

Geochemistry

Notes VI: Differentiation within the earth

I. Composition of the earth/cosmic abundances

II. Structure and composition of different portions of the earth

A. Core/Mantle

B. Crust/Mantle

C. Transitions within the mantle (400 and 660 km discontinuities)

Differentiation: process whereby planets, moons, or asteroids develop concentric layers or zones of different mineralogic or chemical composition.

Fractionation: separation of chemical elements in nature.

Mafic: rich in Fe and Mg (poorer in Si).

Silicic: rich in Si (poorer in Mg and Fe).

Bulk composition: average chemical composition of a mixture of compounds.

Mineralogy: the minerals (solid naturally occurring compounds) in a material.

We can estimate the elemental composition of the earth in a number of different ways (Carbonaceous chondrites, adding together of the elemental concentrations of different portions of the earth weighted appropriately).

When one does this, it is clear that there are differences between cosmic or solar abundances and terrestrial abundances of the elements. These differences can largely be attributed to the different volatilities of the elements under conditions when the solar nebula condensed to make solids. In a gross sense, if one chooses a temperature of 600K, one can roughly reproduce the differences between solar abundances (what you started with) and terrestrial abundances (the elements expected to be in the solid phase at that temperature). This explains, qualitatively the low values of elements expected to be in the gas phase at that temperature (see figures).

The earth is divided into more or less concentric spheres of differing density, and to a certain extent different composition. The biggest jump in density and composition is the core-mantle boundary. We do not have samples from the core,

nor are we likely to ever obtain samples from the core. From its density, from iron meteorites, and from the earth's magnetic field, we infer that it is made largely of Fe, with some Ni and a small amount of a light element (S, O, H, Si, and/or C). The core formed within 100 million years of the formation of most meteorites.

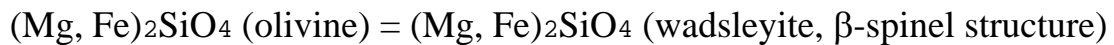
Two possibilities are heterogeneous and homogeneous accretion. Heterogeneous accretion would have Fe metal precipitating out first from the solar nebula and silicates next. Thus, the core could have formed before the silicate portion of the earth, with the silicate portion forming later and added on. Homogeneous accretion would have the Fe metal and silicate phases forming at the same time. Thus, the earth would have initially been homogeneous in composition. The core would have formed from gravitational settling of denser Fe-metal droplets from less dense silicate phases.

We do have samples of the upper mantle (mantle nodules, ophiolite sequences). We have also at the surface, magmas (generally basalts) that come from the mantle. Since we know, to a certain extent, how silicates melt, the composition of the material that partially melted to make basalts can be calculated. We can also calculate the abundances of the elements in the silicate portion of the earth by subtracting the inferred composition of the core from the inferred composition of the bulk earth (e.g. carbonaceous chondrites). In gross terms, the mineralogy of the upper mantle is olivine, orthopyroxene, clinopyroxene, plus an aluminous phase. The basic difference between the composition of the mantle and the composition of the bulk earth is the lower concentrations of siderophile elements (see figure).

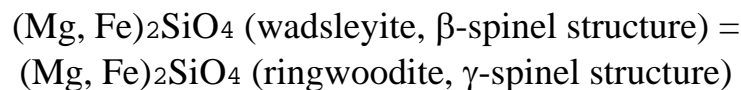
As with the mantle, the continental crust is made of silicates. We can determine the average chemical composition of the crust in a number of different ways. These methods take advantage of the fact that we have many samples of the continental crust, with the main uncertainty having to do with the weighting of the different composition materials to achieve an accurate average. The continental crust is more silicic than the mantle and less mafic than the mantle (i.e. the continental crust is higher in Si concentration and lower in Mg and Fe concentration than the mantle). The mineralogy of the continental crust is plagioclase, potassium feldspar, quartz, some mafic phases, and some hydrous phases. It is higher in alkali metals, alkaline earths, and other large ion lithophiles (LIL's) than the mantle. All of this points to the formation of the continental crust from partial melts derived ultimately from the mantle. The quite likely occurred over an extended interval of time (e.g. a billion years or more), perhaps continuing up to the present.

The oceanic crust is generally intermediate in composition between the continental crust and the mantle. In gross terms, the mineralogy of the oceanic crust is plagioclase and both types of pyroxenes. The oceanic crust is clearly derived from partial melting of the mantle, is tied in to the theory of plate tectonics, and is actively being produced and destroyed today.

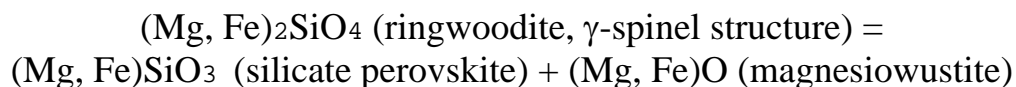
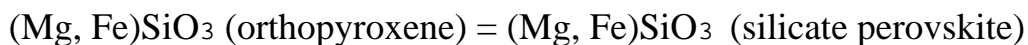
The mantle itself has within it a number of jumps in density, the primary ones being at 400 and 670 km, with the transition zone in between. Consider that just above the 400 km discontinuity, the main minerals are olivine and orthopyroxene. The 400 km discontinuity can be explained by the reaction of olivine to form a polymorph with a more compact (higher density) structure:



Between 400 km and 670 km, wadsleyite transforms to a yet slightly denser polymorph: ringwoodite, which has the γ -spinel structure.



The 670 km discontinuity can be explained by the following reactions that form denser minerals:



All of these reactions have higher density phases on the right side of the equation (and below the transition of interest; i.e. high pressure favors low volume phases). Also, in general the cations have higher coordination number at higher pressure. For example Mg is in VI-fold coordination and Si is in IV-fold coordination in orthopyroxene and in olivine. Whereas Mg is in X-fold and Si is in VI-fold coordination in perovskite. This is a general phenomenon (higher coordination number for cations in denser, higher pressure phases).

Mineralogy and composition of the silicate portion of the Earth

	Mineralogy	Bulk Composition
Continental Crust	plagioclase K-feldspar quartz Fe, Mg minerals (amphiboles, pyroxenes) hydrous minerals (micas, amphiboles)	silicate - silicic
Oceanic Crust	Plagioclase clinopyroxene orthopyroxene (olivine)	silicate - intermediate
Upper Mantle (< 400 km)	olivine orthopyroxene (clinopyroxene) (plagioclase, spinel, garnet)	silicate - mafic
Transition Zone ($400 - 670$ km)	wadsleyite / ringwoodite orthopyroxene	
Lower Mantle (> 670 km)	silicate perovskite magnesio-wustite	