Composition of the Earth

Lecture 2

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Composition of the Earth
Sources of Information

– Our information about composition of the Earth come from two types of the sources:

1. *Direct Sources*

- –From direct observation, ***core samples***, and ***drilling projects***, scientists have been able to study the rock layers near the planet's surface. However, this knowledge is limited. The deepest drill hole, just over 9 miles (15 kilometers) in depth, penetrates only about 0.2 percent of the distance to Earth's center.

Composition of the Earth
Sources of Information

- *Geologists* collect information about Earth's remote interior from several different sources. *Some rocks* found at Earth's surface originate deep in Earth's crust and mantle. *Meteorites* that fall to the planet are also believed to be representative of the rocks of Earth's mantle and core. *Meteor fragments* presumably came from the interior of shattered extraterrestrial bodies within our solar system. It is likely that the composition of the core of our own planet is very similar to the composition of these extraterrestrial travelers.

Composition of the Earth
Sources of Information

2. Indirect Sources

- Another source of information, while more indirect, is perhaps more important. That source is ***seismic***, or ***earthquake***, ***waves***. When an earthquake occurs anywhere on Earth, seismic waves travel outward from the earthquake's center. The speed, motion, and direction of seismic waves changes dramatically as they travel though different mediums (areas called transition zones). Scientists make various assumptions about the composition of Earth's layers through careful analysis of seismic data, a method called subsurface detection.

Meteorites as Indicators of Planetary Compositions

- As we mentioned in Lecture 1, meteorites are of several kinds, with compositions ranging from 100% metal to 100% stone, but they are commonly of a mixture.
- Their relevance to the composition of the Earth hinges on evidence that they were derived from a common source in the solar nebula by a variety of events and processes, and that their total composition is similar to that of the nebula from which the terrestrial planets accreted.
- There are four observations which provide convincing evidence and invite the obvious conclusion that the Earth and other terrestrial planets formed from the same primordial brew:

Meteorites as Indicators of Planetary Compositions

- Almost all meteorites have a common formation age, about 4.57 Ga .
- The meteorites have the same isotopic ratios as one another (and the Earth).
- Abundances of elements in the solar atmosphere (Table 1.) are consistent with the overall composition of meteorites.
- All of the meteorite types can , in principle, be produced from the most primitive type , the carbonaceous chondrites ,by heating and reduction with some segregation of the processed material.

Table 1.
Values are normalized to the abundance of Silicon.

Mass of most abundant Isotope	Element	Sun	Meteorites	Earth
1	H	1003		
4	He	392	-	-
16	O	13.6	2.2	2.22
12	C	4.4	0.33	
20	Ne	3.5		
56	Fe	2.6	1.81	2.14
14	N	1.6	0.001	20ppm
28	Si	1	1	1

Table 1.(continued)

Values are normalized to the abundance of Silicon.

24	Mg	0.91	0.91	1.09
32	S	0.52	0.60	0.20
36	Ar	0.13	20ppb	20ppb
58	Ni	0.105	0.105	0.16
40	Ca	0.092	0.088	0.12
27	Al	0.080	0.082	0.11
23	Na	0.049	0.047	0.013

The Mantle

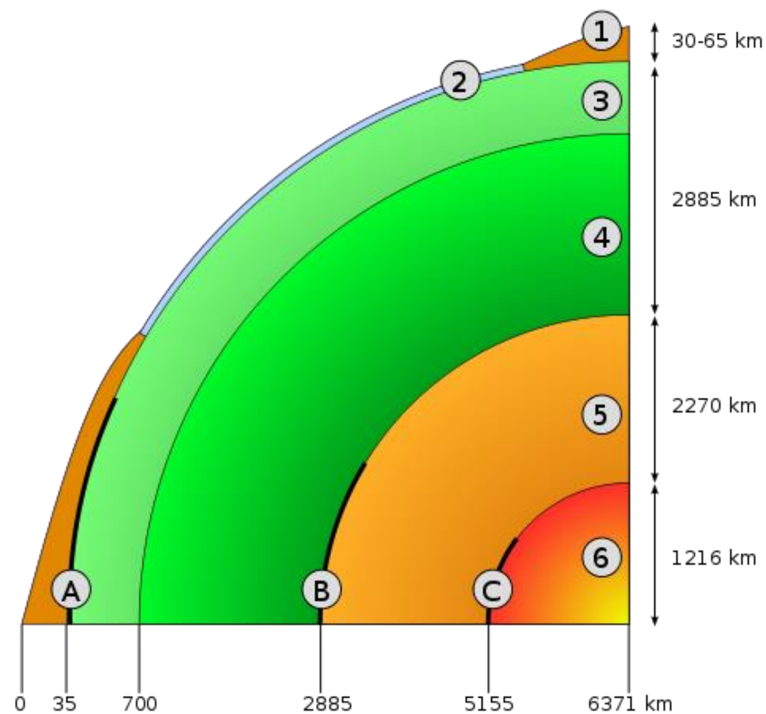
- The mantle starts about 30 kilometers down and is about 2890 kilometers thick (Figure 1).
- The mantle makes up to 82% of the volume of the Earth and 65% of its mass.
- The seismic structure of the mantle points to major discontinuities at 410 km , 600 km and *D''* layer above the core – mantle boundary which also pronounced lateral heterogeneities. The Shallower discontinuities at 410 km and 600 km can be related to phase transformations of olivine.

The Mantle

Figure 1. Structure of the Earth

1. Continental Crust 2. Oceanic Crust 3. Upper Mantle 4.Lower Mantle

5. Outer Core 6. Inner Core A. Moho Discontinuity B.Gutenberg Discontinuity C. Lehmann Discontinuity



The Mantle

- The better known mantle composition estimates from the literature are listed in Table 2.

Table 2. Mantle bulk major elements compositions

Oxides	Hofmann (1988)	Hart and Zindler (1986)	Ringwood (1966)
SiO_2	45.96	46.38	45.2
MgO	37.78	38.12	37.5
FeO	7.54	7.619	8.0
Al_2O_3	4.06	4.097	3.5
CaO	3.21	3.239	3.1
Na_2O	0.332	0.333	0.57

Table 2. (continued)

Cr_2O_3			0.43
MnO			0.14
P_2O_5			0.06
K_2O		0.032	0.13
TiO_2	0.181	0.182	0.17

Composition of the Mantle

- Studies of samples brought from the mantle to the surface of the Earth like , diamonds and xenoliths, by volcanic processes have indicated that the composition of the mantle , up to a depth of 150 km , is dominantly peridotitic , a rock composed of olivine and pyroxene.
- Peridotite is a combination of olivine with two pyroxenex , orthopyroxene and clinopyroxene , with slightly different structures and densities but the same chemical formula. Clinopyroxenes are more variable in composition than orthopyroxenes.

Composition of the Mantle (continued)

-with increasing pressure a third mineral type , garnet , becomes important . Pyrope is a garnet with the formula $Mg_3Al_2Si_3O_{12}$ and a mean atomic weight of 20.156.

- The phase transition in olivine are clearest and explain the seismologically observed boundaries.
- The successive crystal structures of forsterite , with densities extrapolated to zero pressure and 290 k , are listed in Table 3. with transition pressures and corresponding mantle depths. The density increments at the 410km and 660 km boundaries are dominant.

Table 3. Phase transitions in olivine , Mg_2Sio_4.

Crystal structure	P_0 (kg m^{-3})	P_0 Δ(kgm^{-3})	P (Gp_a)	z
Forsterite	3327			
		246	13.7	410
Bspinel (Wadsleyite)	3473			
		75	17.9	520
γ spinel (Ringwoodite)	٣٥٤٨			
		٣٩٥	23.3	660
$Mg SiO_3$ perovskite				
	4107			
+ MgO periclase	٣٥٨٣	~ 60		
	3943			
	(together)	~ 4004	~ 120	~2600
		(together)		
‘post-perovskite’				
+ MgO periclase				

Composition of the Mantle (continued)

- The transitions in pyroxenes are not as sharp and may not contribute to the observed boundaries. But, as in Table 4, they follow a similar trend.
- The lower mantle is dominated by perovskite and magnesiowustite (ferropericlase), with a greater concentration of Fe in the magnesiowustite and perovskite taking up the Al.
- In total mass the (Mg – Fe) perovskite must be dominant , comprising 75% to 80% of the lower mantle , making it the most abundant mineral in the Earth.

Table 4. Phase transitions in orthopyroxene , $MgSiO_3$

Crystal structure	P_0 (kg m^{-3})	ΔP_0 (kg m^{-3})
Enstatite	3204	
		٣٠٩
Garnet	٣٥١٣	
		٢٩٧
ilmenite	٣٨١٠	
		٢٩٧
Perovskite	٤١٠٧	
		$\approx$ 100
‘post-perovskite’	$\approx$ 4200	

The Core

- Seismic measurements show that the *core* is divided into two parts, a *solid inner core* with a radius of 1220 km and a *liquid outer core* extended beyond it.
- The solid inner core is discovered in 1936 by Inge Lehman . The inner core is generally believed to be composed primarily of iron and some nickel.
- Since the average density of the Earth is 5515 kg/m^3, and the average density of surface material is only around 3000 kg/m^3, we must conclude that denser materials exist within Earth's core.

The Outer Core

-The **outer core** of the Earth is a liquid layer about 2260 kilometers thick composed of iron and nickel which lies above the Earth's solid inner core and below mantle. The transition between the inner core and outer core is located approximately 5150km beneath the Earth’s surface.

-The *outer core* is not under enough pressure to be solid, so it is liquid even though it has a composition similar to that of the inner core. *sulfur* and *oxygen* could also be present in the outer core.

The Outer Core

- The temperature of the outer core ranges from 6100 °C near the inner core to 4400 °C in the outer regions.
- Without the outer core, life on Earth would be very different. Convection of liquid metals in the outer core creates the Earth's magnetic field.

  –This magnetic field extends outward from the Earth for several thousand kilometers, and creates a protective bubble around the Earth that deflects the solar winds. Without this field, the solar wind would directly strike the Earth’s atmosphere.

The Inner Core

- The *inner core of the Earth* ,its innermost hottest part as detected by seismological studies, is a primarily solid sphere about 1220 km in radius .
- Based on the abundance of chemical elements , their physical properties and other chemical constraints regarding the remainder of Earth's volume, the inner core is believed to be composed primarily of a nickel iron alloy with very small amounts of some other elements.

The Inner Core

–The temperature of the inner core can be estimated using experimental and theoretical constraints on the melting temperature of impure iron at the pressure (about 330 Gpa) of the inner core boundary, yielding estimates of 5,430 °C. ---The range of pressure in Earth's inner core is about 330 to 360 Gpa (3,300,000 to 3,600,000 atm) and iron can only be solid at such high temperatures because its melting temperature increases dramatically at these high pressures.

The Inner Core

- Recent evidence has suggested that the inner core of Earth may rotate slightly faster than the rest of the planet.
- The inner core rotates in the same direction as the Earth and slightly faster, completing its once-a-day rotation about two-thirds of a second faster than the entire Earth.

The Crust

-The crust covers the mantle and is the earth's hard outer shell, the surface on which we are living. Compared to the other layers the crust is much thinner. It floats upon the softer, denser mantle.

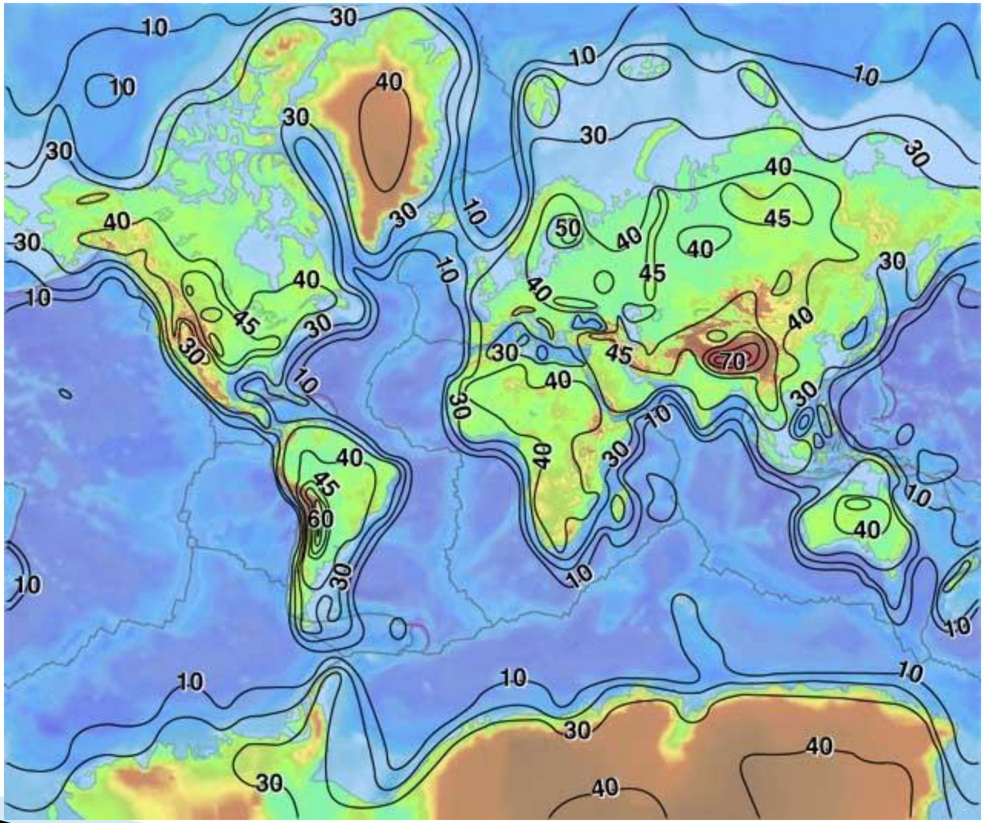
- Most of the crust is either of continental type or ocean basin type and the two are structurally very different.

- The crustal thickness of the ocean basins is about 7 km, including sediments but not the depth of sea water.

- The thickness of the continental crust averages 39 km , with a maximum of 65 km under the Himalaya (Figure 2.)

The Crust

Figure 2. The Contour Map of thickness of the Earth' Crust

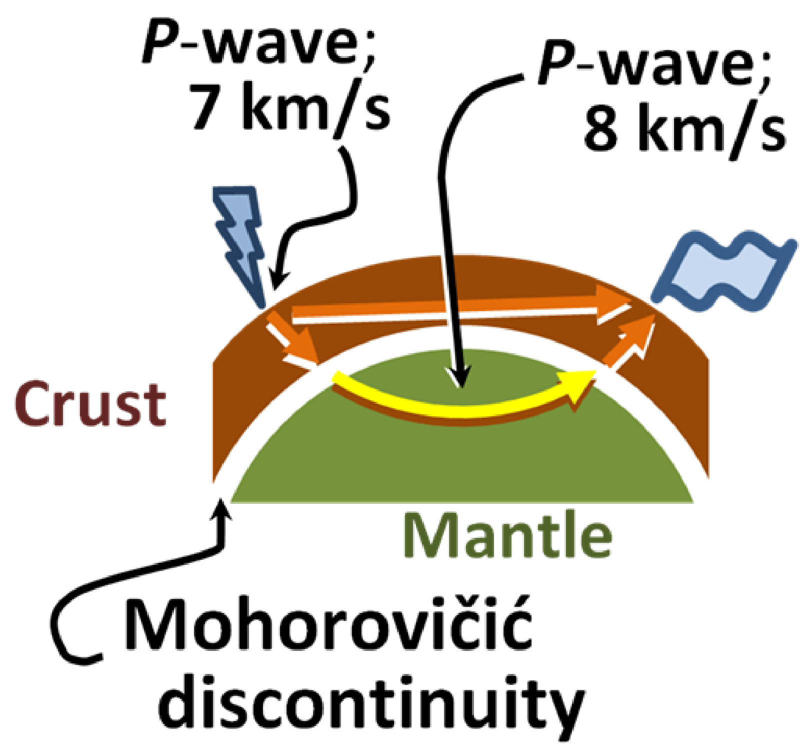


The Crust

- The crust – mantle boundary , the Mohorovičić discontinuity (Moho) , is sufficiently clearly observed by seismology to establish that it is distinct everywhere , except at mid – ocean ridges . At this boundary , there is a sudden change in seismic waves velocities , densities and the elastic constants (Figure 3.)

The Crust

Figure 3.Moho Discontinuity.



Composition and Age of Oceanic Crust

- Estimations of composition of the oceanic crust are based on:

1. Analysis of ophiolites (sections of oceanic crust preserved on the continents).
2. Comparisons of the seismic structure of the oceanic crust with laboratory determinations of seismic velocities in known rock types.
3. Samples recovered from the ocean floor by submersibles , dredging and drilling .

- Oceanic crust generally can be divided into three layers (Figure 4):

Composition and Age of Oceanic Crust

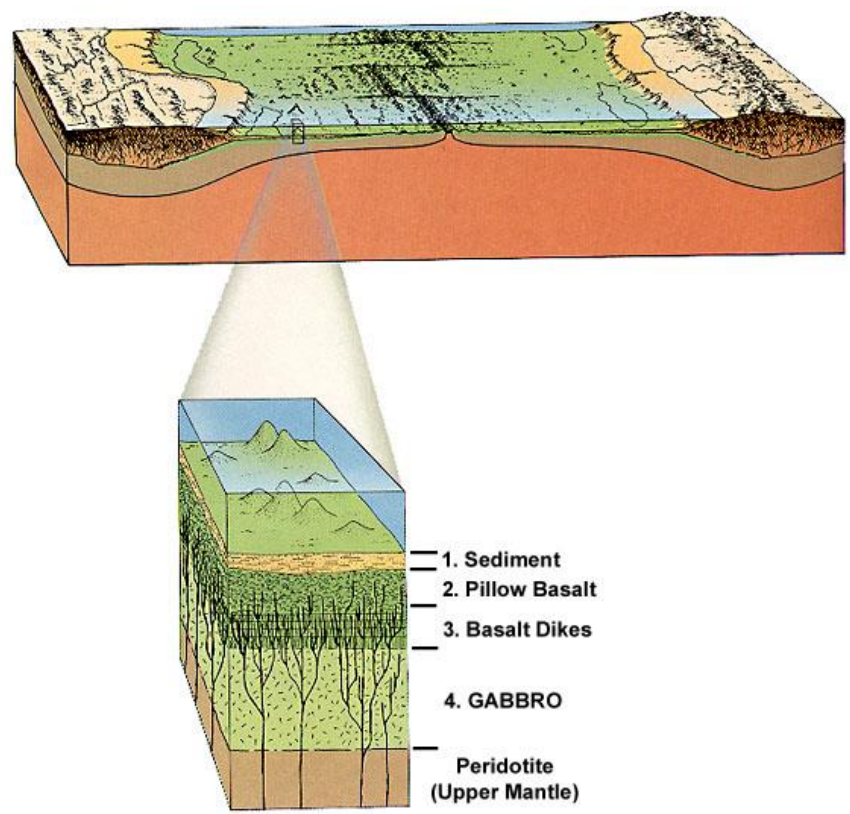
Layer 1: is on an average 0.4 km thick. It consists of unconsolidated or semiconsolidated sediments , usually thin or even not present near the mid-ocean ridges but thickens farther away from the ridges.

Layer 2:could be divided into two parts: layer 2A – 0.5 km thick uppermost volcanic layer of glassy to finely crystalline basalt usually in the form of pillow lava, and layer 2B – 1.5 km thick layer composed of basalt dikes.

Layer 3 : is formed by slow cooling of magma beneath the surface and consists of coarse grained gabbro and cumulate ultramafic rocks. It constitutes over two-thirds of oceanic crust volume with almost 5 km thickness

Composition and Age of Oceanic Crust

Figure 4. Oceanic Crust.



Composition and Age of Oceanic Crust

- Oceanic crust is continuously being created at mid-ocean ridges. The oceanic lithosphere subducts at the convergent boundaries of the tectonic plates.
- The subduction process consumes older oceanic lithosphere, so oceanic crust is seldom more than 200 million years old.

Composition and Age of Continental Crust

- Representative igneous rocks found in the continental crust , in order of increasing SiO_2 content and decreasing (MgO + FeO) are listed in Table 5. These rocks include ***Andesite , Granite*** and ***Rhyolite***.
- ***Andesite*** is a direct product of the subduction zone volcanism.
- ***Rhyolite*** is also volcanic , but clearly more acid .
- The origin of ***granite*** is a subject of debate. It occurs as massive , and apparently very slow , intrusions with assimilation of the intruded rocks.

Composition and Age of Continental Crust

Table 5.

	SiO_2	MgO	FeO + Fe_2O_3	Al_2O_3	CaO	Na_2O	K_2O
Andesite	59.2	3.0	6.9	17.1	7.1	3.5	1.8
Granite	72.9	0.5	2.5	14.5	1.4	3.1	3.9
Rhyolite	74.2	0.3	1.9	14.5	0.1	3.0	3.7

Composition and Age of Continental Crust

- The composition similarity of *granite* to *rhyolite* suggests a similar ultimate source and they may differ only in the degree of reheating and speed cooling.
- The oldest continental crustal rocks on Earth have ages in the range from about 3.7 to 4.28 billion years. The average age of the current Earth's continental crust has been estimated to be about 2.0 billion years.

The Oceans

- Sea water contains 3.5% by mass of solutes , listed in Table 6.
- The solute concentration is locally variable by 10% of this value , but the proportions of the major elements are very consistent.
- Sea water is slightly alkaline , represented by a pH of 8 ,controlled by a continuous exchange of CO_2 with the atmosphere in a balance with CO_3^{2-} , HCO_3^- and Ca^{2+} ions.
- The total CO_2 dissolved in the oceans is about 20 times that in the atmosphere.

The Oceans

Table 6. From Fegley (1995)

Element	Abundance (ppm)
Cl	19353
Na	10781
S as sulphate	2712
Mg	1280
Ca	415
K	399
Br	67
C as CO_2	26.4
N as N_2 gas as nitrate	16.5 0.84

Table 6. continued

Sr	7.8
O as O_2 gas	4.8
B	4.4
Si as silicate	3.09
F	1.3
U	0.0032

The Oceans

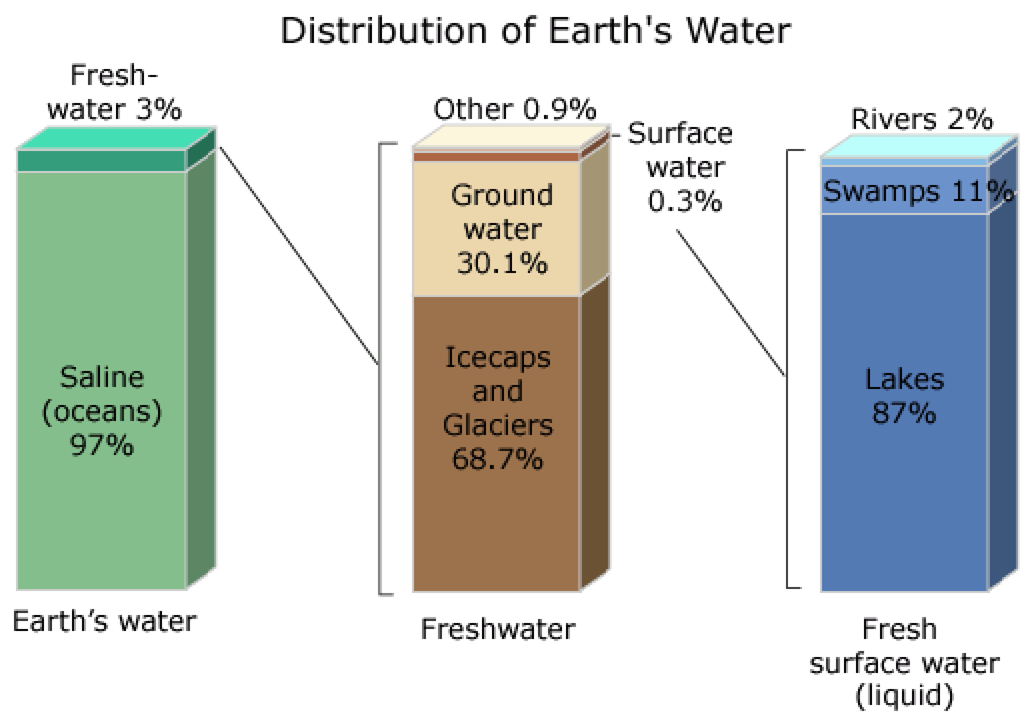
- There is an exchange of solutes with the crust by hydrothermal circulation of sea water through cracks near the mid ocean ridges.
- Exchange with the atmosphere is most obvious . About of 25% of the rain water falling on land flows to the sea in rivers.

Water in the Earth

- Water is only a minor constituent of the Earth as a whole , although it is abundant at the surface.
- Its physical and chemical properties give it a controlling influence on our environment.
- Distribution of Earth’s water is shown in Figure 5.

Water in the Earth

Figure 5.



Water in the Earth

- Water in interstices and hydrated minerals in ocean floor sediments is carried down with lithospheric material in subduction zones , locally lowering the solidus temperature and leading to andesitic volcanism.
- Free water is known to lubricate faults and to release earthquakes that would not occur under dry conditions but it can exist only to moderate depth , possibly limited to the upper crust.

Why water is not more evident on other planets?

- Carbonaceous chondrites contain up to 18% water , of which only a tiny fraction would be required for planetary oceans.
- Mars may once have had surface water that could have produced the features suggestive of erosion if kept liquid long enough.
- The ready escape of hydrogen from dissociated water in the Martian atmosphere would allow dissipation of the water.

Why water is not more evident on other planets?

- In the case of Venus , the very limited water in the atmosphere is not easily explained in view of its ability to retain light gases.
- Satellites of Jupiter have water and even indications of saline liquid oceans underneath deep – frozen capping.

The atmosphere: a comparison with the other terrestrial planets

- Selected data on the atmosphere of the three terrestrial planets are presented in Table 7.
- The most obvious feature of Table 7. is the similarity in relative abundances of the major elements in the atmospheres of Venus and Mars and the great dissimilarity to the Earth.
- Venus and Mars are very different in size , proximity to the Sun and surface temperature ,so the atmospheric similarity suggests a composition close to the primordial one with which all the terrestrial planets started , dominated by CO_2 and N_2 .

The atmosphere: a comparison with the other terrestrial planets

Table 7.
Abundances of Constituent (ppm by volume)

constituent	Venus	Earth	Mars
N_2	35000	780840	27000
O_2	-	209440	1300
Ar	70	9340	16000
CO_2	965000	364 year2000	953200
Ne	7	18	2.5
He	12	5.2	-
CH_4	-	1.7	-
Kr	0.025	1.14	0.3
N_2O	-	0.32	-
Xe	0.019	0.086	0.08
SO_2	185	5×10^{-5}	-

The atmosphere: a comparison with the other terrestrial planets

- The dominant gases in the Venus and Mars atmospheres , CO_2 and N_2 have very similar proportions , inviting the conclusion that they approximate the primordial atmospheres and the early atmosphere of the Earth was similar.
- Most of the Earth's CO_2 has been sequestered as $CaCO_3$ in the shells of marine organisms and fossilized as limestone.

The atmosphere: a comparison with the other terrestrial planets

– Some of the nitrogen has also probably been sequestered by biological activity and buried in the Earth.

- A unique feature of the Earth is its oxygen atmosphere . This is released by photosynthesis , with burial of carbon in reduced form as coal , oil and a much larger mass of less concentrated fossil carbon. This is the most important mechanism for generation of an oxygen - rich atmosphere , but not the only one.

The atmosphere: a comparison with the other terrestrial planets

- Dissociation of water vapor in the upper atmosphere by solar ultra-violet radiation releases hydrogen that may escape to the space , leaving the oxygen gravitationally bound to the Earth.

References

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- Lowrie, W., Fundamentals of Geophysics, Cambridge University Press, 2007.