Lecture 34

Differentiation of Planet Earth – Formation of a Crust

Reading: White Digital Chap 12: p530-549

This is a long notes packet, some of it includes background reading

Today

1. Formation of Earth's Crust

Earth Differentiation: The formation of a crust

We've seen that core formation was probably complete well within 100 Myr of the beginning of accretion, and that it probably involved significant amounts of melting of silicate rock in the mantle.

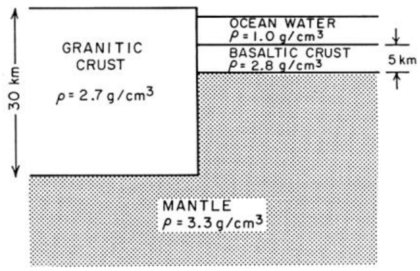
4.45 Ga is 100 Myr after the start of acretion.

Core formation timing suggests that an early planetary crust had also formed by this same time (i.e., by about 4.45 Ga or earlier).

Key questions:

- What kind of crust did we have early on?
- How did it form?
- How has it evolved since then?

Earth Differentiation: The formation of a crust



The relative heights of granitic and basaltic crust floating on the mantle. The granite blocks stand higher because they are thicker and less dense. Because the basaltic blocks stand lower, the Earth's oceans are located above them. The weight of this water pushes down the basaltic blocks a bit further. The symbol ρ used in the diagram stands for density.

The densities of likely crustal materials provide some clues. So do the age distributions of these materials in the geological record.

Overall, the crust is less dense than the mantle, and basically "floats" on it.

The ***continental crust*** is composed of numerous rock types of varying densities but its mean density is about 2.7 g/cm^3. Note that despite the label on the figure, the continental crust ***is not really "granitic."***

Oceanic crust is largely basaltic, of course; its mean density is higher, at about 2.8 g/cm^3.

The formation of Earth's crust

This density difference of only 0.1 g/cm^3 between oceanic and continental crust produces a bimodal distribution of crustal elevation on Earth that is markedly different from that of Venus, which appears to have a uniform density probably basaltic, crust.

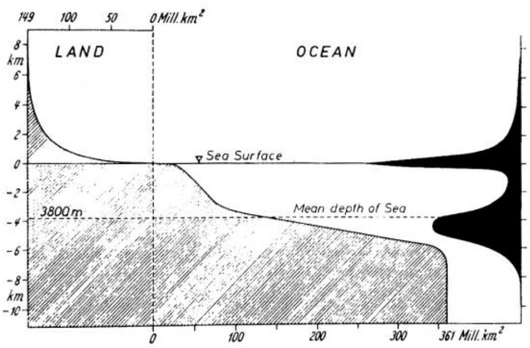
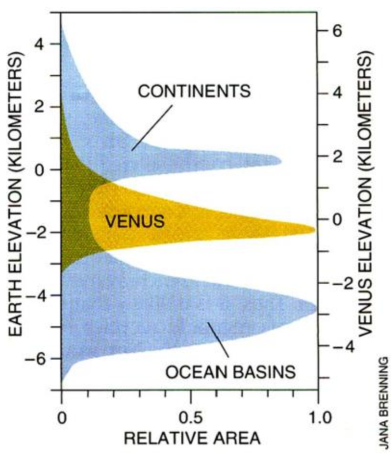


Fig. 1.1. Overall depth distribution of the ocean floor and land elevations (hypsographic curve). *To the right:* frequency distribution of elevations



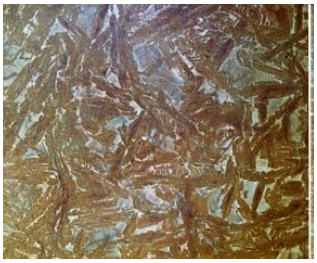
SURFACE ELEVATIONS are distributed quite differently on the earth (*blue*) and on Venus (*gold*). Most places on the earth stand near one of two prevailing levels. In contrast, a single height characterizes most of the surface of Venus. (Elevation on Venus is given with respect to the planet's mean radius.)

Taylor and McClennan, Sci. Amer. 1996

What was the main type of rock in the Earth's early crust?

Probably basalt: The high-temperature melting that occurred very early in Earth history probably produced mainly ***mafic*** magmas, such as we find on the Moon and Mars (and probably Venus). These rocks are more like oceanic crust than present-day continental crust. **Less dense continental-type crust** probably started forming after the early basaltic crust — but not too much later, as we'll see.

Komatiites: These magmatic rocks have even greater density than basalt and are commonly found with basalts in Archean terrains, but the basalts are predominant. ***Komatiites*** are ***ultramafic lavas*** (> Mg and < Si than basalt). They require high mantle temperatures (~1700^{o}C) early in Earth's history and haven't formed in significant amounts since the Early Proterozoic.



http://www3.imperial.ac.uk/earthscienceandengineering/aboutese/hottopic/pasttopics/komatiites

Formation of the crust

Oceanic crust is dense enough that it can be recycled back into the mantle by subduction. In contrast, continental crust strongly resists subduction.

This is why the continents contain rocks dating back billions of years, whereas the oldest crust in the ocean basins is only about 180 Ma.

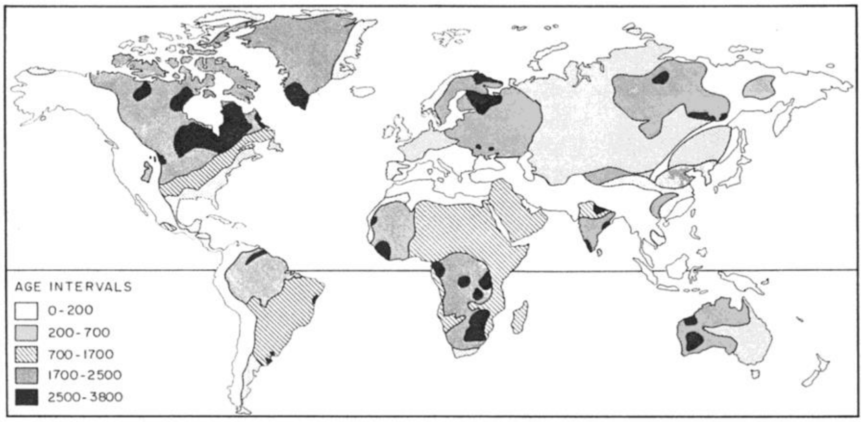
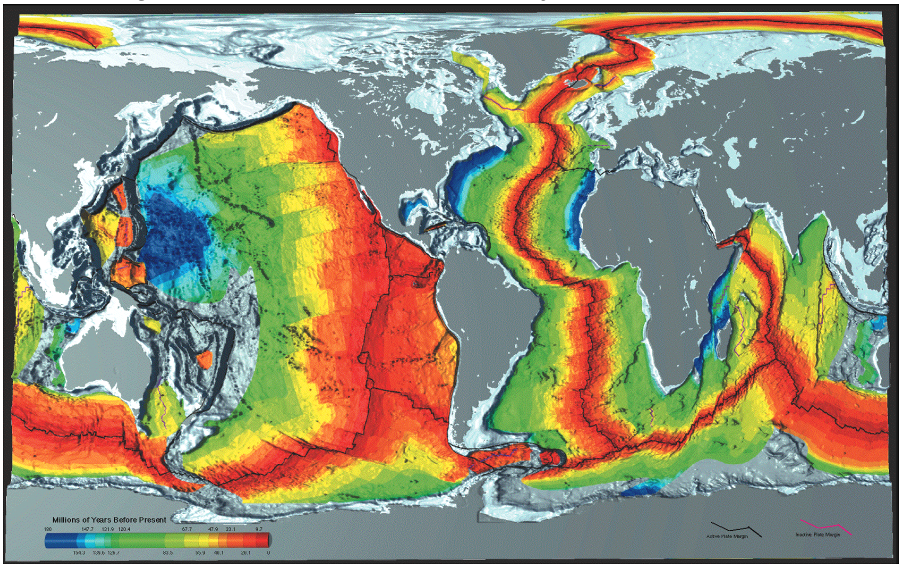


Figure 5-13. **Map showing which portions of the continental crust formed during each of five time intervals:** The age intervals are in millions of years.

The formation of Earth’s crust

Crustal ages in the ocean basins today.



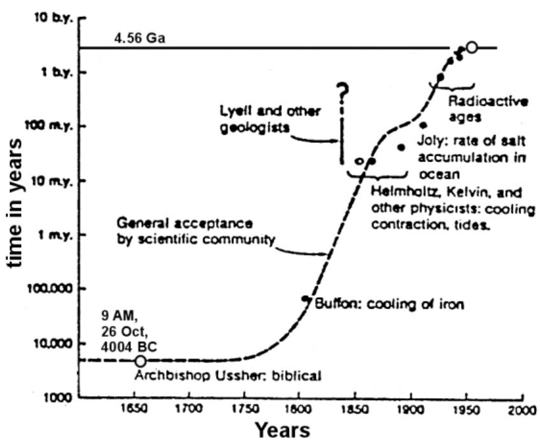
http://www.ngdc.noaa.gov/mgg/image/crustalimages.html

The formation of Earth’s crust

🛠 When did the continental crust form?

Ideas about the age of the earth have changed rapidly over the past few hundred years, but have varied comparatively little since the discovery of radioactivity and it’s application to the geological sciences.

Currently, the **oldest dated rocks on Earth are 4.28 Ga.** They are metamorphosed volcanic rocks, the Nuvvuagittuq greenstones, in northeastern Canada, that have been dated by the ***Sm-Nd method***.



The formation of Earth's crust

When did the first continental crust form?

- The **oldest evidence** we have for continental crust is in ***U-Pb ages*** averaging **4.36 Ga** for **zircon grains** in meta-sedimentary rocks in western Australia.

  These weathering-resistant grains are in **~3.6 Ga** quartz-rich gneisses (originally sandstones). *Before* being incorporated into quartz sands at ~3.6 Ga, they had already been through at least one pass of the rock cycle of rock formation-metamorphism-weathering-erosion-deposition.

- Small outcrops of rocks **≥3.8 Ga** exist on several continents.

- Yet, there are relatively few large areas **>2.5 Ga** exposed in the continental shields today.

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The formation of Earth's crust

The oldest Archean outcrops occur in crustal "**shield**" areas that are surrounded by zones of younger Archean rock, which are themselves surrounded by Proterozoic rock. This pattern suggests the continents grew over time around the Early Archean "nuclei." Large areas of the continents are >1 Ga, so by about 1 Ga much of the crust had been formed.

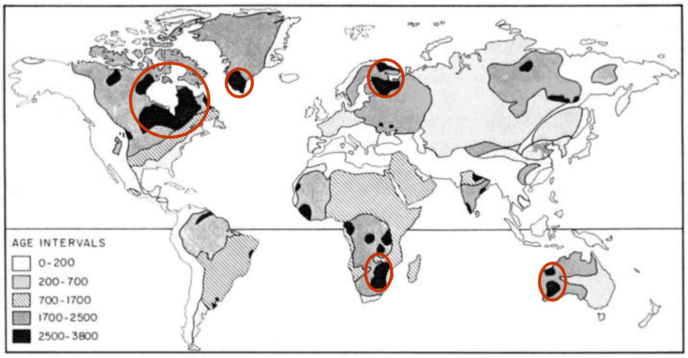

Figure 5-13. Map showing which portions of the continental crust formed during each of five time intervals: The age intervals are in millions of years.

Some of the oldest and best known **shield** areas are highlighted in this diagram.

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The formation of Earth's crust

When did plate tectonisc and subduction start?

In those regions of crust that are **>2.5 Ga**, it is common to find sequences of

- slightly metamorphosed pillow basalts
- cherts
- granite-bearing-conglomerates

known as **greenstone belts.**

These are interpreted as evidence of early volcanic systems ***roughly*** analogous to modern island arcs and back-arc basins.

Komatiites are also found in some greenstone belts.

The formation of Earth's crust

A range of crustal growth models have been proposed, including all possibilities between rapid early growth and slow steady growth to today.

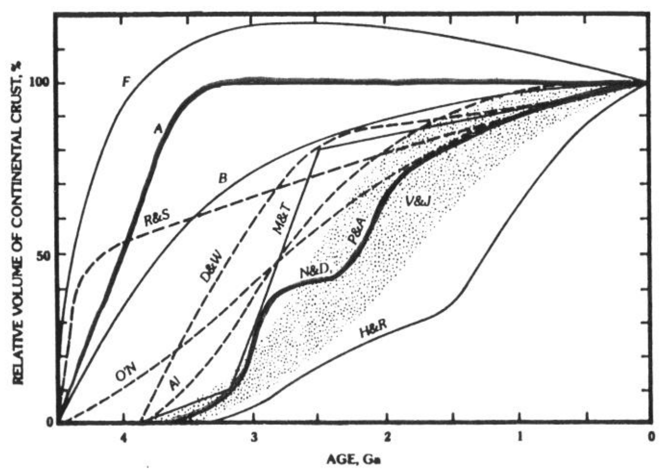
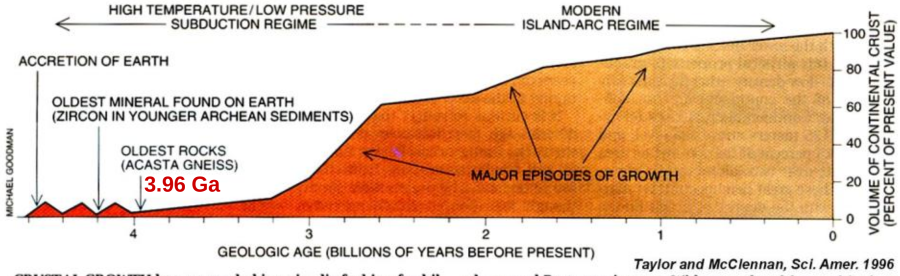


Fig. 1. A selection of crustal growth models. Diagram is a modified version of one given in Reymer and Schubert (1984). Key: *F*—Fyfe (1978), *A*—Armstrong (1981), *B*—Brown (1979), *R&S*—Reymer and Schubert (1984), *D&W*—Dewey and Windley (1981), *O'N*—O'Nions et al. (1979), *Al*—Allègre (1982), *M&T*—McLennan and Taylor (1982), *N&D*—Nelson and DePaolo (1985), *P&A*—Patchett and Arndt (1986), *V&J*—Veizer and Jansen (1979), *H&R*—Hurley and Rand (1969).

The formation of Earth's crust

Bearing in mind the processes of weathering and erosion, mountain building and metamorphism, we ***cannot assume*** the continents grew in a linear or even smooth fashion, ***OR*** that the age distribution of the crust preserved today necessarily tells us how much crust was formed at any given time. Still, most workers agree that a continental growth pattern about like this one best fits the existing age data.



Taylor and McClennan, Sci. Amer. 1996

CRUSTAL GROWTH has proceeded in episodic fashion for billions of years. An important growth spurt lasted from about 3.0 to 2.5 billion years ago, the transition between the Archean and Proterozoic eons. Widespread melting at this time formed the granite bodies that now constitute much of the upper layer of the continental crust.

The formation of Earth's crust

🛠 What is the crust made of?

Recalling the Goldschmidt classification scheme...

🏛 Lithophiles are abundant in the crust. Most of these elements form mostly ionic bonds; most are large ions.

🏛 Siderophiles (with metallic bonding) are much less abundant in the crust. They're mostly in the core.

🏛 Chalcophiles (with mostly covalent bonding) are split between mantle, crust and core.

The major elements in the crust *are the same as* those in the mantle, but the proportions are different.

Because the crust ultimately comes from the mantle via *partial melting*, some elements are enriched in the crust and others are depleted in the crust.

The Composition of Earth's crust

Among the major mineral-forming elements, crustal rocks are enriched in **Na, K, Al, and Si** and in some cases in **Ca and Fe** relative to the mantle. Crustal rocks are depleted in **Mg** and sometimes in **Ca** and **Fe**.

In this table, "basalt" summarizes the oceanic crust and "granite" the high-Si type of continental crust (but remember, average continental crust is **not** granitic, it is intermediate between basalt and granite).

Table 5-3. Chemical composition (in percent by weight) of the two most important rock types in the Earth's crust compared to the composition of Earth's mantle and to the composition of chondritic meteorites.

	Chondritic meteorites	Earth's mantle	Basalt	Granite
O	32.3	43.5	44.5	46.9
Fe	28.8	6.5	9.6	2.9
Si	16.3	21.1	23.6	32.2
Mg	12.3	22.5	2.5	0.7
Al	1.4	1.9	7.9	7.7
Ca	1.3	2.2	7.2	1.9
Na	0.6	0.5	1.9	2.9
K	0.1	0.02	0.1	3.2
Other	5.9	1.7	2.7	1.6

The Composition of Earth's crust

From the table, we can work out these relationships:

$Si/Mg_{mantle} < Si/Mg_{oceanic\ crust} < Si/Mg_{continental\ crust}$

$Si/Al_{mantle} > Si/Al_{oceanic\ crust} > Si/Al_{continental\ crust}$

$Si/Na_{mantle} > Si/Na_{oceanic\ crust} \sim Si/Na_{continental\ crust}$

(the same is true for K as for Na)

Also, $Si/Ca_{mantle} > Si/Ca_{oceanic\ crust} < Si/Ca_{continental\ crust}$

From these relationships we can conclude that:

- Si is more lithophile than Mg
- Na, K and Al are more lithophile than Si
- Ca is reluctantly lithophile (it goes into the oceanic crust more than Si but into the continental crust less than Si).

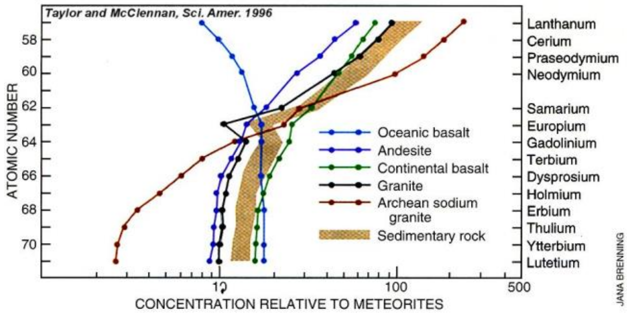
The Composition of Earth's crust

🛠 What about the non-major elements (those that typically don't make major rock-forming minerals)?

Because oceanic crust is relatively homogeneous, we can estimate its average composition through direct measurement of oceanic basalts.

This is difficult to do with the continental crust, because it contains many different types of rocks.

Terrigenous clastic sedimentary rocks, particularly ***shales****,* provide a good estimate of average crustal compositions for elements like the lanthanide rare earths *(here normalized by average chondrite concentrations to give relative values)*.



RARE-EARTH ELEMENT abundance patterns provide characteristic chemical markers for the types of rock that have formed the earth's crust. Although igneous rocks (those that solidify from magma) can have highly variable rare-earth element signatures (*dotted lines*), the pattern for most sedimentary rocks falls within a narrow range (*gray band*). That uniformity arises because sediments effectively record the average composition of the upper continental crust.

The Composition of Earth's crust

We can compare the rare earths and other elements by ratioing (normalizing) their abundances in continental and oceanic crust to their concentrations in ***estimated primitive mantle*** (which, remember, is basically C1 chondrite that's lost its volatiles and most of its Fe, and then had 10% of C1 chondrite added to it).

Recall from our discussion last week that

🏛 incompatible elements ("A") all have

$^{A}K_d$ = [modal conc. of A]$_{solids}$/[conc. of A]$_{melt}$ < 1

🏛 The smaller $^{A}K_d$ is, the more enriched it is in the continental crust. For example, bulk $^{Rb}K_d$ < bulk $^{Nb}K_d$; so Rb is more enriched than Nb.

The Composition of Earth’s crust

We can arrange ***primitive-mantle-normalized data in order of bulk Kd values during mantle melting*** to see how the elements behave relative to one another in the oceanic and continental crust.

If we do this for **average continental crust**, we see that some elements are enriched up to 100-fold (lithophile elements) over estimated primitive-mantle values, and some are depleted by up to 10-fold (siderophile elements and Mg).

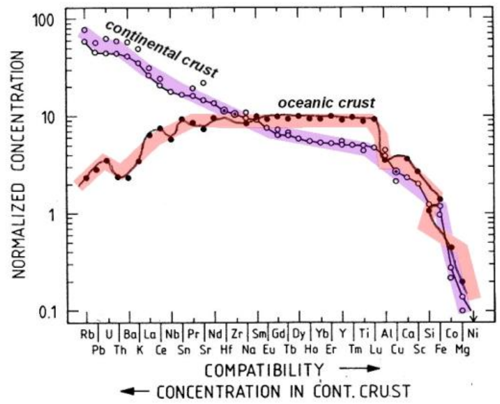


Fig. 1. Average compositions of continental crust (two estimates by Taylor and McLennan, [17], TM1 and TM2) and “normal-type” mid-ocean ridge basalts [4] from Table 1. All concentrations are normalized by division through the respective concentration of the primitive mantle (see also Table 1). The sequence of elements is determined by the order of decreasing concentrations in the continental crust average of Taylor and McLennan, TM1. These concentrations are connected by a solid line.

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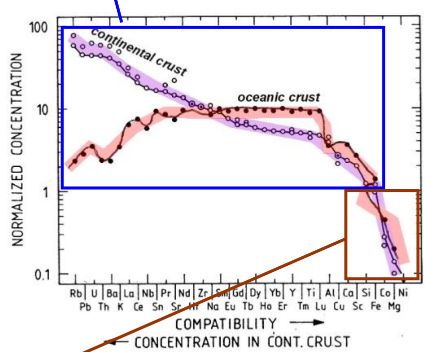
The Composition of Earth’s crust

"incompatible" elements

We call the elements that are enriched in the crust "incompatible" elements because they do not fit into structural sites in the major mantle mineral phases. When the mantle melts, they enter the melt phase and eventually end up in the crust.

Elements that are depleted in the crust are enriched in the mantle residues of melting and are called **“compatible” elements**.



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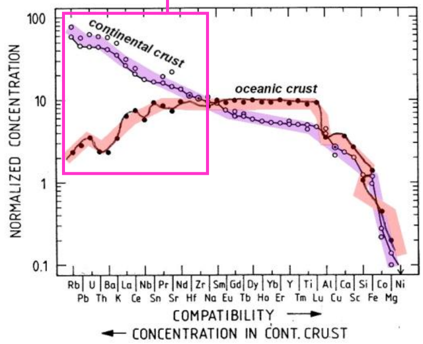
The Composition of Earth's crust

Notice that **average oceanic crust** is roughly a mirror image of average continental crust for the highly incompatible elements (Rb to Na).

This indicates that <u>modern oceanic crustal rocks</u> are, on average, derived from a source in the mantle that has *already been depleted* in the more incompatible lithophile elements.

This sub-reservoir of the mantle produces mid-ocean ridge basalts (**MORB**).

It is commonly referred to as the **"depleted mantle."**



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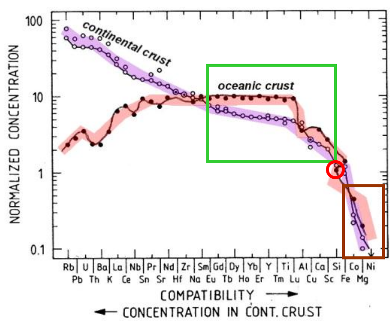
The Composition of Earth's crust

The heavy rare-earth elements, plus Cu, Ca, and Sc (collectively termed **moderately incompatible**) are more enriched in average oceanic crust than in continental crust. Those elements prefer basaltic melts to granitic ones.

*But.... concentrations of both the highly and moderately incompatible elements are higher than in the primitive mantle for both types of crust, because both types are produced from only **partial** melts of the mantle.*

So long as there is a residue and...
$^{A}K_d$ <1 then... $[A]_{melt} > [A]_{residue}$

Finally, notice again that the **siderophiles and Mg** are <u>depleted</u> in both types of crust and that **Si is very similar** to its primitive-mantle abundance in both (i.e., avg. cont. crust isn't really granitic).



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The Composition of Earth's crust

The depletion of siderophiles in both types of crust implies that the crust largely formed ***after*** core formation. (It's possible that an early crust existed while the core was forming; if so, it must have been destroyed later by plate tectonics or late-stage bombardment of planetesimals.)

The overall shape of the primitive-mantle-normalized concentration profiles has led many geochemists to suggest that:

a. the oceanic crust was/is formed from the depleted mantle

And

b. the depletion of the ***"depleted" mantle*** was caused by earlier extraction of the continental crust.

This hypothesis can be tested through modeling in several different ways.

Let's go through just one typical example.

The composition of Earth's crust

Stage 1: First we'll assume the continental crust formed by partial melting of primitive mantle (by 2% partial melting by mass).

This leaves a residual mantle with the primitive-mantle-normalized concentrations shown below, as a function of the distribution (partition) coefficient value.

90% of the melt leaves to form the continental crust; 10% remains in the melted mantle.

Stage 2: The oceanic crust then forms by about 4% of partial melting of this "hybrid" residual mantle.

(We'll get to the specifics of how one makes these sorts of calculations when we discuss igneous rocks next week.)

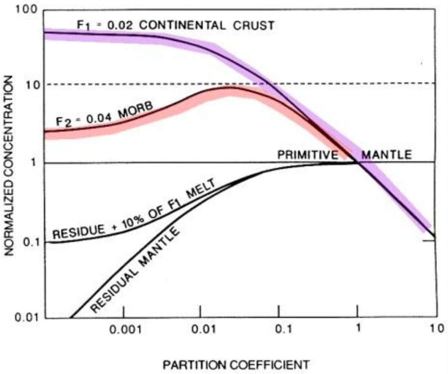
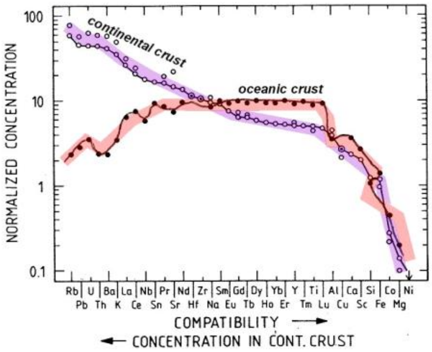


Fig. 4. Effect of retention of a portion of stage-1 melt on the concentrations in the residue and in a stage-2 melt, calculated from equation (4) and $\alpha = 0.1$. *Hofmann, 1988, EPSL*

The Composition of Earth's crust

- Although such a model is clearly much too simple, the first-order match to the observations isn't too bad.



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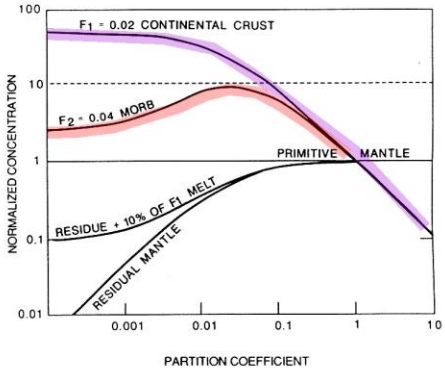

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Hofmann, 1988, EPSL

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The Depleted mantle

If the material that's now in the continental crust originally was part of the primitive mantle, how do we estimate

how much of the mantle was depleted to make the crust? **About 25% to 33%.**

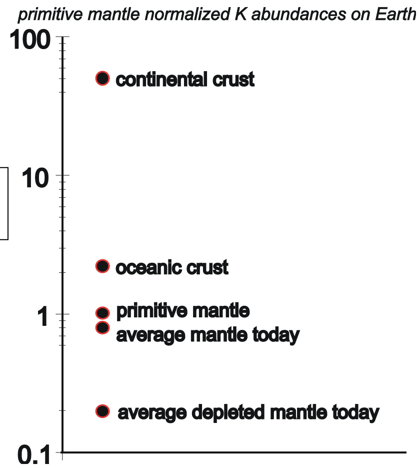
The results of calculations on the next few slides are summarized here, using Chondritic primitive mantle normalized K concentrations:

mantle:

- primitive mantle = 180/180 = 1
- average mantle today = 145/180 = 0.808
- average depleted mantle today = 40/180 = 0.22

crust:

- average continental crust = 9100/180 = 50.6
- average oceanic crust = 400/180 = 2.2



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The Depleted mantle

Here are the calculations…

The total mass of the primitive mantle is estimated from Table 1.1 of a prior lecture:

mass of crust:	2.4×10^{25} g
+mass of mantle:	407×10^{25} g (sum of all 3 zones)
primitive mantle:	409.4×10^{25} g

Table 1.1 Dimensions and masses of the internal layers of the Earth

Region	Depth to boundaries (km)	Mass (10^{25} g)	Fraction of total mass
Crust	0–Moho	2.4	0.004
Upper mantle	Moho–400	62	0.10
Transition zone	400–1000	100	0.17
Lower mantle	1000–2900	245	0.41
Outer core	2900–5154	177	0.30
Inner core	5154–6371	12	0.02

How much of the modern crust is oceanic vs continental?

- By area, oceanic crust is more abundant:
  - oceanic: ~7 km average thickness. ~2/3 earth's surface
  - continental: ~35 km average thickness. ~1/3 earth's surface
- volumetrically, continental crust is more abundant:
  - 7 * 2/3 = 4.7 and 35 * 1/3 = 11.8
  - oceanic = 100% * 4.7/(11.8+ 4.7) = 28.5%
  - continental = 71.5%
- by mass the story is the same:
  - 4.7 * 2.8 g/cm^3 = 13.2 and 11.8* 2.7g/cm^3 = 31.9
  - oceanic = 100% x 13.2/(13.2 + 31.9) = 29.3%
  - continental = 70.7%

The Depleted mantle

Next we do a ***mass balance*** estimate to address how much mantle was "processed" to make the continental crust.

- Let's make a the calculation using K distribution on earth today (K is lithophile and incompatible):

$[K]_{continental\ crust} >> [K]_{oceanic\ crust}$ and $[K]_{core} \sim 0$

As an estimate we will assume that all of the K in the crust is in the continental portion

$mass_{continental\ crust} = 70.7\%\ mass_{all\ crust}$ = 1.70×10^{25} g

$mass_{mantle\ today}$ = 407×10^{25} g

- From the 90%-10% chondritic primitive mantle model, we estimate

  $[K]_{primitive\ mantle}$ = 180 ppm = 0.018%

- Mass $K_{primitive\ mantle}$ = 0.018% x 409.4x10^{25}g = 7.37x10^{23} g

- Average $[K]_{continental\ crust}$ is 9100 ppm = 0.91%
- Mass $K_{continental\ crust}$ = 0.91% x 1.70x10^{25}g = 1.55x10^{23} g

The Depleted mantle

There was 7.37 x 10^{23} g K in the original primitive mantle and now 1.55 x 10^{23} is in the continental crust. The percentage of K in the continental crust is thus = 100 x mass K_{CC}/mass K_{PM}: 100%*(1.55 x 10^{23})/(7.37 x 10^{23}) = **21.0% in the cont. crust**.

- if we adjust for the small amount that is in the oceanic crust too, the value becomes ~ 21.5% of all K is in the crust.

Implications

- nearly 80% of the original K on earth is still in the mantle.

If the K that is in the crust was uniformly extracted from the entire mantle, the average mantle concentration today would be ~80% of the original K divided by the present mantle mass:

0.8 * 7.37 x 10^{23}g/407 x 10^{25}g

= 0.000145g/g = 0.0145 wt% = 145 ppm

So how does this compare with what we think is in the *depleted mantle*?

- The oceanic crust today has ~400 ppm

- Modeling to make average MORB compositions suggests that the **depleted mantle today has only about 10% of this**, or ~40 ppm.

The depleted mantle

Therefore, if the events that removed K to the continental crust were also the events that created the depleted mantle…

…then the ***entire mantle cannot have been depleted*** in the process, because we would expect 145 ppm instead of 40 ppm K in today's depleted mantle.

In other words, the depleted mantle is 145/40 or ≈3.5 times more depleted than expected for whole-mantle depletion.

Conclusion: the K in the continental crust probably came from only about 30% (~1/3.5) of the mantle.

- Similar calculations can be made for each of the other lithophile elements. They all indicate that the depleted mantle is only a sub-reservoir of the mantle **(~25-33%).**

(assuming our estimate of primitive-mantle composition is accurate — remember, that's what all of this is based on!)

The Composition of the Continental crust

The continental crust is essentially a "distillate" of the primitive silicate earth formed of low density material that is rich in lithophile elements.

The mantle residue of continental crust formation is highly depleted in these same materials, and is believed to form the source of mid-ocean ridge basalts.

The continental crust is actually a complex mixture of materials with different lithologies and ages.

We that know it didn't form at one time or from just one process.

Table 12.3. Abundance of Igneous and Sedimentary Rocks in the Upper Crust

Plutonic Rocks (89-92% of total)	Volume %	Sedimentary Rocks (8-11% of total)	Volume %
Granite, Granodiorite	77	Shales	72
Quartz Diorite	8	Carbonates	15
Diorite	1	Sandstones	11
Gabbros	13	Evaporites	2
Syenites, anorthosites, peridotites	1		

From Taylor and McLennan (1985) ... (*via White, "Geochemistry"*).

The Composition of the Continental crust

Knowledge of the bulk continental crustal composition both today and in the past is important for understanding of

(1) how the silicate part of the Earth has evolved through time

(2) the relationship of the crust and mantle to atmosphere-hydrosphere evolution.

The Composition of the Continental crust

Methods to estimate the bulk crustal composition include:

- Direct analysis of known rock types, coupled with weighted averaging.

  Direct analysis is biased by what happens to crop out at the surface and by sampling (i.e., where we happen to take samples and what rock happens to be at a particular sampling location).

- Analysis of "geological mixtures" — fine-grained clastic sediments and sedimentary rocks, particularly shale, loess, and glacial till.

- Geophysical inference (useful for the lower crust).

The Composition of the Continental crust

Geological mixtures:

Geological mixtures integrate over the continental weathering component of the rock cycle for the time period represented by the age of a given sedimentary rock.

Geochemists make ***composites*** of such rocks for a large geographical area or for a particular time range to estimate crustal composition.

The Composition of the Continental crust

Geological mixtures:

The example at right uses ***loess***, the average composition of which compares favorably for most elements to the average upper crustal composition estimated by other methods.

BUT, loess is enriched in elements found in weathering-resistant minerals (Zr, Hf, Si) and depleted in elements that are very mobile (easily leached) during weathering (e.g., Na, Ca).

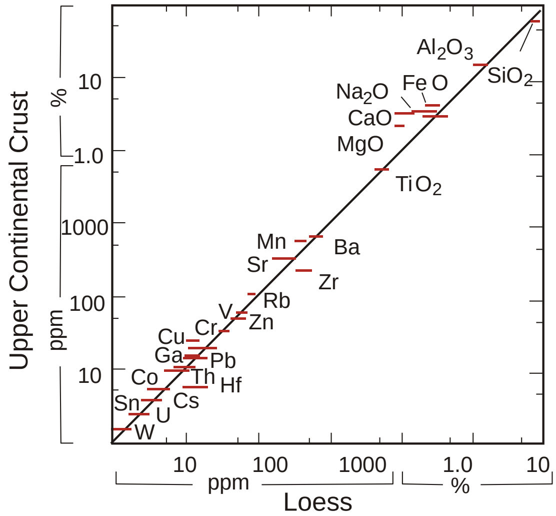


Figure 12.26. Comparison of elemental concentrations in loess with estimated upper crust. From Taylor and McLennan (1985). *modified from White, "Geochemistry"*

The Composition of the Continental crust

Geological mixtures:

Shale composites: if one only considers elements that are not easily leached from ***clay minerals*** (e.g., the rare-earth elements), shales work very well.

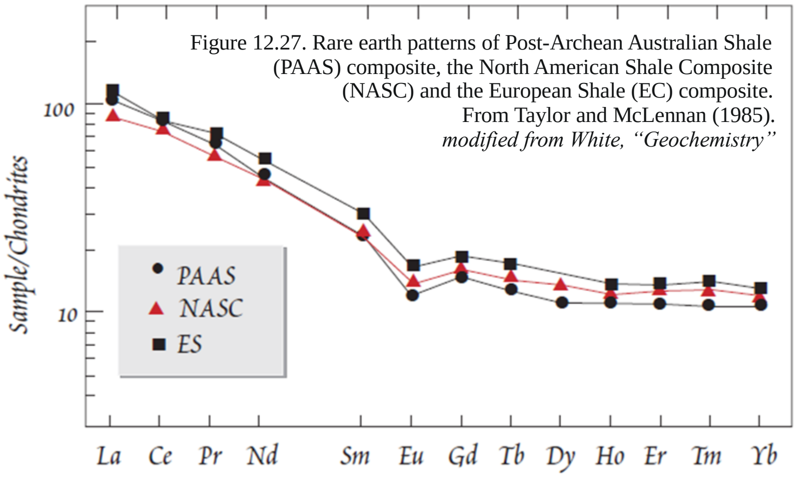


Figure 12.27. Rare earth patterns of Post-Archean Australian Shale (PAAS) composite, the North American Shale Composite (NASC) and the European Shale (EC) composite. From Taylor and McLennan (1985). *modified from White, "Geochemistry"*

The Composition of the Continental crust

Geological mixtures:

A number of authors have estimated the average continental crust composition using data from these and similar approaches.

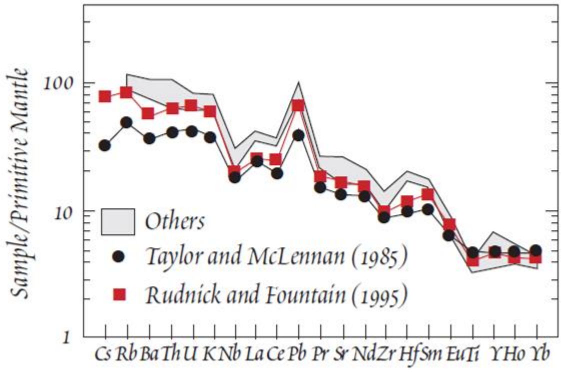


Figure 12.32. Comparison of incompatible element enrichment of estimated bulk crustal composition of Taylor and McLennan (1985), Rudnick and Fountain (1995) with other estimates (Weaver and Tarney, 1984; Shaw et al., 1986; Wedepohl, 1995). From Rudnick and Fountain (1995).

modified from White, "Geochemistry"

The Composition of the Continental crust

It is interesting that these averages are very similar to the compositions of SiO_2-rich ***andesite*** lavas erupted at modern island arc volcanoes. Note the distinctive **depletions in Ta and Nb**, and large **enrichments in Pb.** This bolsters arguments that the bulk of continental crust is produced in arcs.

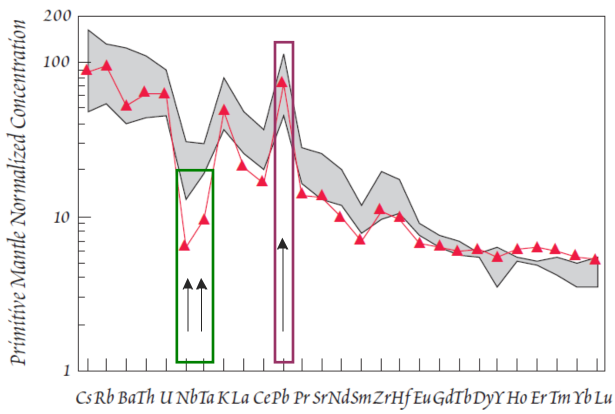


Figure 12.38. Comparison of incompatible element concentrations in a silicous andesite from the Banda arc (red stars) with the range of estimated concentrations in the continental crust (gray field). Both share a relative depletion in Nb and Ta and a relative enrichment in Pb.

modified from White, "Geochemistry"

The Composition of the Continental crust

These methods ***<u>work well for the upper crust</u>***, but it is much more difficult to estimate ***<u>deep crustal composition</u>*** from what can be observed at the surface.

<u>Assuming the deeper crust composition is similar to the upper crust:</u>

(1) gives a *crustal density that is too low*.

(2) yields a *bulk composition that's too enriched in lithophiles* for estimates of primitive-mantle depletion.

(3) yields a crustal *heat flow that's much too high*.

It thus appears that the lower crust and middle crust are *not composed of the same relatively <u>high-Si material</u>* as the upper crust. This inference is consistent with:

- rare outcrops of deep crustal rocks (i.e., containing high-P minerals)
- the known effect of temperature on seismic wave propagation.

The Composition of the Continental crust

Seismic data indicate the continental crust generally has a ***three-layered structure***.

Higher temperature slows the propagation of seismic waves through rock of a given composition, yet P and S wave velocity increases with depth.

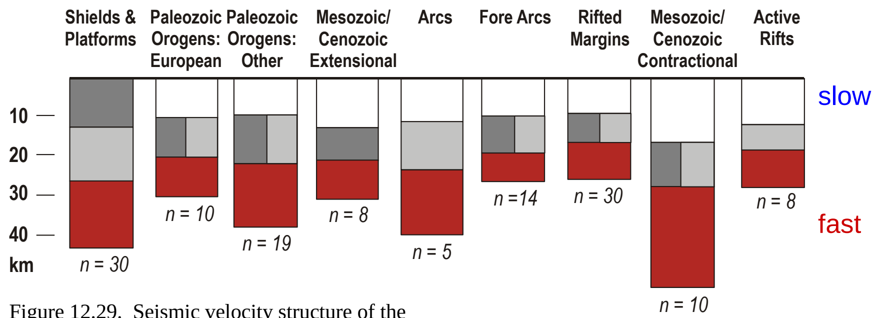
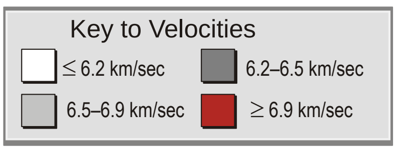


Figure 12.29. Seismic velocity structure of the continental crust, illustrating its 3-layered nature. Velocity structure falls into 9 types. The number of profiles used to construct each type is shown below each type. From Rudnick and Fountain (1995).
modified from White, "Geochemistry"



The Composition of the Continental crust

Alnmost all ***heat production within the crust*** today is from radioactive decay of ^{232}***Th,*** ^{238}***U*** and ^{40}***K***. All three of these elements are incompatible elements in the mantle and are strongly lithophilic, so their concentrations in crustal rocks generally increase as Si content increases.

- Heat production leads to higher temperature, which slows seismic wave speed.
- Heat production in the crust is broadly correlated with SiO_2 content (positive correlation). Thus seismic velocity is also correlated with SiO_2 (but it is a negative correlation).

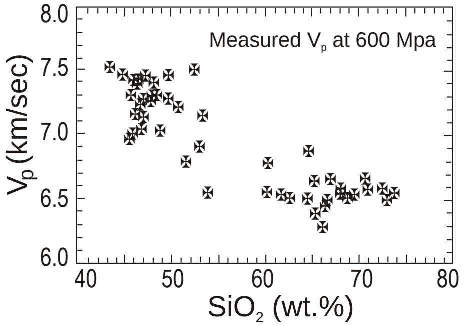


Figure 12.30. Correlation between measured seismic velocity (v_p) and SiO_2 concentration. From Rudnick and Fountain (1995). *modified from White, "Geochemistry"*

The Composition of the Continental crust

Estimates of Lower and middle crust compositions can then be made from the relationship between:

♦ seismic velocities and SiO_2

♦Th, U and K content relative to SiO_2 for different crustal rock types

♦ the ratios of other elements to Th, U and K in surface rocks.

Such estimates indicate that the **lower crust** is **significantly more Mg-rich, Si-poor,** and **less enriched** in the most **highly incompatible elements** than the upper crust.

The middle crust is intermediate between the two.

The BULK continental crust is <u>broadly andesitic</u> (not granitic).

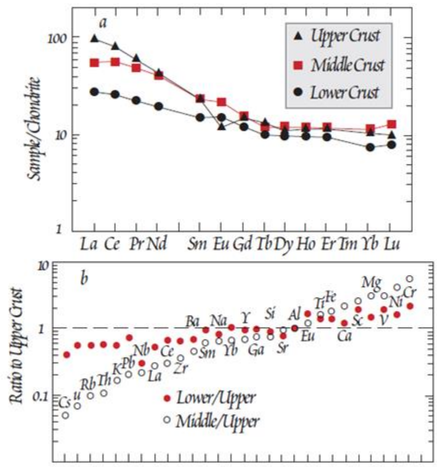


Figure 12.31. (a). Comparison of chondrite-normalized in upper, middle and lower crust. (b). Elemental enrichment or depletion of the middle and lower crust relative to the upper crust. From Rudnick and Fountain (1995). *modified from White, "Geochemistry"*