Reading notes on KKV Ch 2: The interior of the earth

2.1 EQ SEISMOLOGY

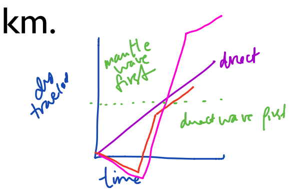
seismic waves, their speed
double couple model and focal mechanisms. elastic rebound theory
--EXPLAIN how the fault plane and auxiliary plane are different than a fault plane and its conjugate
seismic tomography - like medical xrays - an energy source, illuminates the volume, and detected on the other side. in medical you know the energy and the distance travelled - all delays and attenuation of energy arrival at the detector can be attributed to complex paths and rigidity of materials. in earth, beat down the uncertainties by using more and more earthquakes and more and more stations.

tomography techniques typically use one type of wave at a time. For body waves (p and s) use travel time, better for deeper imaging of velocity structure. surface waves can be better for picking up anisotropy and shorter wavelength changes.

Iterative - between velocity structure and raypath. this process improves earthquake location and magnitude estimation.

2.2 VELOCITY STRUCTURE OF THE EARTH

Moho was discovered in 1909. Key observation was that at 200 km from epicenter, p-wave arrivals were before predicted because the crustal paths were at 5.6 km/s and the mantle speed was 7.9 km/s. calculated depth was 54 km. same pattern is found globally - strong velocity contrast from 5.5-6 to 8 km/s at depths of 20 (new cont or rift) -80 (Himalaya) km. mean 40 km.



Made my own diagram - purple is direct wave.
red is a path to a station near the epicenter
pink is a path to a station farther from epicenter.
key way of showing path length increase is to have distance toward station decrease initially.

Similar Conrad discontinuity within crust (1925) marking transition from felsic (5.5 km/s) to mafic (6.5 km/s). Was supported by petrologists/differentiation models (SIAL and SIMA). Not present everywhere. Most places, velocity increases gradually with depth, corresponding to gradients in composition as well as water content, fracturing, etc.
Oceanic Moho depth is 6-7 km (everywhere)

Problem - detection of lower velocity layers is difficult - they generate no faster arrivals, are poor reflectors, and increase attenuation.

Low velocity zone (LVZ) present between ~100-300km. mantle transition zone 410-660 km with stepwise increases in velocity corresponding to phase changes.

2891 km - Gutenberg Discontinuity: the core mantle boundary. 5150 km: inner core. No transition zone, it's a sharp contact.

2.3 COMPOSITION OF THE EARTH

General paradigm used in geochemistry and geodynamics: That the average composition of the solar system (expressed as ratios of elements) is primordial and local variations are caused by segregation processes. Therefore, very ancient rocks (e.g. chondritic meteorites) preserve pre-segregation ratios of heavier elements, while the solar atmosphere provides ratios of light elements. The moment of inertia of the earth-moon system provides an estimate of siderophile to lithophile volumes which is similar to average meteorites. Sort of. Massive data tweaking goes on though. To fully understand earth's composition, we have to match its chemical and physical properties, density-depth structure, seismic velocity structure, magma compositions, etc. These datasets are not perfectly integrated but active research.

2.4 THE CRUST

Continental

Direct sampling at the surface of exhumed rocks - abundant to middle crust, lower crust (>35 km) are more rare. Very deep (>50 km) quite rare, not very extensive. Xenoliths bring up lower crust and upper mantle, sometimes isolated crystals from much deeper, but effects of transport must be taken into accoung.

Pressure gradient with depth 30 MPa/km (=0.3 kbar/km)
Conductive geotherm averages 25°C/km but can be colder (<10 in subduction zones) to hotter (50 or higher in geothermal areas). At the Moho, thermal gradient decreases by 50% because of no radiogenic heat production.
top few km - high gradient in elastic moduli due to crack closing

Ways of estimating continental composition:
- past theories = granite (65-70 wt % SiO_2) but average continental crust is more dense than granite (granite=2.67, average crust = 2.8)

- radiogenic heat flow related to K, Th, U concentrations - andesite to granodiorite (60-65% SiO_2) with K_2O <1.5 wt %.
- deep sea sediments = repository of all weathering continental rocks - produces slightly more mafic estimate with 60% SiO_2

Lower crust is thicker in recent orogens; velocity of 6.8-7.7 km/s Vp indicates it must be mafic. At the calculated PT conditions, the lower crust may be granulite or diorite if dry. In thicker parts, should transition to eclogite if cold enough. This transition makes plagioclase go to garnet and pyroxene - very dense. if water is present, amphibolite instead of eclogite. Velocity constraints match a mixture of amphibolite and granitic rock (mafic to intermediate composition and hydrated).

Keep in mind that these values are averaging over large volumes, so compositional heterogeneity could create a mixed value that matches a rock which is not actually present! Xenoliths with lower crustal mineral assemblages are very heterogeneous.

How does lower crust become mafic?
1. melt extraction
2. mafic restite underplating

THE OCEANIC CRUST:
oceanic crust is 6-7 km thick (depth from sea floor to Moho) and average depth of the oceans is about 4.5 km. Some thick and thin patches on seafloor can be related to magma supply during formation (although what controls magma supply is not well understood). Seismic velocity structure shows distinct layers (3 known in the 1970s; more complexity today)

Layer 1: Vp= 1.6-2.5 km/s - Sediments
Thickness and composition vary throughout oceans but always have lower seismic velocity than igneous crust below. if near land, could be terrigenous sediments e.g. siliciclastics. pelagic sediments - brown clay, chert. Average 0.4 km but varies from 0-2km.

Layer 2: Vp=3.4-6.2 km/s - basaltic crust
Velocity variation is related to volcanic architecture and alteration- could be quite porous. Strong magnetic signature observed when exposed above Layer 1 eg. at ocean ridges or areas of little sedimentation. Geochemistry overwhelmingly

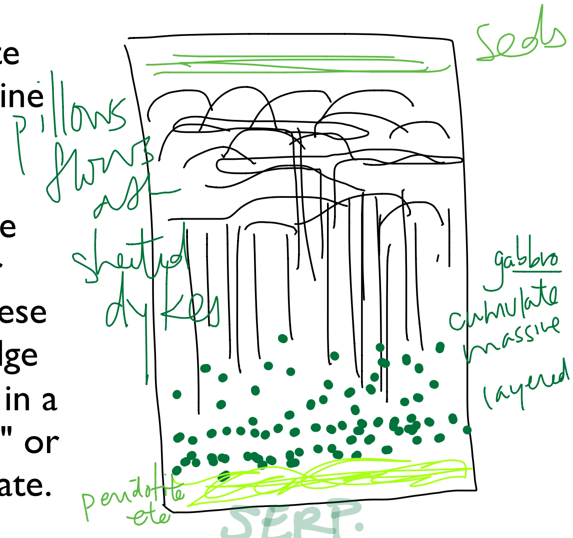
olivine tholeites, remarkably uniform across the globe. Basalt formed at mid ocean ridges and flank volcanism is rapidly altered - just hot rock + sea water causes the alteration of olivine, pyroxene and plagioclase to varying amounts of amphibole, zeolites, clays, carbonates, quartz. Thus, the rock is rendered less dense and more volatile rich. Hydrothermal circulation associated with the ridge volcanic systems play a big role so degree of hydration can be quite variable, between areas and even between layers in the same area (hence velocity range)

Layer 3: Vp = 6.8-7.5 - gabbro and cumulates
Velocity observations could be matched by partially serpentinized mantle, but Poisson's ratio (extracted from Vp:Vs ratios) argues against this because serpentine is very low rigidity so has a high Poisson's ratio. Interp to be the chambers or ponds of mafic magma, slow crystallizing in lower crust, some crystal fractionation/settling. Exhumed by transform ridges - direct observations of plutonic textures. GOT THIS FAR 1/14/14

2.5 OPHIOLITES

Again, presenting this historically because otherwise it makes no sense. Ophiolites are characteristically green chunks of terrane dominated by mafic volcanic and intrusive rocks and marine sediments. It is from these isolated, fault bounded and often intensely deformed blocks that the geological correlations to the seismic layers described above are typically made. Ophiolites are typically FUBAR'd so the correlations to structural thickness of units and geometry are not very good.

1960s- critical coalescence of evidence of plate tectonics coming from on-land studies of marine rocks. Moores and Vine (Geologist and Geophysicist, respectively) proposed that the different rock types found in Troodos ophiolite in Greece corresponded to the different layer identified from seismics. The idea was that these were chunks of oceanic crust (Mid-Ocean Ridge Basalt (MORB)) which got somehow jammed in a subduction zone and ended up "OBDUCTED" or somehow thrusted up onto the over-riding plate.



Problems with the hypothesis that ophiolites are MORB:
- if they were formed at a MOR, then passively rode to a trench, they would have pure MORB geochemistry but in fact they often show arc contamination in the

magmas.
- some have forearc and some have backarc signatures, and some look like rifting continental crust e.g. Red Sea signature (don't ask me what those signatures are)
- dates - not much datable material but the few available seem to show that magma production and eruption and structural emplacement on the upper plate happened essentially synchronously
- "sole" of ophiolites (usually shear zone in the mantle rock where the ophiolite has thrust onto continental rocks) is often hot. antigorite vs. crysotile, evidence for hydrothermal activity during emplacement.
-some ophiolites contain big layered cumulates - implies big active magma chamber with lots of recharge. this has never been imaged on a MOR where magma layers tend to be sill shaped and thin.
- thrusting up there wrecks them!! and no marker beds really. but thicknesses seem too great. At first this led to way too many types of ophiolites! None of them has the full package. Could blame this on structural deformation - but most people accept now that they are all different.
- extensive VMS, hydrothermal alteration zones - important for ore deposits.
- records of submarine hydrothermal systems - insight into heat flow (25% of mantle heat venting through this mechanism)
- important for element circulation - source of base metals, sulphur to the oceans.

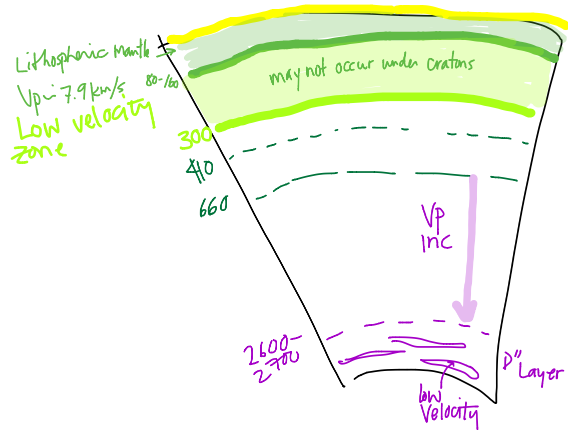
So - form very fast, by voluminous mantle-derived volcanism, but with some subduction zone influence.

2.8 MANTLE

Extends from Moho down to the core (so 0-70km to 2981 km). As far as we know, it is nearly all the same rock type with small anomalous patches which may be remnants of subducted slabs, or volatile-rich patches derived from slabs. The major element composition is pretty constant - it is peridotite. This means <45% SiO_2, with a lot of MgO and FeO. The heterogeneities are best displayed by minor and trace elements (in other words - not with the naked eye!)

Ways of sampling the mantle:
- emplaced slivers in the continents (ophiolites)
- dredge from exposed mantle in slow-spreading ridges
- xenoliths brought up by magma

The major minerals are olivine and pyroxene. These minerals undergo significant phase changes at certain P/T conditions, leading to transitions in mantle density and rigidity at the depths of the threshold conditions.



Eclogite (high P/low T metabasalt) has similar seismic velocity, so was once considered a candidate for mantle composition. BUT olivine has a very strong seismic anisotropy and the upper mantle has this property, so probably it is mostly olivine.

Most of the peridotites we see are "depleted" (have already given up some basaltic melt) so in theory are not representative of the bulk mantle. Thus geochemists made up an imaginary rock called pyrolite (1 part MORB + 3 parts olivine). Unsurprisingly, if you melt this pyrolite in a laboratory you get basalt. However it doesn't reproduce trace elemental abundances. DF: "If you melt anything you get basalt".

If upper mantle is melting/ making MORB for the last .... forever - then the bulk chemistry is evolving. Leads to questions whether whole mantle is convecting or not. Since MORB has basically no incompatible radioactive elements, MORB source mantle must be depleted completely. However, heat flow calculations show that some radiogenic heat must be produced in the mantle . So, are the K, U and Th hanging out in the lower mantle? BUT - seismic tomography shows cold blobs penetrating down to deeper mantle, even settling into the D" layer. This suggests convection/mixing must go down to the core mantle boundary. Tomographic estimates - IDENTIFIABLE old slabs are 16% of mantle volume.

Low velocity zone - weird!! Conventional wisdom looks at the high Vp:Vs and suggests a few % melt is present. Others argue for water - but water causes melting - what about shear heating? or grain size reduction? perhaps embrittlement due to high pressure leads to increased cracking? There is also high electrical conductivity.
LVZ roughly corresponds to the depth of transition from dislocation creep to diffusion creep at 1 cm grain size. smaller grains (in the dislocation creep) have higher attenuation and lower shear wave velocity. also - arguments about retaining water or melt in shearing mantle. Only dislocation creep produces

seismic anisotropy - and strong anisotropy can be observed down to 160-200 km.

Transition zone - 410-660 km
pressure-induced phase changes most likely.
410: olivine to spinel (wadsleyite has beta-spinel structure)
- minor discont at 520 where wads. goes to ringwoodite (gamma-spinel)
660: ringwoodite to perovskite + magnesiowüstite
Exact position shifts with local temp variations- eg. below subduction where it's cold, transitions are deeper.
where other minerals present in the mantle - e.g. garnet - composition is not so uniform amongst garnets that the phase change forms a continuous surface.

Lower mantle
Seismic tomography shows heterogeneities, but trend of velocity increasing with depth is continuous. it is unknown whether the heterogeneities are lithological or thermal or both.

A general layer 200-300 km thick lying along the cmb called the D" which has a somewhat reduced velocity, high heterogeneity. Might be a reaction zone between lower mantle peridotite and the liquid iron. this might produce free metal alloys and non metallic silicates, don't really know, very strange. These melt pockets have been suggested to be the source for hot-spot plumes. Ultra low velocity zones (10% decrease in v) might be sills of a few % melt. they are 5-40 km .

2.9 CORE
Core radius 3480 km, cmb is 2891 km from the surface.
Outer core: 2891-5150 - blocks all S-waves. the rotation of the inner and outer core materials gives rise to the geodynamo! Estimated flowing rate is 10 km/year (compare to mantle circulation rate of 1-10 cm/year). Outer core is turbulent! low viscosity.

Inner core = 1220 km
Moon = 1737 km
Discovered in 1936 by Lehmann (as a surface).
Evidence for solid inner core - SKS waves
Velocity structure is spatially heterogeneous on small scales (< 1km).

Outer core is freezing and inner core is growing at rate of about 1 mm/yr. outer core surface is a sharp reflector but surprisingly rough - some have suggested that Fe-Ni "snowflakes" freezing in the outer core create drifts on the inner core boundary. wow. These are seen as low-density mountains on the surface.

Composed of <90% iron, 4 % nickel (best guess given the observable properties and chondritic abundances e.g. chromium might have similar properties but is far rarer so unlikely. also, metallic meteorites tend to be fe-ni, showing that other differentiated bodies (or early earth) had fractionated to an fe core and silicate mantle. however! moment of inertia says core density is slightly too light, must contain some light element in unknown %

Composition: Fe-Ni-light element - could be O, Si, S or P? Won't know until we know how these things complex with Fe and Ni at super high P/T and what the resulting velocity effects would be.   Bulk densities are >10,000 kg/m3

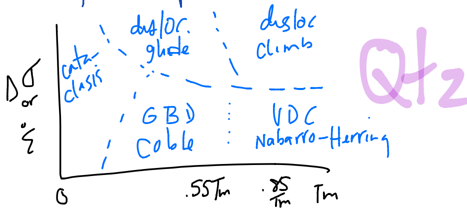
Diamond anvil cell goes up to 300-400 GPa, similar to the outer core. higher pressures are achieved in shock waves.

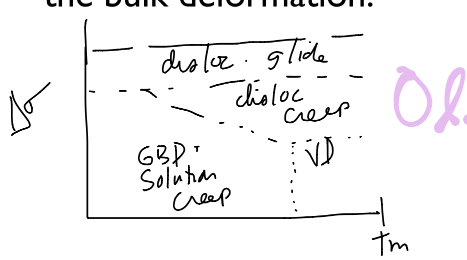
STRUCTURAL GEOLOGY REVIEW
Define Rheology - the relationship between stress and deformation
Key points:
Plastic - continuous, nonreversable deformation
Viscous - stress is proportional to strain rate - NOT LIQUID!
Mantle convection is completely crystal plastic deformation. Always solid and coherent.
Brittle fractures - opening vs. shear mode. Anticracks?
shear stress = normal stress * coefficient of friction + cohesion (for frictional shear failure)
Crystal Plastic Deformation

$$\Delta\sigma = \left(\dot{\varepsilon}/A\right)^{1/n} e^{E/nRT}$$

A: constant
n = stress exponent
R = gas constant
E = activation energy

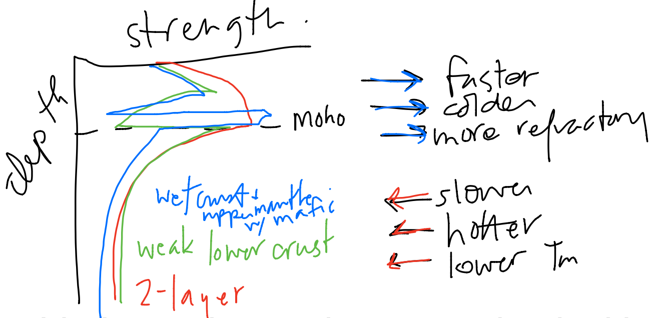
In any deforming rock, multiple deformation mechanism are active - this is an empirical description of the rheology that can be fit to any one or the bulk deformation.





Combinations of mechanisms -> faster than any one mechanism e.g. Superplastic Creep (gbs + grains squish a bit by dislocation glide/climb to fit past each other) is very efficient in metals, might occur in lower mantle, controversial.

Regardless, all mech are temp sensitive and composition sensitive and strain rate sensitive and differential stress sensitive.



Models with a weak layer sandwiched between strong layers are known as "jelly sandwich" models - these are predicted when quartz is taken as the mineral of the crust (weakens at 400°) or when wet layers are allowed. Thus, oceanic plates are pretty solid whereas this jelly sandwich approach suggests there may be horizontal poorly coupled zones within some continental crust.

MEASURING DEFORMATION AND FLOW IN THE EARTH
Continental faults are wider, more diffuse than oceanic (often)

1. Seismicity - by using focal mechanism of each earthquake, possible to see in aggregate which way motion is occurring in a brittle portion of crust. Scale of seconds, mm - 10 m
2. GPS - surface velocity field scale of years, cm
3. Geologic estimations of fault slip rates scale of 1000s years and longer, meters.
4. Synthetic Aperture Radar/InSAR - tiny deformations on scale of days to years

These methods sample different timescales - they only occasionally match up! This will help detect areas of higher vs. lower strain rates - (no internal strain = plate or microplate!)

MANTLE DEFORMATION
- Seismic anisotropy = mantle shear zone? infer flow patterns? shows areas that developed a pattern during flow but does not indicate whether flow is continuing, overlaps current and inherited fabrics. Lower mantle is isotropic - probably because dislocation creep is less dominant, so flow directions can't be mapped in

this way. There is a weak horizontal fabric - not known whether this is a CPO or an SPO. Only under central pacific and Southern Africa there are anomalies with weak vertical fabrics - could this display upwelling?
- observe surface motions (e.g. post-glacial rebound) using one of the previously mentioned techniques. Assume plate is rigid/elastic and all motion is attributed to mantle flow -> calculate required flow.

ISOSTASY - didn't manage to get here in lecture.
Depth of compensation: where the lithostatic load is equal everywhere because thick parts are low density and thin parts are high density