Note - MUST review the Isostasy stuff we skipped from previous chapter!!

Continental rifts affect whole lithosphere. Book says "deviatoric tension". Nerds. "Rift" is reserved for major features, not used for localized extensional features found in every tectonic environment.

By its very nature, rifts move the active features away from the axis of deformation (similar to MOR) so old structures become inactive (e.g. passive margins). As in ocean crust, passive margins subside isostatically due to cooling, and having thinner continental crust than the adjacent areas not affected by rifting.

Failed rift: AULACOGEN. Separated, thinned crust, basin, some rift volcanics, seds characteristic of topographic relief in continental interior e.g. redbeds, fluvial-lacustrine.

Rift structure depends on the pre-existing structure of the continent that rifts.
Old cold strong = narrow rift with steep faults. E.g. Baikal, EAR, Rhine graben.
Warm young weak = broad, distributed faulting. e.g. B&R, Aegean Sea
Rifts can be very magma productive or barely at all. May produce continental flood basalts or very tiny volumes of weird, highly fractionated/derived magmas.
Rifting modifies crustal structures so although rifts may preferentially localize along pre-existing discontinuities, it is sometimes difficult to determine the relative importance of each in producing the final structure.

NARROW RIFTS
South of Afar triple junction, rifting = 6-7 mm/yr, distributed across several overlapping rift strands. The rift axial basins are created by steep normal faults, and different throw rates on either side results in tilting/asymmetry of the basin floor - "half graben". Preferred half changes along strike, creating oppositely rotated variations in different sub-basins. faults "flower structure" near surface so Rift Valley walls are stepped across different fault strands creating structural terraces. the isostatic compensation is slightly delayed behind faulting, but uplifts rift flanks as they are unloaded by inward-dipping normal faults. The slower side is dropped inward, creating basin-dipping monocline. Tilting means that beds deposited in basin floor are wedge shaped, so change in dip/thickness can be used with bedding ages to track basin development. Basin-bounding faults show max offset in the center and decrease to ends where transfer zones create weird dip and horizontal axis rotations as faults propagate and grow., accommodating

changes in orienation, position and rate between adjacent grabens. Faults continue steeply down to cut lithosphere, NO LISTRIC FAULTS so little rotation at the surface.

BDT occurs near 12-15 km, very shallow, since it's hot. deepens away from the ridge axis to a normal depth of 25-30 km. this demonstrates that rifts are weak links in the continents. In Ethiopia, about 50% of rift velocity is accommodated seismically, the rest is aseismic. Abundant normal eq, many parallel to main rift faults but many at all kinds of random strikes, showing that in detail fault network within major grabens is very complex. In the Red Sea and Gulf of Aden, N-S extension is predominant in focal mechanisms. shows relative separation of Saudi Arabia NEward away from triple junction, but not parallel to divergent rift-bounding faults. Offset series of magmatic centres down ridge axis - most microseismicity is associated with magma movement while large earthquakes are mostly on rift-bounding faults.

Magmatic underplating - common to see high-velocity layers thickened continental crust off axis - ponding of mafic magmas? timing - is this a pre-rift ponding when a hotspot is the cause of initiation?

Heat flow - very high at surface in ridge axis, consistent with geotherms 50-100°C!! (Q = 70-100 mW/m2) in EAR. Baikal rift has lower heat flow (40-60 mW/m2) and no volcanism. Low-velocity zone beneath EAR is 75 km wide and reaches down to 200 km. not centred under axis. shear wave splitting studies show vertical fabric, could be zones of melt or could be aligned olivine, either way things are flowing up there.

BASIN AND RANGE -
similar distributed rifts in Aegean Sea? smaller. Both are areas of recently deformed and accreted continental crust.

it's not really a general model- only one on earth now. lithosphere is thinning over an area 500-800 km wide, been extended ~100% (by 250 km) in last 16 Ma. (strain = 1, time = 16 Ma = 5e-14/s). Microseismicity is above 15 km depth, similar brittle layer thickness as for other rifts near the ridge axis, but much wider. Historical seismicity ~M7 in Fairview and Wasatch detachment. So many faults, recurrence interval on each is 1000s years. Even though seismogenic crustal thickness is consistent across B&R, the moho depth is deeper in the east (30-40 km) and thins to 20 km in the west. so - temperature structure is not coupled to lithospheric structure. Thickness variety may pre-date extension, but extension is also strongly non-uniform. changes in fault dip in space and time control the balance between extension and exhumation.

Sierra Nevada and Colorado Plateau are rigid blocks with heat flow 40-60 mW/m2 -(similar to rift axis heat flow in Baikal Rift). Colorado Plateau is 50 km thick crust - maybe that Nevada and Utah were this thick after Mesozoic orogenies and before Cenozoic crustal thinning - "Nevadaplano" model based on Altiplano? Motion between those two rigid microplates is 9.3 mm/yr. In between, crust is broken up into half grabens, spacing of ranges is ~30 km. Current relief is 1.5 km from peaks to sed valley floors.

Deformation has not been time averaged across the B&R - older faults on eastern side, currently active on east and west but relatively stable in the center. Dextral component distributed across B&R but concentrated in the Walker Lane/Eastern California Shear Zone. Juxtaposition of two plate boundaries?? Partitioning? adding distributed and localized dextral shear sums to about 25% of plate rate now between Pac and Nam.

- lots of steep discrete faults on surface, fewer with depth? listric (totally unlike EAR). Listric faults means that stress resolved on fault changes with depth, and the degree of rotation/extension accommodated by slip is depth variable and exhumation variable. unloading facilitates doming, usually begins after 10-20 km of displacement at < 30°. The up-doming is run-away and results in hot core complex rocks exhuming. also rotates normal faults to unfavorable positions so stimulates the development of new steeper faults.
**** fig 7.14 in the textbook - find sources? ***

TECTONIC PROBLEMS
- how does strain partition between brittle and ductile layers? How can fault blocks rotate so much at surface (horiz axis rotation), but the Moho is relatively smooth (from geophysics and magnetotellurics). Requires sub-horizontal ductile detachment within the crust.
**** MUST BE A GOOD IMAGE FOR THIS****
Got this far

Low velocity mantle imaged to 300-400 km depth. way deeper than in EAR. B&R is 500° hotter at same depth than North America. Surface topography is most strongly controlled by temperature structure and whole region is high, although it has thinned. velocity structure suggests partial melt.

- B&R IN CONTEXT - causes? slab window initiation? 2 eras of extension?

Volcanic activity - pre- and syn-extension.

LARGE IGNEOUS PROVINCES
"LIP" - can be millions of km3 (e.g. ontong java) or <1 M km3 (EAR, Columbia River).
Oceanic - Ontong Java and Kerguelen.
Causes variable - hot spot emergence? rift? chicken? egg? Some not associated with extension. May be synchronous with rifting or pre- or post-date rifting by millions of years.
Some are very fast, short violent volcanic periods - 75% of lava in 3 My. Deccan traps (K-T) < 1 MY. duration may vary with underlying causes? What melts so much mantle at once??

Continental rifts - geochemistry of magmas.
Alkali basalts (rich in Na, K, Ca relative to MORB) and things that go with those like LILE (Ba, Rb, Sr, Pb) and LREE. Tholeiitic basalts which come from high % partial melting compared to MORB. Bimodal - basalt comes with rhyolite/dacite, but basically no andesite. So the question is, what melts stuff?
1. heating - e.g. a hot plume arrives from below.
2. pressure drop - occurs within plume during uplift, also could be due to unloading when crust extends
3. add water - post subduction hydrated mantle perhaps?

Felsic magmas contain signature of mantle source, so likely product of crustal assimilation and fractionation from basaltic primary melt. Rift magmas and OIBs in common come from an enriched mantle source (enriched in incompatible elements). One explanation is that rifting activates some mantle which has been essentially sequestered in the lithosphere of the rifting plate, so didn't loose its incompatibles. BUT "enriched" sources are all over the place, probably the earth has processes for re-enrichment, since OIB have the same pattern.

Temporal pattern in EAR - small % deep melting at first, with larger % shallower melting later. consistent with plume source. Melt enriched zone is biggest at about 150 km depth - likely source. Shape is not like a single plume, it is a broad swath, maybe many plumes, or maybe it's reactive to surface rift?

Low velocity zones exist below Baikal and Rhine Graben but these are only slightly lower velocity than surrounding mantle - probably thermal expansion more than partial melt.

RIFT INITIATION

Requires horizontal extensional stress in excess of tensile strength of lithosphere.

Causes -

1. farfield plate motions result in diverging margin
2. thermal buoyancy creates gravitational potential directed outward
3. oversteepening/overthickening/collapse
4. asthenospheric traction on the base of lithosphere

Some of these are inherited in the plates and some require mantle activity. How much tensile stress? integrate strength curve over lithosphere to get some idea. Ballpark = 3E13 N/m at heat flow of 50mW/m2. If heat flow twice as high (as in B&R) then strength reduced by an order of magnitude! 1970s estimates of stress at rifts are on order 10^12 - obs since only very hot or weak plates will rift. suture zones and other pre-existing weakness may be weakest link, help start extension going.

STRAIN LOCALIZATION AND DELOCALIZATION

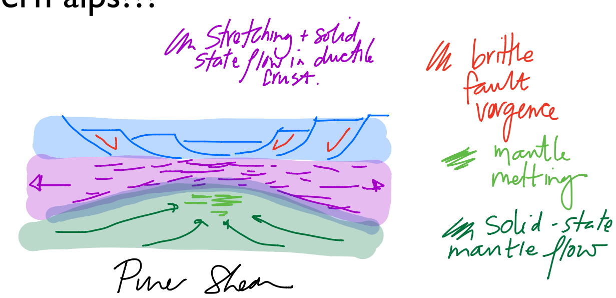
Strain-weakening processes cause localization - development of shear fabrics.

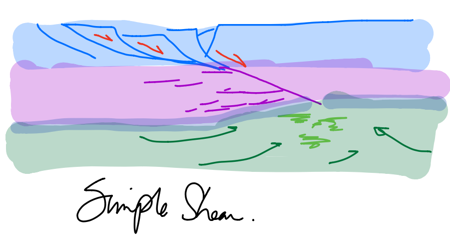
Kinematic modeling

**** show Jean Brun model for the southern alps??? *******

MECHANICAL MODELS:

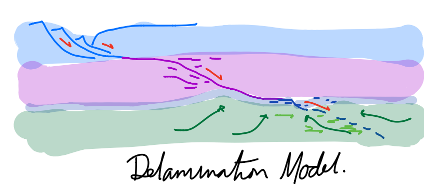
Pure Shear - symmetric upper crustal faulting, mid crustal detachment, lower crustal symmetric stretching. predicts exhumation of lower crust only with extreme extension.





Simple Shear - asymmetric upper crustal faulting, inclined detachment cutting lower crust, carries on through to asthenosphere, predicts melt source off axis of upper crustal rift.

Delamination model - mid-crustal detachment extends a long distance laterally



along rheologic contrasts - ramps and flats. effective for exhumation. favors core complex formation - because layers remain unbroken, and high lateral stretching is concentrated shallow.

How do these effect the strength of the rifting plate?
unloading causes mantle flow - heat advection, warms plate. but warm upwelling material gets cooled as rising, so is weaker near surface than it had been at depth. thinning crust and rising mantle means that the levels previously dominated by felsic rock are replaced with ultramafic rock which is much stronger. so net change in strength might be an increase at some depths.

each of these processes has different rate dependency, so the competition between them can be estimated for different extension rates if a localization model is selected.

For the same total stretching, high extension rates (-13 to -14/s) increase geotherm/heat flow more than slow extension rates (-16/s). If thinning zone is week, it can extend fast, no need for cutting into stronger ridge flanks - localized strain and strain weakening. For very slow rifting, a broad thermal anomaly in crust and mantle delocalizes deformation. less likely to fully rupture/separate continental crust (note this is from models, no examples are given)

LOWER CRUSTAL FLOW -
Overburden gradients normal to rift axis - drive lateral flow. Crust in thinned rift axis is compressed by gravitational gradients from the sides - strengthening the deeper ridge axis and pushing deformation toward the sides of the rift. This effect most pronounced for thin deep rifts. In old cold crust, thin deep rifts. in hot young crust, wider zones favoured.
Drives lateral flow, encourages channelization of flow

LITHOSPHERIC FLEXURE
Border fault scarps bounce upward due to unloading
The amount and rate of uplift is related to the effective elastic Thickness (Te) of the lithosphere. This incorporates the strength contributed by ductile layers as well, so is usually thicker than the seismogenic zone. The plate strength affects rift structure - strong plates = narrow deformed zone, long faults that cut deeper.

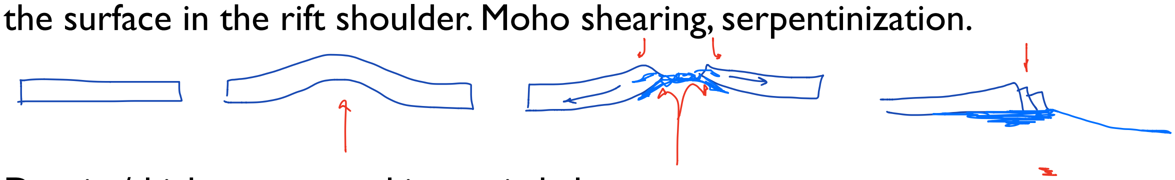
Strain weakening

Causes - deformed rock is more deformable - brittle strength, also grain boundary sliding

In a weak crustal layer, the faults don't survive very long - slip a little, rotate, go inactive, new faults develop. if the layer is strong and or thin, faulting won't cause such a dip in the stress field. Thus stress on the fault remains high and fault continues to deform. Thin crust - deformation is focused in the mantle, so controlled by mantle flow laws - strong, distributed deformation. Similar effect if lower crust is mafic and thick. If lower crust is very weak, stretching and decoupling - core complexes. Magmatic activity heats crust, accentuates weakness.

Rifted continental margins
Some have no volcanics! Examples: w Iberia, S. Australia, Labrador Sea-Newfoundland basin.
Magmatic rifts have a high velocity lower crust under the rift shoulders - underplated gabbro (never sampled directly)

Rift Shoulder:
10s km wide zone over which crustal thickness and composition decreases from normal continental crust to oceanic crust. transitional zone is dominated by block translation and rotation, and magmatic architecture if rift is magmatic. Rift edge faults are often buried in marine sediment. flood basalts along the rift edge -> thicker than normal ocean crust along the rift margin, declines to normal when magmatic activity transitions to normal marine. Nonvolcanic margins may have extensive crustal thinning from faulting - resulting in bringing mantle at or near the surface in the rift shoulder. Moho shearing, serpentinization.



Density/thickness control isostatic balance
thinned continental crust (which is low density) means heavier rocks higher in section - increase bulk density. ditto gabbroic underplating.
thermal structure lags behind, cooling continues out to 100 MY. and more.

CASE STUDIES
EAST AFRICAN RIFT
n Tanzania - E Kenya: Young (5Ma) in thick old continent. Lithosphere has been

thinned by 30-50%. Rifting developed along an old suture between the Archean Tanzanian craton and Proterozoic units to the east (East African Orogen). Present-day rift segmentation roughly follows the changes in old orogen direction. A LOT of magma in most of the segments - intrusion and crustal lengthening are taking up a lot of the stretching

THE WILSON CYCLE
Periodicity of ocean formation by rifting, ocean closure, re-rifting. Explains the balance of surface area on the globe.