

# Role of Earth's Mantle in Water and Gases in the Environment

## Term Paper

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## Abstract

Earth's mantle plays an important role in the material present in the environment and can be considered as the major contributors to the material found on the surface of the planet. This contribution was made essentially during the formation of Earth between 4.56 to 3 billion years ago while it accreted by *drowning* the heavier material and keeping the lighter components on the surface forming continents and initial ocean beds. However, today this contribution is in the form of *degassing* processes and tectonic procedures (such as mid-oceanic ridges spreading and volcanic eruptions) through which gasses and water and carbon are transmitted to the environment. These materials are usually kept in Earth's mantle from earlier at its birth and are transmitted into it through tectonic processes like subduction.

In this study, I have considered the basics of these processes. Through this work, some of the basic theories and concepts which are essential for a basic understanding of the subject are presented and are finally accompanied by some numerical figures as a demonstration of how the studied system works. Also some evidence are mentioned to support the general ideas which are referenced alphabetically at the end of the paper.

## 1 Introduction

The Earth as we know today was formed  $4.55 \pm 0.07 \times 10^9$  years ago (Patterson, 1956) from the solar nebula. Patterson (1956) in his famous paper estimated the age of the planet using radiometric dating of meteorites (carbonaceous chondrites) considering lead isotopes (Fig. 1). After that time, Earth

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started to accrete its heaviest materials down deep the planet when would form the Cores later on and keep the lighter ones at the surface or near to it forming the Mantle and the Crust. This resulted in a process called differentiation which led to a *layered* structure for the planet (Fig. 2).

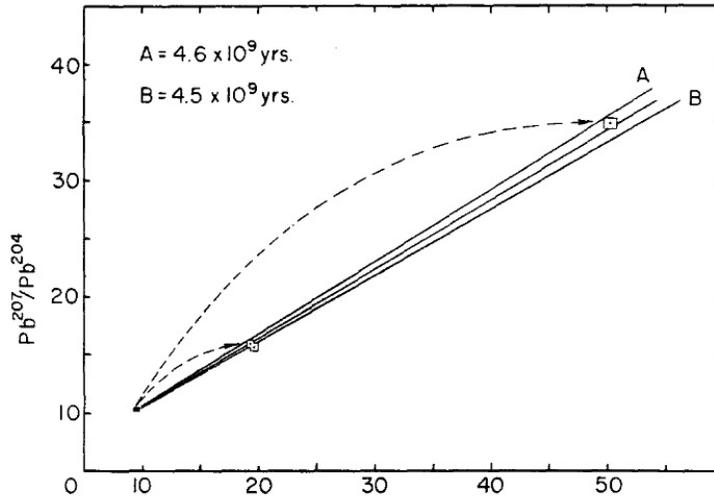


Figure 1. The lead isochron for meteorites and its estimated limits. The outline around each points indicates measurement error (Patterson, 1956).

## 1 – 1 Earth’s Inner Structure

The Earth’s structure is layered ad as different physical evidence approve, this layering is global, neglecting some local anomalies here and there. The innermost layer of the spherical earth<sup>3</sup> is the Earth’s inner core which is made of heavy metals (e.g. iron) in solid state and is surrounded by a liquid layer called the outer core. Above the outer core exists Earth’s mantle which is a semi-liquid solid. Mantle itself is divided into several layers, the most prominent of which are Upper and Lower mantle. The upper mantle in the first look is constructed from three dominant layers by boundaries called *transition zone* (Fig. 3). These so-called boundaries are phase transition in the crystal lattice of the most abundant minerals in the Earth’s mantle such as olivine. Above all these layers, Earth’s crust is floating. The structure of inner earth and its composition is highly affected by high pressures and temperatures which increase by going down through the Earth.

<sup>3</sup> Earth has an irregular shape which is *approximated* as a sphere for the sake of convenience. However for the purpose of this paper we shall continue to call the Earth a *sphere*.

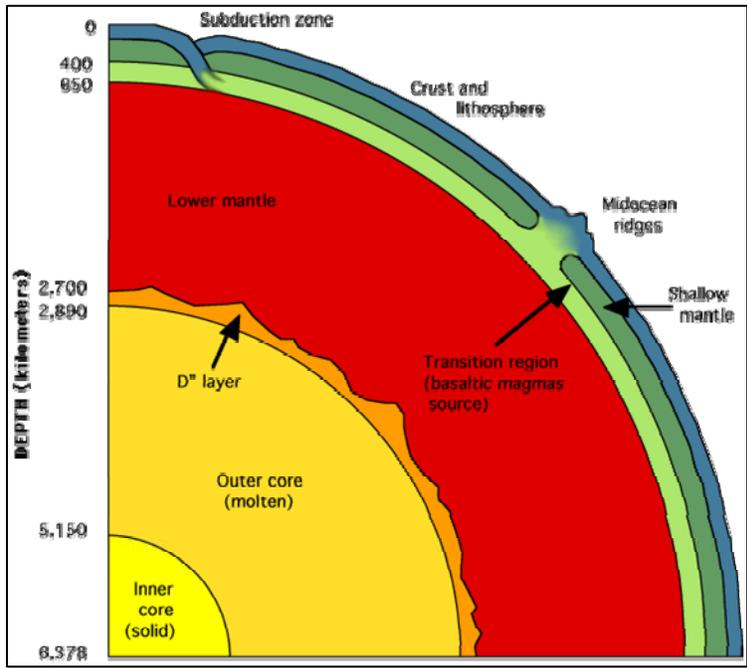


Figure 2. The layered structure of the Earth. General tectonic features are presented in this figure (Seligman, 2011).

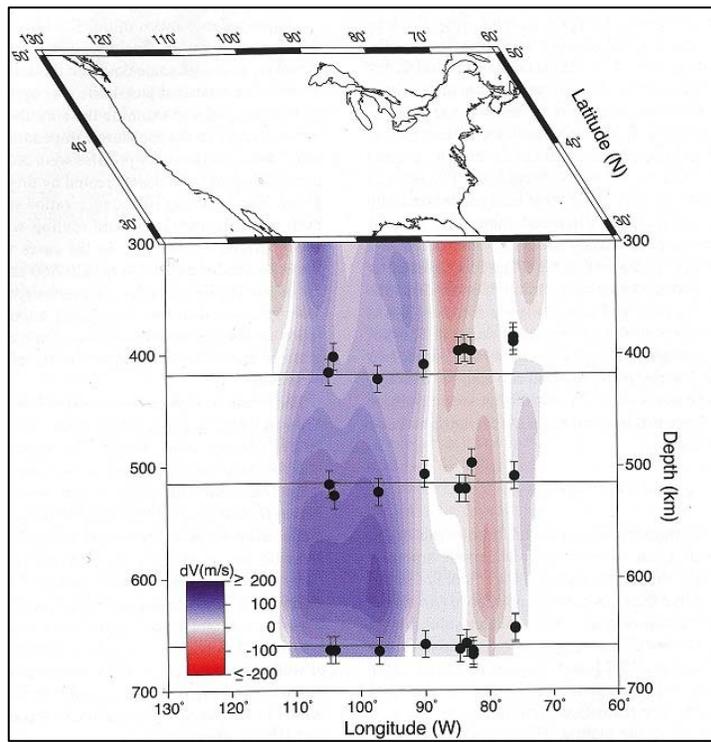


Figure 3. Topography of transition zone discontinuities sliced across 28° N. Horizontal lines are global mean depths for three discontinuities (Courtier and Revenaugh, 2006).

## **1 – 2 Water in Earth's Mantle**

Water controls tectonics by affecting the strength and deformation mechanisms of minerals (Kavner, 2003) and thus the rheology of rocks (Karato, 1998; Mei and Kohlstedt, 2000). It also controls weathering and all low temperature geochemical reactions that generate sediments from rocks. Liquid water covers 70% of Earth's surface, but constitutes only about 0.025 wt% of the planet's mass - far less than Earth is thought to have contained during accretion and before core formation (Jacobsen and Van der Lee, 2006). Hydrogen loss during accretion must have been extensive, and there is compelling evidence that degassing of the mantle with greater than ninety percent efficiency has led to the formation of Earth's oceans (Rüpke *et al.* 2006). However, the mass fraction of liquid water on Earth (0.025 wt% H<sub>2</sub>O) is still on the order of ten times less than the water content of mid-ocean ridge magmas (0.2-0.3 wt% H<sub>2</sub>O), and about half of what model "enriched mantle" sources contain which is about 0.04 wt% H<sub>2</sub>O (Jacobsen and Van der Lee, 2006). Perhaps rather than asking from where did Earth's water originate, we should be asking to where has Earth's water gone? The general belief is that the mentioned amount of water is now stored in the structure of minerals in the mantles. In this view, mantle could be considered as a huge water reservoir (van der Lee and Wiens, 2006; van der Meijde, *et al.*, 2003).

## **1 – 3 Gasses in the mantle**

Mantle also contributes to the amount of gases in the atmosphere. These gases are generated in a process called *degassing*. The most dominant gases in this process are carbon dioxide and nitrogen. To describe and study these gases, noble gases also play an important role in studying these processes.

Carbon dioxide (CO<sub>2</sub>) is an important terrestrial volatile (Saal, et al, 2002) that is often considered to exist in the deep Earth interior (Schrauder and Navon, 1993). The presence of carbon dioxide or carbonates in the Earth's mantle strongly affect the stability of partially molten rocks in subducting slabs and magma, and the mantle's physical properties (e.g. density, conductivity, and diffusivity). In

various thermal and chemical conditions, carbon dioxide converts into a wide variety of chemical species such as diamond, graphite, carbon monoxide, carbonates, and hydrocarbons (Nakajima, et al, 2009). Thus, the chemical and physical stabilities of carbon dioxide at high pressures and temperatures is critical to understanding the origin and budget of Earth's deep carbon species (Dasgupta and Hirschmann, 2010).

The geological history of nitrogen ( $N_2$ ) is not well understood. The study of this element in mantle-derived samples is severely complicated by its generally very low abundance (Marty et al, 1995; Javoy and Pineau, 1986) which makes nitrogen sensitive to atmospheric contamination and, more generally, to addition of surface-derived nitrogen (such as organic N). Calibration of nitrogen relative to argon in mantle-derived samples presents several advantages. First, it provides the opportunity to evaluate surface contamination because the  $^{40}Ar/^{36}Ar$  ratio in the mantle is much higher than the atmospheric value of 295.5. Second,  $^{40}Ar$  originates from the radiogenic decay of  $^{40}K$ , providing a well constrained chronological and geochemical framework, whereas  $^{36}Ar$  (or  $^{38}Ar$ ) is primordial in origin (Marty, 1995).

Rare (noble) gases have proved to be particularly useful in modeling the early evolution of the Earth's atmosphere (Ozima and Podosek, 1983). But it is not straightforward to extend this approach to the main volatile species (such as hydrogen, carbon and nitrogen as mentioned above) that comprise the atmosphere, hydrosphere and sediments, as these elements are chemically reactive and may have experienced different geodynamic histories. A way around this problem is to calibrate major volatile species relative to rare gases (Marty and Jambon, 1987; Zhang and Zindler, 1993; Trull et al, 1993).

Helium (He), argon (Ar), neon (Ne), krypton (Kr) and xenon (Xe) form the group of rare gases that are relatively inert and do not unite in nature among themselves or with other elements and hence also known as 'noble gases'. The source of these gases is believed to be from the accreting planetessimals, which were the building blocks of our planet. Melting of the planetessimals due to mounting compressional forces, augmented by heat from decaying radioactive elements in them as well as from freshly impacting bodies, are supposed to have generated a magma ocean. Chemical differentiation of this magma followed, an outcome of which was the *outgassing* or the release of gases that were present originally in the planetessimals. The purged gases that surfaced are believed to have formed the primeval atmosphere.

The purged gases that surfaced are believed to have formed the primeval atmosphere. Though this is the established view of the origin of earth and various gases including noble gases, over the past few decades, planetary evolutionists seem to be shifting to the earlier nebular-disc model or the chemical-condensation-sequence model of origin. According to this model, the extremely hot primordial nebular gas disc cooled, giving rise to a central plane of solid compounds, minerals, surrounded by nebular gas atmosphere. These solid compounds gradually clumped to form chunks or planetessimals or the planetary nucleus, which on attaining sufficient mass could hold a solar-composition proto-atmosphere. The latter, however, was steadily removed by the intense solar wind (blow-off) but not before incorporation of the noble gases and other volatile elements in the magma ocean that had formed (Harper and Jacobsen, 1996).

## 2 Minerals in the Mantle

The most abundant minerals in the Mantle are known to be silicates which are described below. The transition zone and upper mantle contain about eighteen percent of the Earth's mass. Seismology data and research of high temperature and pressure minerals indicate that these regions consist mostly of  $Mg_2SiO_4$  and  $MgSiO_3$  minerals. The dominant mineral has the stoichiometry of  $Mg_2SiO_4$  and several polymorphs (minerals with the same composition but different structures).

The  $Mg_2SiO_4$  polymorphs include ringwoodite, wadsleyite, and olivine (the latter is the most abundant (~ 70%) and most deformable mineral in the upper mantle (Christensen, 1984; Nicolas and Christensen, 1987)). In each polymorph, silicon is in tetrahedral coordination with oxygen and magnesium is in octahedral coordination with oxygen. The polymorphs differ in the way these polyhedra are arranged (

The highest-pressure polymorph of  $Mg_2SiO_4$  occurs at the base of the transition zone and is called ringwoodite or  $\gamma$ - $MgSiO_4$ . It is isostructural with spinel ( $MgAl_2O_4$ ). In the middle of the transition zone at about 520km, ringwoodite changes to wadsleyite or  $\beta$ - $MgSiO_4$ . Wadsleyite can hold a lot of water – up to about three percent by weight. If it is saturated, the mantle may hold a volume of water equal to about twenty oceans. The last  $MgSiO_4$  polymorph is olivine, occurring at the top of the transition zone

(Fig. 4). The structure of olivine, in addition to those of ringwoodite and wadsleyite, is difficult to visualize (Evans and Grove, 2004). Natural olivines, however, contain at least one other component ( $\text{Fe}_2\text{SiO}_4$ ) in addition to  $\text{Mg}_2\text{SiO}_4$ , so that the  $\alpha+\beta$  equilibrium is divariant rather than univariant (Bina and Wood, 1987).

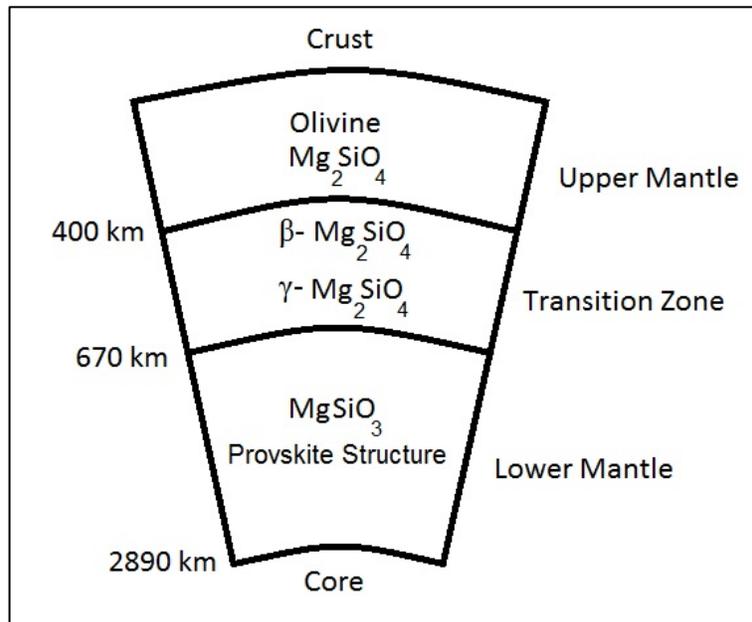


Figure 4. Different phases of  $\text{Mg}_2\text{SiO}_4$  as a function of depth (modified from Evans and Grove, 2004).

The evidence to this structure model is seismological in nature. Tomographic models such as those illustrated in Fig. 2 and Fig. 5 are produced by considering the fact that velocities of seismic waves varies as a function of density, elastic moduli or directivity of crystal lattices).

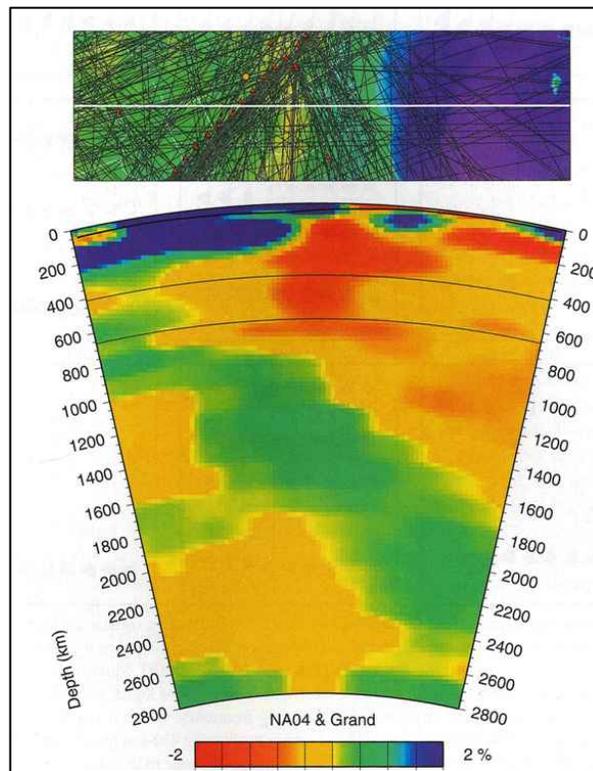


Figure 5. An example of the tomographic models used to interpret the structure of inner Earth. This picture illustrates the S wave velocity model beneath the eastern USA (Moho – 660 km). The green east-dipping anomaly in the lower mantle represents cold lithosphere from the subducted Farallon Plate (van der Lee and Wiens, 2006).

### 3 Degassing Process of the Mantle

Earth’s atmosphere which surrounds the planet today is a remnant of its accretion in the early stages of its life. However, Earth’s mantle has kept contributing to the Earth’s atmosphere through a process called *degassing*. During this process, gases are emitted from the magma in the mantle and are transferred into the atmosphere through tectonic procedure such as ocean ridge spreading and volcanism. The process through which gases are transmitted to the surface is complicated and is a function of many parameters e.g. gases’ solubility in the magma and the magma’s composition and of course the transferring process itself. The scope of these processes is way beyond this study. However, in the following, I have tried to present the most important and interesting features.

The degassing process leads to the emission of many different kinds of gases into the environment, the most dominant of which are carbon dioxide and nitrogen as mentioned in the introduction in more

detail. However, as also mentioned before, the study of the processes dealing with these gasses is easier by investigating the emission of noble gasses by the mantle.

### **3 – 1 Mantle degassing of noble gases**

Unlike gases like hydrogen, oxygen and nitrogen, which are highly reactive and could combine with other elements to form stable chemical compounds over geologic time, the noble gases being inert, are believed to have escaped from the earth's interior to the surface and atmosphere during the early degassing phase. A comparison of earthly abundance of these gases and other elements with those in the meteorites, the extra-terrestrial bodies which are also part of the solar system retaining the primordial composition, show certain disparities. While there is a general agreement with all elements, the noble gases show deficiencies, particularly the lighter ones among them, as they were supposed to have escaped from the gravitational pull of early earth. Especially in the case of Xe, the heaviest rare gas, deficiency was found to be maximum and this was attributed by some to absorption by shales and Antarctic ice caps, though this was later disproved (Wacker and Anders, 1985; Ozima, 1986).

Several aspects of the physics and chemistry of the noble gases have made them useful for tracing the structure and evolution of the earth's interior. The volatile nature of their isotopes, the different half-lives of their parents ( $^{40}\text{K}$ ,  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and the extinct  $^{244}\text{Pu}$ ,  $^{129}\text{I}$ ) and the wide range of their atomic size and number have helped to gain a good insight about mantle magmatism, episodes of degassing, formation of oceanic and continental crusts, intra-crustal magmatic processes, recycling, or in short, the earth's evolution through time (Harper, *et al*, 1996; Kunz *et al*, 1998).

During partial melting of the mantle, the noble gases are expelled and dissolved in the melt. Their solubility is explained in terms of a dissolution process in *holes* or *channels*, the accommodating sites in the glass or silicate structure. The distribution of these *holes*, controls the *ionic porosity* of the melt (i.e. the difference between bulk volume of material and calculated volume of constituent anions and cations) and this factor is thought to regulate the abundance of noble gas in the silicate structure (with a few exceptions) (Broadhurst *et al*, 1992).

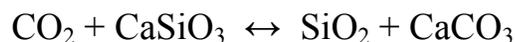
Since the potential of noble gases as geochemical tracers is much connected to their solubility in

silicate melts, investigation of the parameters that influence this in melts of different compositions have increasingly engaged researchers, especially after the development of the diamond anvil cell for conducting high pressure experiments.

Several experimental studies on rare gas solubilities in silicate liquids and glasses, at pressures below 2.5 GPa, have been conducted earlier and Ar solubility tests have been done to pressures above 2.5 GPa, up to 5 GPa, which corresponds to pressures at 150 km depth in the mantle. Initial experiments with pure SiO<sub>2</sub> melt showed increasing Ar solubility till about 5 GPa and a decrease thereafter. In order to observe the trend, they chose natural olivine [(MgFe)<sub>2</sub>SiO<sub>4</sub>], a mineral close to mantle composition, and repeated the experiment (Sankaran, 2010).

### **3 – 2 Recycling of carbon dioxide**

On geologic timescales CO<sub>2</sub> cycles between rocks, often by way of the ocean and atmosphere. These refractory reservoirs include carbon in the mantle, carbon in continental carbonates, carbon in reduced form mostly in continental shales, and carbon (mostly carbonate) in or on the seafloor. The small volatile reservoir (ocean plus atmosphere) recycles through carbonate rock in a hundred thousand to a million years. Over longer periods, free CO<sub>2</sub> is dynamically controlled by processes that form carbonates at low temperatures and processes that decompose carbonates at high temperatures by (Urey) reactions of the form (Sleep and Zahnle, 2001),



Magnesium and, under reducing conditions, iron carbonates can form by analogous reactions. Figure 6 represents a summary of the modern CO<sub>2</sub> cycle. In this figure, five significant reservoirs have been considered: the atmosphere (R<sub>atm</sub>); free carbonate in the ocean (R<sub>ocean</sub>); carbonate lying upon (R<sub>pel</sub>) or veined within (R<sub>bas</sub>) oceanic basalt; carbonates on continental platforms (R<sub>con</sub>); and CO<sub>2</sub> in the mantle (R<sub>man</sub>).

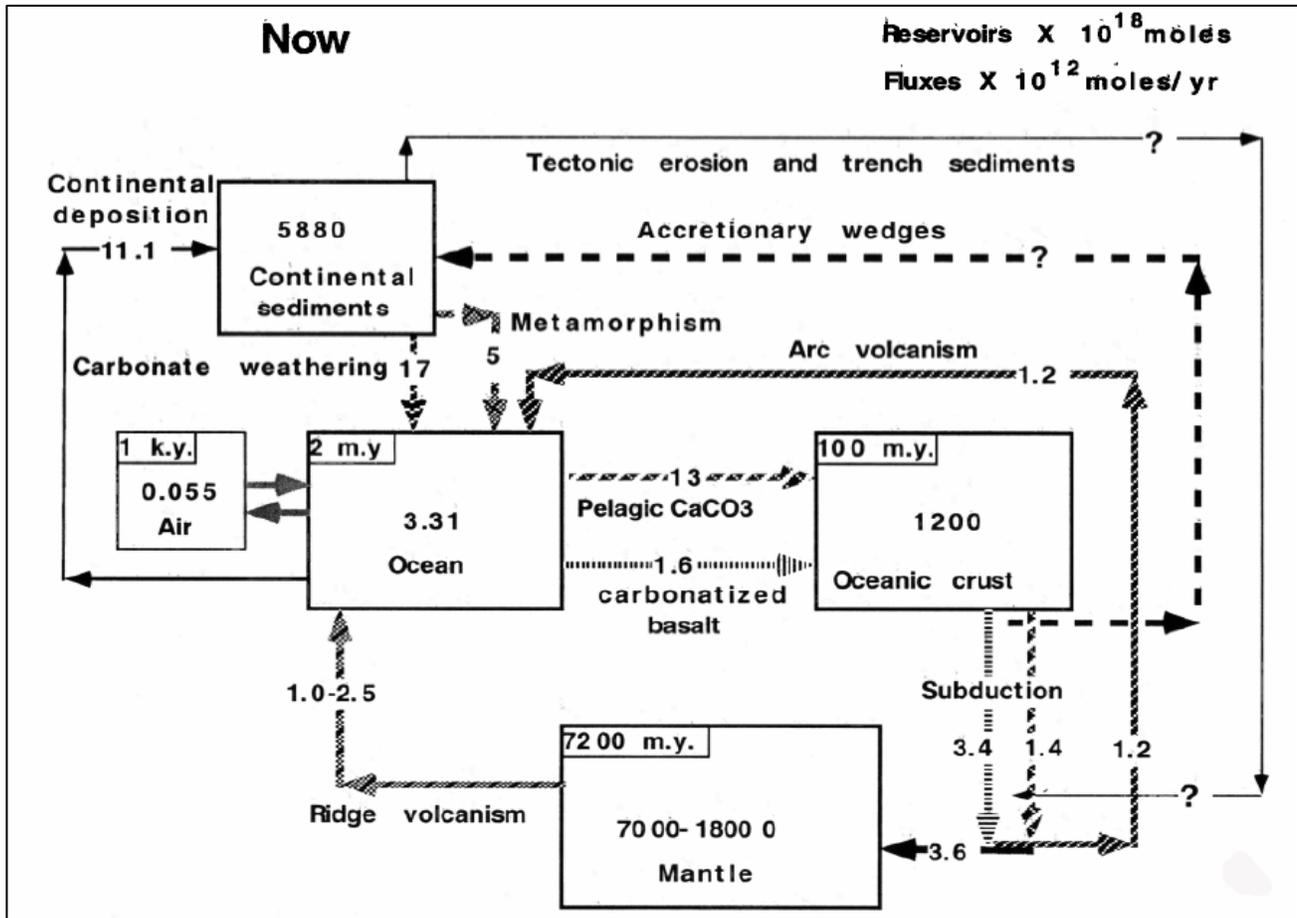


Figure 6. The modern CO<sub>2</sub> cycle, shown with reservoirs (boxes) and fluxes (arrows). The current residence times are shown in the corners of the reservoirs (Sleep and Zahnle, 2001).

Carbon is then recycled into the mantle through processes such as subduction. This process is depicted Fig. 7 in which the numbers represent global fluxes (in units of  $\text{tmol yr}^{-1}$ ). Pelagic carbonates and carbonates and carbonatizes basalt in oceanic crust layer 2A (hatched) enter the subduction zone at rates  $1.4 \times 10^{12}$  and  $3.4 \times 10^{12}$  mole per year respectively. Unknown amount of this material are scraped off and accreted by the continent. Trench sediments and tectonic erosion from the continent add a comparable, albeit also unknown, amount of CO<sub>2</sub> to the slab. Arc volcanoes remove  $1.2 \times 10^{12}$  mol per year before the slab reaches the mantle (Sleep and Zahnle, 2001).

My calculation shows that the net contribution of mantle is  $1.1 - 2.6 \times 10^{12}$  moles/yr which is (considering the CO<sub>2</sub> molar mass of  $\sim 44$  g/mol) roughly equal to  $\sim 4.8 \times 10^7$  tons. Considering the net amount of water flux in the environment (derived in the class) we have:

$$\text{Net water flux} = 500,000 \text{ km}^3/\text{yr} = 5 \times 10^{14} \text{ m}^3/\text{yr} \approx 5 \times 10^{17} \text{ kg}/\text{yr} = 5 \times 10^{14} \text{ tons}/\text{yr}$$

Therefore, the ratio of net flux of CO<sub>2</sub> through the mantle to that of water in the environment would be about  $1.06 \times 10^{-10}$  which is negligible. BUT it is important to notice that such a process is tectonic in nature and is very slow (only significant in geologic time) as opposed to atmospheric processes which are quite fast.

In a completely hypothetical comparison<sup>4</sup>, if we consider a subduction process to be effectively considerable in 1 Ma as opposed to a complete atmospheric cycle which takes six month (1 year by approximation), then the atmospheric process is  $10^6$  times faster than the geological one. Thus:

$$\begin{aligned} \text{Net water flux (in the rate of 1 million years)} &= 5 \times 10^{14} \text{ tons}/\text{yr} / 10^6 \\ &= 5 \times 10^8 \text{ tons}/\text{yr} \end{aligned}$$

which is only 10 times more than the CO<sub>2</sub> flux!!! An interesting result!!

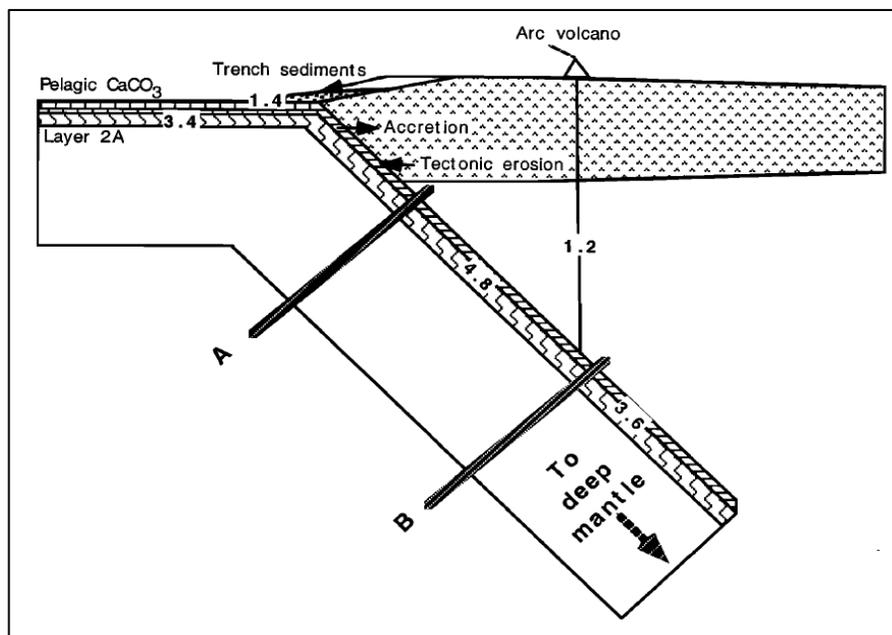


Figure 7. Carbon involved in the subduction process (Sleep and Zahnle, 2001)

<sup>4</sup> My calculation here is not based on a strict scientific method, but on simple common sense measure.

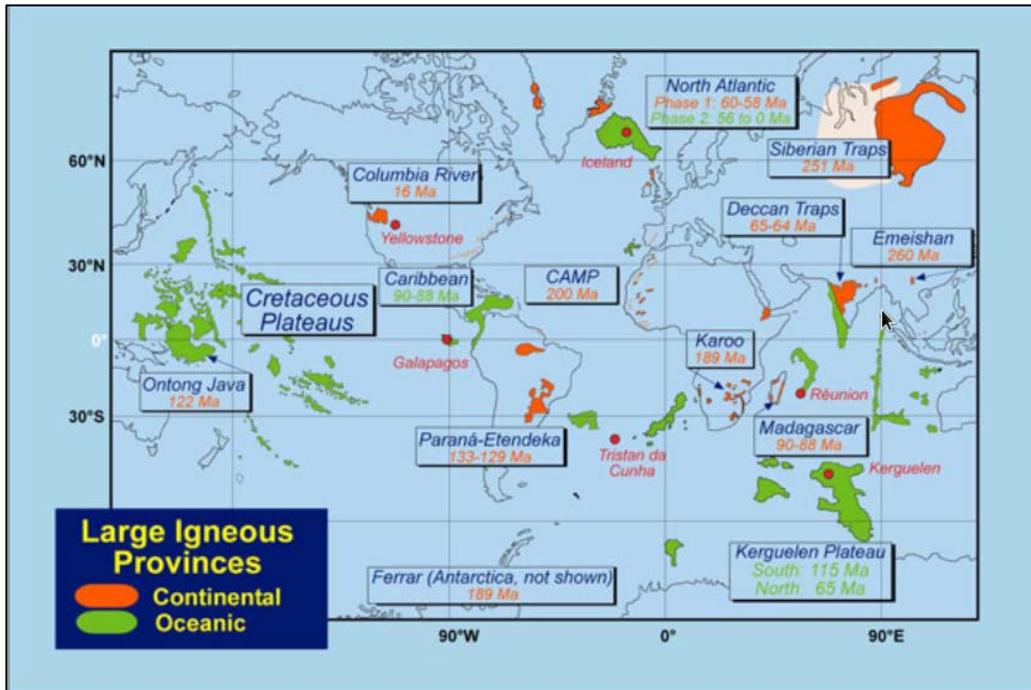


Figure 8. Large igneous provinces in the world (Sanders, 2005)

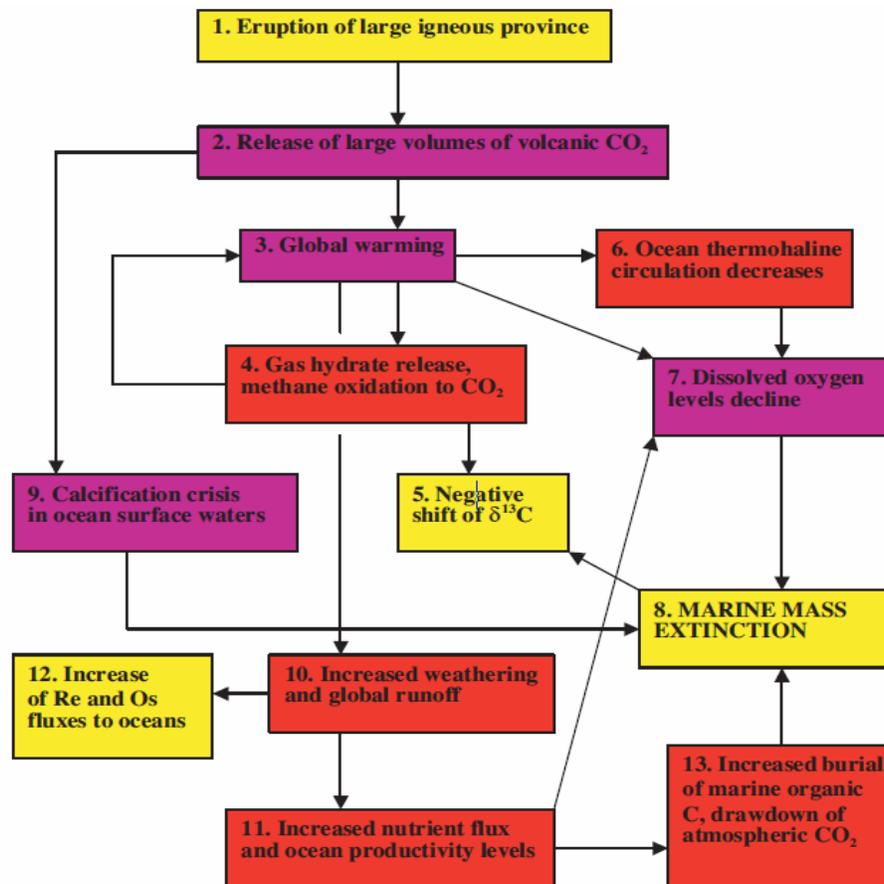


Figure 9. Contribution of mantle to the environment through volcanic eruptions (Wingall, 2005).

The degassed carbon can be transferred into the atmosphere by several means, one of which is volcanic eruptions. Major volcanic eruptions have pumped out enormous amounts of CO<sub>2</sub> into the environment. The frozen magma from these huge volcanic eras and areas have formed large igneous provinces (Fig. 8).

### 3 – 3 Mantle degassing of carbon dioxide

At pressures above 40 to 60 GPa and temperatures of 300 to 1000 K, carbon dioxide transforms into a range of silicate-like extended solids: four-fold CO<sub>2</sub>-V (Iota *et al*, 1999; Yoo *et al*, 1999; Serra *et al*, 1999), pseudo-six-fold CO<sub>2</sub>-VI (Iota *et al*, 2007) coesite-CO<sub>2</sub> (c-CO<sub>2</sub>) (Sengupta and Yoo, 2010) and amorphous a-carbonia (a-CO<sub>2</sub>) (Santoro *et al*, 2006). These are fundamentally new solids, consisting of 3D network structures of carbon atoms covalently bonded with oxygen atoms, largely in CO<sub>4</sub> tetrahedra similar to those of silicate minerals (Hemley, 1987).

Above 40 GPa, carbon dioxide transforms into a wide range of covalently bonded extended polymorphs V, VI, *c*, and *a* phases, each with a characteristic Raman-active  $\nu_b$  (C-O-C) bending vibron at around 700–1000 cm<sup>-1</sup> (Fig. 10). Upon further compression to 220 GPa, we found that each of these phases became nonmetallic amorphous solids, as evident from the complete loss of their vibrans and their optical transparency. These amorphous phases remain stable down to 10 GPa, where they slowly transform back to molecular phase I (Yoo *et al*, 2011).

Extended ionic CO<sub>2</sub> solids over broad pressure–temperature conditions, relevant to the Earth’s mantle. The presence of ionic extended solids and CO<sub>2</sub> decomposition products provides an alternative chemical mechanism for the delivery of light elemental impurities, such as oxygen or carbon, from greenhouse gas CO<sub>2</sub> to carbonates in the ocean bottom and the Earth’s crust by mineralization. They are then transformed to extended CO<sub>2</sub> in descending slabs into the deep mantle by carbonate mineral dissociation. Eventually, extended CO<sub>2</sub> in Earth’s core–mantle boundary decomposes to oxygen and carbon, thereby, forming deep carbon species (such as Fe<sub>3</sub>C) in the Earth's outer core (Yoo *et al*, 2011).

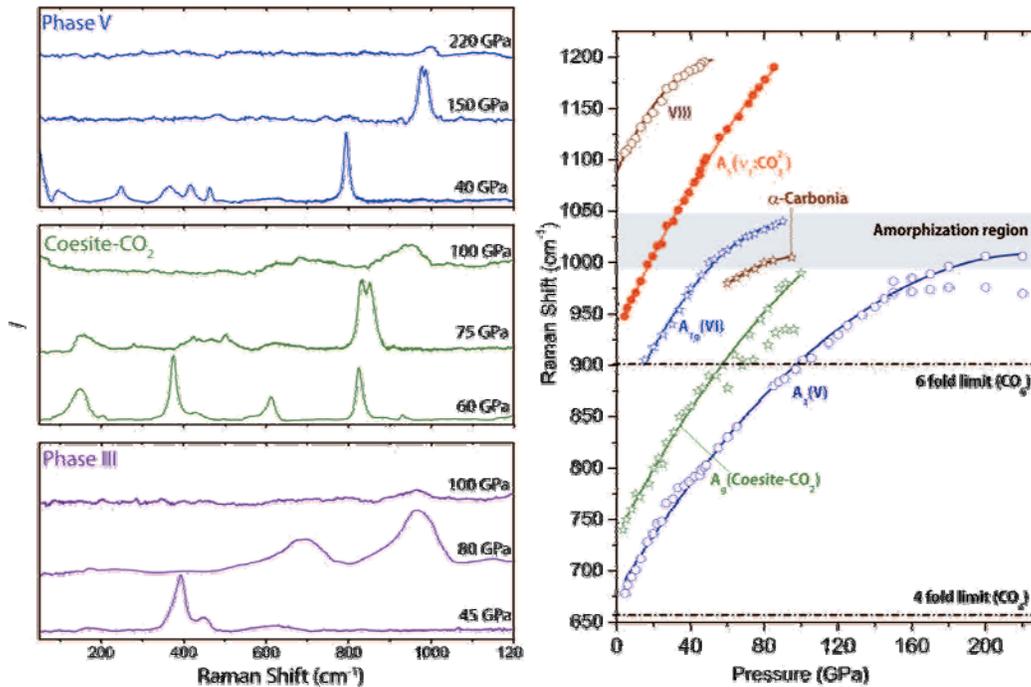


Figure 10. Left: Raman spectra of carbon dioxide phases to 220 GPa, showing the pressure-induced amorphization of top: fourfold CO<sub>2</sub>-V via a new high-pressure phase V' above 150 GPa, middle: coesite- CO<sub>2</sub> (c-I) via a high pressure-form (c-II), and bottom: phase III via *a*-carbonia, at ambient temperature. Right: Pressure dependencies of the major ν<sub>b</sub> vibrons of carbon dioxide phases, illustrating that pressure-induced amorphization occurs well beyond the sixfold vibron limit around 1000–1050 cm<sup>-1</sup> (hatched area) (Yoo *et al.*, 2011)

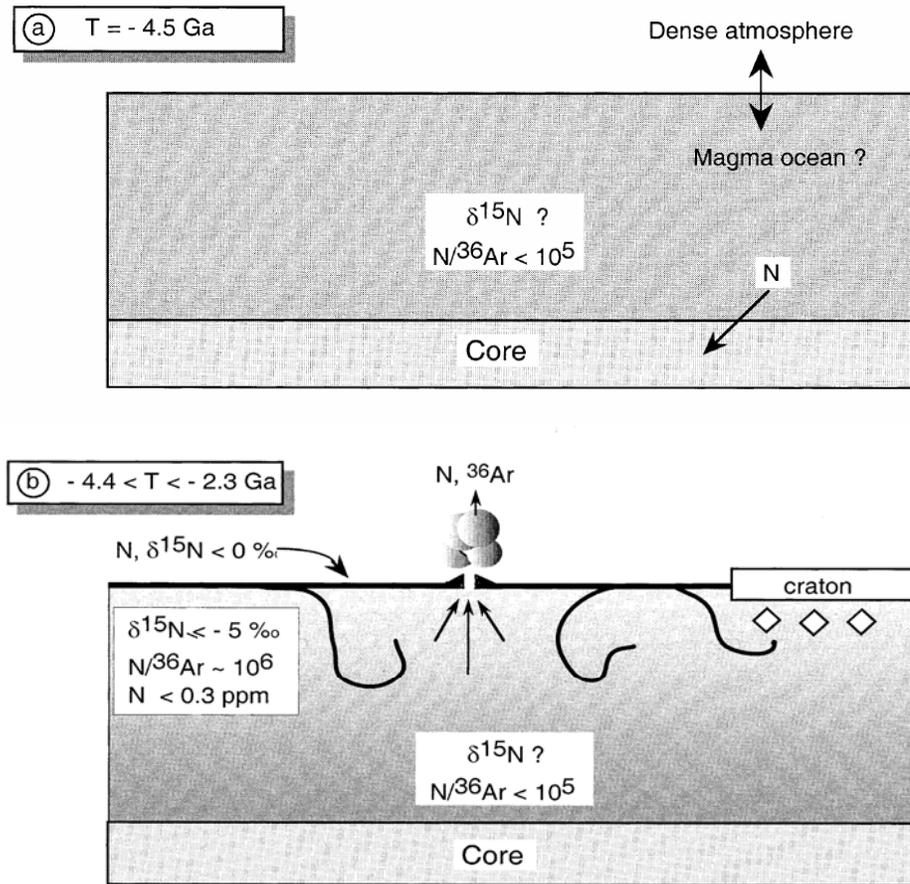
### 3 – 4 Mantle degassing of nitrogen

Mantle fluids sampled by mid-ocean ridge basalts and by diamonds are depleted in the heavy isotope of nitrogen, <sup>15</sup>N, by about 3–5 parts per mil relative to atmosphere, suggesting a common nitrogen end-member since at least the Archean. In contrast, deep mantle material sampled by mantle plumes (Kola Devonian magmatic province, Iceland, Loihi Seamount, Hawaii, Society Islands) is enriched in <sup>15</sup>N by up to 8 parts per mil, as are post Archean sediments. Several independent lines of evidence strongly suggest that mantle nitrogen is mostly recycled. Notably, the ratio between nitrogen and an incompatible lithophile element like potassium is nearly constant between the surface of the Earth and the different mantle reservoirs, whereas the ratio between nitrogen and a noble gas like <sup>36</sup>Ar varies over two orders of magnitude between these reservoirs (Marty and Dauphas, 2003).

Nitrogen isotopes are potentially important in this context because there exists a gross isotopic heterogeneity between nitrogen in the mantle sampled by diamonds and mid-ocean ridge basalts (MORB) which are depleted in  $^{15}\text{N}$  relative to atmospheric  $\text{N}_2$  (mantle  $\delta^{15}\text{N} \approx -5\%$ , where  $\delta^{15}\text{N} = [({}^{15}\text{N}/{}^{14}\text{N})_{\text{AIR}} - 1] \times 1000$ ) and nitrogen in sedimentary and crustal rocks which are enriched in  $^{15}\text{N}$  by a few parts per mil (Cartigny *et al.*, 1997).

Several lines of evidence point to a recycled origin for mantle nitrogen sampled by present-day plume-related lavas as well as by MORBs, despite differences in the respective N isotopic compositions. The isotopic composition of recycled nitrogen has changed with time. Nitrogen metabolized in the Archean might have lacked the  $^{15}\text{N}$  enrichment characterizing modern organic matter.

History and evolution of mantle nitrogen degassing processes could be depicted as Fig. 11.



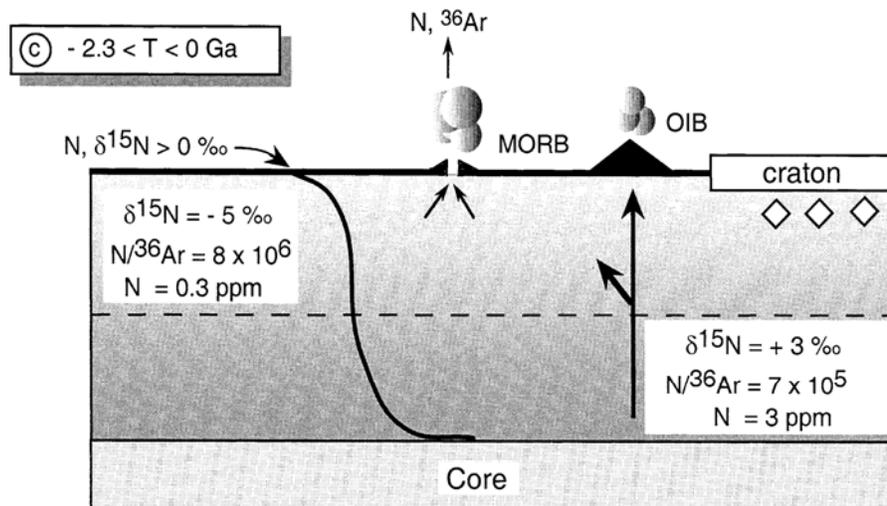


Figure 11. The geological nitrogen cycle from Archean to Present. (a) 4.5 Ga ago, nitrogen was preferentially partitioned into the core relative to argon, lowering the  $N/^{36}\text{Ar}$  ratio below  $10^5$ . Knowledge of the initial isotopic composition of mantle nitrogen is not required by the present model. Some remnant of a light N component could still be present in the mantle and could account for the very light N isotopic compositions rarely observed in diamonds or in other mantle derived minerals (if these compositions are not due to isotopic fractionation). (b) In the Archean, light nitrogen was progressively recycled, mostly in the upper regions of the mantle, and the deep mantle was isolated from downgoing slabs. (c) From the Proterozoic to Present, recycled material transporting nitrogen enriched in  $^{15}\text{N}$  was able to reach the deepest regions of the mantle (Marty and Dauphas, 2003).

## 4 Water Cycle in the Mantle

As mentioned before, the missing water of the Earth probably resides in the deep mantle. Only 1000 ppm  $\text{H}_2\text{O}$  by weight, or 0.1 wt%  $\text{H}_2\text{O}$  of this water (uniformly spread) would equate the mass of Atlantic Ocean (Jacobsen and Van der Lee, 2006). This residence is in the form of minerals' water content. These minerals include peridotites (which are generally made up of iron, magnesium, silicium, hydrogen and oxygen) which are silicates that were described before:



Even today, water keeps being *pushed* into the mantle through processes such as tectonic subduction. *Injection*<sup>5</sup> of water achieved through a process called dehydration of plates (vs. hydration

<sup>5</sup> Injection is a word used by me, but it makes sense in the first look, however one should not mistake it for the real physical

of oceanic plates). Oceanic crust becomes hydrated through hydrothermal alteration at mid-ocean ridges and through low-temperature alteration at the sea floor. Sediments contain both chemically bound and pore water which is a very important point to remember (the case for pore water is depicted in Fig. 15 as we shall refer to it later). Bend-faulting at the trench outer rise may lead to additional hydration of the cold lithospheric mantle (Fig. 12).

We assume that any water recycled back into the mantle at subduction zones is instantaneously mixed into the convecting mantle. The *true* characteristic mixing time of the mantle is certainly higher – maybe even on the order of Ga (Ten, *et al*, 1998). Mantle water is outgassed during mantle melting at hotspots and mid-oceanic ridges as mentioned before. The efficiency of water outgassing is controlled by the *incompressibility* of water during mantle melting and the solubility of water in the produced melts. Water solubility in near-surface melts is very low so that it is efficiently outgassed during sub-aerial hotspot volcanism. At mid-oceanic ridges, at 2500 m water depth, water solubility in melts is higher. However, the MORB source is dry and depleted and may have experienced a primary melting event during plume melting. It thus appears that 50% is a lower bound for water outgassing efficiency during melting, i.e. half of the primary mantle water during melting at hotspots, mid-ocean ridges, and arcs is outgassed into the atmospheres (Rüpke *et al*, 2006).

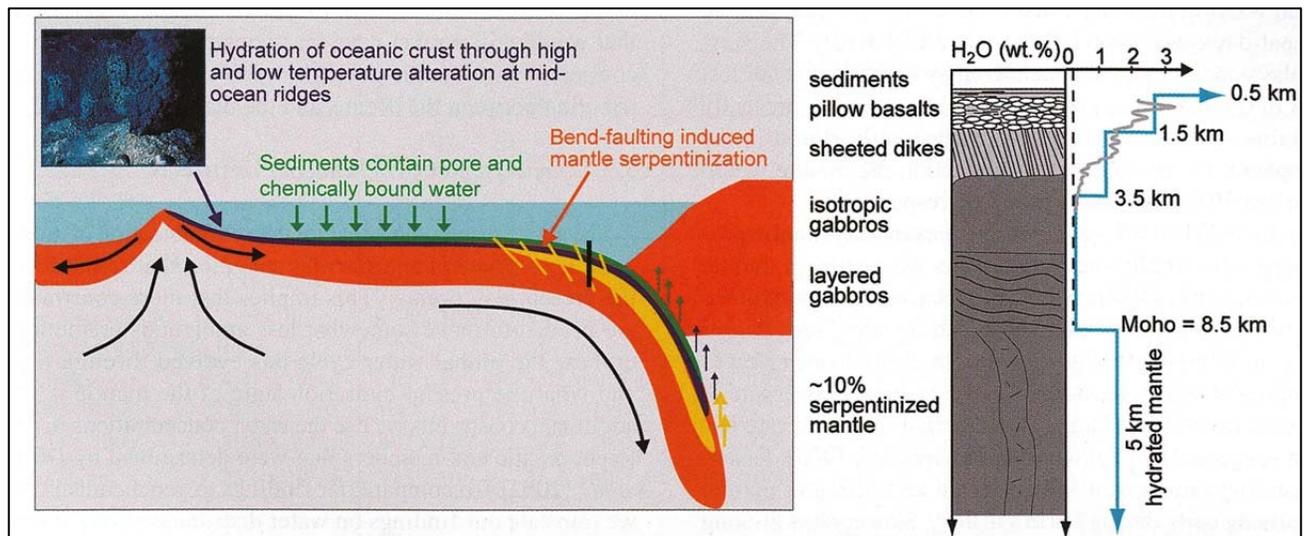


Figure 12. Hydration of oceanic plates (Rüpke *et al*, 2006).

or chemical processes called with this name.

Mantle water is stored in the predotites in different formations and thus creating different phases of *wet* silicates as opposed to *dry* silicates (Fig. 13).

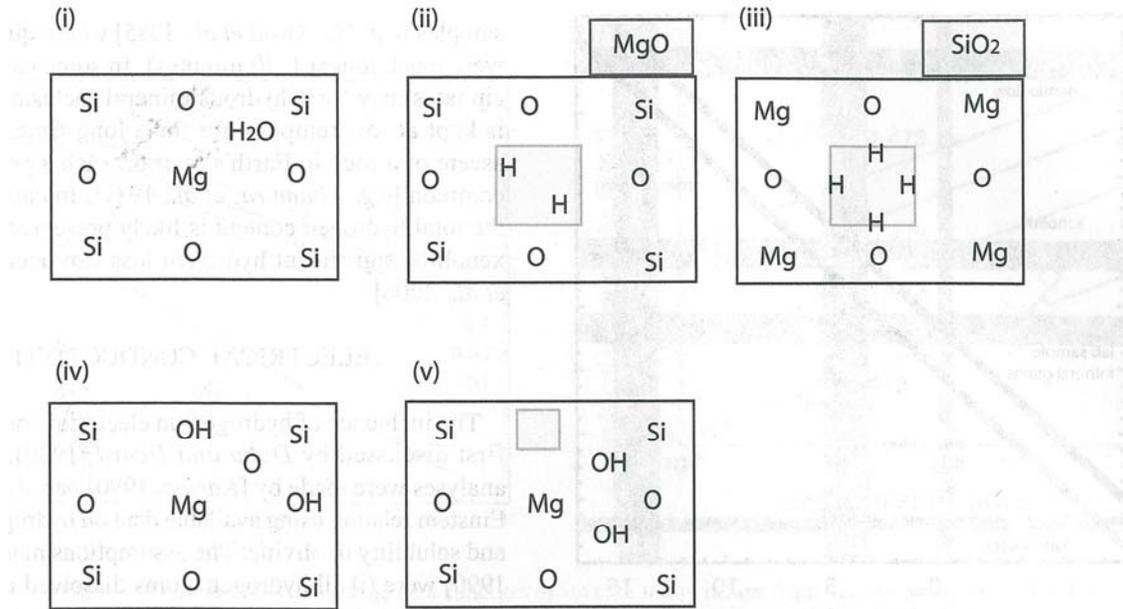


Figure 13. Mechanisms of dissolution of water (hydrogen) in silicates. Mechanisms (ii) and (iii) are associated with an explicit volume change. A volume change also occurs to a lesser extent in mechanisms (i), (iv) and (v) (Karato, 2006).

Density of these silicate thus vary which in turn would result in seismic velocity variations that could be detected through seismic tomography (Table 1).

Table 1. Density variations of peridotites in fixed pressure (Smyth and Jacobsen, 2006)

	$\rho_{STP}$ (g/cm <sup>3</sup> )	Bulk Modulus(GPa)
Olivine	3.36	129
Wadsleyite (dry)	3.57	172
Wadsleyite (wet)	3.51	155
Ringwoodite (dry)	3.70	188
Ringwoodite (wet)	3.65	177

Pressure and temperature are two important factors in values of elastic moduli of minerals. These two factors vary to a great extent as the depth increases. Complicated diagrams and charts are presented by numerous studies to predict and explain the behavior of minerals and their water contents, an example of which is shown in Fig. 14.

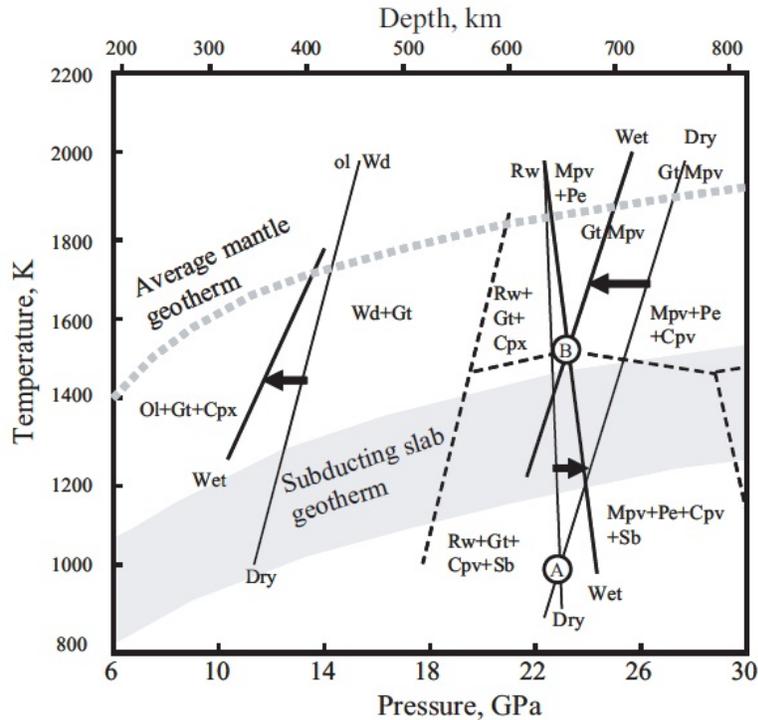


Figure 14. Phase boundaries in peridotite and basalt under dry and wet conditions. The stability fields of wasleyite and ringwoodite expand under wet conditions at low temperatures whereas the post garnet transformation shifts to lower pressures under wet conditions. The grey dotted curve is the average temperature of the mantle. The shaded area represents the temperature range of the slabs. The phase boundaries of the post-spinel and post-garnet transformations cross at around 1000 K (A) under dry conditions and 1400 K (B) under wet conditions. Rw, ringwoodite; Sb, superhydrous phase B; Pe, periclase. (Ohtani and Litasov, 2006).

However, this alone could not explain the behavior of water. Numerous studies are focused on explaining the behavior of water in such extreme conditions. An example of the results is shown in Fig. 15.

The water content of these minerals could be released while reaching the surface through tectonic processes as mentioned before.

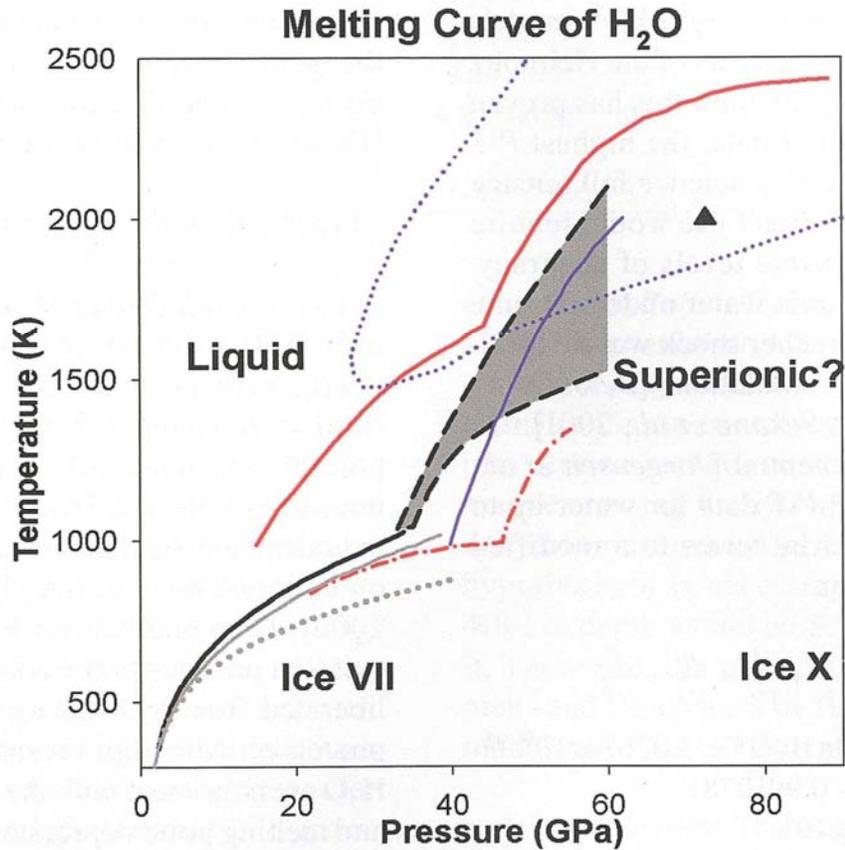


Figure 15. Melting curve of H<sub>2</sub>O at high P-T (Lin *et al*, 2006)

## 5 Conclusions

Earth's Mantle plays in the significant role in the origin and destiny of essential environmental elements (e.g. water and gases). Liquid water constitutes only 0.025 wt% of the planet's mass. Tectonic activities are effective factors which should be considered while dealing with many environmental issues. Phase transition of silicates and waters plays a key role in the structure of inner earth and could be considered as both the source and destination of water, CO<sub>2</sub>, N<sub>2</sub>, etc. Water is contained both as chemical and pore form in the minerals in the mantle. To interpret the behavior of water in the mantle (due to enormous pressure and temperature) mineral and water phase diagrams obtained in high-tech labs (like that of Ohtani and Litasov, 2006) are quite handy.

Net flux of CO<sub>2</sub> in the mantle is about of  $1.1 - 2.6 \times 10^{12}$  moles/year (equivalent to  $\sim 4.8 \times 10^7$  tons). My calculations show that this amount is quite negligible as compare to that of annual water flux (we should not forget that atmospheric and environmental processes are much faster than tectonic activities). N<sub>2</sub> concentration drops an order of magnitude between the phase transition and the surface (3 ppm to 0.3 ppm) and its history of release is difficult to interpret. To interpret and investigate the behavior of these gases, the history of noble gases is especially helpful.

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