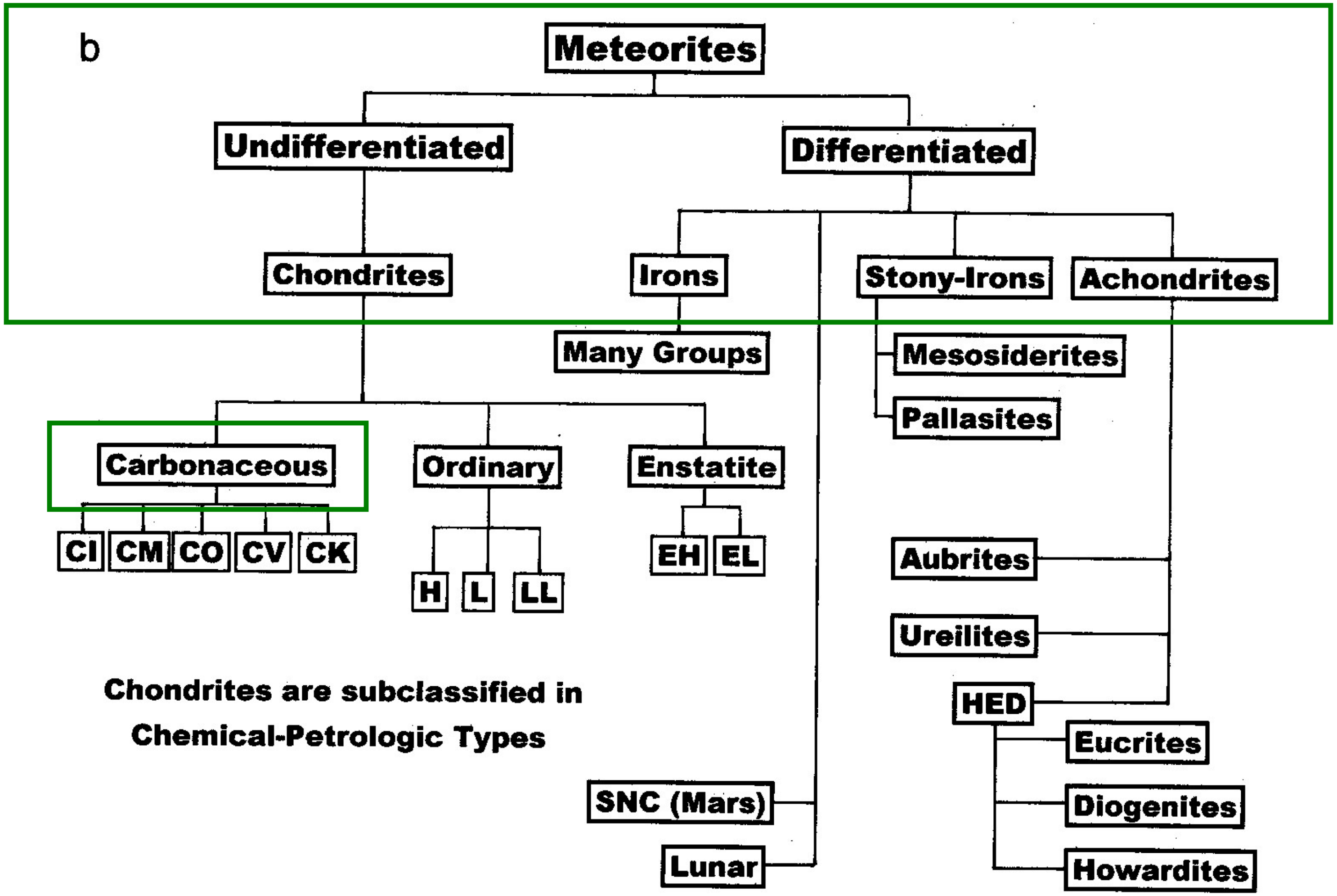
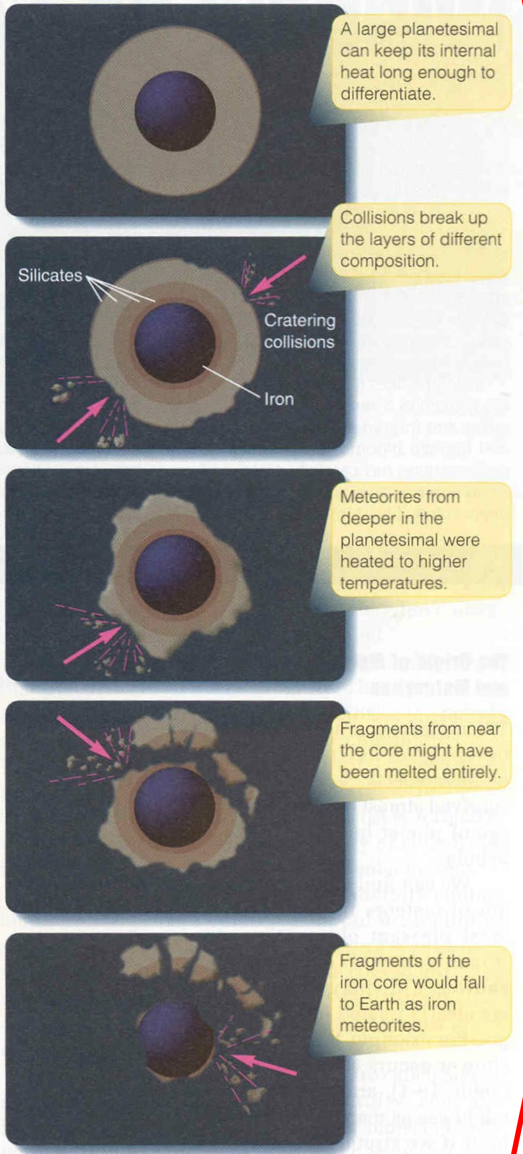


Chondrites are subclassified in Chemical-Petrologic Types

Differentiated Asteroids/Meteorites

The Origin of Meteorites



A large planetesimal can keep its internal heat long enough to differentiate.

Collisions break up the layers of different composition.

Meteorites from deeper in the planetesimal were heated to higher temperatures.

Fragments from near the core might have been melted entirely.

Fragments of the iron core would fall to Earth as iron meteorites.

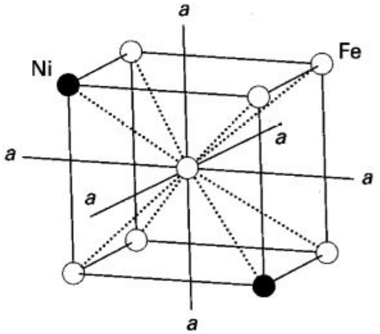
Figure 19-4
Planetesimals formed when the solar system was forming may have melted and separated into layers of different density and composition. The fragmentation of such a body could produce many types of meteorites. *(Adapted from a diagram by C. R. Chapman)*

- Stones and Metals from differentiated planetesimals?
  - S = mantles
  - M = cores

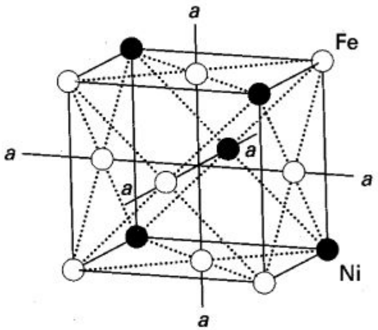
  - Stony-Irons from interface

From the Astro 1050 text Horizons, by Seeds

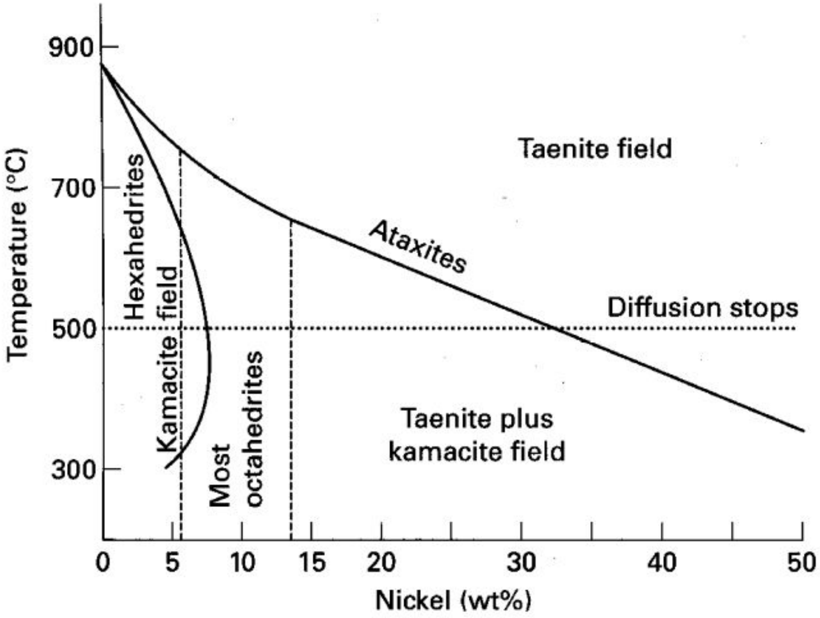
Widmanstätten structure

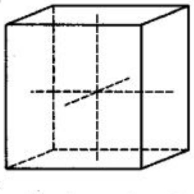


Body-centered crystal lattice, kamacite



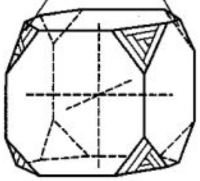
Face-centered crystal lattice, taenite

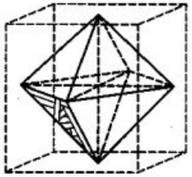




Taenite hexahedron

Growth of kamacite plates



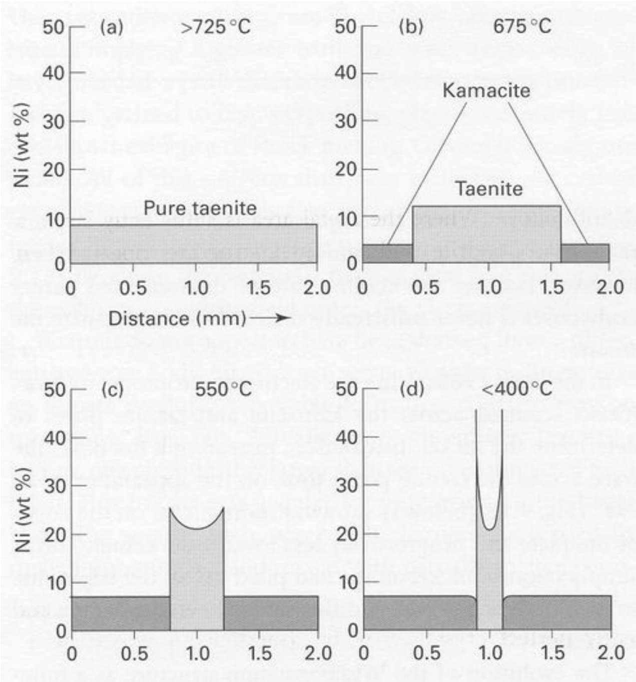


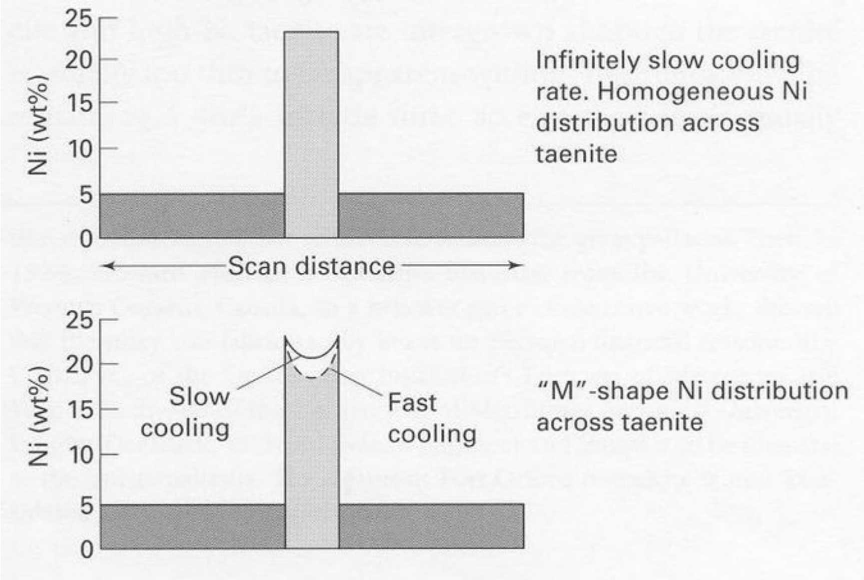
Octahedron

- Two iron-nickel minerals
  - kamacite
  - taenite
- Stability changes with T and %Ni
- Low T Kamacite grows at corners of Taenite crystals as meteorite cools and leaves Taenite stability field

From Norton: Encyclopedia. of Meteorites

Cooling rates



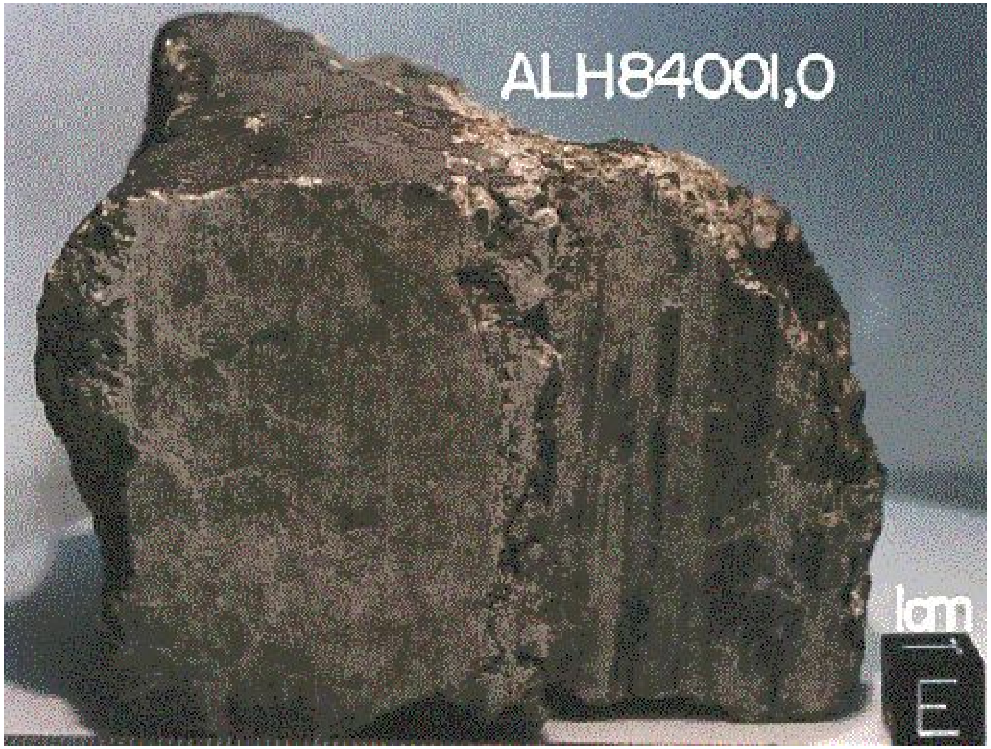


From Norton: Encyclopedia. of Meteorites

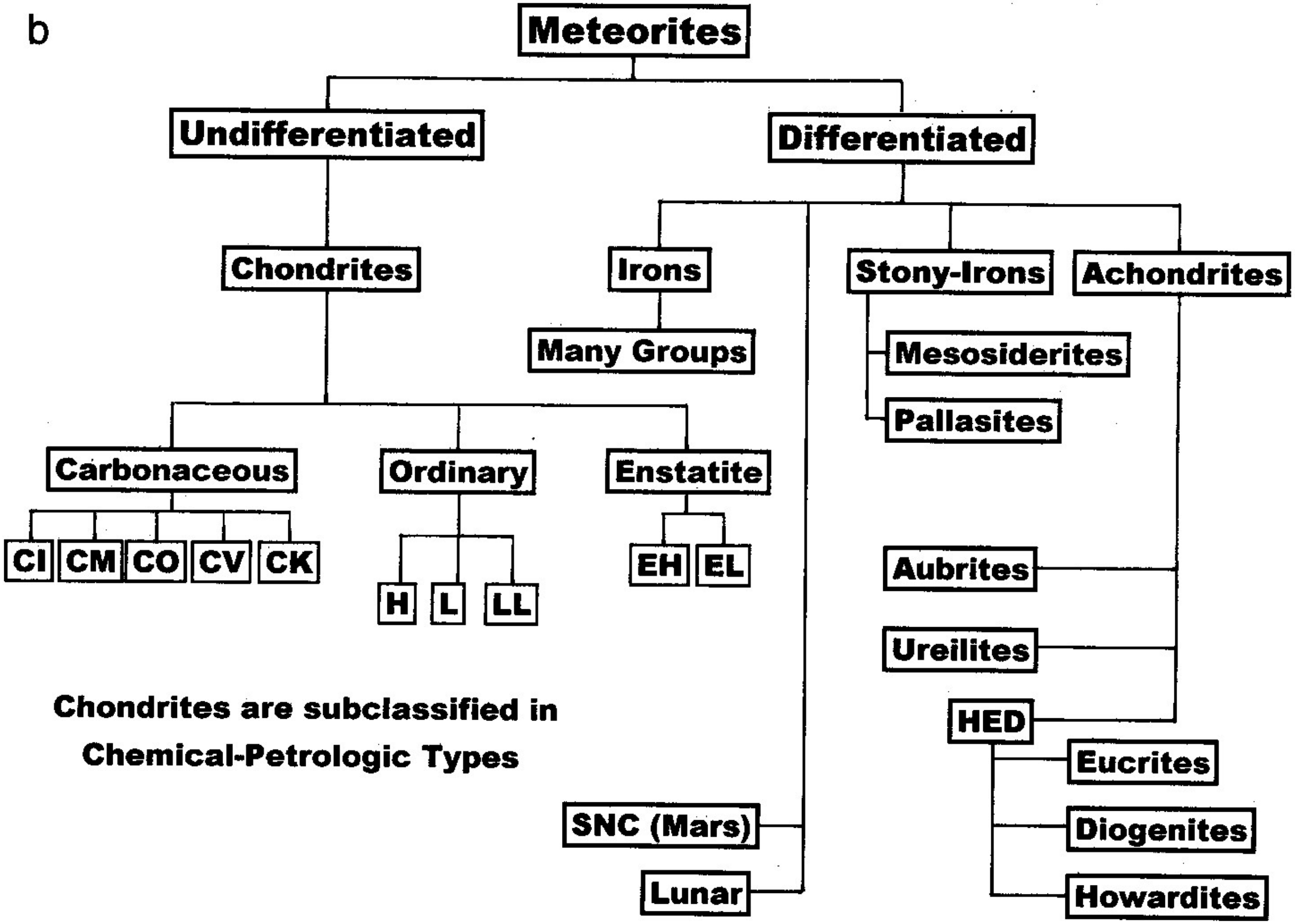
- Nickel diffuses into remaining taenite as it is forced out of newly forming kamacite
- Diffusion rate is slower in taenite so nickel piles up at the boundary
- The slower the cooling the more nickel can diffuse, and the more uniform the taenite will become
- Typical cooling rates are roughly 1 – 10° C / 10^6 years
- Implies planetesimal diameters of 200 – 400 km
  (or slightly shallower burial in a larger body)

Meteorites from other planets

- Possible Lunar and Martian Meteorites
  - Age of activity is a clue to origin
  - Chemical composition and Isotopes help further in identification
  - We’ll return to this Martian Meteorite when we discuss life



The undifferentiated meteorites



Chondrites are subclassified in Chemical-Petrologic Types

Asteroids / Meteorites are the “fossil” record left from the nebula

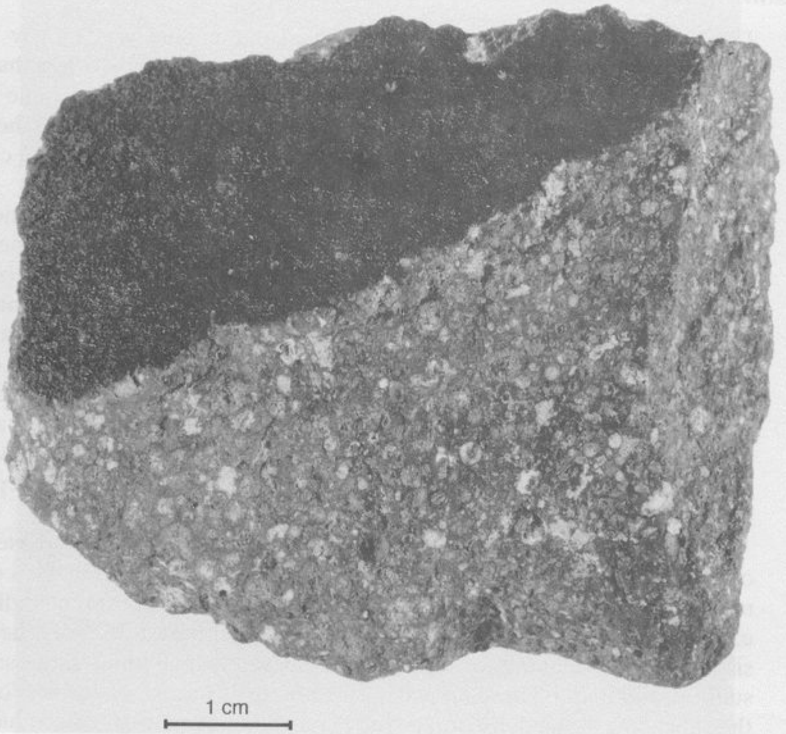


Figure 1.8 A fragment of a chondritic meteorite that fell in Allende, Mexico, in 1969. The black coating at the top of the specimen is fusion crust, melted by atmospheric friction as the meteorite streaked through Earth's atmosphere. The near face of the specimen is a broken surface, exposing the unaltered chondritic material inside the fusion crust. The chondrite is an aggregate of small bodies (chondrules, refractory inclusions) that formed in earliest times, in the primitive solar nebula. (Smithsonian Astrophysical Observatory photograph)

- Allende meteorite
- Fall on Feb. 8, 1969 near Pueblito de Allende in Mexico
- Carbonaceous chondrite (most primitive)
- Age ~ 4.5 × 10^9 years

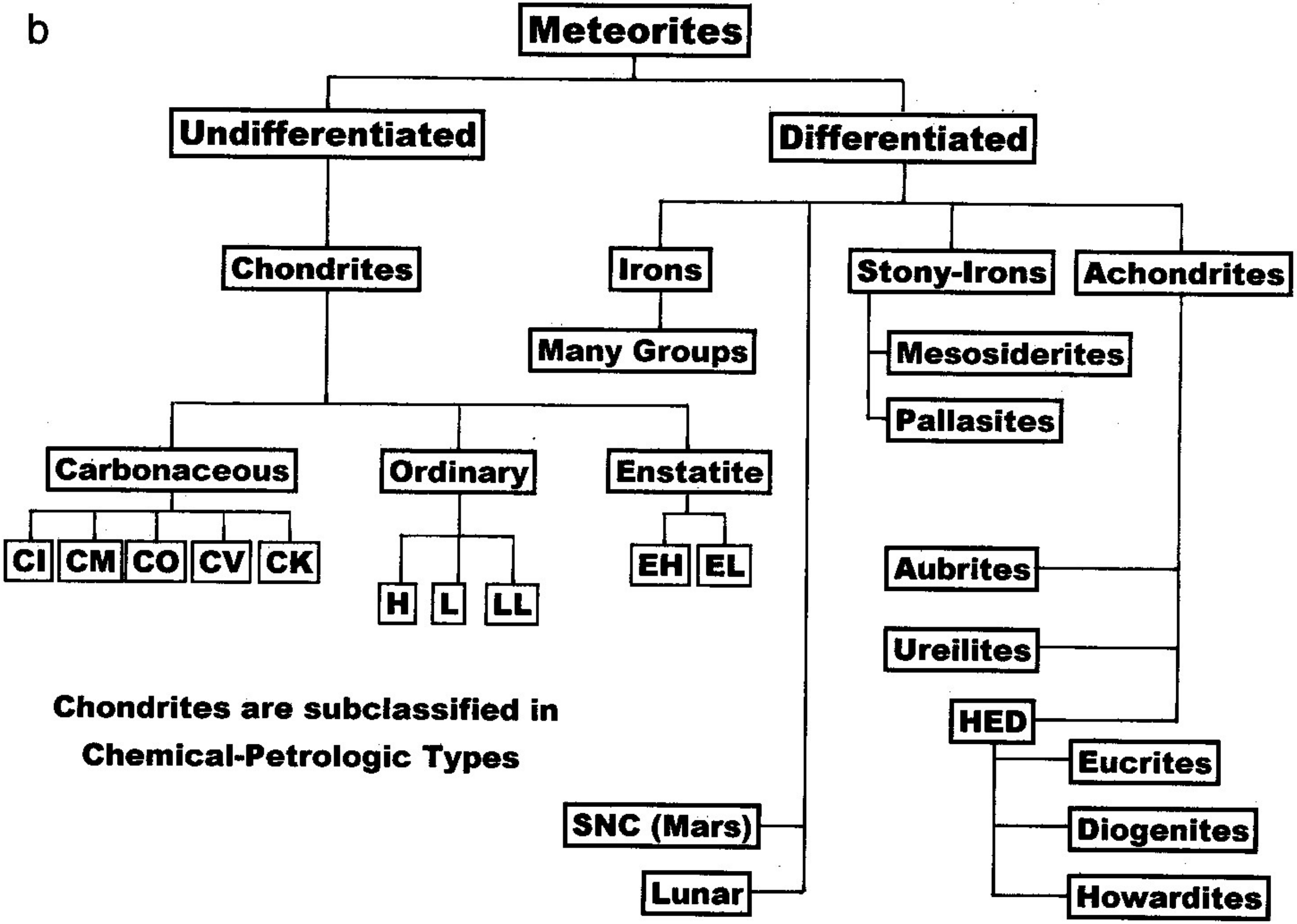
Wood Fig. 1.8

Results from Analysis of Meteorites

- Ages
  - Almost all have ages of ~4.5 billion years
- Composition
  - Most primitive ones are a <u>mixture</u> of materials predicted by condensation model
  - Isotopic signatures show some material solidified within a few million years of element creation in supernova
  - Could be evidence of supernova trigger to star formation
  - Might also be signature of "stardust" grains
- Processing
  - Widmanstaaten cooling rates imply few 100 km diameter bodies
  - Chondrules are a mystery
    - Some sort of short high temperature events taking place
      - Lighting?
      - Shocks?
      - Impacts

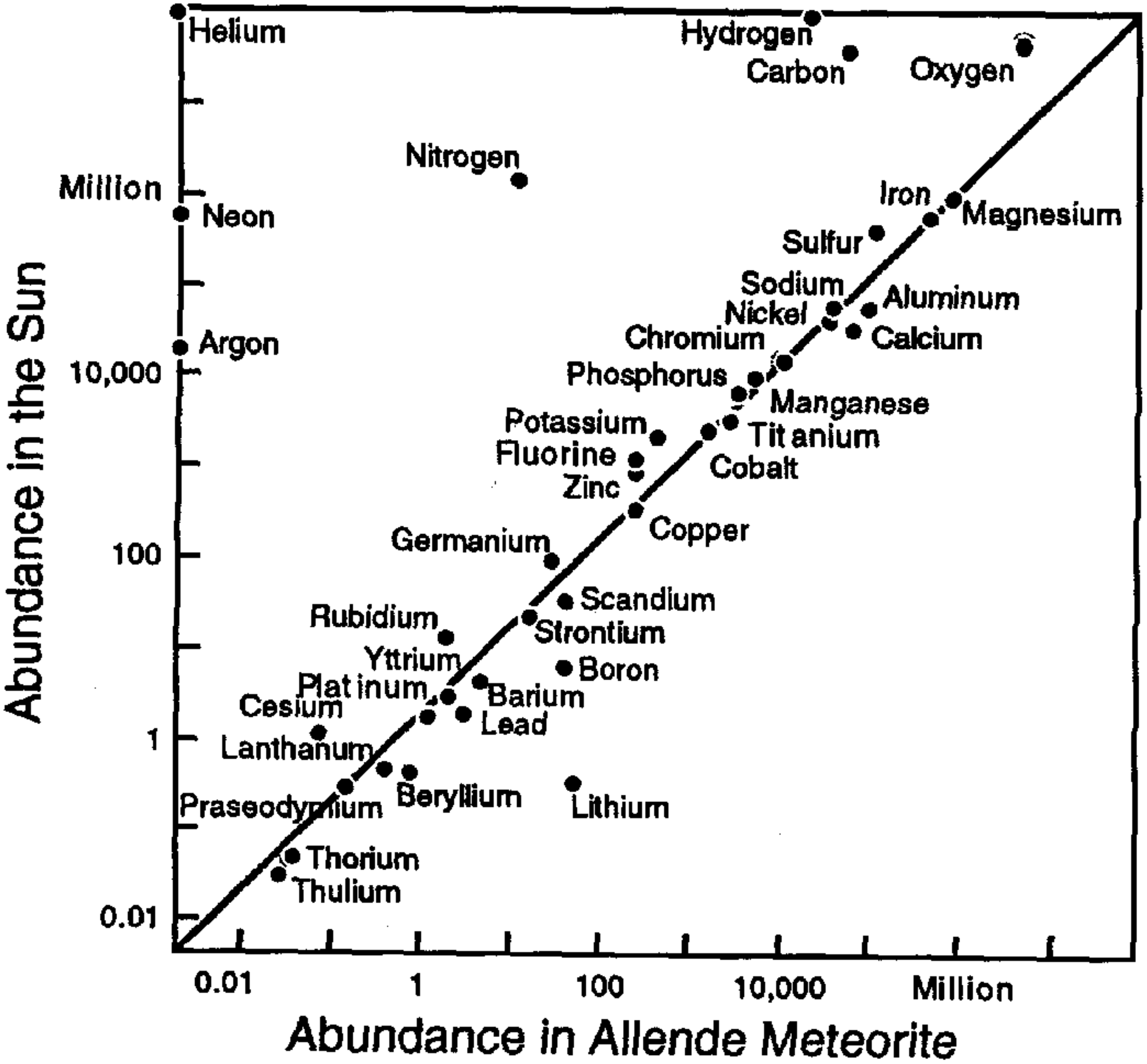
Types of Meteorites

b



Chondrites are subclassified in Chemical-Petrologic Types

Chemistry of Chondrites



Components within primitive meteorites

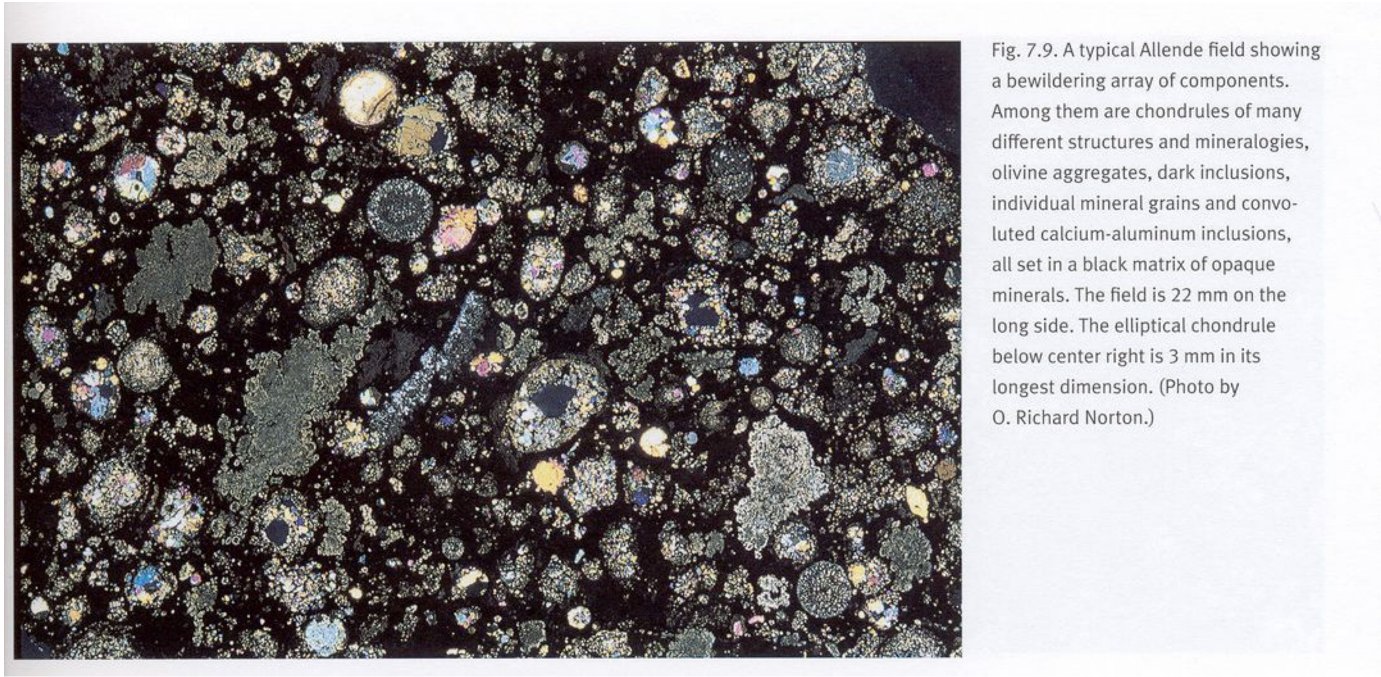


Fig. 7.9. A typical Allende field showing a bewildering array of components. Among them are chondrules of many different structures and mineralogies, olivine aggregates, dark inclusions, individual mineral grains and convoluted calcium-aluminum inclusions, all set in a black matrix of opaque minerals. The field is 22 mm on the long side. The elliptical chondrule below center right is 3 mm in its longest dimension. (Photo by O. Richard Norton.)

From Norton (2002) The Cambridge Encyclopedia of Meteorites

- Chondrules
- CAI (Calcium Aluminum rich Inclusions)
- Matrix of phyllosilicates, FeO, Fe, FeS, C compounds

Crystalline structure in chondrules

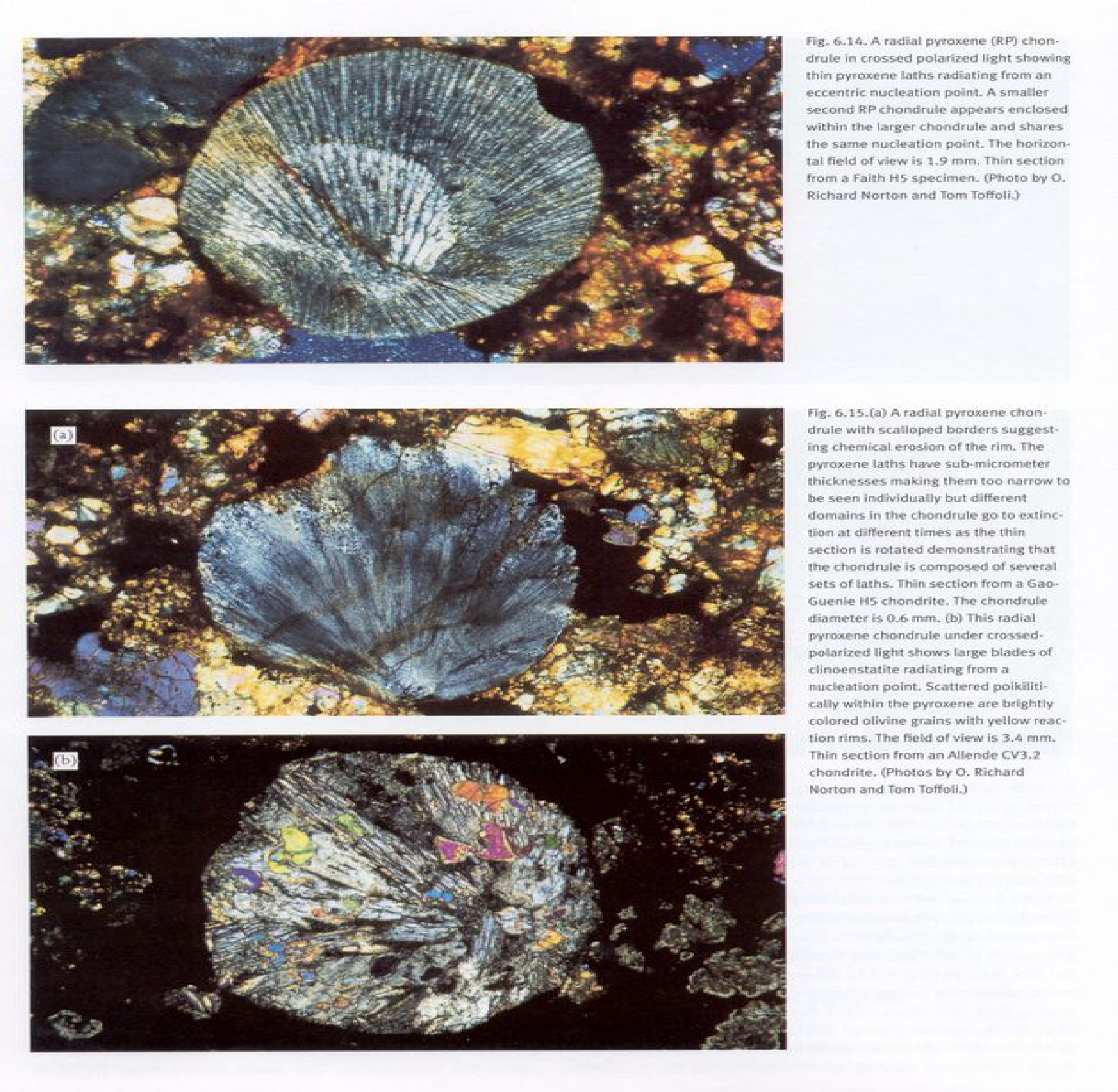


Fig. 6.14. A radial pyroxene (RP) chondrule in crossed polarized light showing thin pyroxene laths radiating from an eccentric nucleation point. A smaller second RP chondrule appears enclosed within the larger chondrule and shares the same nucleation point. The horizontal field of view is 1.9 mm. Thin section from a Faith H5 specimen. (Photo by O. Richard Norton and Tom Toffoli.)

Fig. 6.15.(a) A radial pyroxene chondrule with scalloped borders suggesting chemical erosion of the rim. The pyroxene laths have sub-micrometer thicknesses making them too narrow to be seen individually but different domains in the chondrule go to extinction at different times as the thin section is rotated demonstrating that the chondrule is composed of several sets of laths. Thin section from a Gao-Guenie H5 chondrite. The chondrule diameter is 0.6 mm. (b) This radial pyroxene chondrule under crossed-polarized light shows large blades of clinoenstatite radiating from a nucleation point. Scattered poikilitically within the pyroxene are brightly colored olivine grains with yellow reaction rims. The field of view is 3.4 mm. Thin section from an Allende CV3.2 chondrite. (Photos by O. Richard Norton and Tom Toffoli.)

- Spherical shape shows solidification from liquid droplet
- Radial pyroxene structure shows rapid crystallization from nucleation point

From McSween (1999) Meteorites and their parent planets

Crystalline structure in chondrules

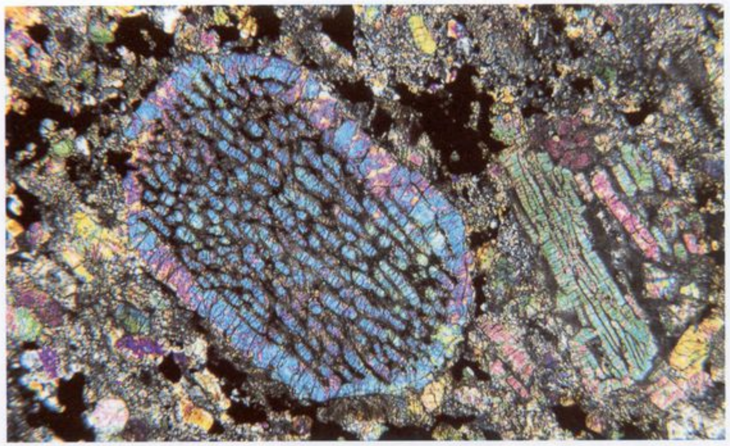


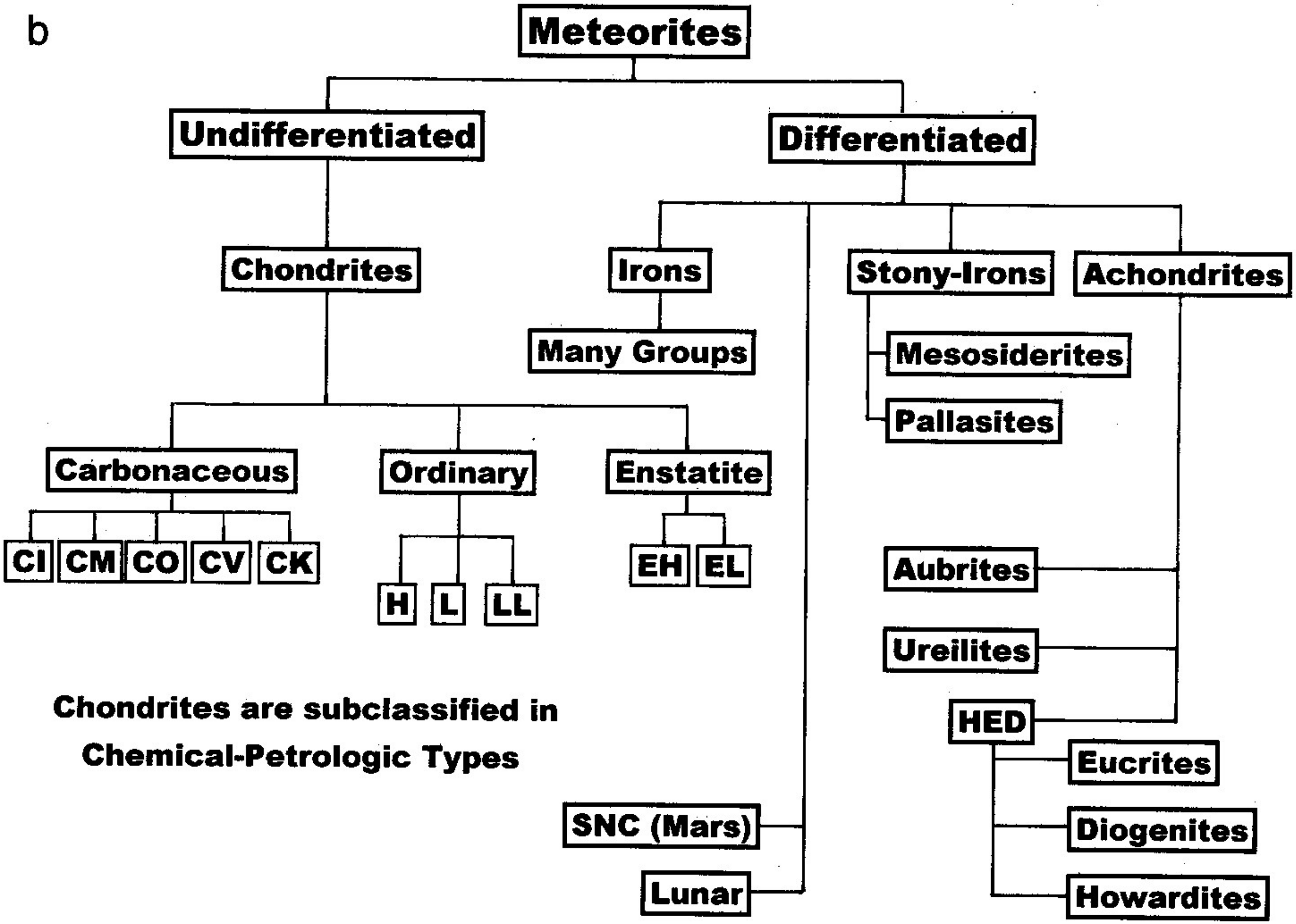
Fig. 6.16. An ellipsoidal barred olivine (BO) chondrule with parallel bars of olivine and an attached thick olivine rim. Both bars and rim share the same interference colors under crossed-polarized light and go to extinction simultaneously showing the entire structure is a single crystal in optical continuity. Thin section from a Mbale L5/6 chondrite. The major axis of the chondrule is 1.7 mm long. (Photo by O. Richard Norton and Tom Toffoli.)

Fig. 6.17. A polysomatic barred olivine chondrule showing several sets of parallel olivine bars oriented at different angles to each other resulting in different interference colors and extinction points. A thick rim encloses the polysomatic bars except at the upper edge where the rim has been disrupted. Thin section from an Allende CV3 chondrite. The horizontal field of view is 2.1 mm. (Photo by O. Richard Norton and Tom Toffoli.)

- Barred olivine chondrules also indicate quick cooling times
- Reproduced in lab experiments with cooling rates of ~1000^{o}C/hr

From McSween (1999) Meteorites and their parent planets

Types of Meteorites

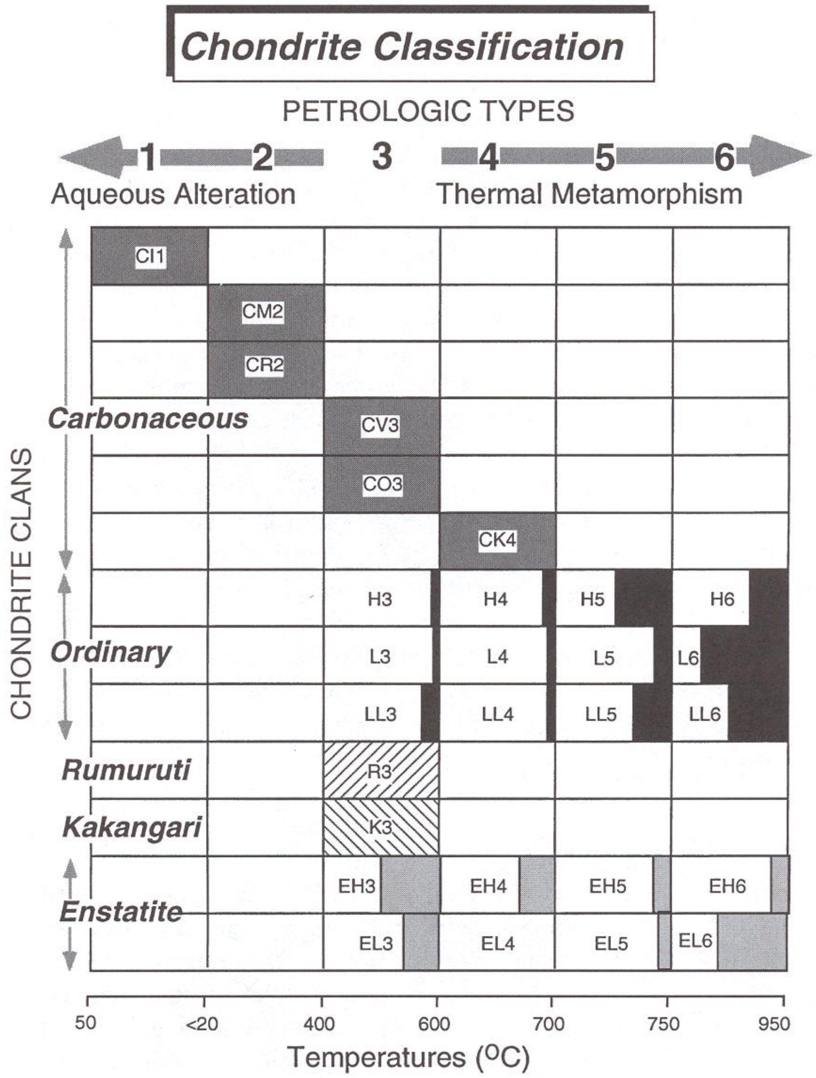


b

- **Meteorites**
  - **Undifferentiated**
    - **Chondrites**
      - **Carbonaceous**
        - **CI**
        - **CM**
        - **CO**
        - **CV**
        - **CK**
      - **Ordinary**
        - **H**
        - **L**
        - **LL**
      - **Enstatite**
        - **EH**
        - **EL**
  - **Differentiated**
    - **Irons**
      - **Many Groups**
    - **Stony-Irons**
      - **Mesosiderites**
      - **Pallasites**
    - **Achondrites**
      - **Aubrites**
      - **Ureilites**
      - **HED**
        - **Eucrites**
        - **Diogenites**
        - **Howardites**
    - **SNC (Mars)**
    - **Lunar**

Chondrites are subclassified in Chemical-Petrologic Types

Carbonaceous Chondrite Classification



From McSween (1999) Meteorites and their parent planets

The leading "C" means carbonaceous chondrite

The group: "I", "M" etc. denotes chemical composition, named for a "type" meteorite such as Ivuna, Mighei, Vigarano, etc.

- The letter is arbitrary since the "type" meteorite is in turn just named after the town where it fell

The number 1-6 denotes petrologic type, based on types of alteration of chondrules and grains

- Not all groups come in all petrologic types, since there is usually some (poorly understood) causal connection between original composition and alteration history

Example: The "Allende" meteorite is a "CV3"which means it is a carbonaceous chondrite, is chemically similar to the "Vigarano" meteorite, and shows little aqueous alteration or thermal metamorphism

^{26}Mg Isotopic Anomalies in CAI inclusions

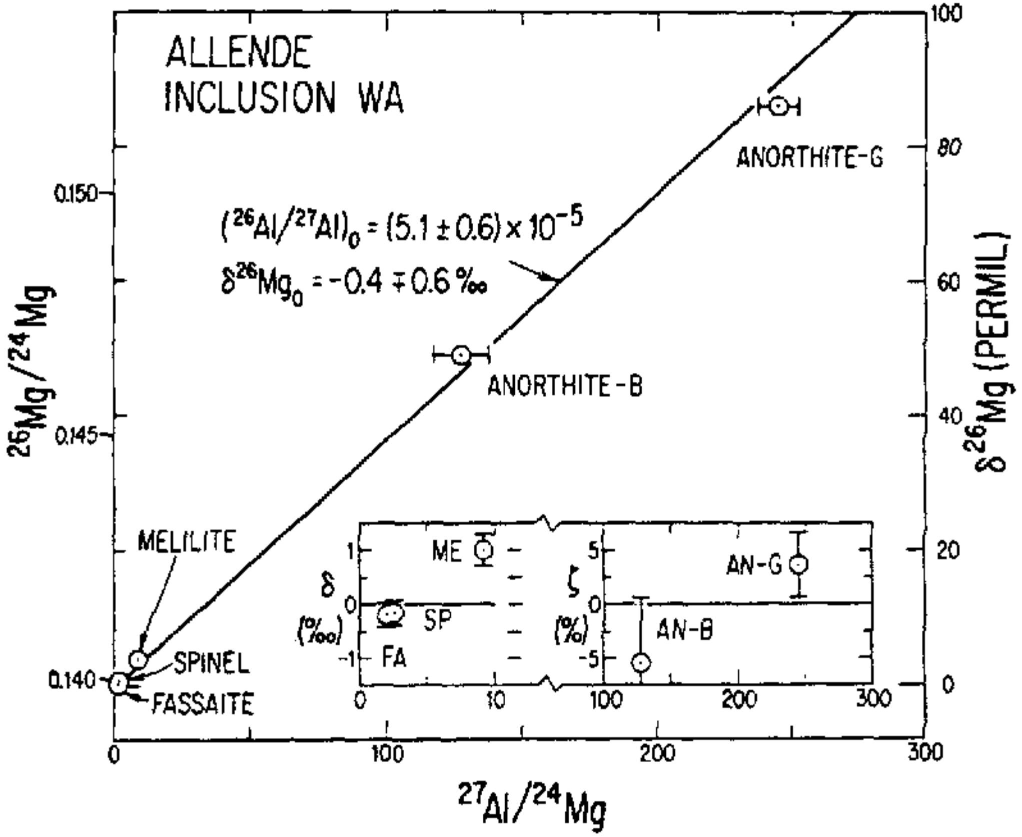
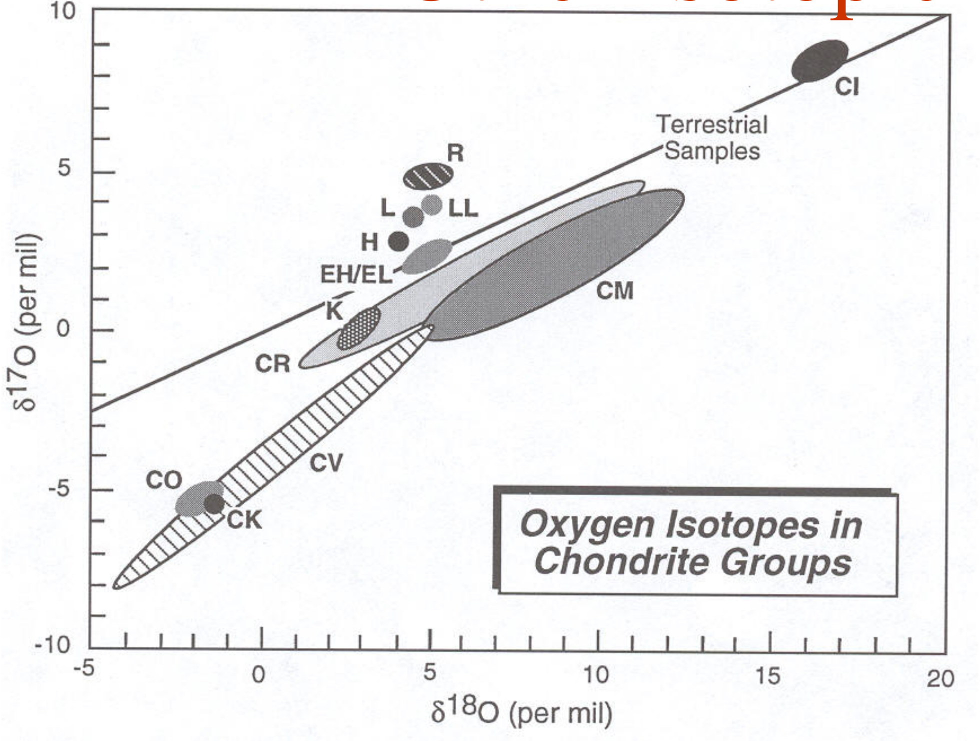


Fig. 15.1.4. Correlation of ^{26}Mg/^{24}Mg with ^{27}Al/^{24}Mg in Allende inclusion WA (figure from Lee et al. 1977). The quality of the correlation clearly indicates that the ^{26}Mg isotopic excesses are due to decay of ^{26}Al.

- ^{26}Al→ ^{26}Mg
- Amount of ^{26}Mg proportional to amount of ^{27}Al
- So it was present as Al when minerals formed
- ^{26}Al was “live” even though half-life is only 0.75 My
- Lots of other isotopic anomalies

Other Isotopic Anomalies



From McSween (1999) Meteorites and their parent planets

- Chemical effects can "fractionate" (change) isotopic ratios <u>**very slightly**</u>
  - Why: Even if "chemistry" of ^{17}O and ^{16}O are the same, mass is very slightly different, so for example speed in gas of heavier ^{17}O is slightly less than speed of lighter ^{16}O.
  - Whatever fractionation happens in $^{17}O/^{16}O$ ratio, effect will be twice as great for $^{18}O/^{16}O$ ratio, since mass difference is twice as great.
  - Above is plot of excess $^{17}O/^{16}O$ vs excess$^{18}O/^{16}O$, with "standard mean ocean water" = (0,0)
  - All samples affected by fractionation alone plot on line of slope ½
    All samples from the Earth plot on this line.
- Some meteorites don't plot on the slope ½ line – they plot on a slope 1 line:
  - It is as if some pure ^{16}O had been added to these meteorites.
  - Conclusion: Solar nebula not completely mixed (homogenized) at start

Addition of pure ^{16}O

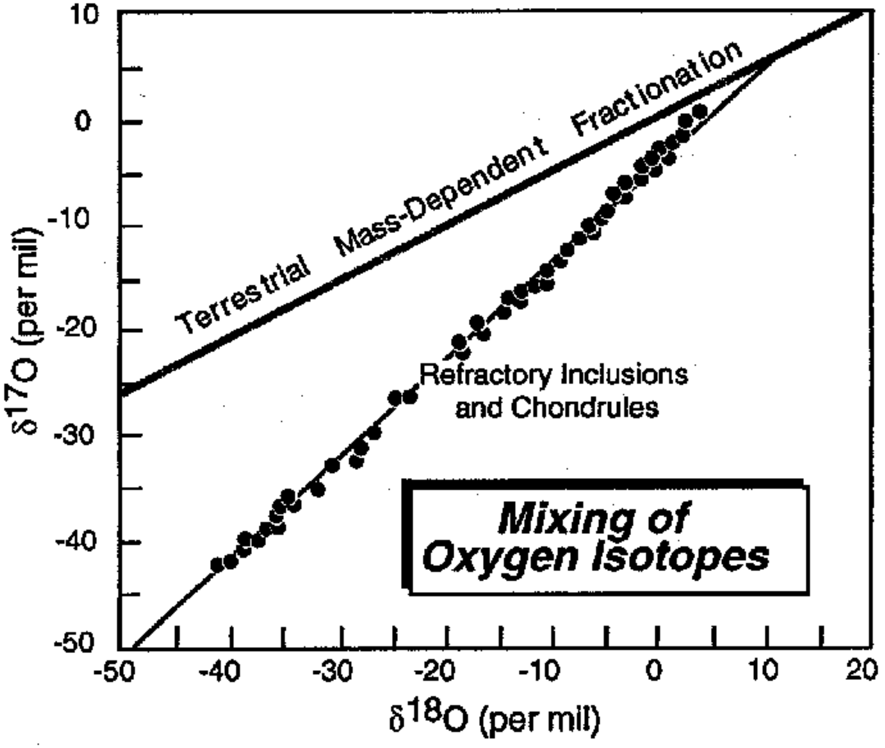


Figure 2.18: Oxygen isotopes in the refractory inclusions and chondrules of carbonaceous chondrites fall along a mixing line between pure ^{16}O and normal solar system oxygen, possibly plotting near the intersection of the mixing line with the terrestrial mass-dependent fractionation line. The steep slope of the mixing line indicates that this variation cannot be explained by the fractionation processes that occur on Earth. The δ notation used to describe the oxygen isotopic composition is defined in the caption for Figure 2.5. All analyses were made by Robert Clayton and co-workers (University of Chicago).

From McSween (1999) Meteorites and their parent planets

Asteroid Composition

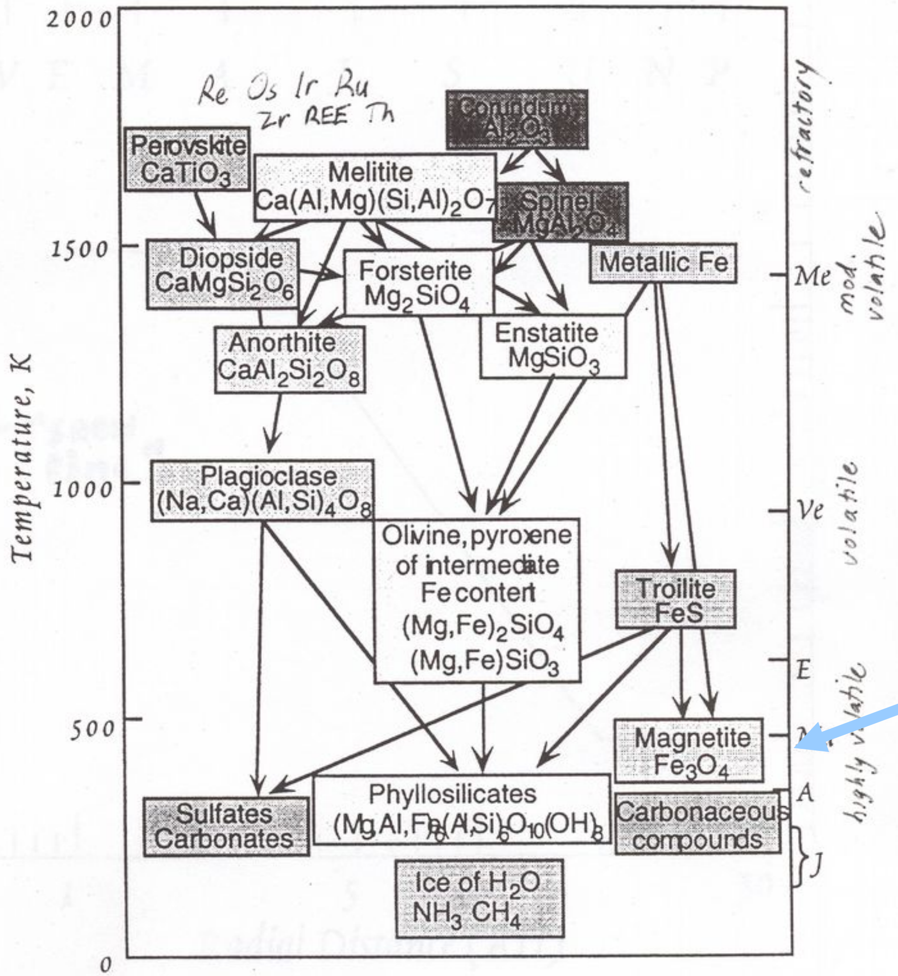


Figure 10.33. Simplified mineralogical condensation sequence.

- If unaltered expect:
  - Hydrated silicates
  - Carbonaceous compounds
  - Sulfates
  - Carbonates

Asteroids

Primitive Meteorite Components and the Condensation Sequence

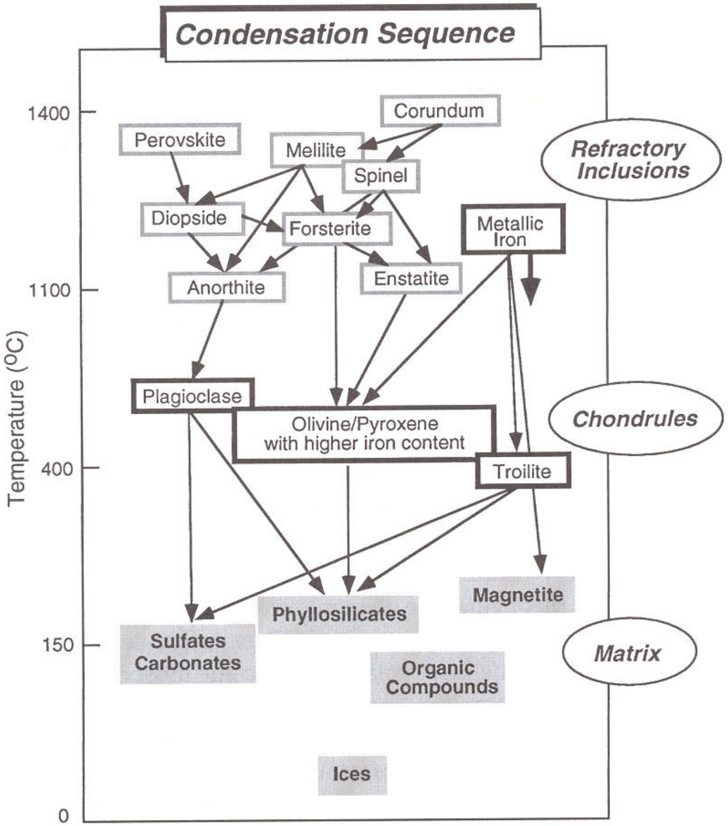


Figure 2.15: The order of appearance of minerals from a cooling nebular gas of cosmic composition has been predicted from theoretical calculations and is schematically summarized in this figure. Minerals like perovskite, melilite, and corundum that form at high temperatures condense directly from the gas, whereas those that form at lower temperatures result from reactions of the gas with previously condensed minerals (reactions are indicated by arrows). The condensation of metallic iron is suppressed, relative to forsterite and enstatite, at lower pressures (indicated by a large arrow). Although this condensation sequence is probably an oversimplified view of the formation of solid matter in the solar system, it does predict the occurrence of minerals that comprise refractory inclusions, chondrules, and matrix. The calculated condensation sequence is based on the work of Larry Grossman (University of Chicago).

- Components seen in primitive meteorites are minerals predicted from various stages of the condensation sequence

- The fact they appear together demonstrates that "equilibrium model" is at best an approximation

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Explanation for compositional gradient in asteroid belt?

- ^{26}Al → ^{26}Mg with half-life of 0.73 million years
- May provide a heat source for melting some of the asteroids
  - The inner asteroids tend to be differentiated
  - The outer ones tend to be undifferentiated
  - However solar energy difference is NOT enough to do this
  - Inner orbits are faster, and asteroids in inner orbits may sweep up debris and be assembled faster.
- Different speed of assembly may determine fate:
  - Inner objects form faster, when Al was "live"
  - Outer objects form later, when Al was "dead"
- But (Levison *et al.* 2009) recently suggested that outer belt asteroids are trans-Neptunian objects scattered in during "heavy bombardment" episode.

Results from Analysis of Meteorites

- Ages
  - Almost all have ages of ~4.5 billion years
- Composition
  - Most primitive ones are a <u>mixture</u> of materials predicted by condensation model
  - Isotopic signatures show some material solidified within a few million years of element creation in supernova
  - Could be evidence of supernova trigger to star formation
  - Might also be signature of "stardust" grains
- Processing
  - Widmanstaaten cooling rates imply few 100 km diameter bodies
  - Chondrules are a mystery
    - Some sort of short high temperature events taking place
      - Lighting?
      - Shocks?
      - Impacts?

A more realistic view of solar nebula

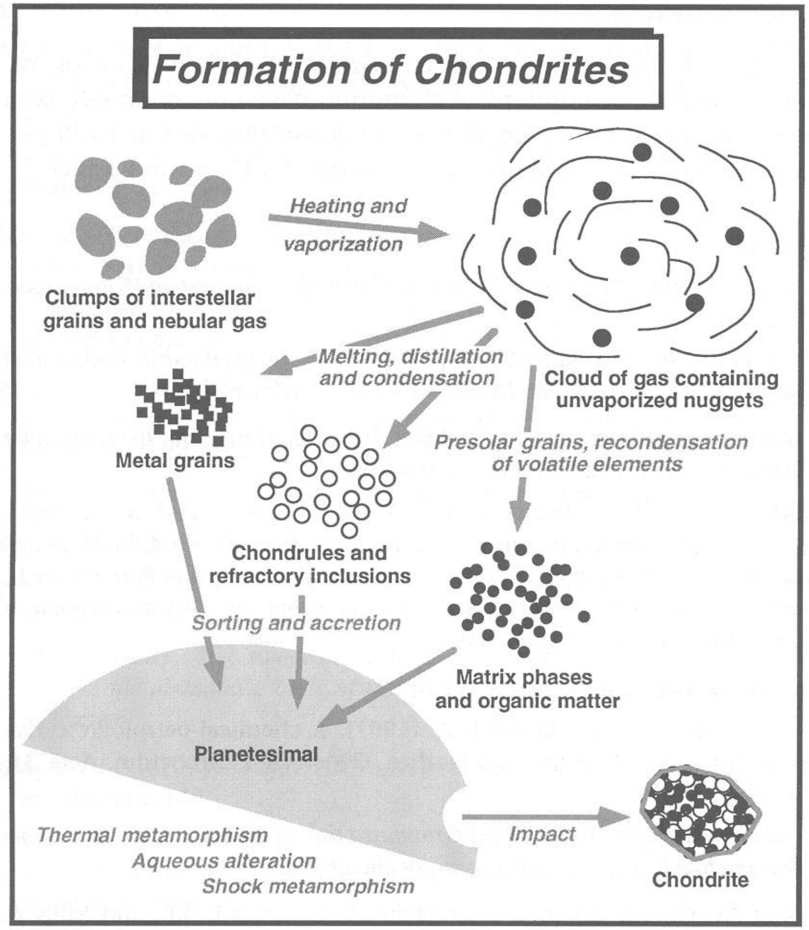

Figure 2.19: The formation of chondrites involved a series of complex steps, as illustrated in this figure.

- Condensation model provides "paradigm"
- Deviations from model show more complex history
  - Material not all heated to enough to vaporize
  - Not uniformly mixed
  - Different stage condensates partially separated and sometimes modified or sorted
  - Further modified after accretion in planetesimals

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Some Current Questions Regarding Early Solar System #1

- Nature of the short heating process producing chondrules?
  - Lightning?
  - Shocks?
  - Winds and circulation of material within the disk?

- Nature of heating causing differentiation of some (mostly inner) asteroids?
  - Heat from decay of live ^{26}Al in faster forming inner planetesimals? (outer ones may have formed more slowly after ^{26}Al had decayed)

- Timeline for the early processes (simplified version from Terra et al. follows)
  - 4.566 Ga Allende high temperature inclusions form
  - 4.560 Ga Allende chondrules form
  - 4.560 Ga Upper limit on age of Allende matrix
  - 4.558 Ga Magmatism begins on planetesimals
  - 4.553 Ga Reequilibration metamorphism in chondrites
    4.45 Ga
  - 4.40 Ga "End" of magmatism on asteroids

Some Current Questions
Regarding Early Solar System #2

Implications of the “Nice” model for dynamics and orbits:

Giant Planets migrate slowly due to interaction with cloud of planetesimals

Jupiter moves slowly in, Saturn moves slowly out

If Jupiter and Saturn reach 1:2 resonance, their orbits become eccentric

This disrupts orbits of many other bodies, scattering them over much of solar system

- Controls final location of Uranus and Neptune?
- Scatters outer planetesimals into current “Kuiper Belt” locations?
- Causes “late heavy bombardment” of Moon at ~3.9 Ga?
- Clears much of original material out of asteroid belt?
- Delivers icy region planetesimals into outer regions of asteroid belt? (Levison *et al.* 2009)
- Delivers H_2O rich asteroids and “comets” to Earth?