

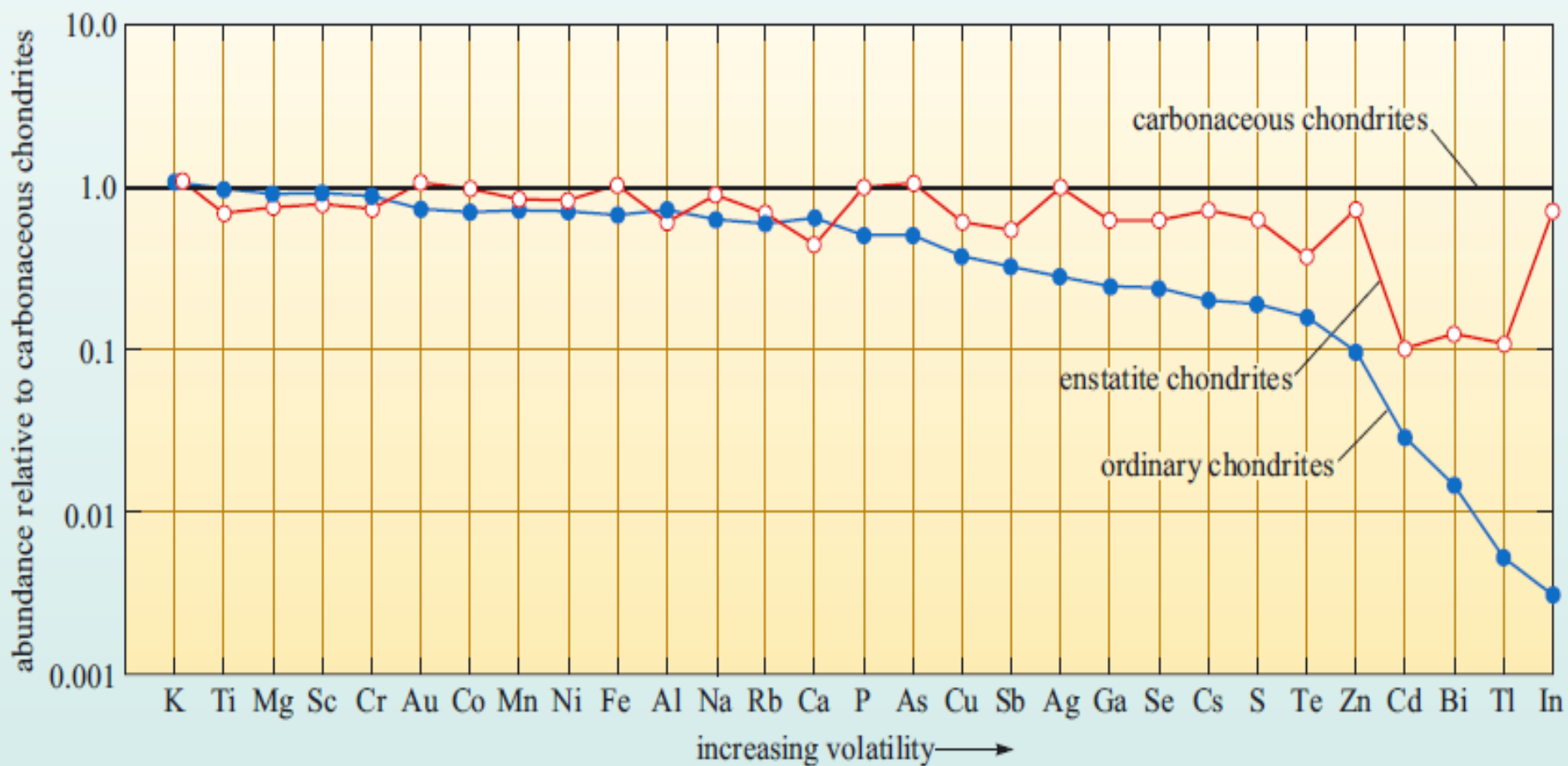
## **The most primitive material?**

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.



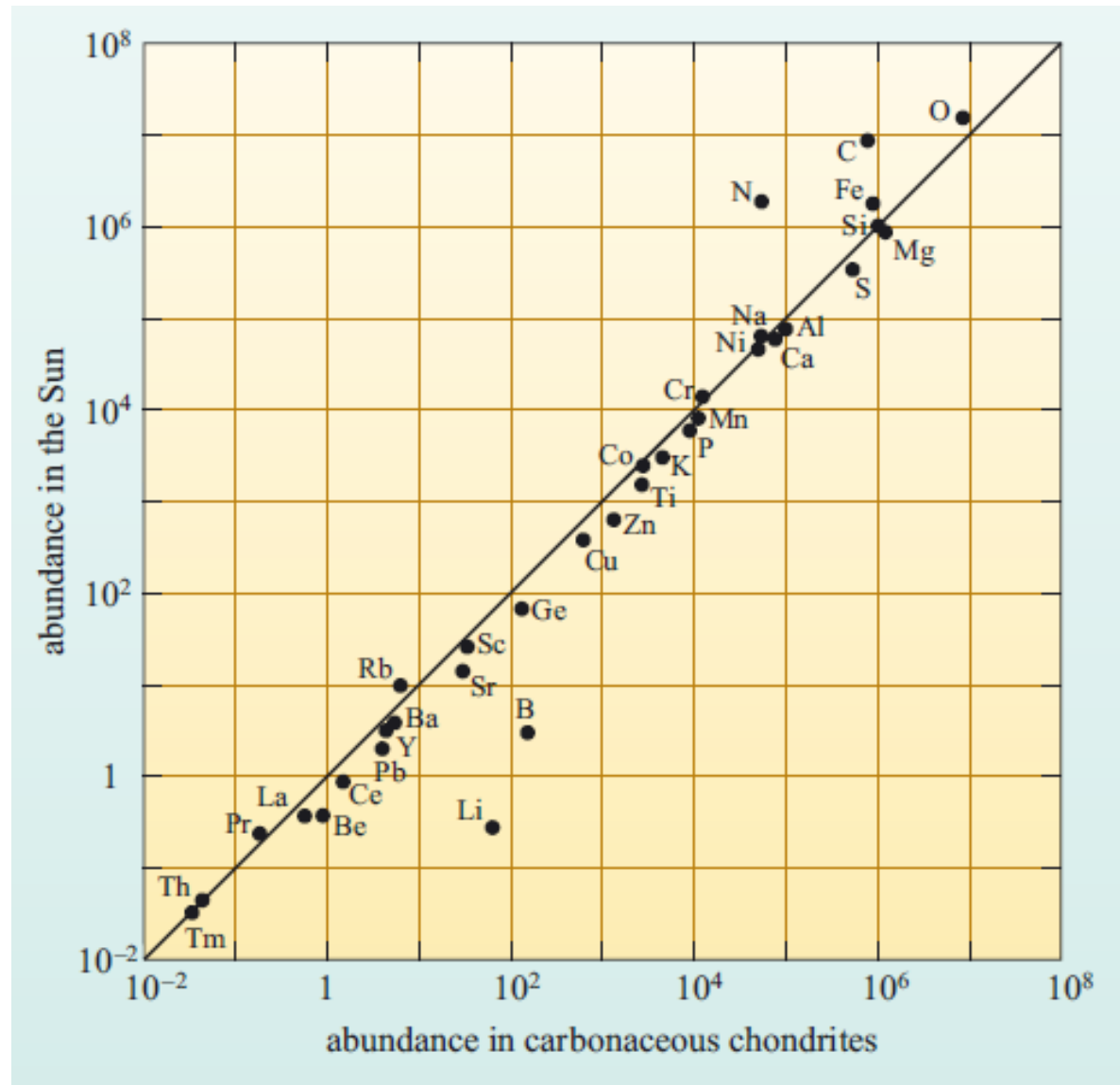
**Figure 1.19** Comparison of the abundances of selected volatile elements in enstatite, ordinary and carbonaceous chondrites. Element abundances are normalised to carbonaceous chondrites. (McSween, 1987)

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 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?

Fortunately 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

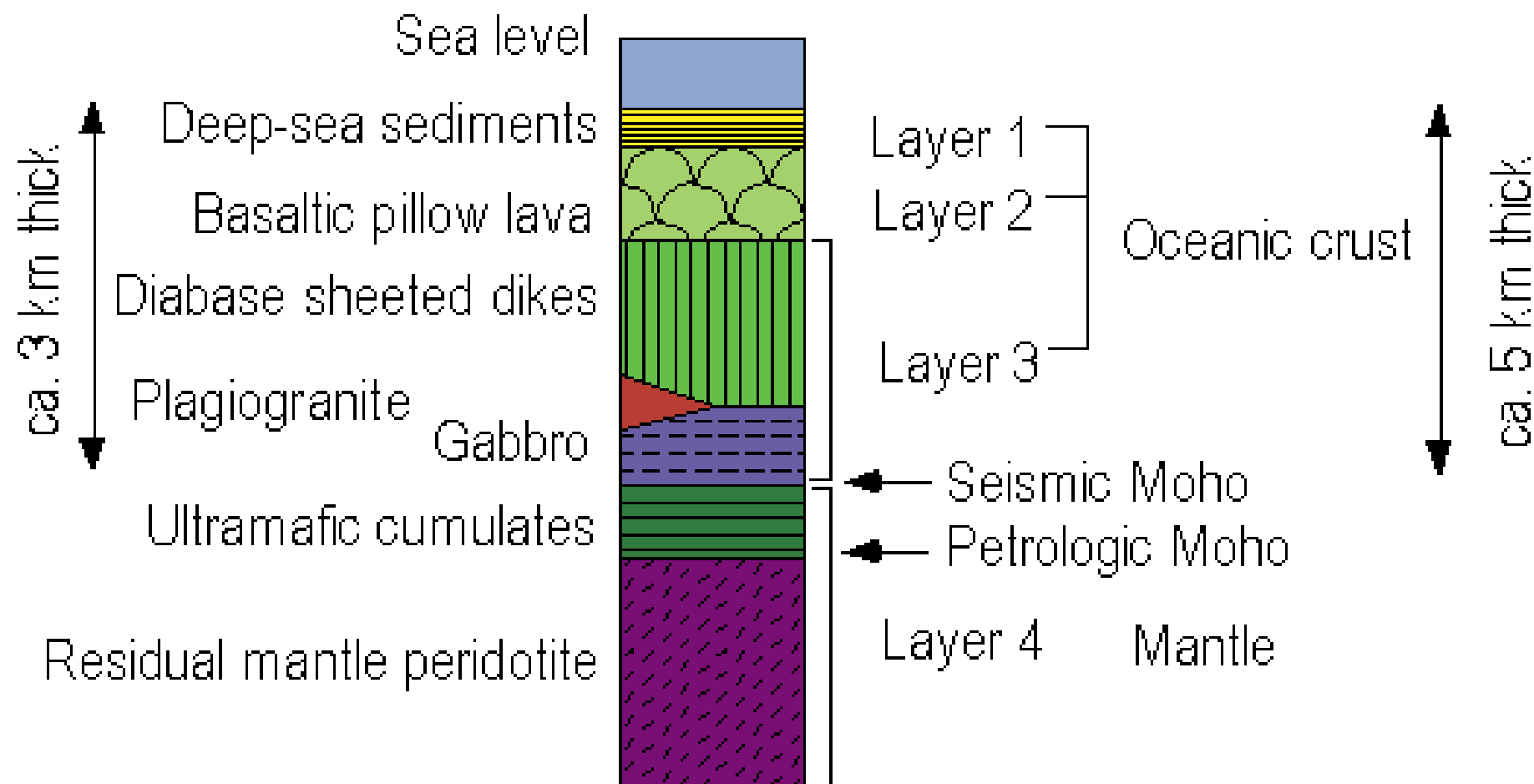
distinctive because of green colour contrast with the grey black colour of the host volcanic rocks.

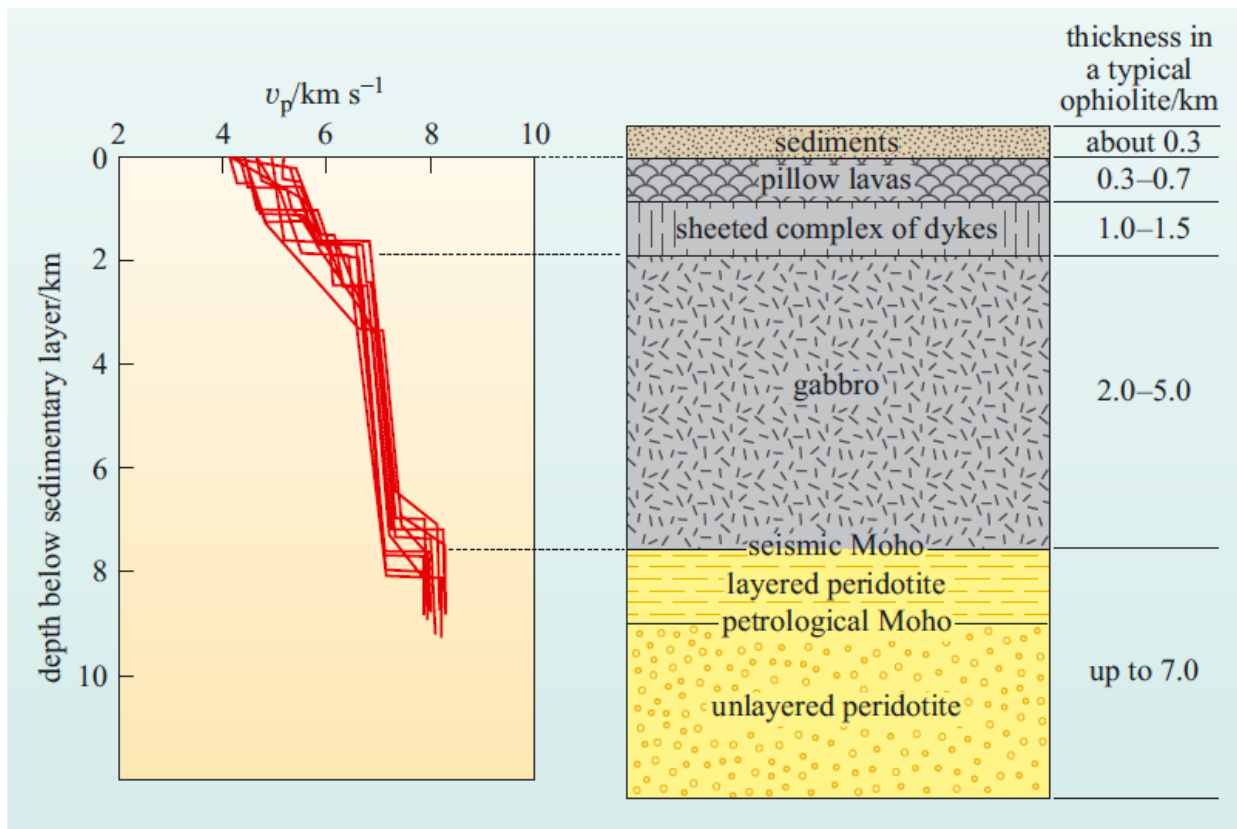
Termed as **peridotites**, rich in minerals olivine and pyroxene silicates rich in magnesium and iron.

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

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

# Ophiolite succession and seismic layers of oceanic crust





**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

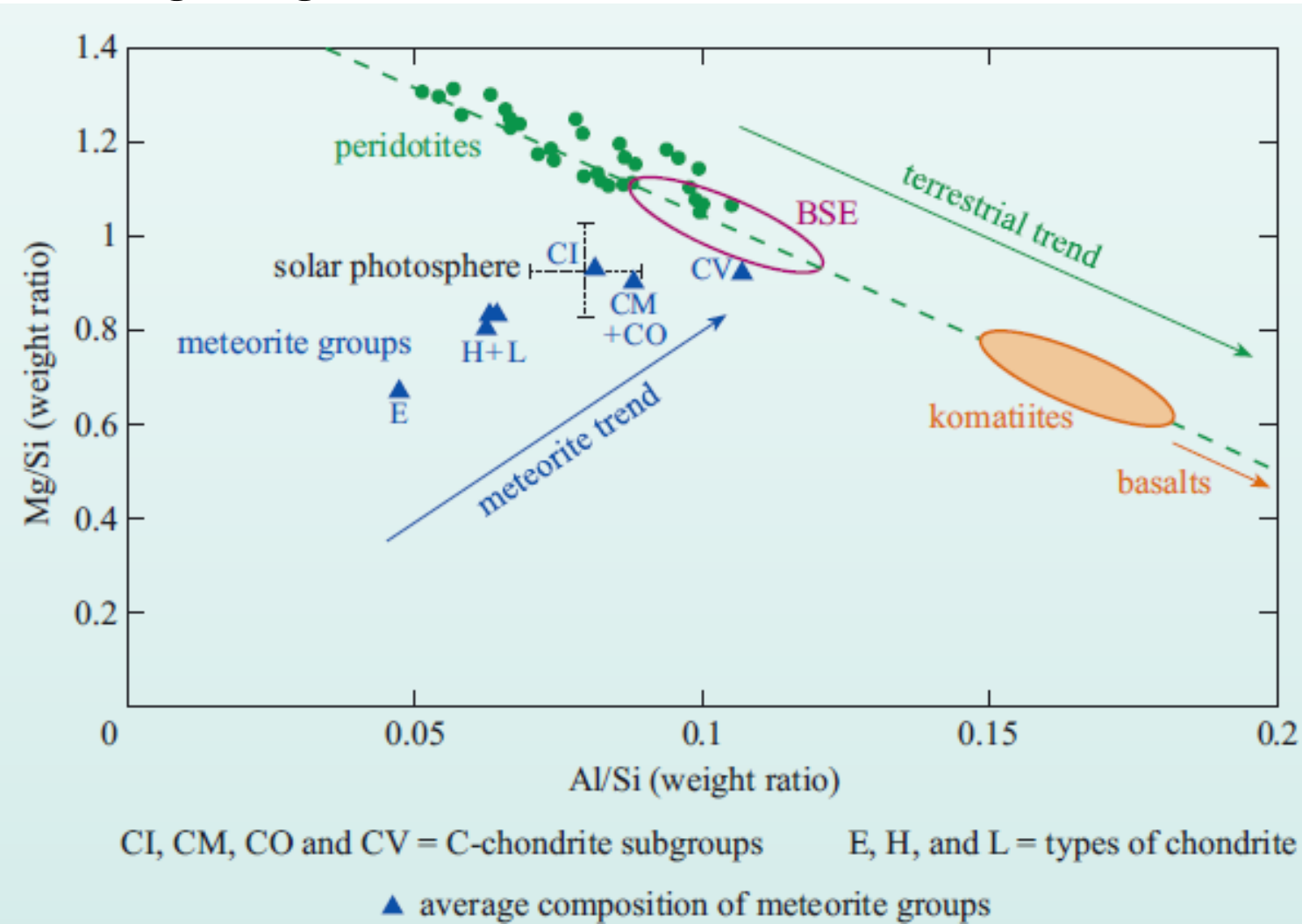
**Following accretion, a deep terrestrial magma ocean...**

**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 comparison of element ratio is used, here Mg/Si against Al/Si in both meteorite and mantle samples used.



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.

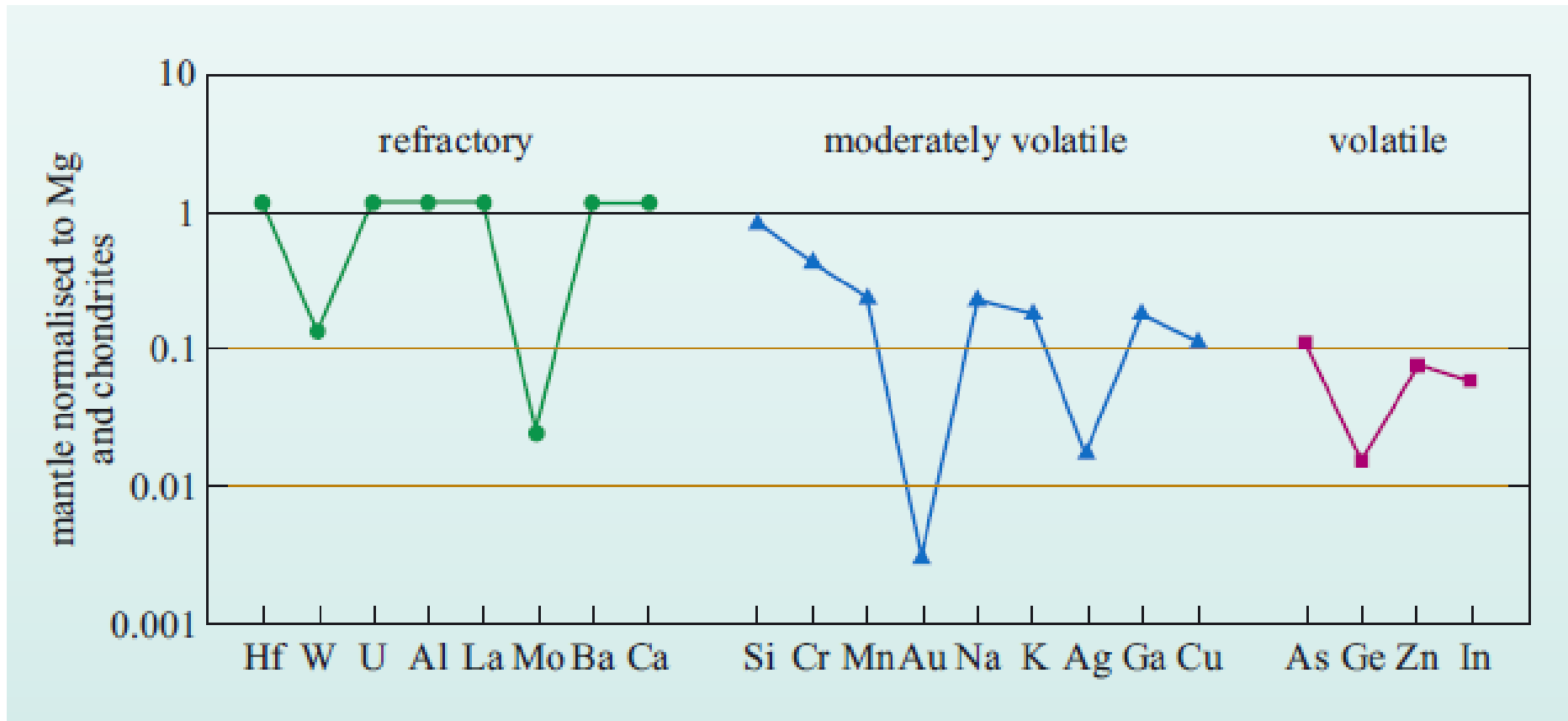
Basaltic magma is derived from the mantle by a process known as partial melting.

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

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

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

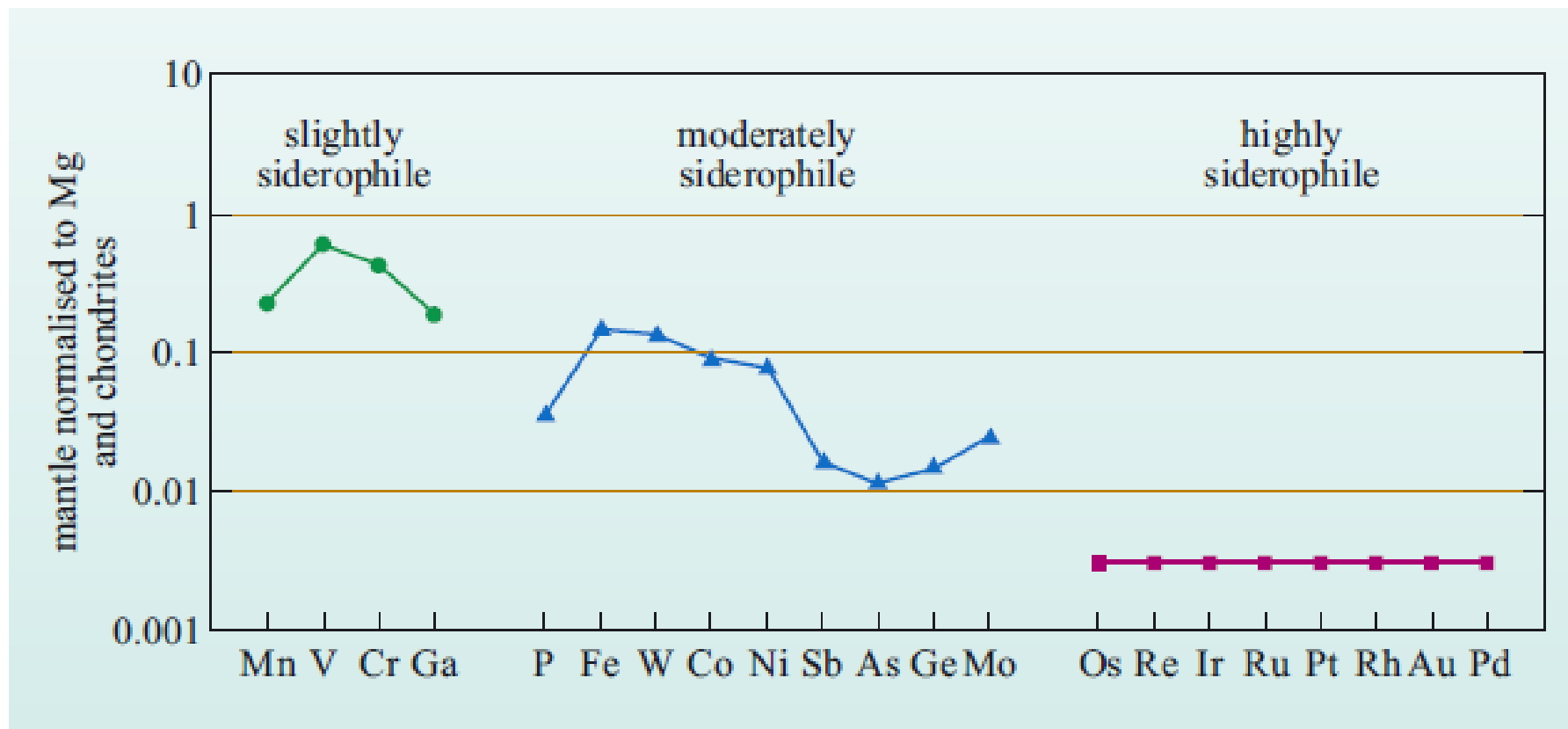
In the case distribution coefficient is between molten metallic iron and solid silicate minerals.

The convention is for the numerator ( $C_i$ ) to be allocated to the liquid a and  $C_i$  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.



A useful way of referring to the rate of decay of a radionuclide is by its **half-life** ( $t_{1/2}$ ), which is the time required for half of the parent atoms to decay.

On substituting  $n = \frac{n_0}{2}$  and  $t = t_{1/2}$  into Equation 2.4:

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}, \text{ where } \ln 2 \text{ is the natural log of } 2. \quad (2.5)$$

The number of radiogenic daughter atoms formed ( $D^*$ ) is equal to the number of parent atoms consumed (Figure 2.1). So:

$$D^* = n_0 - n \quad (2.6)$$

The total number of daughter atoms ( $D$ ) consists of those produced by radioactive decay after time  $t$  (i.e.  $D^*$ ) plus those already present at time  $t = 0$  (i.e.  $D_0$ ), that is:

$$D = D_0 + D^*. \quad (2.7)$$

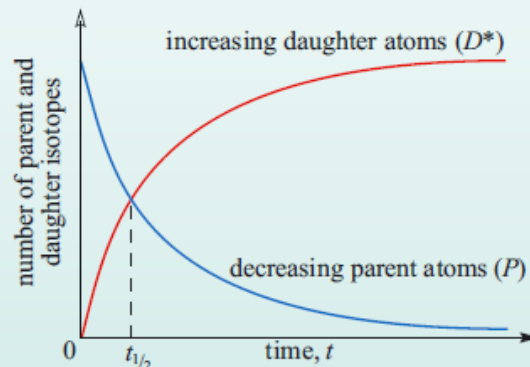
As  $D^* = n_0 - n$  (Equation 2.6) we can substitute  $D^*$  in Equation 2.7:

$$D = D_0 + n_0 - n$$

Since  $n_0 = ne^{\lambda t}$  (from Equation 2.4):

$$D = D_0 + ne^{\lambda t} - n$$

$$D = D_0 + n(e^{\lambda t} - 1) \quad (2.8)$$



**Figure 2.1** The changing number of parent and daughter atoms during radioactive decay. This illustrates that the growth of radiogenic daughter atoms ( $D^*$ ) is the mirror image of the decay curve of the number of parent atoms ( $n_0$ ). The half-life ( $t_{1/2}$ ) is the time taken for half of the parent atoms to decay (at which point  $n_0 = D^*$ ).

**Table 2.1** Naturally occurring radioactive decay systems of geochemical and cosmochemical interest.

Parent	Decay mode*	Decay constant ( $\lambda$ )/ y <sup>-1</sup>	Half-life/y	Present heat production <sup>‡</sup>	Daughter isotopes	Measured ratio
<sup>40</sup> K	$\beta^+$ , e.c., $\beta^-$	$5.54 \times 10^{-10}$	$1.28 \times 10^9$	2.8	<sup>40</sup> Ar, <sup>40</sup> Ca	<sup>40</sup> Ar/ <sup>36</sup> Ar
<sup>87</sup> Rb	$\beta^-$	$1.42 \times 10^{-11}$	$4.88 \times 10^{10}$		<sup>87</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr
<sup>147</sup> Sm	$\alpha^\dagger$	$6.54 \times 10^{-12}$	$1.06 \times 10^{11}$		<sup>143</sup> Nd	<sup>143</sup> Nd/ <sup>144</sup> Nd
<sup>187</sup> Re	$\beta$	$1.59 \times 10^{-11}$	$4.35 \times 10^{10}$		<sup>187</sup> Os	<sup>187</sup> Os/ <sup>188</sup> Os
<sup>232</sup> Th	$\alpha$	$4.95 \times 10^{-11}$	$1.39 \times 10^{10}$	1.04	<sup>208</sup> Pb, <sup>4</sup> He	<sup>208</sup> Pb/ <sup>204</sup> Pb, <sup>3</sup> He/ <sup>4</sup> He
<sup>235</sup> U	$\alpha$	$9.85 \times 10^{-10}$	$7.07 \times 10^8$	0.04	<sup>207</sup> Pb, <sup>4</sup> He	<sup>207</sup> Pb/ <sup>204</sup> Pb, <sup>3</sup> He/ <sup>4</sup> He
<sup>238</sup> U	$\alpha$	$1.55 \times 10^{-10}$	$4.47 \times 10^9$	0.96	<sup>206</sup> Pb, <sup>4</sup> He	<sup>206</sup> Pb/ <sup>204</sup> Pb, <sup>3</sup> He/ <sup>4</sup> He
<sup>26</sup> Al	$\beta^-$	$9.5 \times 10^{-7}$	$0.73 \times 10^6$		<sup>26</sup> Mg	<sup>26</sup> Mg/ <sup>24</sup> Mg
<sup>129</sup> I	$\beta^-$	$4.41 \times 10^{-8}$	$1.57 \times 10^7$		<sup>129</sup> Xe	<sup>129</sup> Xe/ <sup>130</sup> Xe
<sup>146</sup> Sm	$\alpha$	$6.73 \times 10^{-9}$	$1.03 \times 10^8$		<sup>142</sup> Nd	<sup>142</sup> Nd/ <sup>144</sup> Nd
<sup>182</sup> Hf	$\beta^-$	$7.78 \times 10^{-8}$	$8.9 \times 10^6$		<sup>182</sup> W	<sup>182</sup> W/ <sup>184</sup> W
<sup>244</sup> Pu	$\alpha$ , SF	$8.45 \times 10^{-9}$	$82 \times 10^6$		<sup>n</sup> Xe	<sup>n</sup> Xe/ <sup>130</sup> Xe**

\*  $\alpha$  = alpha decay (<sup>4</sup>He);  $\beta^-$  = beta decay (electron or positron); e.c. is electron capture; SF is spontaneous fission.

† The production of <sup>4</sup>He from <sup>147</sup>Sm decay is insignificant compared with that produced by decay of U and Th.

‡ Heat production averaged for the whole Earth in units of 10<sup>-12</sup> W kg<sup>-1</sup> of Earth material (not of the isotope).

\*\* *n* can be 124, 126, 128 or 129, all of which are produced by <sup>244</sup>Pu fission. Element symbols are listed in the Appendix.

