

GY 112 Lecture Notes

Evolution of Plate Tectonics as a Theory

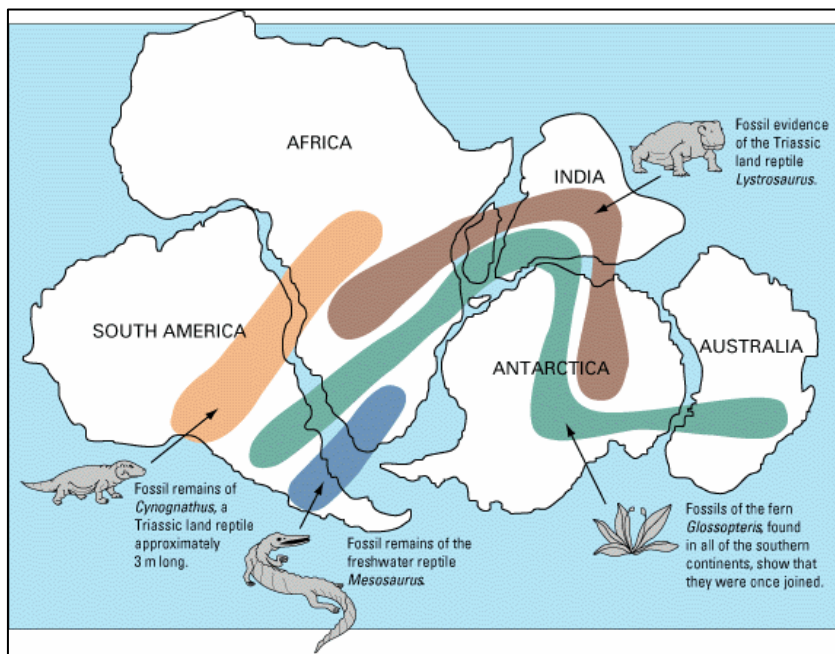
Lecture Goals:

- A) Mountain Building before Plate Tectonics
- B) The evidence in favor of Plate Tectonics
- C) New ideas

Textbook reference: Levin 7th edition (2003), Chapter 5; Levin 8th edition (2006), Chapters 1, 2 and 5 (and a lot of stuff that Doug read somewhere)

A) Mountain Building before Plate Tectonics

By now, most of you should already be familiar with **Alfred Wegener** and his “radical ideas”. In the early 1900’s, Wegener proposed that the continents has shifted positions relative to each other over time. His evidence was centered around South America and Africa. Any child (and even some GY 112 students) can see how the two continents look like they fit together and to be fair, we should again point out that Wegener was not the first to see this fit. Sir Francis Bacon in 1620 mentioned it and in 1782, Benjamin

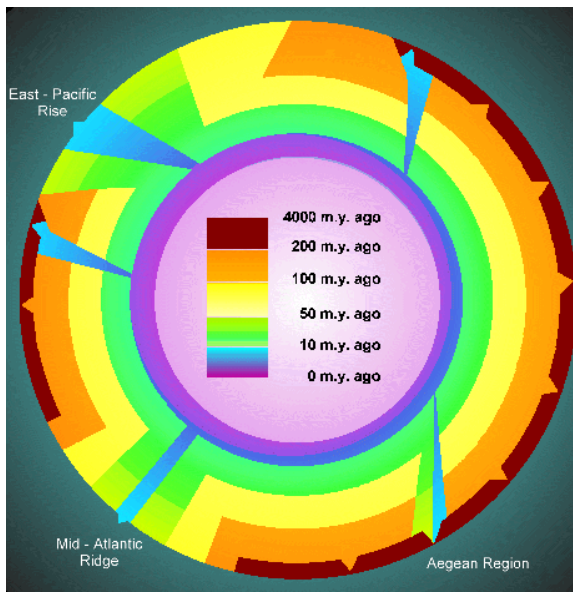


Franklin even stated that the surface of the Earth resembled a shell, “capable of being broken and distorted by the violent movements of the fluid on which it rested”. Noted French scientist Antonio Snider-Pellegrini suggested that the continents were connected during the late Carboniferous Period (Pennsylvania to those of us that

reside in the USA) based upon similar plant fossils in Europe and North America. Edward Suess, an Austrian geologist, took this one step further when he recognized similar plant fossils between South America, Africa, India, Australia and Antarctic. In the late 1800’s, he proposed that all of these continents were part of an ancient larger continent which he called **Gondwana**, a name we still use today. So why do we give most of the credit for continental drift to Wegener? Because he reviewed all of the data, first proposed a true super continent and put it all together into a book. I guess the saying “he who publishes first, is first” holds here. The hypothesis of **Continental Drift** was official born in 1915 with the publishing of his book *Die Entstehung der Kontinente und Ozeane* (Translation: *The Origins of Continents and Oceans*) which you can still buy from Amazon.com and other sources. Here is the reference to the translated copy:

Wegener, A., 1966. *The Origin of Continents and Oceans* (Translated by John Biram), Dover Publications, New York, 246p.

As stated previously, few scientists at the time supported Wegener's "new radical idea". I have several old geology textbooks (circa 1940) that pooh-poohed Wegener's idea. They state (and this was correct at the time), "that apart from circumstantial data, there was absolutely no supporting evidence for this new idea of Continental Drift". For example, no mechanism of movement was given (In fact, we still don't really know how this works today!). Interestingly, the authors that were most negative about Wegener's ideas were those most silent about how mountains actually formed. They went into great detail about the types of rocks forming mountains, their ages and their geomorphology, but their origins were not discussed. Well this is not entirely true. Volcanic mountains were reasonably well understood. But mountain belts were much more than just volcanoes. Geologists recognized that great compressive forces had to have been at work to form the Alps and Rockies, but the mechanism by which it occurred was not yet clear. Despite the silence in text books about mountain building, there were some ideas that were suggested, but they were (like Wegener's Continental Drift) largely unsubstantiated. Here are three of my favorites:



1) Expanding Earth. Some felt that the drift of continents and the vastness of oceans could be explained through the expansion of the Earth's crust. In other words, the Earth is swelling. Surprisingly, there is some data out there that might (if you squint hard enough) support this idea and there are still proponents of the idea (e.g., the image to the left came from a recent geological paper). A larger Earth, one that has swelled, spins more slowly on its axis than a smaller one. This is the same principle that an ice skater uses to spin fast during a pirouette. She (or he) starts to spin and then pulls her (or his) arms inward which decreases her (or his)

size thereby increasing her (or his) spin speed. The opposite would hold (i.e., spin would decrease) if the ice skater extended her (or his arms) outwards. The Earth's spin has indeed been slowing over time. About 500 million years ago, the Earth spun about 25% faster than it does today. The supporting evidence is paleontological in nature. Certain animals which secreted skeletal material and shells (e.g., foraminifer) indicate that the day was only 18 hours long some 500 million years ago. In other words, the Earth has indeed slowed its spin, but this is not because the Earth is swelling. Gravitational forces between the Earth and our moon has slowed our spin. The moon is much less massive than the Earth and has suffered much more dramatic slowing. In fact, the moon spins only once during its revolution around the Earth. That's why we only see one side of it. It is locked toward us. The gradual slowing of the Earth's and moon's spin has other

connotations as well. In order to conserve momentum within the Earth-moon system (yet another law of physics), the two had to move apart from one another. Long ago, the moon was much closer to the Earth than it is today. The tides must have been amazing back then. Tidal flats would have been extensive over much of the coastal areas of the planet. There is evidence supporting this in the rocks. However, the evidence does not necessarily support an expanding Earth. Given how well plate tectonics works in explaining geological phenomenon, I personally think the expanding Earth hypothesis is nonsense.

2) **Contracting Earth.** This idea is just the opposite of the expanding Earth hypothesis. Some felt that the Earth must have contracted as it cooled over time. The result was wrinkling (i.e., mountains). There is no evidence that I am aware of that supports this idea at all.

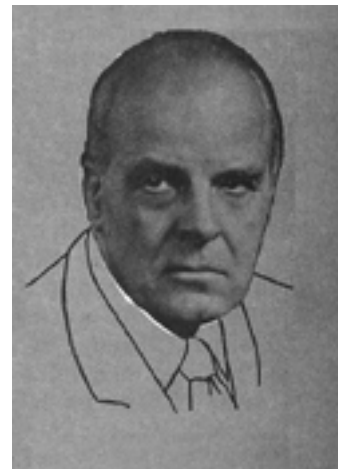


3) **Worlds in Collision.** I didn't mention this in class and won't discuss it much here, but you should be aware that some ideas about the Earth were spiritual in nature. Immanuel **Velikovsky** (pictured left) published a book called *Worlds in Collision* in 1950. He did extensive research (albeit limited to the Bible and other religious texts) that led him to conclude that the Earth had been on the receiving end of numerous close encounters of the astronomical kind. Venus and Mars almost hit us resulting in massive upheavals on this planet. Velikovsky never said that mountains formed this way, but he did believe that the Great Flood and the parting of the Red Sea (as told in the Bible) were caused by these encounters. If you are a Geology

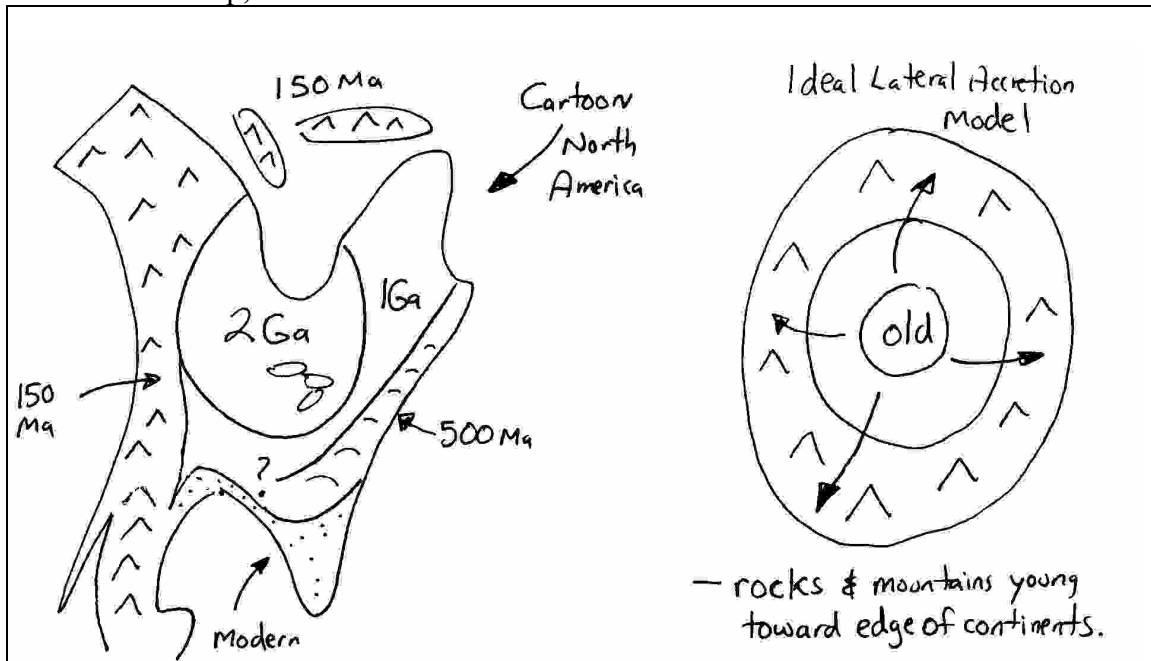
Major, or a scientist in training, do yourself a favor and read up on Velikovsky's ideas. I do not endorse them (in fact I think that they are absolutely hilarious), but if you are going to become a scientist, you must be able to reject an idea based upon fact. When Velikovsky's book was published, the scientific community apparently jumped all over it. I suspect that it was because of the religious overtones (science and religion will never be totally comfortable with one another). Read the book yourself, then decide if it's ideas are right or wrong. Here is the reference:

Velikovsky, I (1950). *Worlds in Collision*. Double Day, Garden City, NY.

There is one other idea about mountain building that we need to discuss. It was the most widely accepted idea at the time (by geologists anyway) to account for the formation of the mountains. It was formulated in the 1930's by **Marshall Kay** (pictured to the right) and others and at the time, seemed to fit most of the data that was available. Radiometric dating suggested that North America was "zoned" like an onion. The oldest rocks seemed to be in the center of the continent. The youngest rocks (and the mountains seemed to be along the

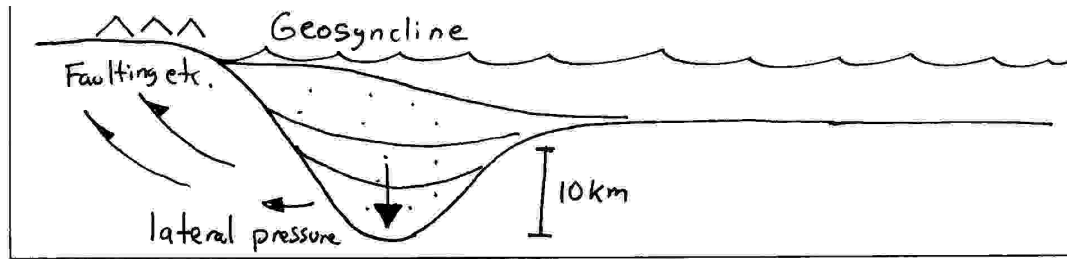


edges. The cartoon below illustrates this. To North American geologists, it seemed as if the continent had grown laterally. Mountains were accreted to the outside edges over time. (I wonder how our geo-colleagues in Europe, Asia and Australia felt about this idea. Check a map, mountains are not

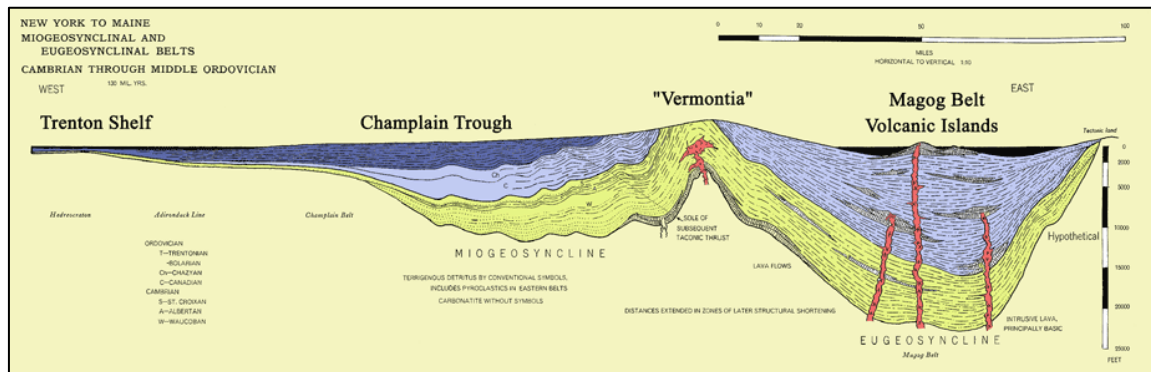


distributed equally along the edges of those continents). “**Lateral accretion**” was largely a North American idea. Marshall Kay and others suggested that mountains were built up along the edges of continents because in part, of the sediment that was dumped by rivers and other depositional systems along the coastline in trough-like structures called “**geosynclines**” (This term was first used by Dana, a true geo-God back in 1873, but it had many meanings). Kay suggested that the weight of the sediment caused the crust to be locally depressed into a trough (AKA a geosyncline). As the geosyncline subsided, more sediment could be added causing more subsidence etc. It is true that sediment can depress the crust (e.g., the Mississippi delta has caused a significant amount of subsidence and compaction), but geosynclines were thought to be up to 12 or 14 km deep. This thickness of sediment was derived on the basis of the sedimentary rocks that comprised portions of mountain belts like the Appalachians and the depths of some trenches that surrounded modern continents (e.g., western South America). The pressure exerted by the sediment fill within the geosynclines was thought to be great enough at the base to cause compression of the rocks adjacent to the geosyncline. The result was thrust faulting, folding and metamorphism within a ridge (called a **geanticline**) along the continental side of the geosyncline (in other words, a mountain belt). You can read about this idea in the following book:

Kay, M (1951). North American Geosynclines, *Geological Society of America Memoir* 48, 143p.



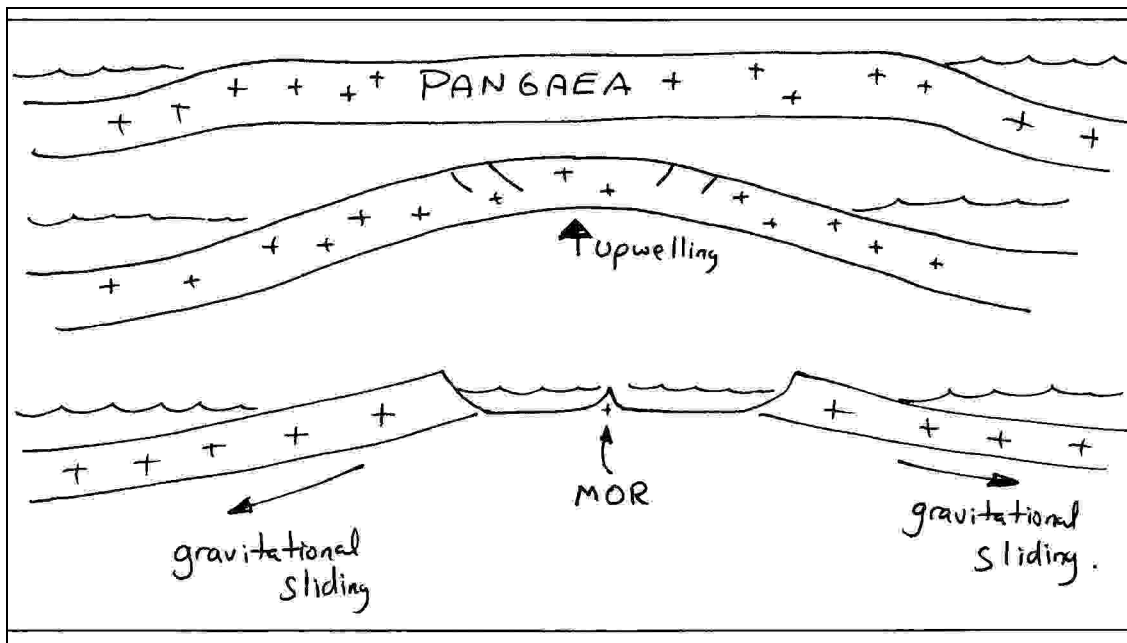
The image below is one of Kay's cross sections from the northeaster part of the United States and more or less shows the morphology of a geosyncline. It shows some of the subdivisions of geosynclines (mio- and eu- divisions) which, like geoanticline, are no longer in use. The term geosyncline is still used today, albeit for a different situation.



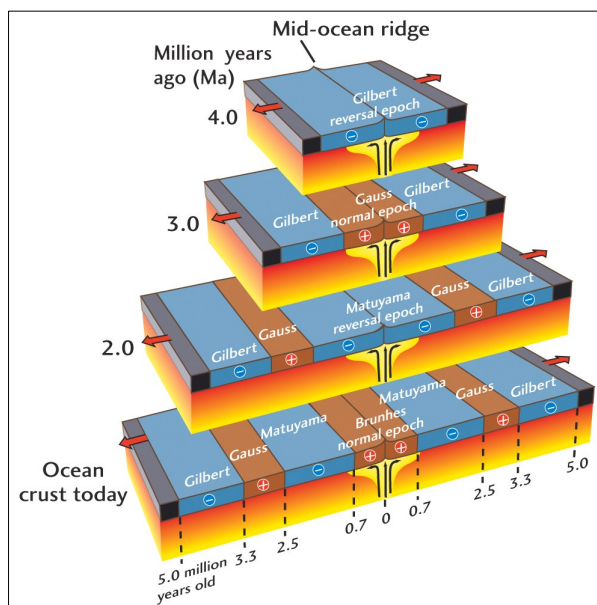
Continental Drift was still out there as an idea, even during the time of geosynclines and geoanticlines, but until evidence was found supporting it, it was not widely accepted. That evidence was built up gradually starting in about 1930.

B) The evidence in favor of Plate Tectonics

Wegener may have first suggested continental drift, but others have been credited with the origins of Plate Tectonic Theory. Reginald Daly (1926) suggested that continental drift could be induced through uplift of a continent (he used Wegener's Pangaea as an example), followed by gravitational sliding (see diagram at the top of the next page). He even felt that the Mid-Atlantic Ridge (it was apparently known at this time, though it's age was not), was a left over fragment of continental crust (it is not, but at least he could account for it).



Another person credited with the first real ideas about plate tectonics was Arthur Holmes. He published a manuscript in 1931 suggesting that sialic (or felsic) crust atop less rigid basaltic crust was being pulled apart by sub-crustal flow. The flow, he felt may have been driven by **convection currents** under mid oceanic ridges that sunk under mountain ranges and island arcs. This is exactly what we teach you today.



You have already been told that following World War II, a lot of technology was applied to the science of the Earth and that a lot of it came together in the late 1950's during the International Geophysical Year. What followed can only be described as an explosion of evidence in favor of Plate Tectonics. **Hess** (1963) and **Dietz** (1961) confirmed the ideas of a German (Kober) who in 1923 predicted the existence of a worldwide system of ocean rises and ridges. Density analyses of rocks suggested that continental crust and oceanic crust would be have differently in the presence of convection (continental crust being less dense

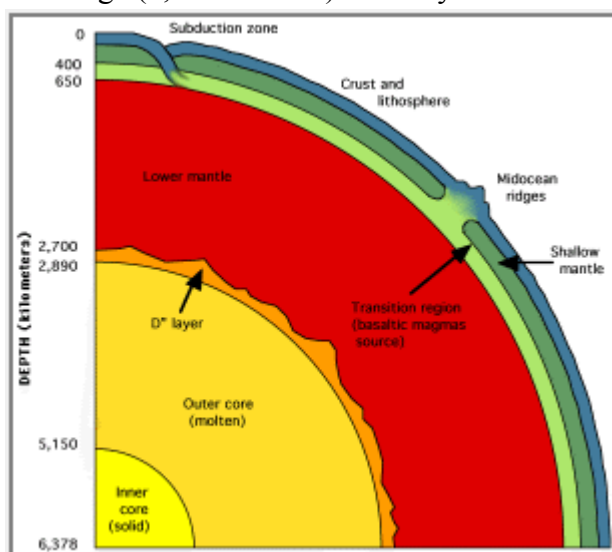
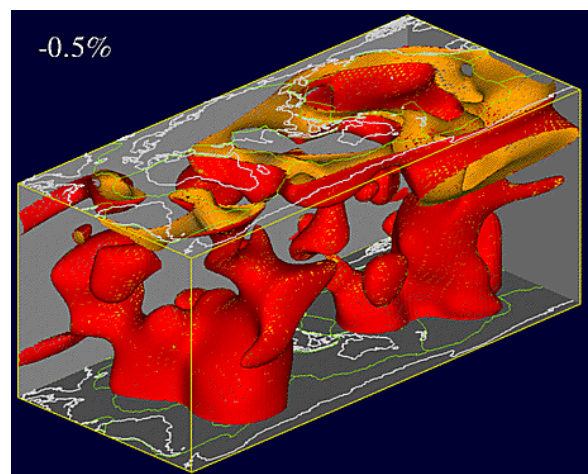
would surf on top of the oceanic crust). But the major piece of evidence in favor of Plate Tectonics was paleomagnetic dating. Once the ocean floor was dated (it is much younger than the continents), and **paleomagnetic** "stripes" were found on the sea floor (ocean crust is youngest along the ridges and gets older (symmetrically) away from the ridges toward the continents), few critics of Plate Tectonics remained.

When I was an undergraduate student in the early 1980's, Plate Tectonics had been accepted for about 10 or 15 years. It was still a young theory, so we spent a lot of time talking about how it evolved and who the major players were behind its evolution. One name that kept turning up was **J. Tuzo Wilson**. He wrote several classic papers about the "New Plate Tectonics" including one that I still remember to this day. In fact, it is a paper that I require all of the students I teach in a Marine Sciences Graduate course to read. Its was called "*Did the Atlantic Close and Then Open Again*". Wilson looked at the rocks comprising the Appalachian Mountains (especially in Newfoundland) and saw evidence of former Oceanic rocks within the mountains. This paper really opened my eyes up to Plate Tectonics and how things could be resolved using geology. At the time I was majoring in Chemistry. I switched to Geology, in part because of Professor Wilson's insight. I have never regretted that decision. To this day, I feel that Geology is the only science that truly requires imagination and lateral thinking. If you are a daydreamer, this branch of science is for you. Here's the full reference to Wilson's paper;

Wilson, J.T. (1966) Did the Atlantic Ocean close and then open again? *Nature*, 211, p676-681

C) New ideas

Theories are not static. They are constantly tested and are constantly evolving. In the past several years, new technologies have developed that have allowed us to refine Plate Tectonic theory. One of these technological developments is called **seismic tomography**. It essentially allows seismologists to model convection (see image to the right) and boundary layers within the Earth's interior. Recent work (e.g., the last couple of years) has revealed that the boundary between the mantle and the outer core is "lumpy" not smooth like an onion. These lumps comprising the **D-layer** are huge (1,000s of km³) and may be the



remains of lithosphere that descended through the mantle. I admit considerable confusion over this. We believe that the lithosphere is less dense than the mantle, so I don't quite accept that it could sink all the way through the mantle to get to the boundary. Some people have suggested that the lithosphere can sink because it is always cooler than the mantle it is sinking through (it takes time for the slab to heat up to the ambient temperature). Once it gets to the boundary, it floats on top of the outer core (which is metallic and much more dense). Once the slab (now a lump)

heats up to the ambient temperature down there (thousands of degrees), it may suddenly rise upwards. We have now directly observed mantle plumes in the mantle and under hotspots (another recent development). Perhaps the plumes are the remains of lithosphere now rising back to the surface.

Another recent development is the diamond anvil. This device is simple, but no one really thought about doing it until just a few years ago. You take 2 cut diamonds, attach them to metallic plates in a press and align them point to point. When you squeeze the plates together, all of the force is concentrated at the points. We can now duplicate the pressures at the center of the Earth. That means we can now model the chemical reactions that occur within the Earth. A lot of weird stuff seems to happen down there including mineral phase changes. Interested in all this stuff? I suggest that you track down the following reference. It's where I learned about it:

Vogel, S (1995) *Naked Earth: The New Geophysics*. Penguin Books, New York, NY.

Important terms/concepts from today's lecture

(Google any terms that you are not familiar with)

People

Alfred Wegener (again!)

Hess

Marshall Kay

J. Tuzo Wilson

Velikovsky

Terms

Gondwana

Continental Drift Hypothesis

Expanding Earth Hypothesis

Contracting Earth Hypothesis

Convection/convection currents

Geosyncline

Lateral Accretion

Paleomagnetism

Seismic tomography

D-layer