The Sun, Meteorites and bulk composition of the Earth

How the planet formed initially?

Solar system includes- asteroids, comets and planetary satellites.

2 types of planets-

1. Terrestrial planets, small rocky bodies orbiting close to the SUN (e.g Earth)
2. Gas giants- follow more distant orbits in the colder outer reaches of the Solar system.

Planetary formation is linked to the formation of stars themselves. Stars are now widely considered to form from clouds of gas, mostly hydrogen and helium,

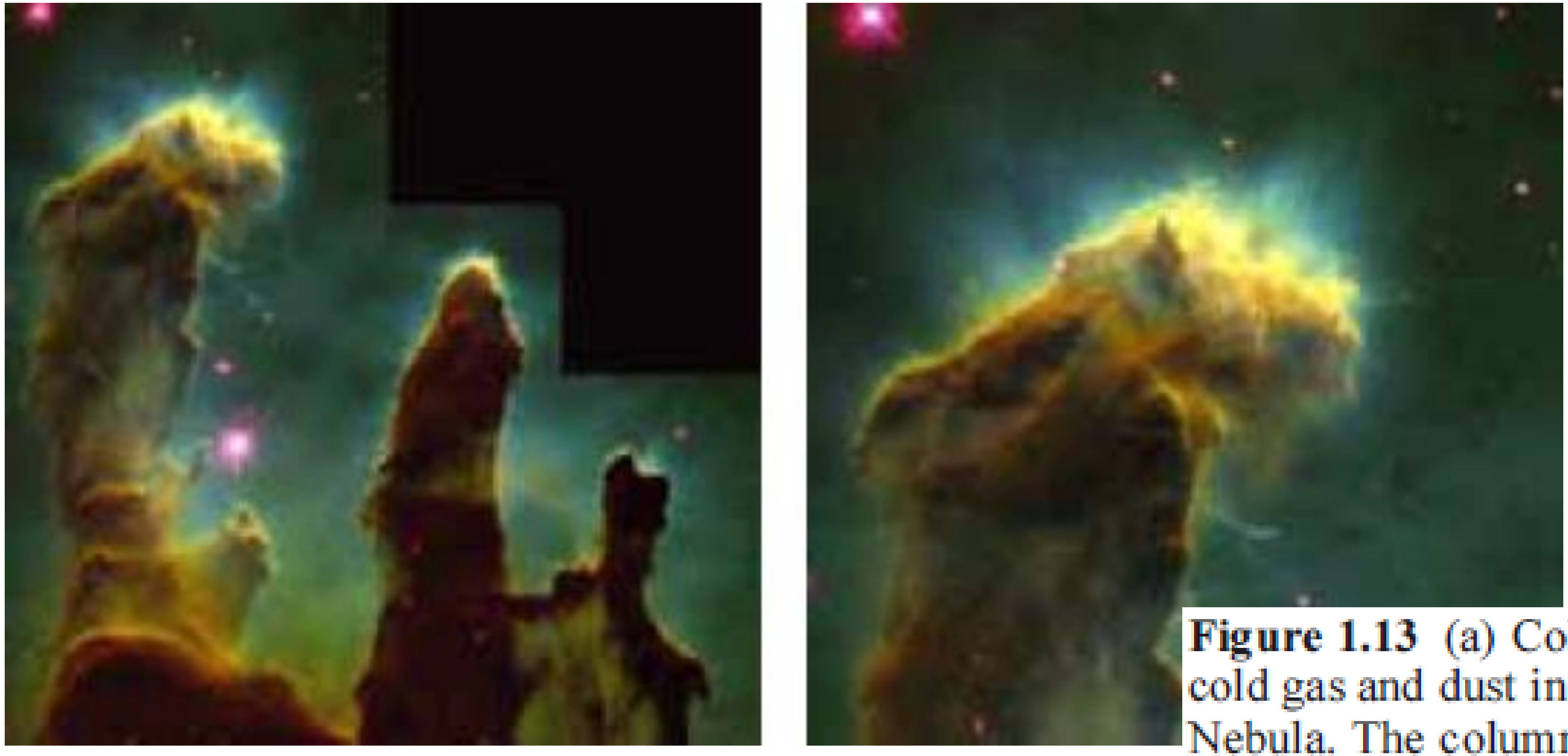
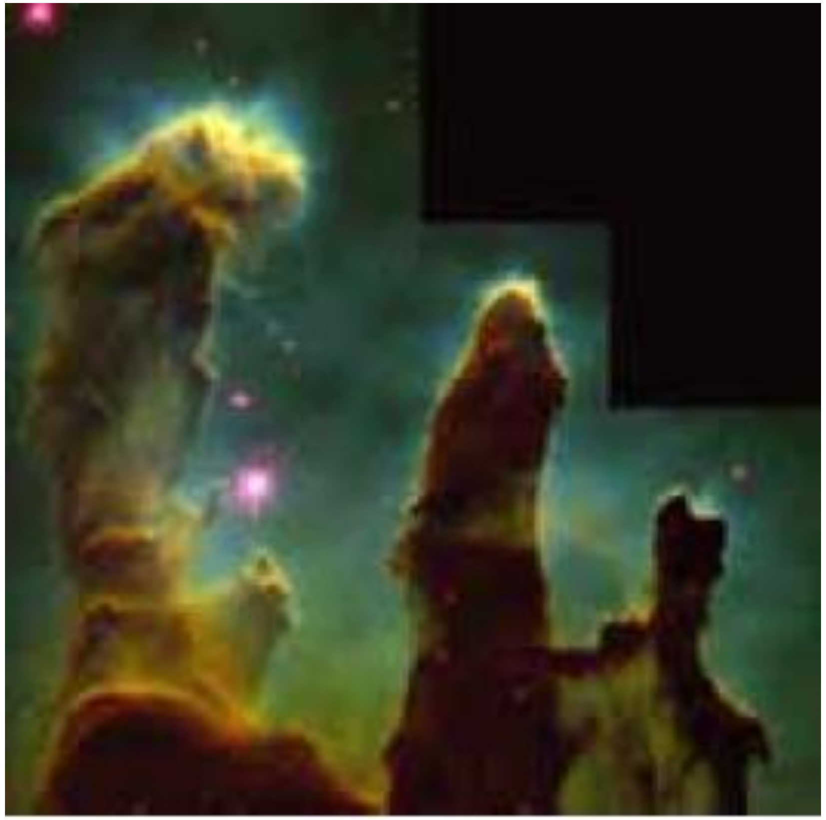


Figure 1.13 (a) Columns of cold gas and dust in the Eagle Nebula. The columns protrude from the wall of a vast cloud of molecular hydrogen and are up to four light-years long. In places the interstellar gas is dense enough to collapse under its own weight, forming young stars that continue to grow as they accumulate more and more mass from their surroundings.

The **Hubble Space Telescope** (**HST**) is a space telescope that was launched into low Earth orbit in 1990, and remains in operation. With a 2.4-meter (7.9 ft) mirror, Hubble's four main instruments observe in the near ultraviolet, visible, and near infrared spectra. The telescope is named after the astronomer Edwin Hubble.

To get some idea of the scale of the gas clouds, you
See in the diagram, individual columns are up to 4 light-years
Long and emerge from an even larger and more diffuse cloud
of gas and dust.



Small globules protruding from the
Ends of the gas ‘fingers’ that have
Been dubbed evaporating gaseous
Globules (EGGs) within which the
Density of the gas has increased to
Such an extent that the cloud is
Locally collapsing to form a star.
These EGGs are roughly the size of
Our Solar System.

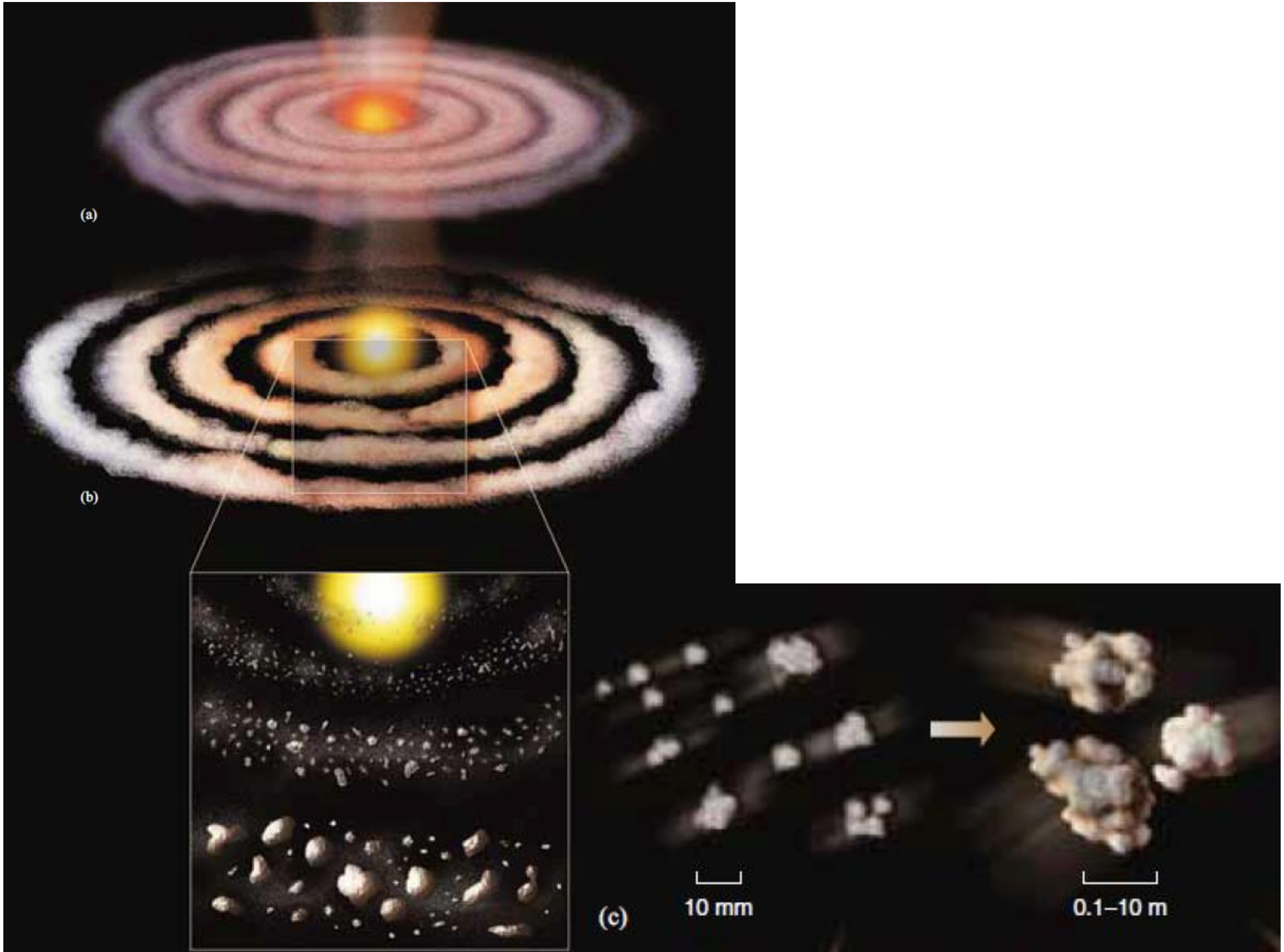
Formation of the Solar System
It all started around 4.6 Ga.

1. Condensation of the solar nebula and accretion

Gravitational collapse of an interstellar dust cloud dominated
By Hydrogen and Helium, traces of metallic and silicate dust, H_2O,
CH_4, NH_3....

Once the sun started to shine, the heat vaporised most of the
Dust and ices and the vapour was transported further away
From the Sun by the early intense solar wind.

Condensed particle of dust stick together ....it took ~10,000 years
In the inner orbits, these clumps would have been dominated
By silicates and metal, their composition is preserved in the most
Primitive of the chondritic meteorites...

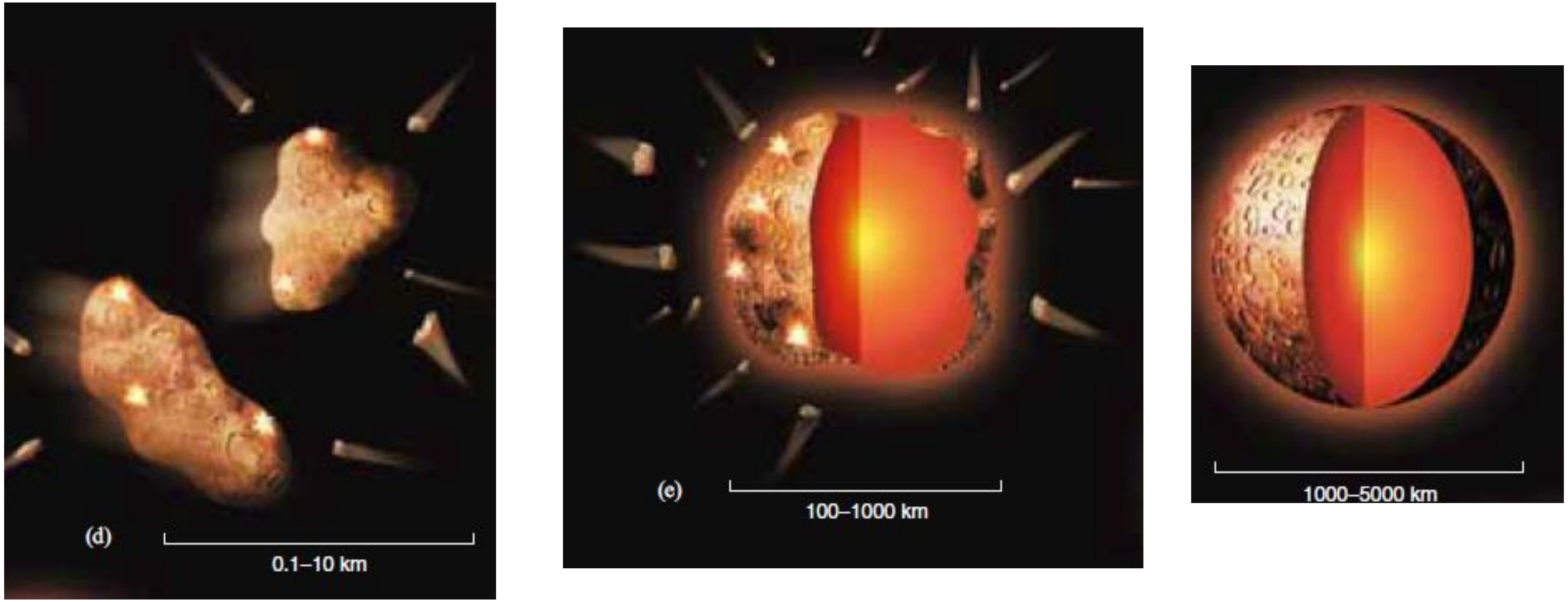

(a)
(b)
(c)
10 mm
0.1–10 m

2. Formation of Planetesimals and development of planetary embroys

Particle collision continued increasing the size of clumps
Producing a profusion of bodies ranging in size from
0.1 to 10 km in diameter, termed **planetismals** (tiny planets)

Slowly during accretion, larger bodies would begin to heat up
Because of the release of kinetic energy as smaller bodies impacted.

It is estimated that the **planetary embryos** (up to A few thousand km in size) would have swept up any remaining planetismals within a few thousand years.


(d)
0.1–10 km
(e)
100–1000 km
1000–5000 km

3. **Planetary Embryos, giant impacts and assembly of a planet**
Next stage of growth would have been slower.
Giant impacts between 2 embryos probably fragmented both
Of the impacted bodies with the debris subsequently recombining
To form a new, larger body.

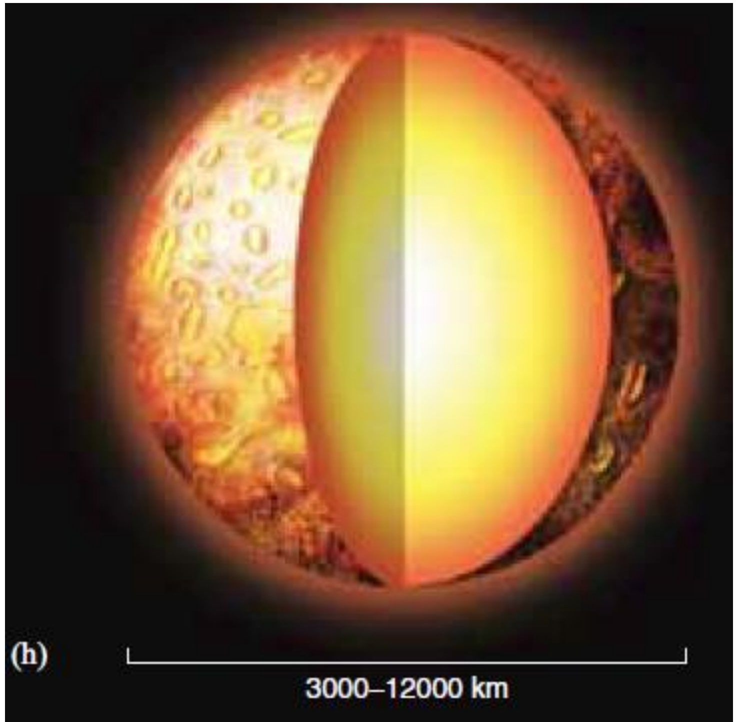
The heat released was enough to melt the newly combined mass
Creating a molten mantle of silicate material known as magma
Ocean. Metallic material sank through the
magma ocean and formed A dense
metallic core, producing a differentiated
planetary embryo.

Completion of a terrestrial planet formation

Giants impacts would have continued to take place and it Might have taken 10 Ma for the terrestrial planet to reach Half of the size and about 100 Ma to reach and build an Earth sized planet.

Once the last giant impact had occurred to form Moon.....

Of course accretion continues... but too small to be noticeable. Even today,,,accretion rate to the Earth today, including dust Particles is ~10*7 kg/y.



So,,,overall, we see that following steps involved
During planet formation

-Condensation of gas to form dust particles
-Accretion of dust to form planetismals
-Larger collisions between planetismals to form planetary embryos
-planetary embryos with giant impacts made planets

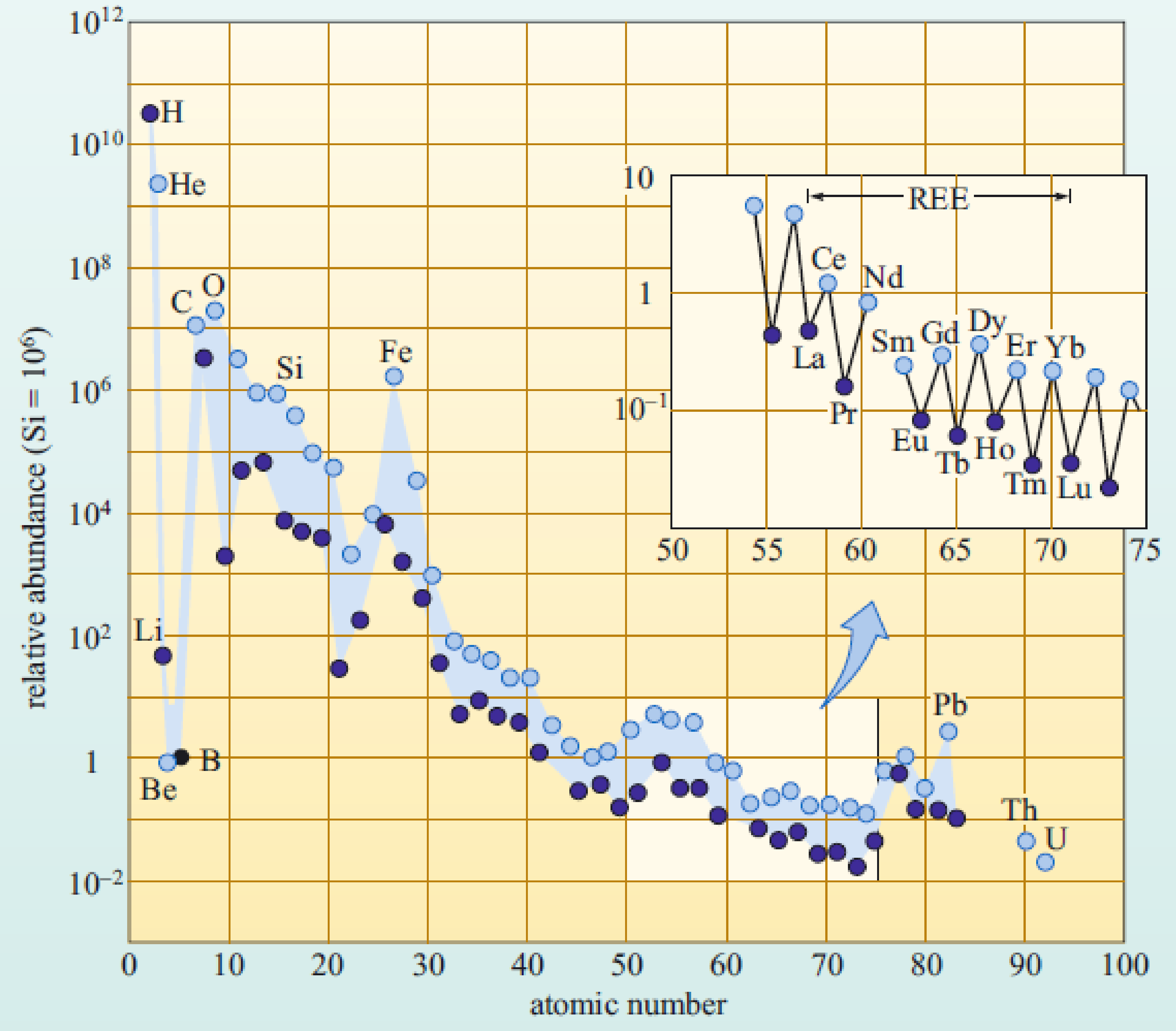
The composition of the Earth is related to the composition Of Solar Nebula, as most of the material from the solar Nebula condensed to form the Sun, the composition of the Earth is also related to that of the Sun.

The SUN

-Study of electromagnetic radiation to study SUN
-SUN Atmosphere, different chemical elements absorb radiation
at specific wavelengths.
By this Astronomers gain knowledge of the compositions
of the distant stars and galaxies.

Amount of light absorbed is proportional to the amount of an
element present in the Sun's atmosphere ...

No absolute abundance but relative....in our case, we see this
In a plot, relative to a nominal abundance of Silicon,,,10*6 atoms.



relative abundance (Si = 10^6)
atomic number
H
He
Li
Be
B
C
O
Si
Fe
Pb
Th
U
REE
Ce
Nd
La
Pr
Sm
Gd
Dy
Er
Yb
Eu
Tb
Ho
Tm
Lu

See the abundance of Fe and Pb,,,
Both are extracted from the ore bodies by industrial processes,
Fe is ~1,000,000 times abundant in the SUN than Pb.
Au (Gold; 79) and Pt (Platinum; 78) are comparable to Pb, but
Au and Pt are regarded as being much rarer and of greater value.

Why Pb more abundant in the Earth than the precious metals?

Earth's crust formation and its composition is due to many processes since planetary accretion.

Different Elements have different geochemical properties and so respond in contrasting ways during geological and planetary processes.
Pb has concentrated more in crust while Fe in Mantle and core.

Elements condensation from the solar nebula

Solar nebula...hot to start...cooled slowly

Different chemical elements gradually condensed according to their individual volatilities.

Many elements have boiling point much higher to be considered Significantly in our everyday experience. However in a very low Pressure condition of nebula, difference in their boiling points Becomes important.

For example- Al2O3 (Alumina) has vaporisation temperature 3500 K under atmospheric conditions (10*5 N/sq. Meter), but in the lower pressures of the Solar nebula (10 N/sq. Meter), it reduces to 1700 K.

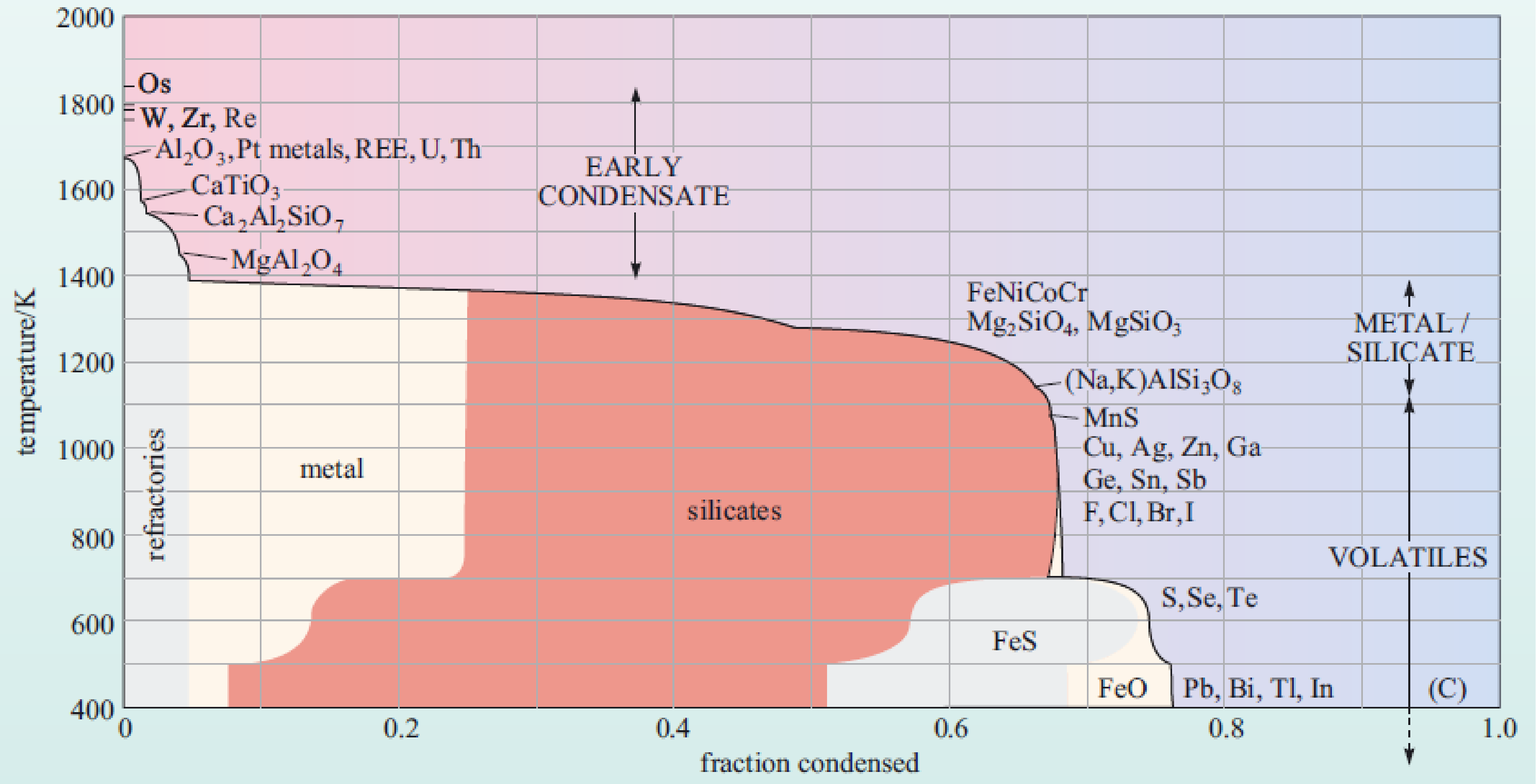


Figure 1.16 The condensation sequence of the solar nebula at a pressure of about 10 N m^{-2}. The *x*-axis represents the fraction of the nebula that has condensed at the temperature given on the *y*-axis. The curve is annotated to show which elements and compounds condense at which temperatures. At this low pressure, all materials condense from gases to solids directly without an intervening liquid phase. (K = kelvin = T °C + 273) (Morgan and Anders, 1980)

What are the proportions of the dominant components of the condensate?

The early condensates, or refractories, comprise 5% of the total. This is followed by metals, which comprise 20% of the total, and silicates, which comprise 40% of the total. The remainder includes volatiles and ices. The condensate is dominated by silicates and metals.

If the temperature in the solar nebula decreased outwards from the proto-Sun, can you suggest a mechanism that might have produced the terrestrial planets (Mercury, Venus, Earth and Mars) and gas giant planets (Jupiter, Saturn, Uranus and Neptune)?

Given the sequence of condensation in Figure 1.16, then volatile elements and ices would only condense when the temperature of the solar nebula dropped below 300 K. Perhaps such cold conditions only occurred beyond the orbit of Mars.

Meteororites

Second source of information of Solar system

They contain material thought to be representative of the early solar nebula.

Mostly derived from asteroid belt, possibly planetary embryos
Probably resulted from gravitational disturbances caused by Jupiter, perturbing the orbits of individual asteroids and causing repeated violent collisions that resulted in further fragmentation rather than accretion.

Meteorites come in a variety of compositions, but can be broadly classified into-

Stony meteorites, dominant of silicate minerals

Iron meteorites, primarily composed of metallic iron

Stony-iron meteorites, a hybrid of the other two.

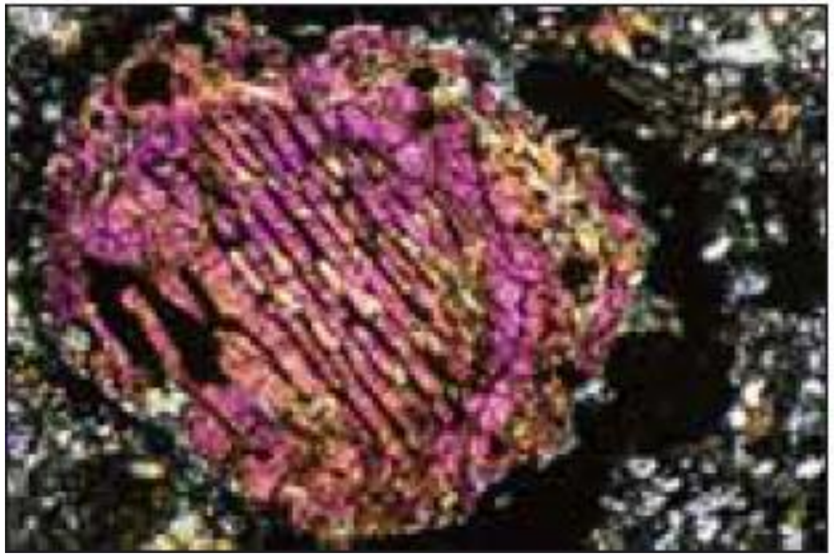
(a)

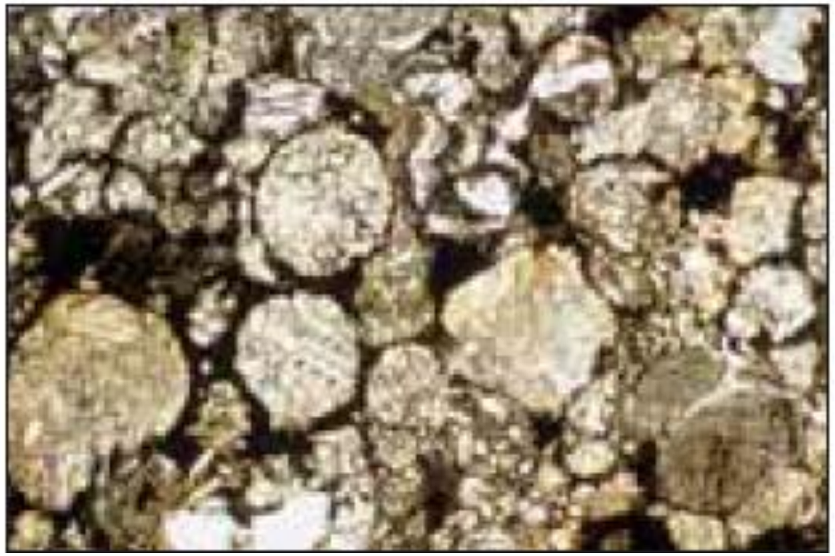
(b)

Iron and stony-iron meteorites have undergone an amount of chemical processing described as **"Differentiated"**
- Enrichment of Fe and Ni due to removal of some or all of the silicate minerals

Stony meteorites account for up to 95% of all known meteorite falls and are subdivided into **chondrites** and **achondrites**, depending on whether they contain **chondrules** or not. Chondrules are small, roughly spherical globules of silicate minerals of 0.1-2mm in size.

Shape and crystallinity suggest that they were once molten in a low gravitational field, indicating that they formed away from major planetary bodies, either on the surface of planetesimals or or even within the solar nebula.





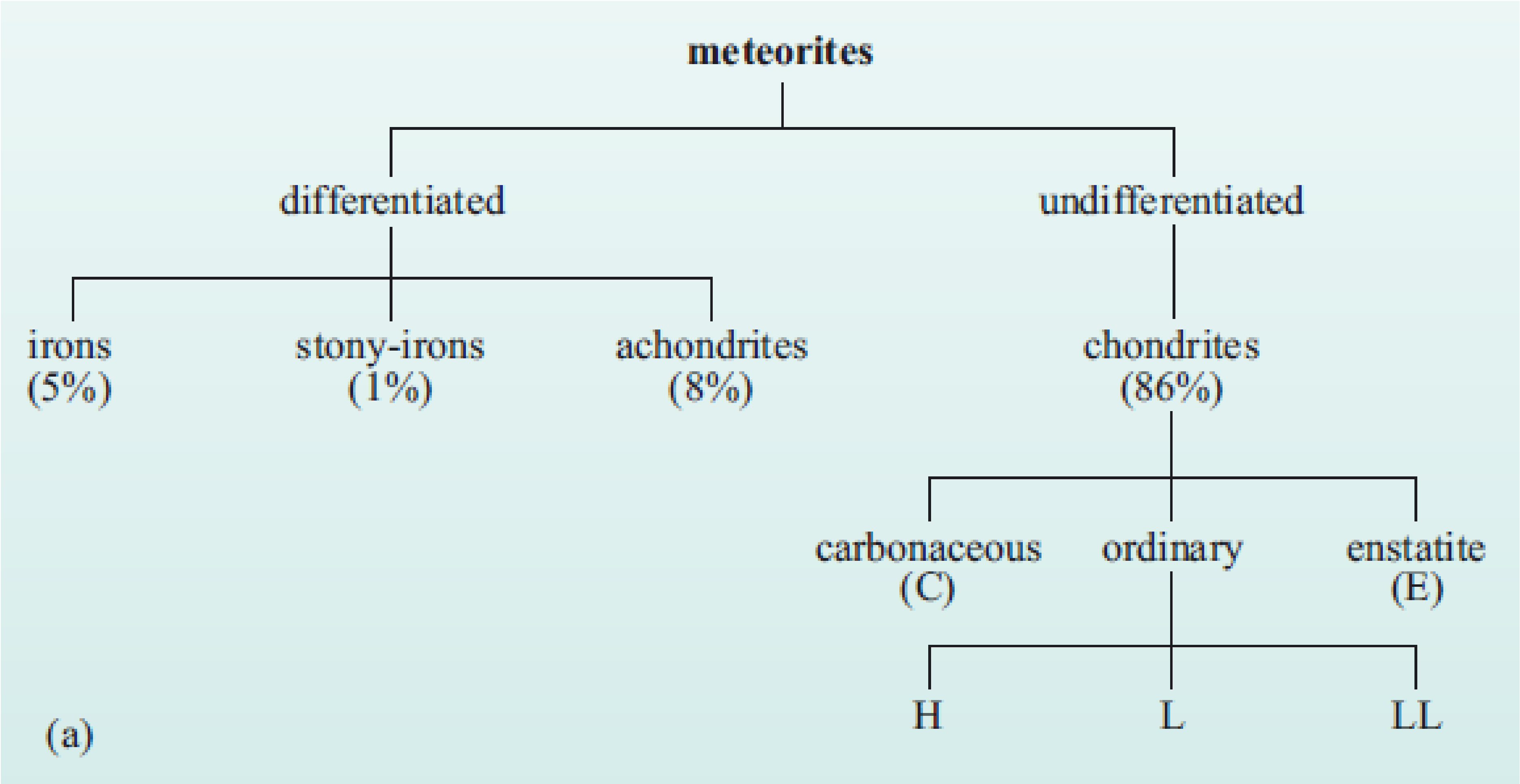
matrix; (e) a relatively large mm-sized chondrule from a carbonaceous chondrite (Bokkeveld meteorite), showing individual crystals within it; (f) a collection of individual chondrules, each less than 1 mm in diameter, from an ordinary chondrite (Sharps meteorite). (Natural History Museum)

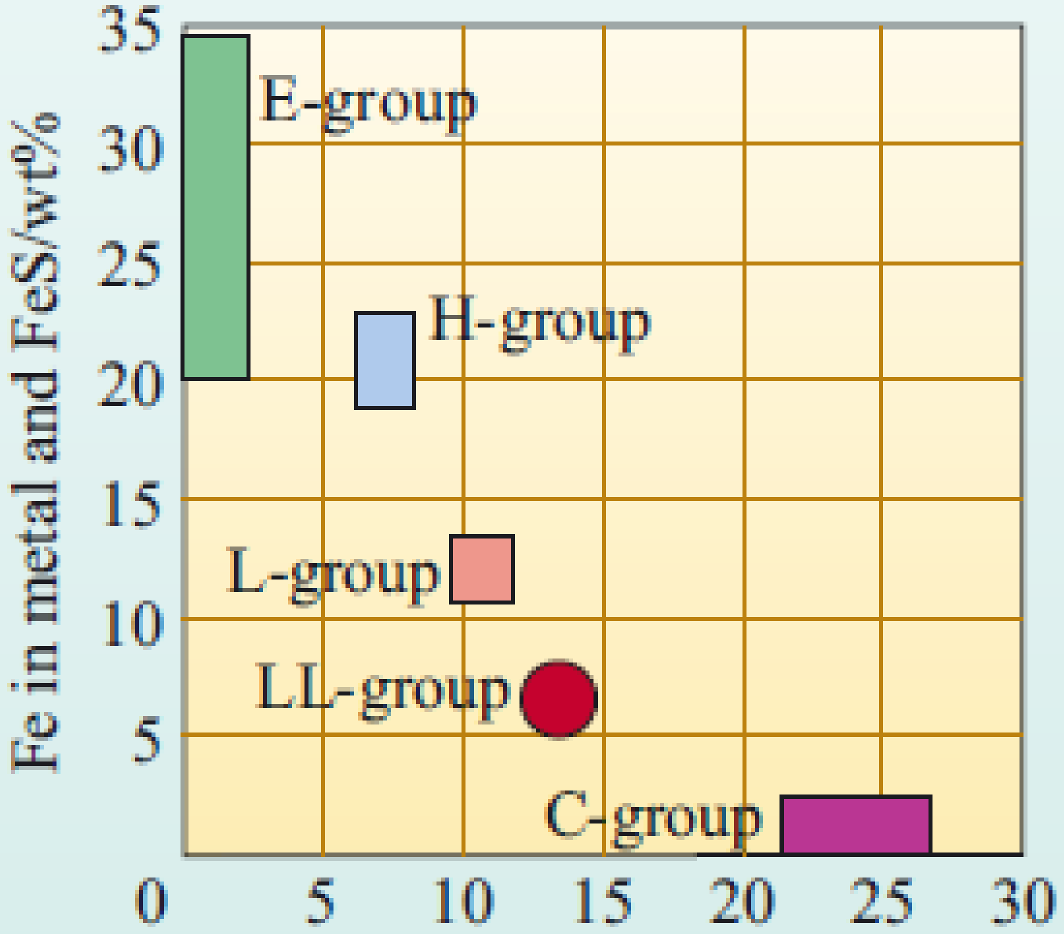
Achondrites- constitute only about 10% of all stony meteorite falls. Their textures suggest reminiscent of terrestrial Igneous rocks and are classified as differentiated meteorites along with iron and stony-irons.

Chondrites- are classified based on their mineralogy-

1. **Ordinary chondrites-** most abundant type
2. **Enstatite (or E-) chondrites-** rich in Enstatite ($MgSiO_3$)
3. **Carbonaceous (or C-) chondrites-** non biogenic carbon rich organic compounds in addition to silicates minerals.

Again ordinary chondrites are subdivided according to their iron Contents and their oxidation state (reflected in the amount of iron In silicate minerals) relative to that in chemically reduced phases Such as metallic iron and sulfides.


meteorites
differentiated
undifferentiated
irons
(5%)
stony-irons
(1%)
achondrites
(8%)
chondrites
(86%)
carbonaceous
(C)
ordinary
enstatite
(E)
H
L
LL
(a)



Fe in metal and FeS/wt%
35
30
25
20
15
10
5
E-group
H-group
L-group
LL-group
C-group
0
5
10
15
20
25
30
Fe in silicate/wt%

(b)

Considering this overall classification, what do you consider to be the dominant process in meteorite differentiation?

The separation of a metallic phase from the silicate minerals.

The most primitive material?

The compositions of iron meteorites reflect processes that have taken place within a planet-sized body (or planetary embryo) where temperatures were at one time high enough to melt the silicates and the metallic phases and allow them to separate as a result of gravity. Thus, in our search for the most primitive composition, the differentiated meteorites can be rejected, leaving the chondrites. But which of these represents the most primitive material?

Volatiles will be lost easily from a meteorite as due to lowest condensation temperature.

Assuming that condensation from the solar nebula continued without disturbance at low temperatures, the most primitive should contain abundance of volatile elements in the same proportion as in the Sun.

A comparison of the compositions of the different meteorite group reveals an overall similarity in the abundances of elements found in high-temperature early condensates and increasingly diverse concentration of the more volatile elements.

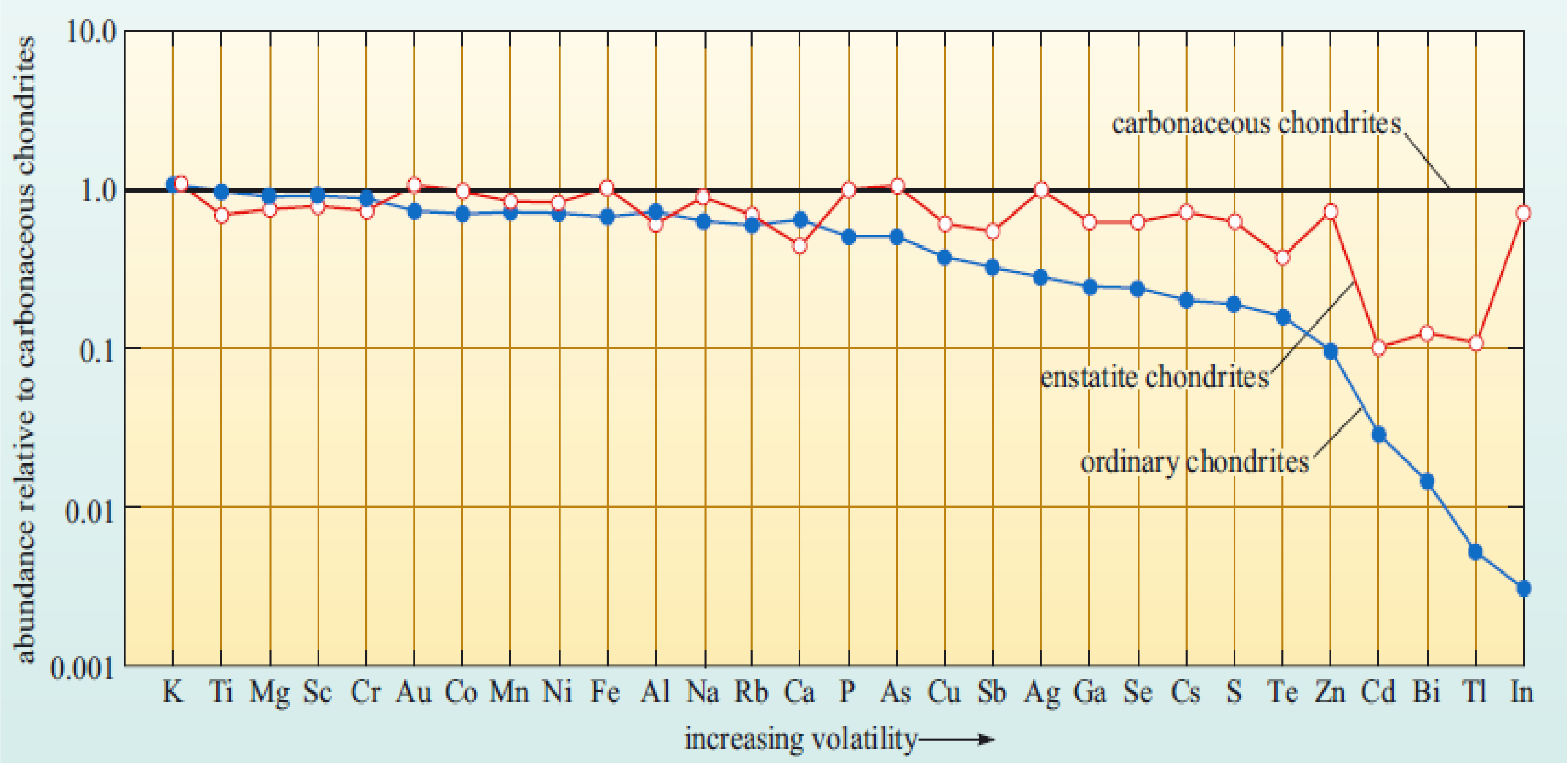


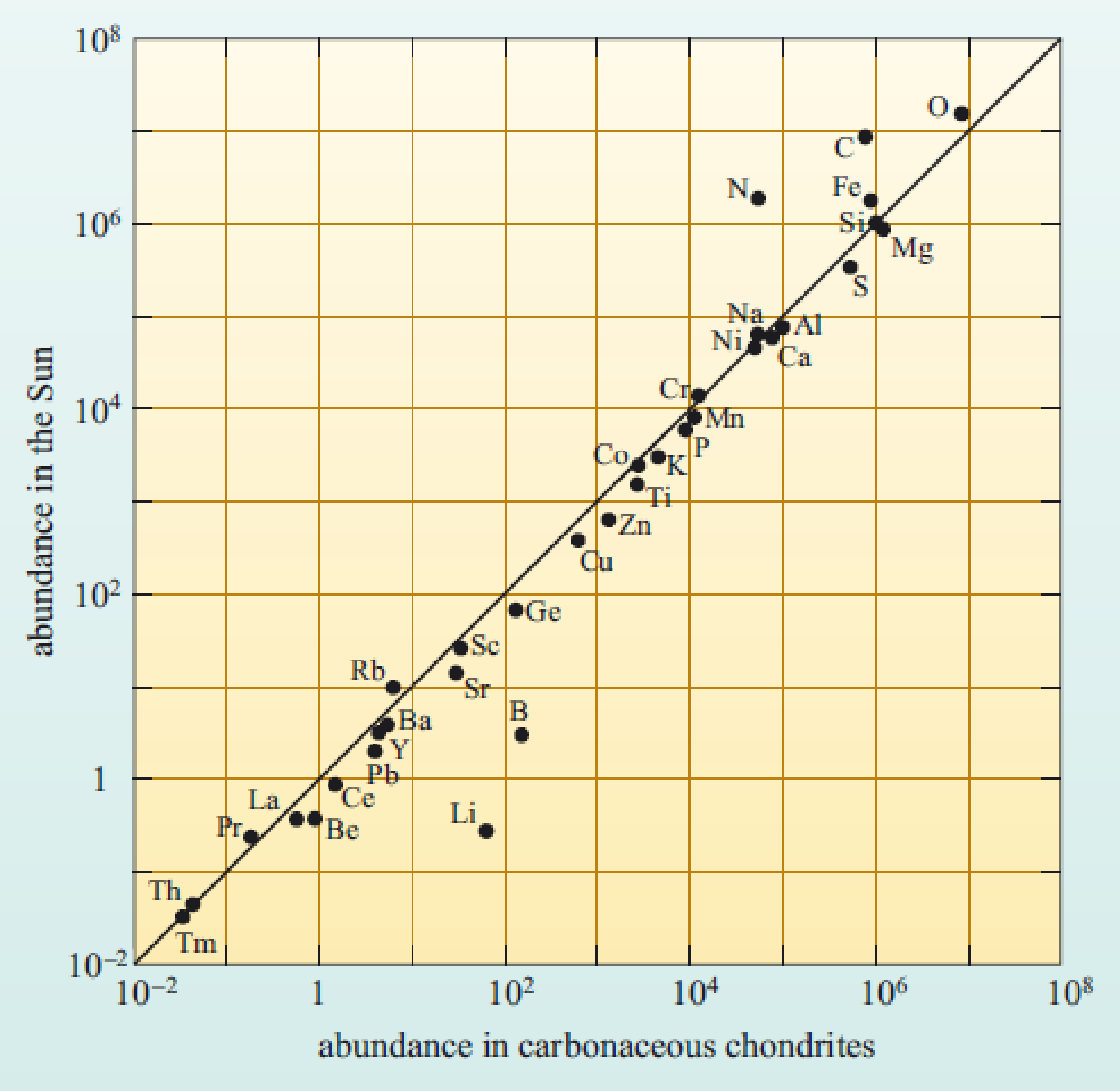
Figure 1.19 Comparison of the abundances of selected volatile elements in enstatite, ordinary and carbonaceous chondrites. Element abundances are normalised to carbonaceous chondrites. (McSween, 1987)

Which types of chondrite do you consider to be the most differentiated and which type the least differentiated?

The ordinary chondrites have lost a greater proportion of their volatile elements and so are more differentiated than the E-chondrites. The C-chondrites are therefore the least differentiated because they have not lost their volatile elements.

Thus C-chondrites appear to be have been least affected by processes after their formation.

This conclusion is borne out when their elemental compositions are compared with those of the **solar photosphere**, outer layer of the SUN.



The correlation for most elements is very good-

Li and B are depleted in the solar compositions relative to C-chondrites as they are used up in nuclear fusion reactions in the SUN.

C and N are relatively depleted in C-chondrites because They are amongst the most volatile elements.

Overall, it gives remarkable match between carbonaceous chondrites and Sun, gives confidence to take it as primordial material of the Solar System.

The composition of Earth layers

Seismic investigations suggest a two fold division into a dense core and an overlying mantle.
-Earth crust- 0.4 % of the Earth mass
Mantle – 68%

Which meteorite will give the best indications of the composition of planetary layers?

Earth is a differentiated planetary body, so the differentiated meteorite will give the best indications of the compositions of planetary layers.

The likely compositions of the core and mantle should now be
 fairly obvious-
Core- dense alloy of Iron and Nickel
Mantle- silicates composition- achondrite-rich in Mg.

How can we test these ideas?

Fortunatly volcanic and tectonic processes brings out mantle
 rocks analogue to some meteorites..direct comparison possible

but no such sample of core, so comparison between core
 and mantle is less direct.

The Earth's mantle-
Accidental fragments of rocks- xenoliths
distinctive because of green colour contrast with the grey black colour of the host volcanic rocks.
Termed as **peridotites**, rich in minerals olivine and pyroxene silicates rich in magnesium and iron.

Laboratory measurements of the density of peridotite (about 3200 kg m^{-3}), and their P-wave speeds (approximately 8.0 km s^{-1}), are a close match for the measured properties of the upper mantle.

Ophiolites- obducted oceanic crust- sedimentary rocks overlie rocks of basaltic composition, overlie peridotite.

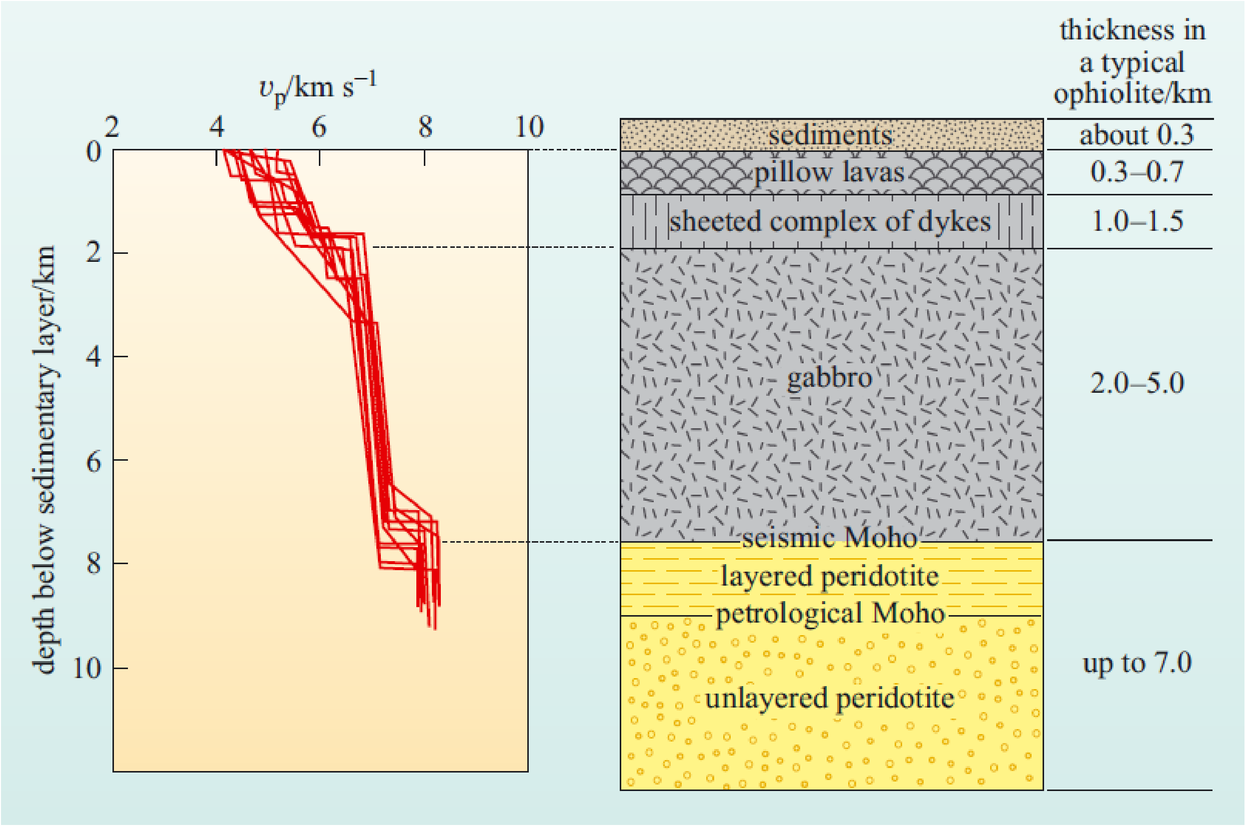


Figure 4.7 Seismic profile of 142 Ma-old oceanic crust in the Atlantic Ocean off the coast of Florida that lies beneath the surface layer of sediment. It shows a layered crustal structure that can be correlated with the layered geology seen in ophiolites. (Seismic profiles from White et al., 1992)

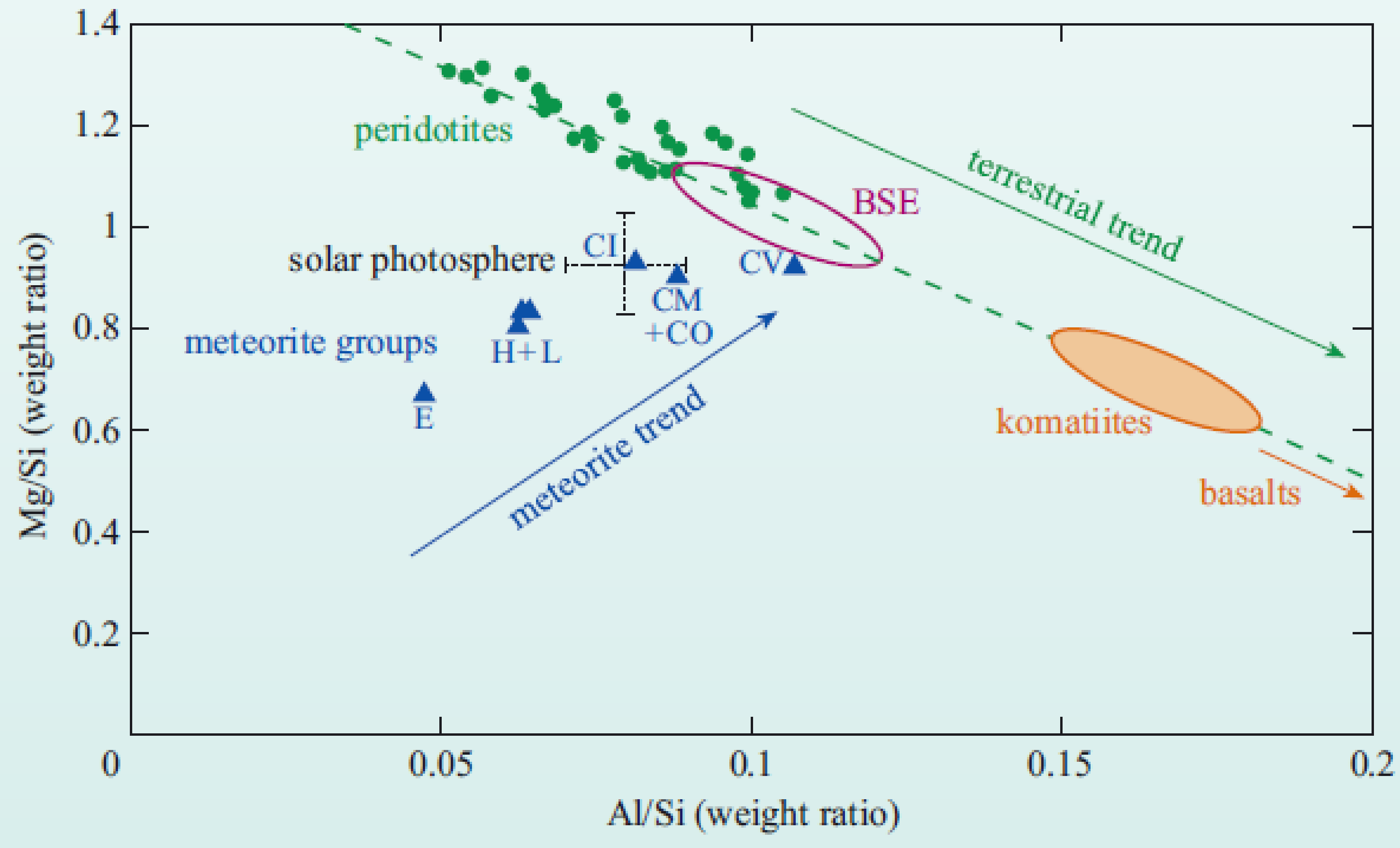
The peridotites found in ophiolites can be classed into two types based on their physical appearance: layered and unlayered. These are distinguished in Figure 4.7, but as they have the same P-wave velocities they cannot be distinguished seismically. The seismically defined Moho (i.e. the **seismic Moho**) is therefore interpreted as marking the shallowest occurrence of peridotite. Layered peridotites are thought to originate by crystallisation of olivine in magma chambers at constructive plate boundaries within oceanic crust, so the top of the mantle is best defined as being the

Following accretion, a deep terrestrial magma ocean…

Siderophile elements (Fe-Ni) to the core, leaving behind the early (primitive) silicate mantle/ BSE (bulk silicate Earth).

From the primitive silicate earth, the crust (continental and oceanic) was extracted from the early primitive mantle.

Direct comparisons between peridotite and carbonaceous chondrite are less easy because the mantle represents the silicate residue after core formation.
However, some camparison of element ratio is used, here Mg/Si against Al/Si in both meteorite and mantle samples used.



CI, CM, CO and CV = C-chondrite subgroups E, H, and L = types of chondrite

▲ average composition of meteorite groups

Peridotite shows a negative trend and reveals that composition of mantle is not constant – Mantle is heterogeneous

The cause of this variation are indicated by the position of basalts and komatiites lies on the extension of the peridotite.
Basaltic magma is derived from the mantle by a process known as partial melting.

Average meteoritic composition define a positive trend, in contrast to peridotites. Although the origin of variation remains unclear, the intersection of the positive meteorites trend with the terrestrial array has been used to define the composition of the primitive mantle.

Although Chondritic Earth model has been used as a standard for many decades, it is established that the bulk silicate Earth does not have a composition represented by any meteoritic group and so not directly comparable with the solar photosphere.

Only class of meteorite that do fall on the terrestrial array are an unusual group of meteorites designated CV

Other elements can be investigated in a similar way, relative to CI meteorite.

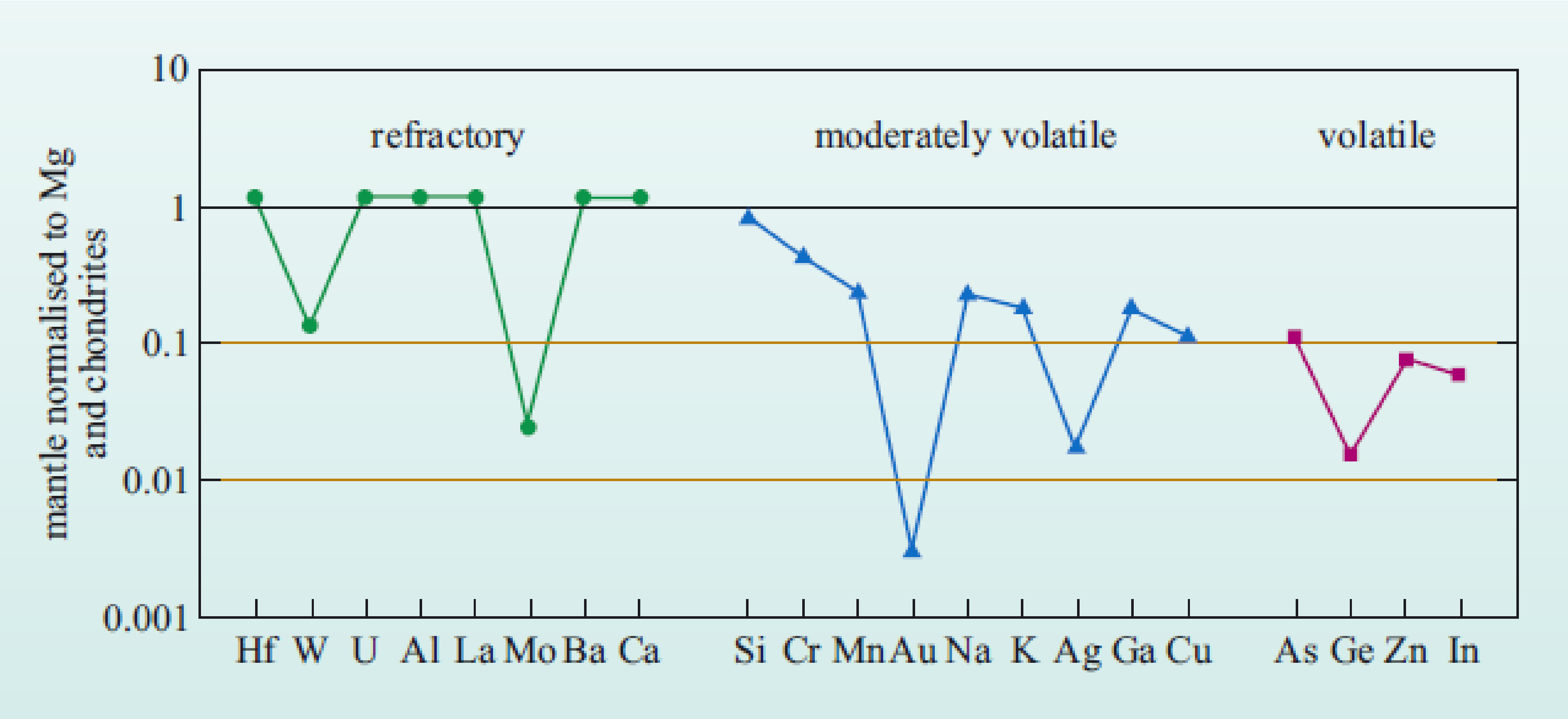


Figure 1.22 The abundances of selected trace elements in the bulk silicate Earth normalised to the composition of CI meteorites, in order of increasing volatility from left to right. (Abundances taken from McDonough and Sun, 1995)

The abundances of the different elements are all normalised to that of Mg, and it shows that elements such as aluminium (Al), calcium (Ca) and uranium (U) retain the same relative abundances in the Earth's mantle as they have in CI meteorites and hence the Sun.

Relative to CI meteorites, the Earth's mantle is depleted in volatile elements and this may in part explain the difference between the estimated bulk composition of the Earth and the different meteorite classes....

Earth has lost a greater proportion of its volatile components compared with meteorites.

Basic geochemical and cosmochemical properties
Three major phases- 1. metal
2. Silicate and
3. Sulfide in meteorites and other natural
Materials.

Elements that are found in the metallic phase of a
natural system are referred to as **siderophiles** (from the Greek, sideros, meaning iron and philos, meaning like or love – literally iron-loving).

They contrast with those
elements that preferentially bond with oxygen, especially in silicate or oxide structures, which are known as **lithophiles** (from the Greek Lithos meaning stone).

There is also a subgroup of lithophile elements that tend to be gaseous at the Earth’s surface, notably H, C, N, O and the noble gases, that are referred to as **atmophiles**.

A third major grouping refers to elements that frequently occur bound with sulfur and these are known as **chalcophiles** (from the Greek khailos, meaning copper, an element commonly found as a sulfide).

Electronegativity (E)- the ability of an atom to attract electrons and so form a negatively charged ion.

Lithophiles- E <1.6; forming positive ions that bond with negative oxygen ions.

Chalcophile- 1.6 < E < 2.0; they more readily form covalent bonds with elements such as S.

Siderophile- 2.0 < E < 2.4; most readily form metallic bonds.

Elements with E >2.4, such as O, N and the halogen elements, F, Cl, Br and I, readily attract electrons to form negative ions and form ionic bonds with the lithophile elements with low E

$$D = \frac{\text{concentration of element } i \text{ in phase } a}{\text{concentration of element } i \text{ in phase } b}$$

$$D = \frac{C_a^i}{C_b^i} \qquad (1.7)$$

In the case distribution coefficient is between molten metallic iron and solid silicate minerals.

The convention is for the numerator (Ci) to be allocated to the liquid a and Ci the denominator (b) to be allocated to the solid b. Thus, a lithophile element will have a D value of <1
and a siderophile element will have a D value of >1.

In these systems elements that partition into a solid phase are said to be **compatible**, whereas those that are excluded and concentrate in the silicate liquid are said to be **incompatible**.

Core formation involved the gravitational separation of molten metallic iron from silicate melt or solid crystals.

By analogy with iron meteorites, which are considered to be representative of the cores of small planetary bodies, this iron selectively removes a number of other elements that, because of their chemical properties, bond more easily with iron than they do with silicates; W is one of these so-called siderophile elements

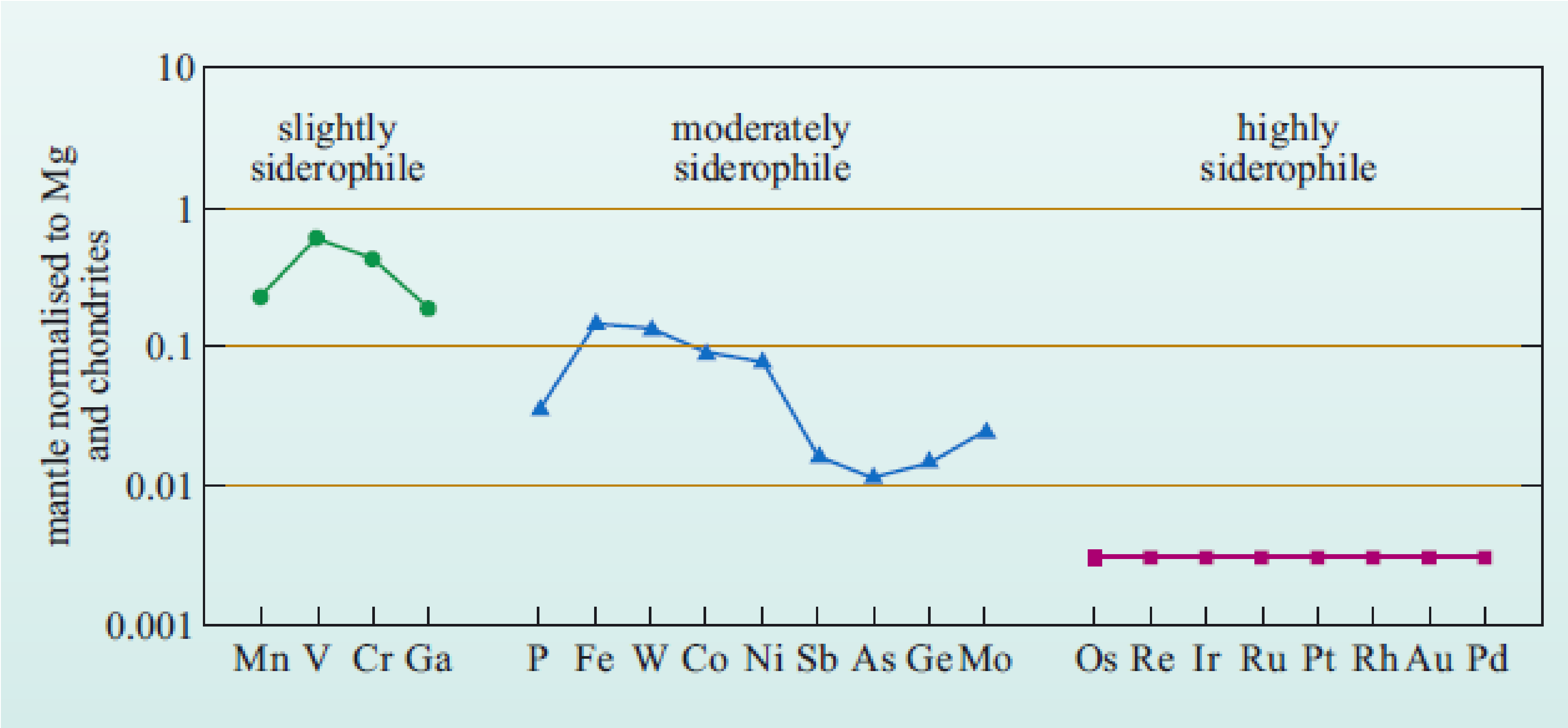


Figure 1.24 Abundances of the siderophile elements in the Earth's mantle relative to CI meteorites. (Data from McDonough and Sun, 1995)

Elements on the right are increasingly siderophile. Clearly, the more siderophile elements are more depleted in the Earth's mantle

Present-day composition of the Earth's mantle may be similar to that of some C-chondrites. The ratios of refractory lithophile elements (e.g. Ca, Al, Mg, U, Th and rare earth elements) in the mantle are similar to those in chondritic meteorites generally, indicating a close link with primordial (solar) abundances.

But the mantle is depleted in both volatile and siderophile elements.

The latter are now presumably concentrated in the core, whereas the volatile elements were probably lost during accretion or even earlier during condensation from the solar nebula. The important result, however, is that the abundances of elements within the mantle are controlled systematically by their geochemical and cosmochemical properties.