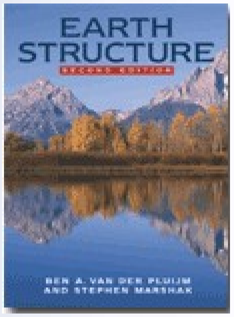
Lecture 10

Rifting, Seafloor Spreading, and Extensional Tectonics

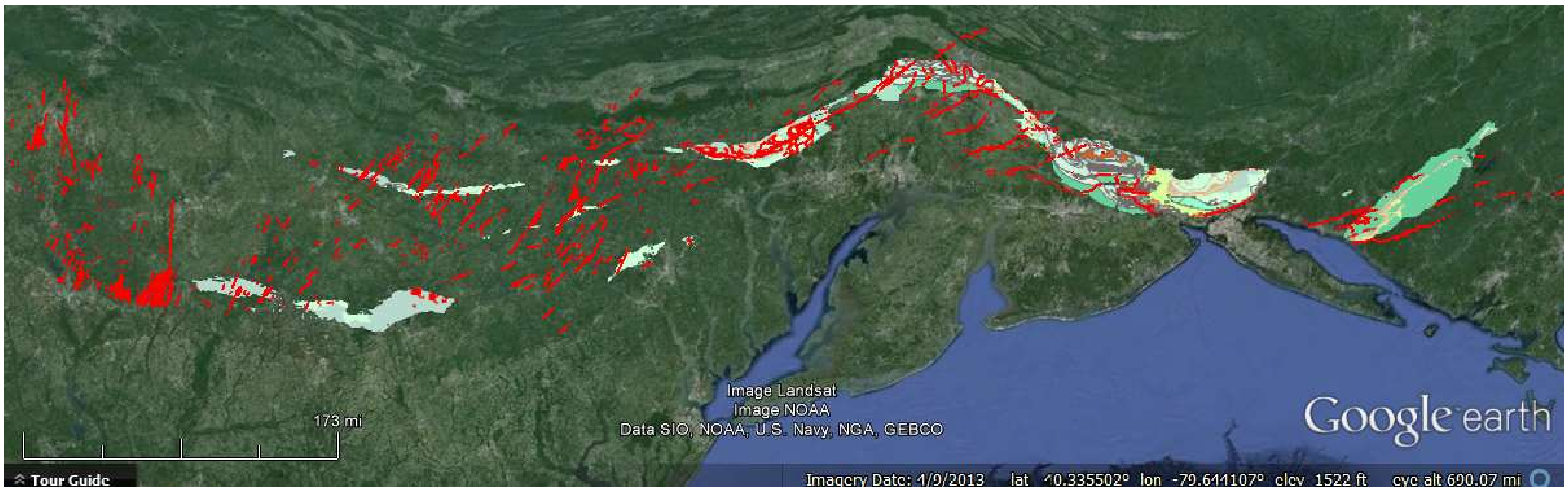
Chapter 16



Earth Structure (2nd Edition), 2004
W.W. Norton & Co, New York

Slide show by Ben van der Pluijm

- Introduction into plate tectonic concepts and terminology
- Focus on extensional tectonics and brittle fracture systems before delving into deeper conditions of pressure and temperature associated with tectonic convergence and mountain building.
- Particular focus on the Newark basin of eastern, Pa, NJ, and Southern NY

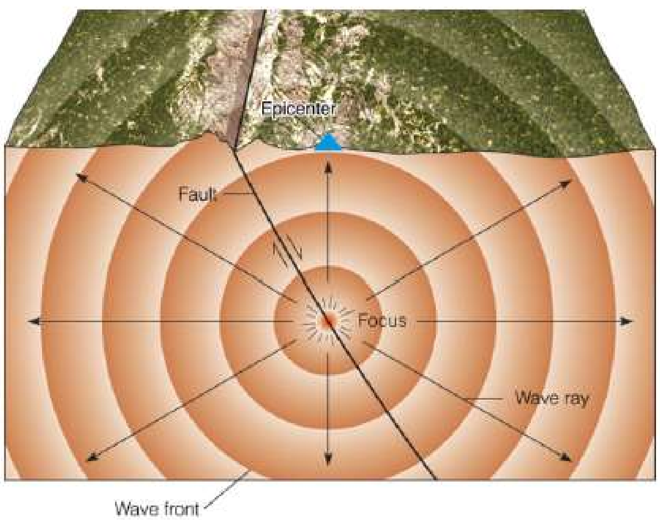


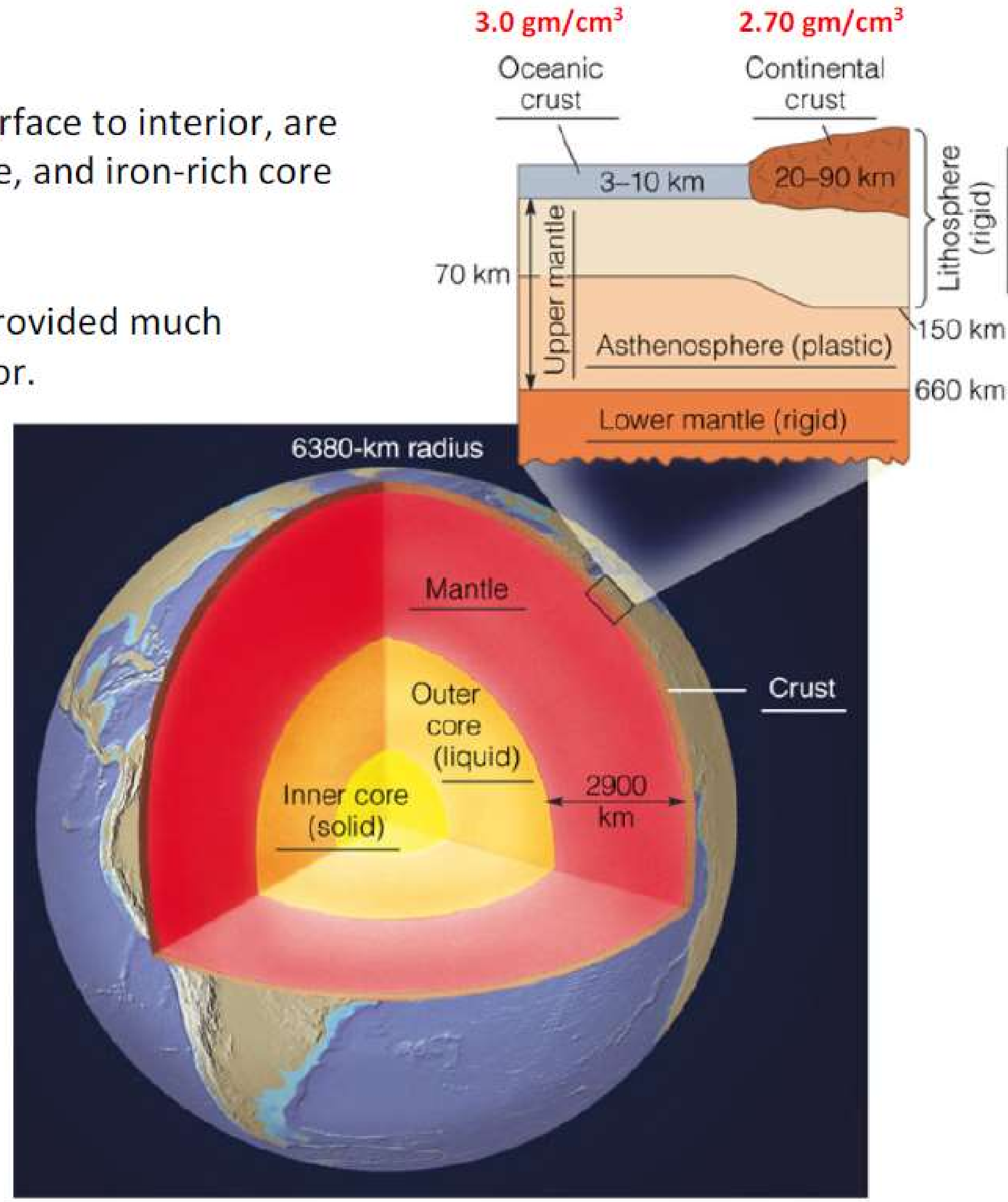
EARTH'S INTERIOR

- The concentric layers of Earth, from its surface to interior, are oceanic and continental crust, rocky mantle, and iron-rich core of liquid outer and solid inner parts.

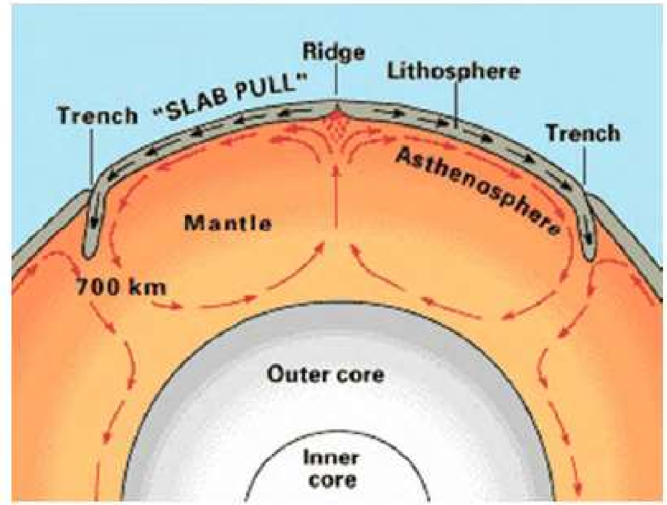
- Studies of P- and S-wave behavior have provided much important information about Earth's interior.

- Additional information has come from comparisons with meteorites, laboratory experiments, and studies of inclusions in volcanic rocks.





TECTONICS and OROGENY



- TECTONICS (from the Latin *tectonicus*, meaning "building") is concerned with the orogenies and tectonic development of cratons and tectonic terranes as well as the earthquake and volcanic belts which directly affect much of the global population.
- OROGENY (from the Greek *oros* for "mountain" plus genesis for "creation" or "origin") refers to forces and events leading to a large structural deformation of the Earth's lithosphere (crust and uppermost mantle) due to the engagement of tectonic plates.
- Response to such engagement results in the formation of long tracts of highly deformed rock called orogens or orogenic belts.
- *Orogens* develop while a continental plate is crumpled and is pushed upwards to form mountain ranges, and involve a great range of geological processes collectively called *orogenesis*.

Earth’s Crustal Tectonic Plates and Boundaries

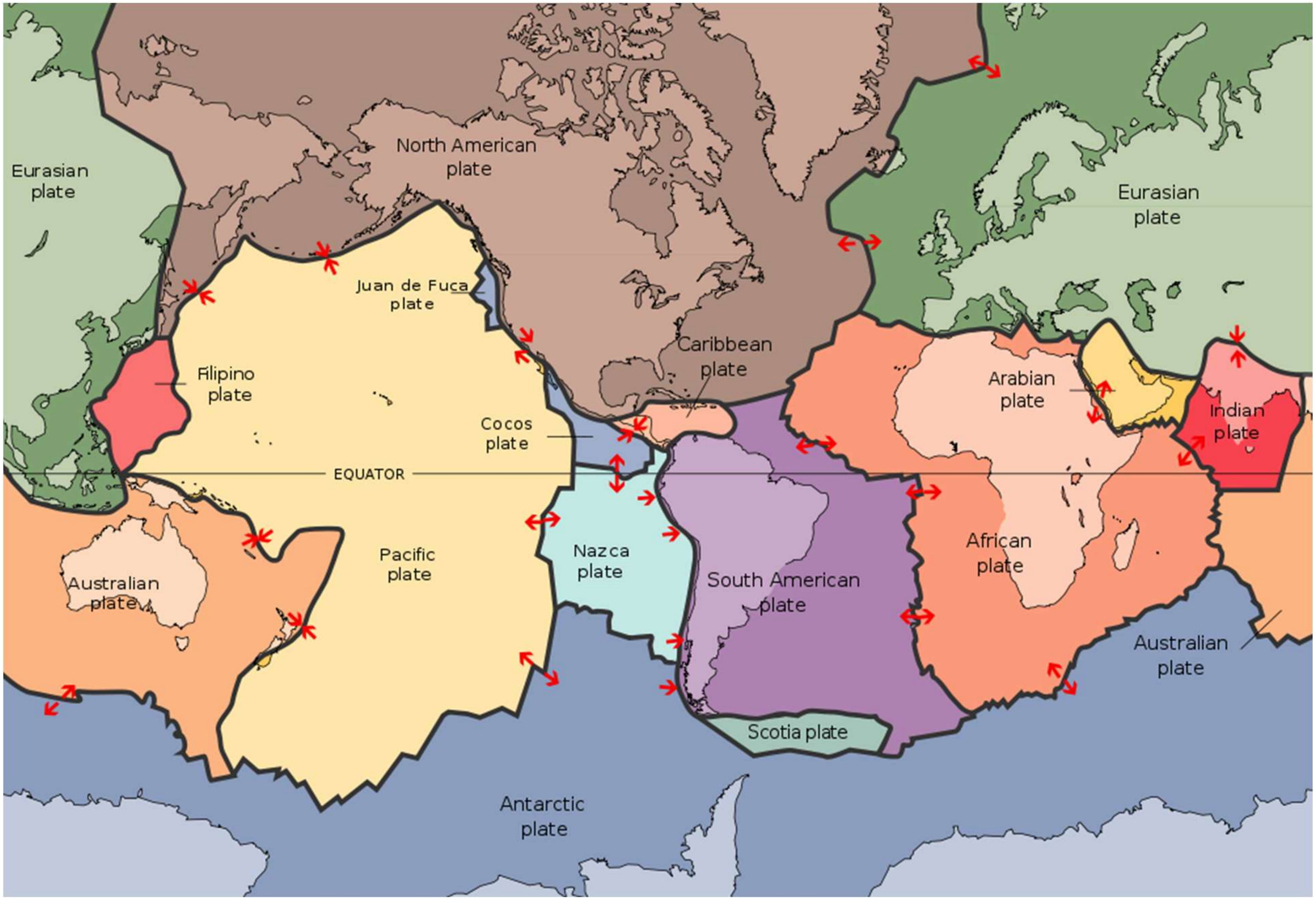
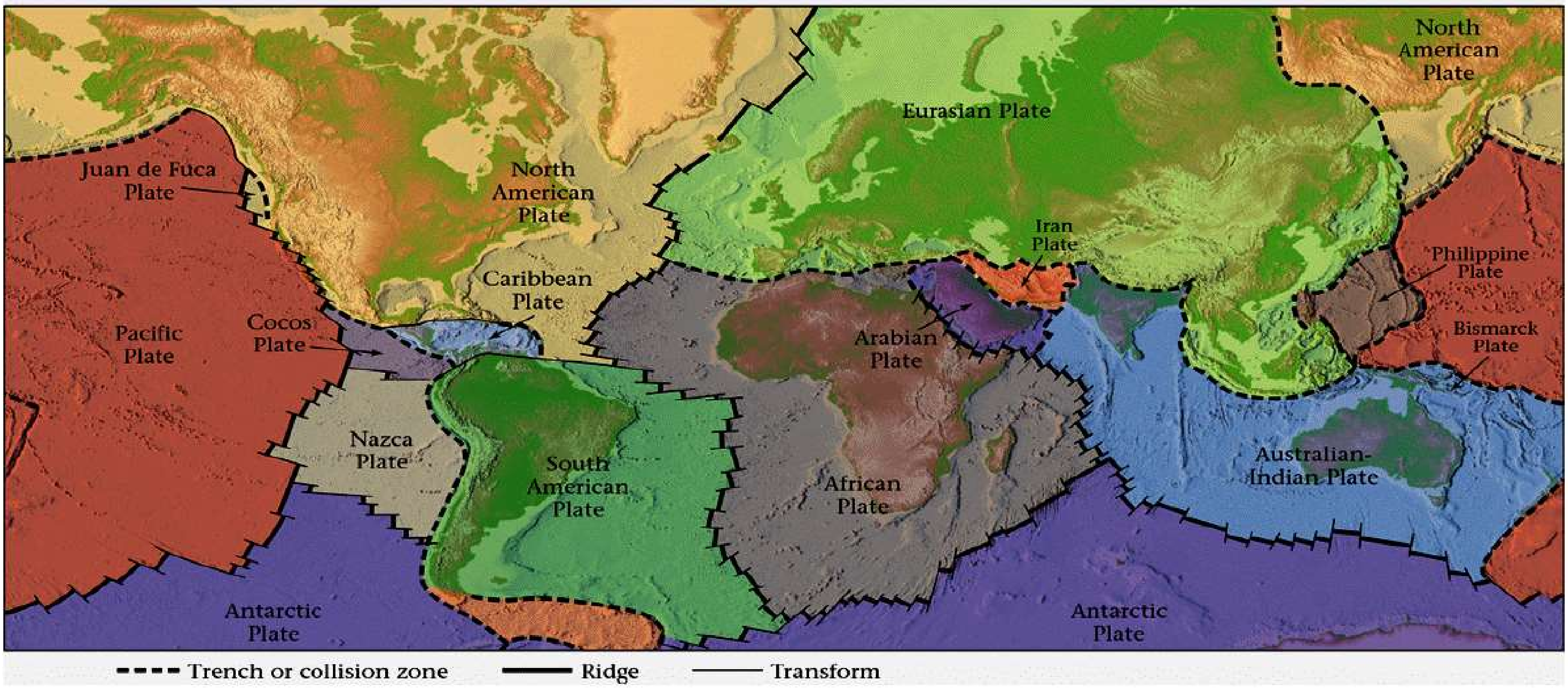


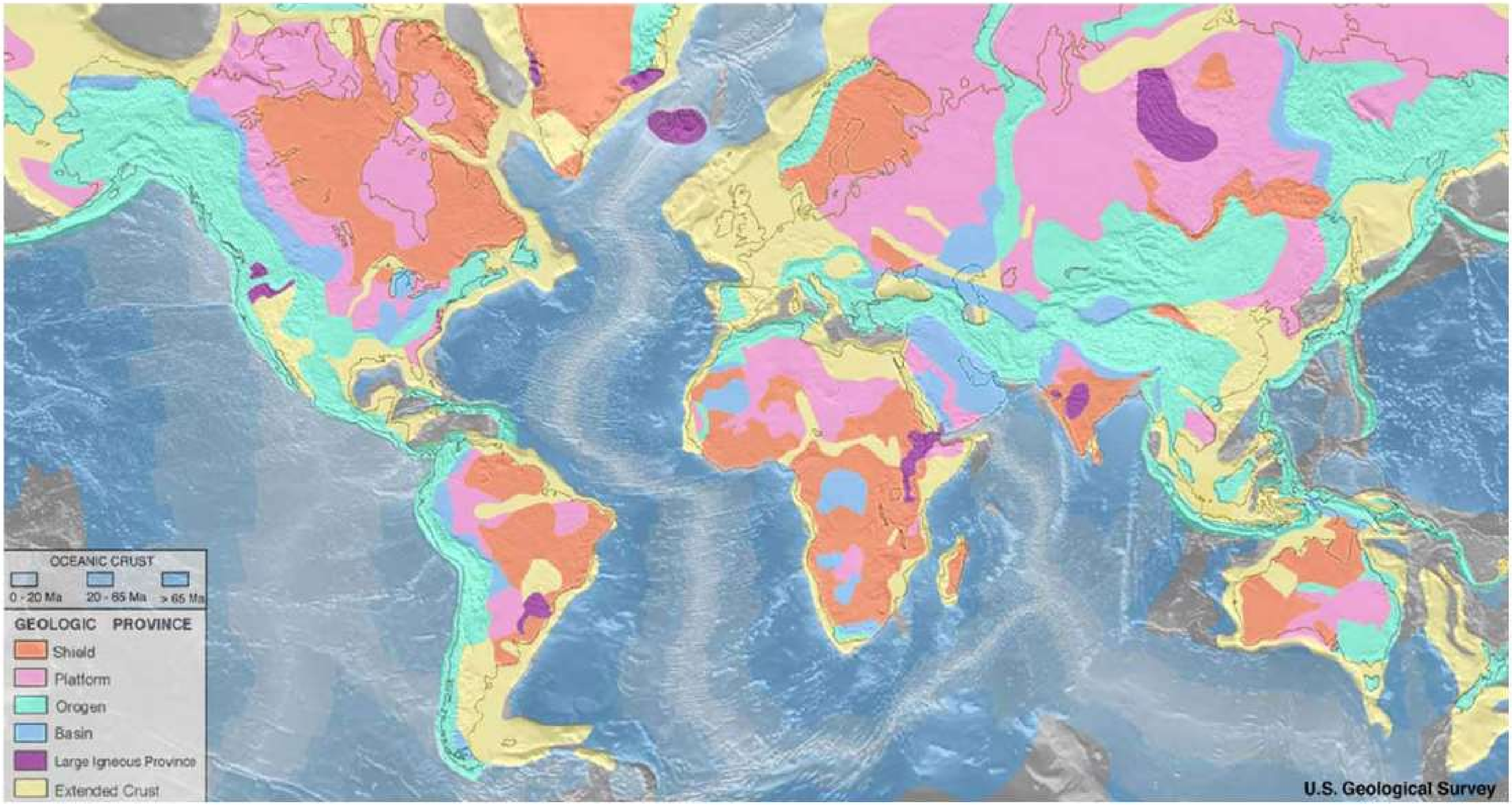
Plate-tectonic theory is widely accepted because it explains so many geologic phenomena, including volcanism, seismicity, mountain building, climatic changes, animal and plant distributions in the past and present, and the distributions of natural resources.

For these reasons, it is known as a *unifying theory*.



GEOLOGIC PROVINCES

- A ***craton*** is the stable core of a continent.



- A ***shield*** is a broad exposed area of a continent's craton, and all continents have at least one shield.

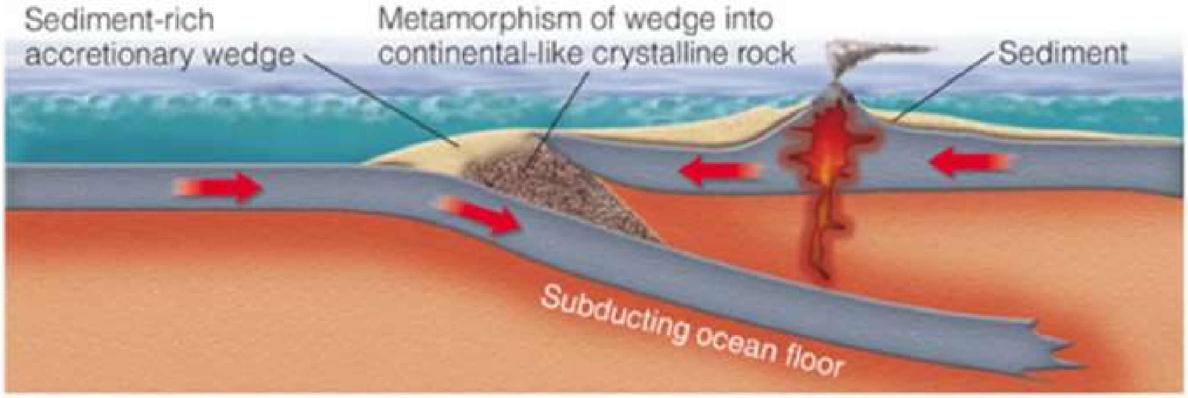
CRATONS, SHIELDS, AND OROGENESIS

- The ***craton*** is the stable core of a continent.

- A ***shield*** is a broad exposed area of a continent's craton.

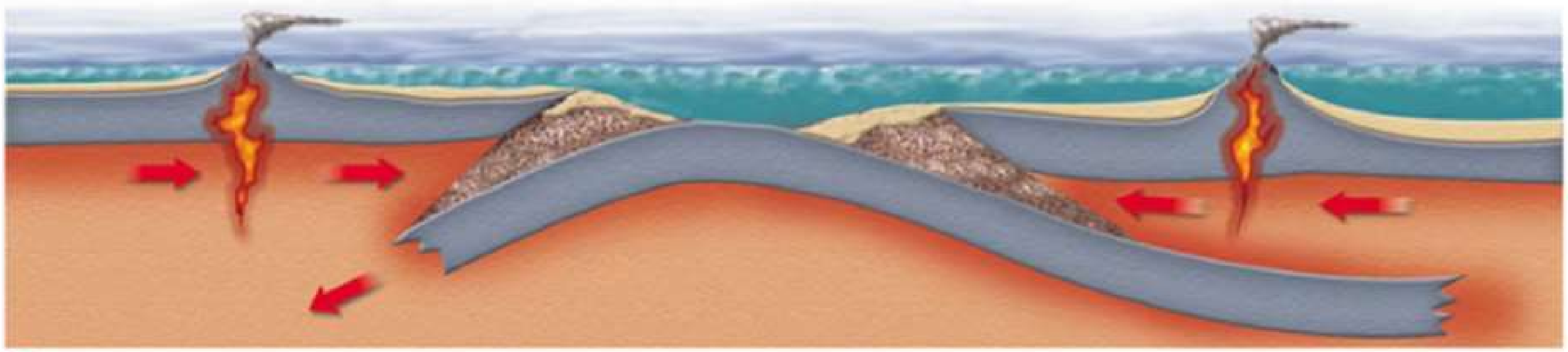
- All continents have at least one shield.

- Cratons form by the accretion of eroded continental material, island arcs, and igneous rocks on continental margins produced during orogenesis.

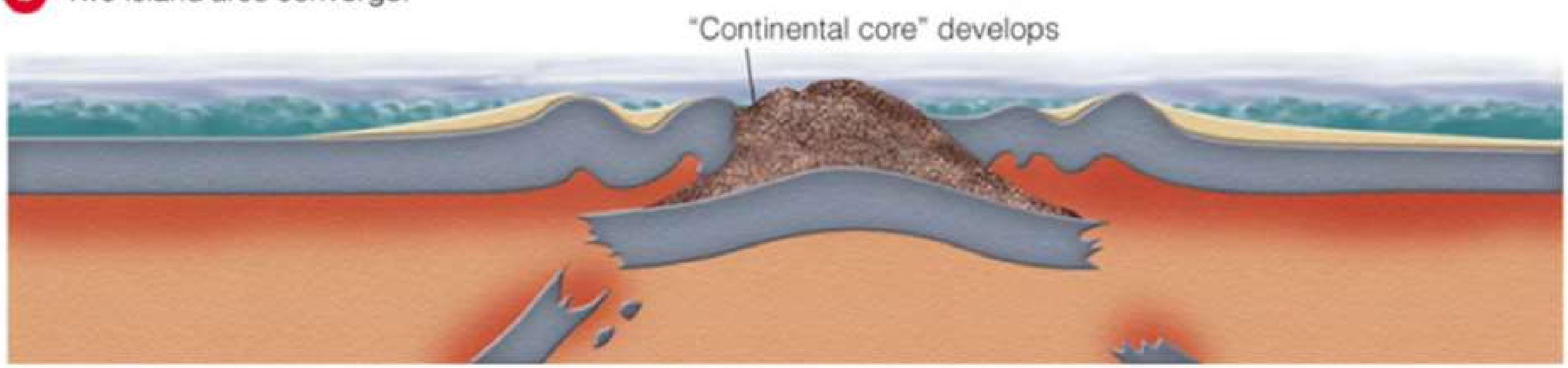


a Development of an island arc from oceanic-oceanic plate convergence.

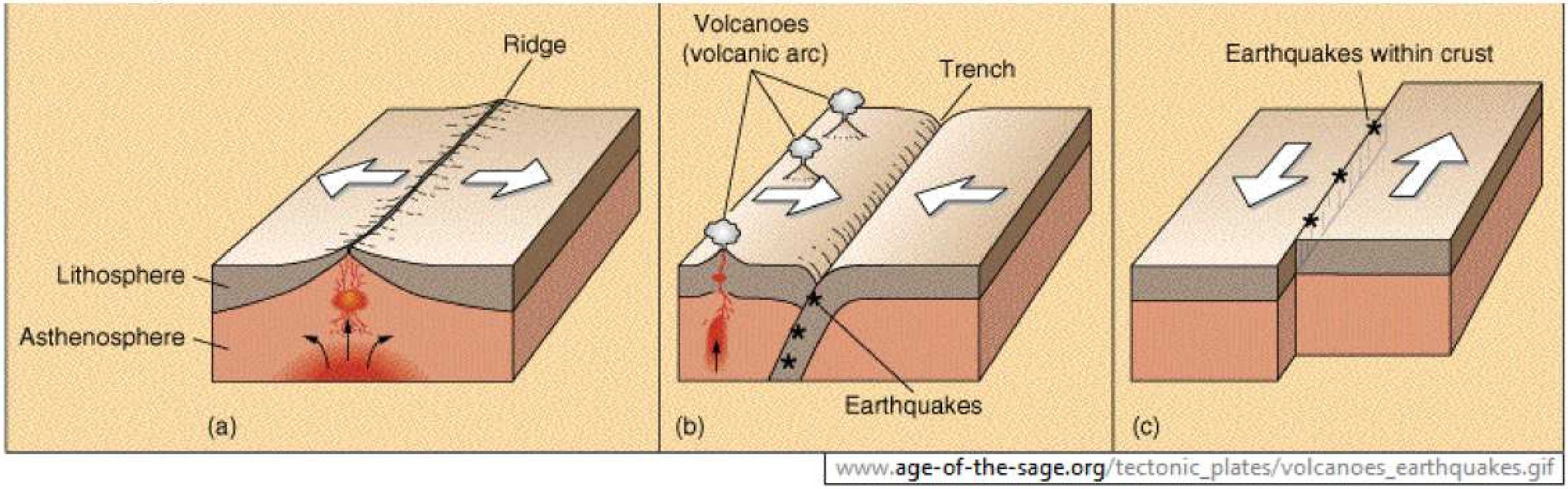
- Cratons originated by the accretion of eroded continental material, island arcs, and igneous rocks on continental margins produced during orogenesis.



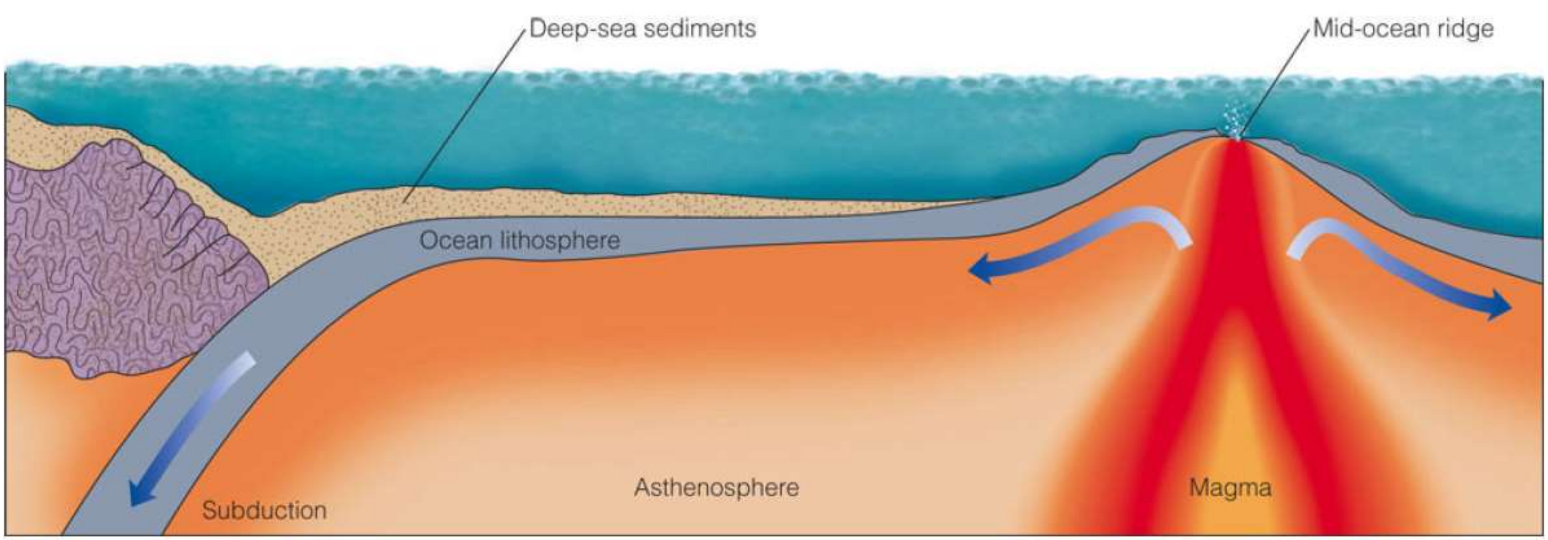
b Two island arcs converge.



c Proto-continent develops.

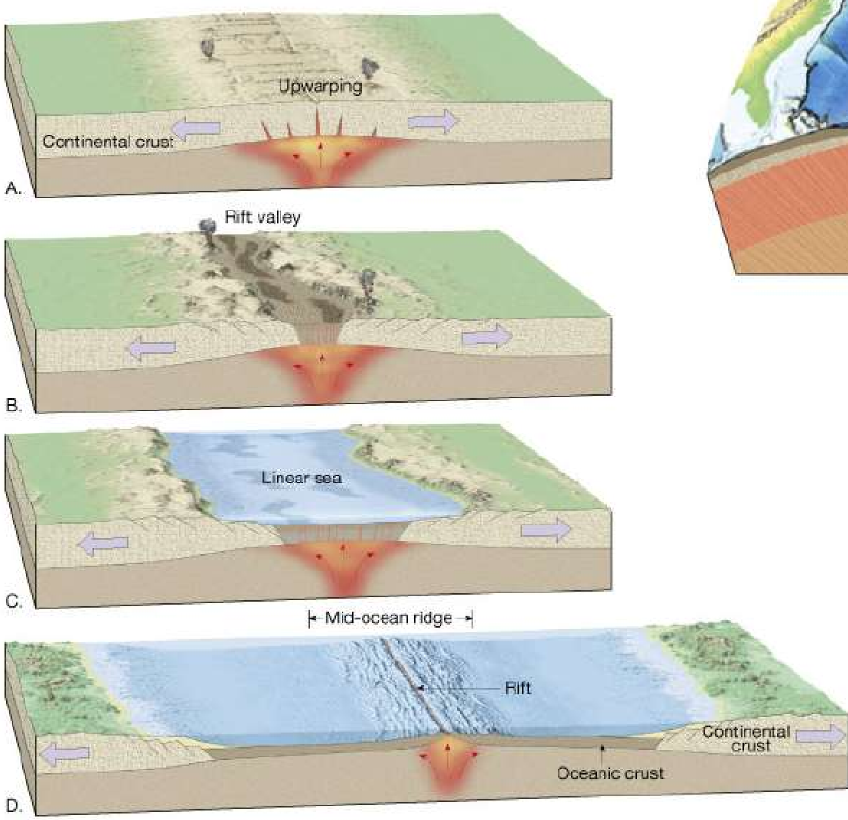


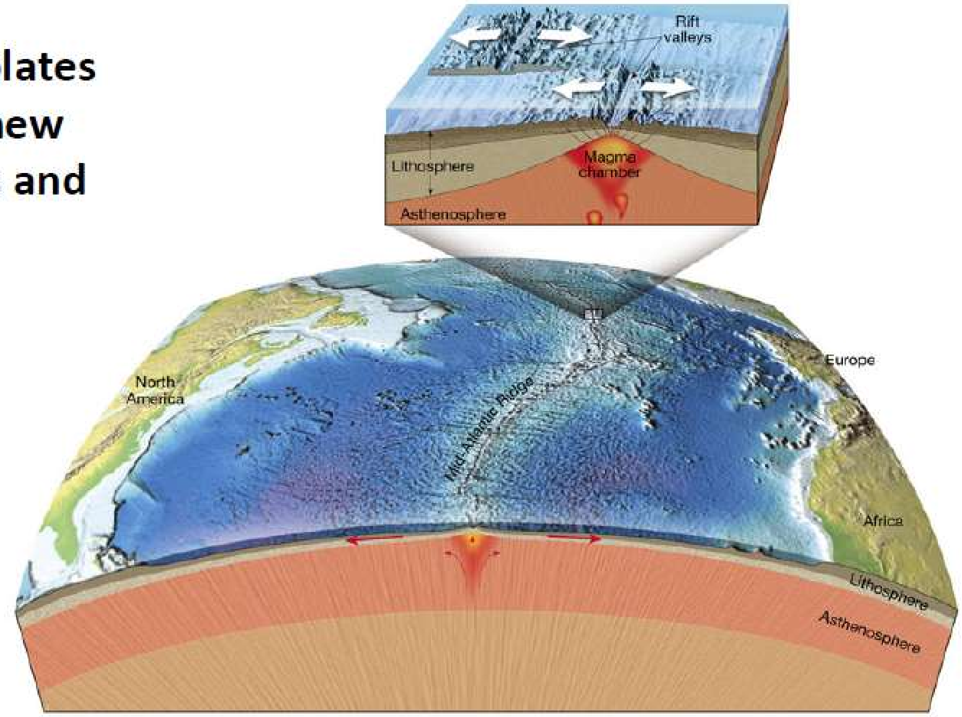
Note that oceanic crust is thinner than continental crust



Divergent boundaries are where plates move away from each other and new crust is formed along ocean ridges and in continental basins

Type 2 continental





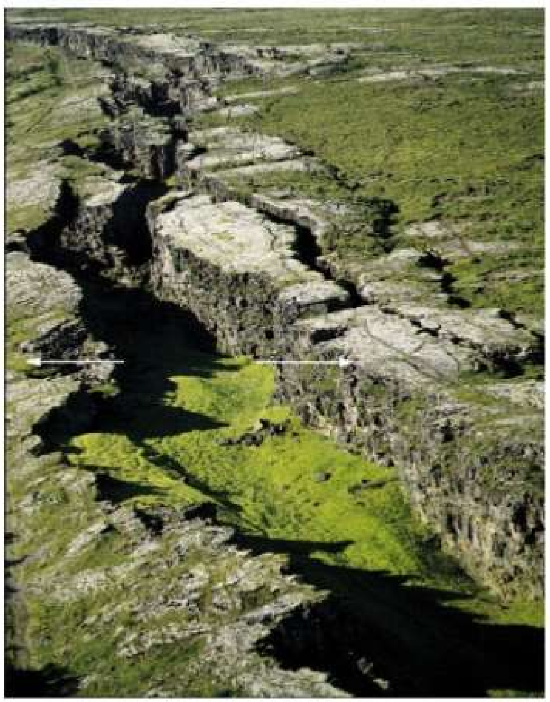
Type 1 oceanic

Two different types but have something in common

Continental divergent boundaries

Wright, T.J., C. Ebinger, J. Biggs, A. Ayele, G. Yirgu, D. Keir, A. Stork, 2006, Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode, Nature, 442, 291-294

East-African rift



all-geo.org/highlyallochthonous/wp-content/uploads/2010/07/iceland_rift.jpg

Icelandic rifts

Continental Rifting and rift systems

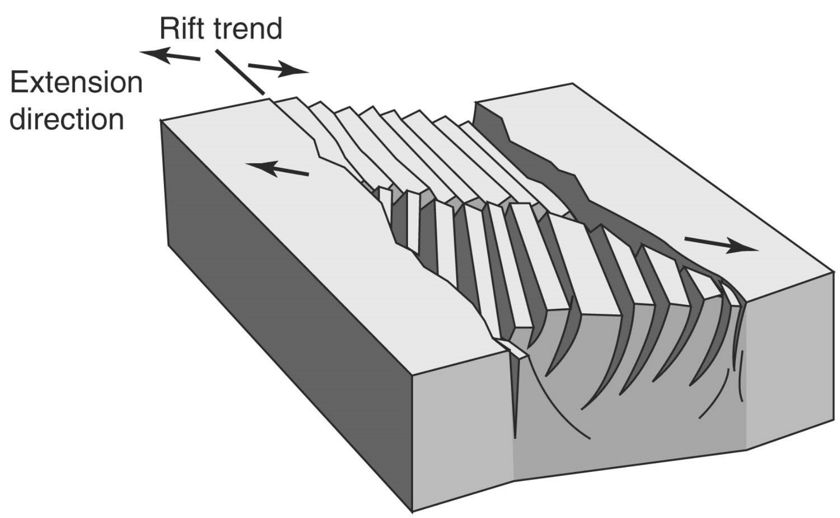
- **Continental rifting** (or simply "**rifting**") is the process by which continental lithosphere undergoes regional horizontal extension.

- A **rift** or **rift system** is a belt of continental lithosphere that is currently undergoing extension, or underwent extension in the past.

- During rifting, the lithosphere stretches with a component roughly perpendicular to the trend of the rift

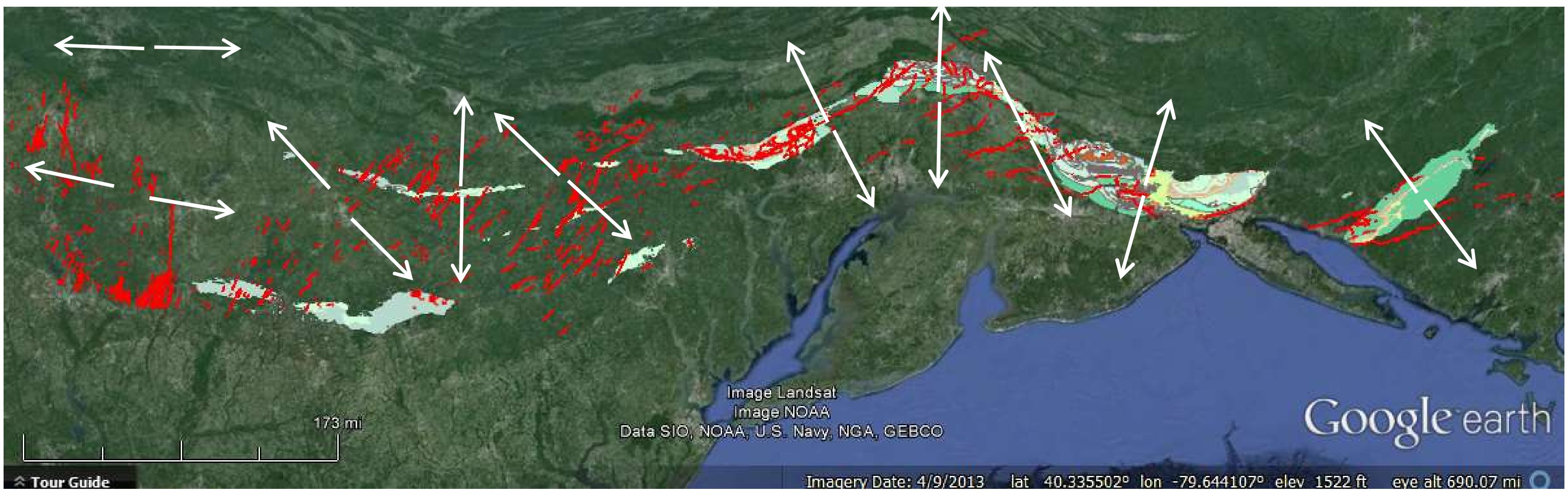
- An oblique rift occurs when the stretching direction is at an acute angle to the rift trend.

- Active versus inactive rifts



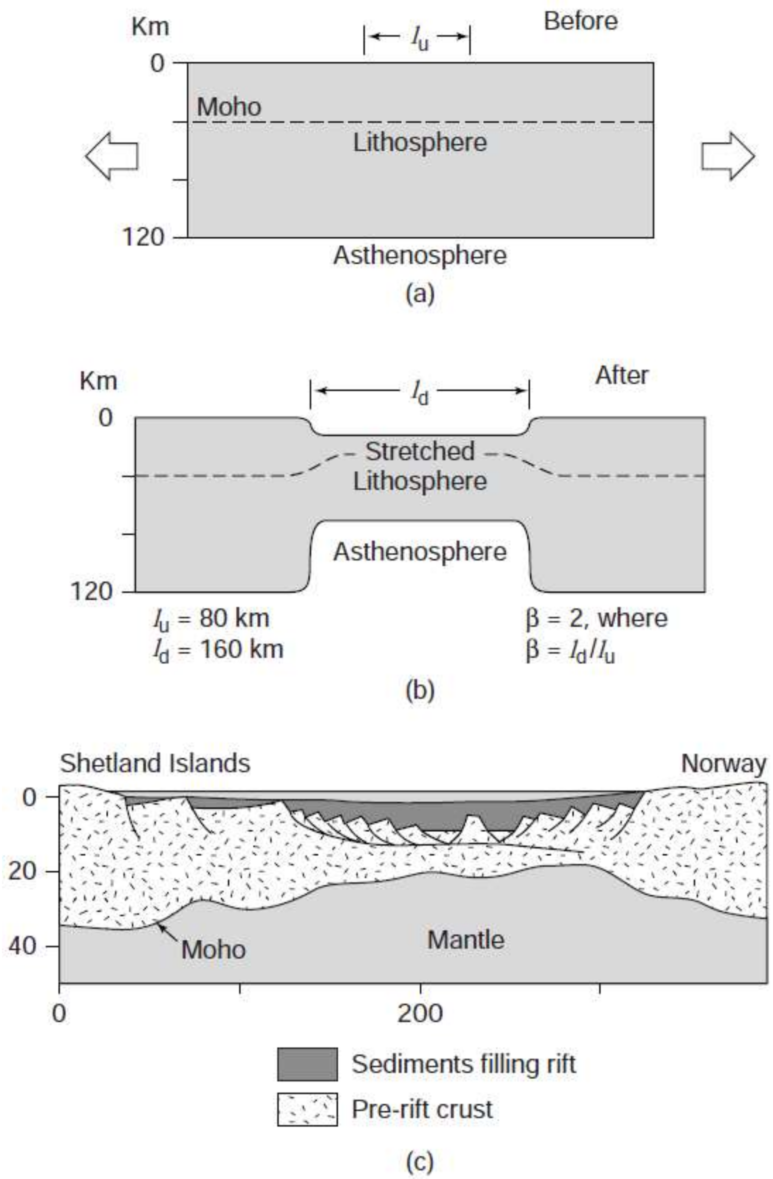
- *In rifts, or zones of horizontal extension, the maximum principal stress (σ_1) in the crust is due to gravity and must be vertical, while the least principal stress (σ_3) trends roughly perpendicular to the rift axis (except where oblique rifting occurs).*

- Thus, basalt that rises into the crust in rifts forms subvertical **dike swarms,** arrays of many parallel dikes, that strike parallel to the rift axis.



Early Jurassic diabase or dolerite dike swarms along the US Eastern margin

Stretching of the Lithosphere Fig. 16.4



a) Cross section showing unstretched lithosphere that is 120 km thick before rifting

- The *undeformed length* (l_u) notes the span that will evolve into a rift is 80 km wide

b) After rifting, the lithosphere has thinned and stretched to a deformed thickness of 60 km and length (l_d) of 160 km.

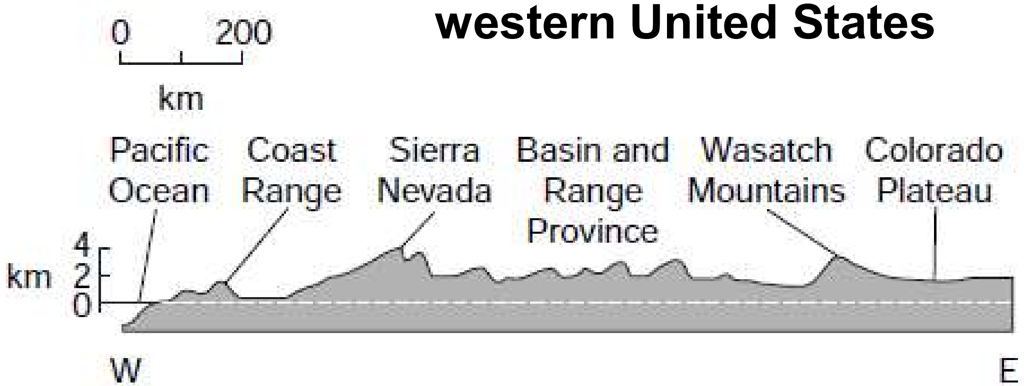
- The strain that results from rifting is assigned the variable **β, called the stretching factor**; in this example, $\beta = l_d/l_u = 2$.
- The larger the value of β, the greater the amount of stretching and thinning. A value of β = 2 means that the lithosphere has thinned by 50%.

c) In reality, the crust portion of the lithosphere stretches by developing normal faults. The simplified cross-section through the Viking Graben (North Sea) shows normal faulting and overall thinning of the crust.

- The depression formed by rifting has filled with sediment.

Topographic profiles and maps of two rift Fig. 16.21 and GE

The Basin and Range Rift of western United States



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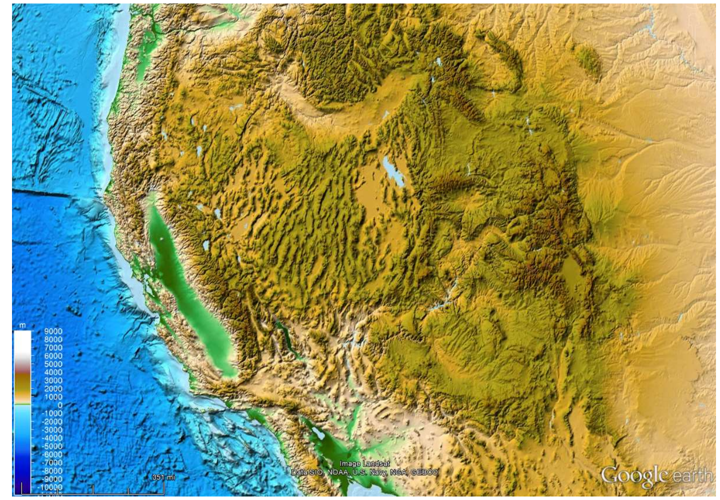
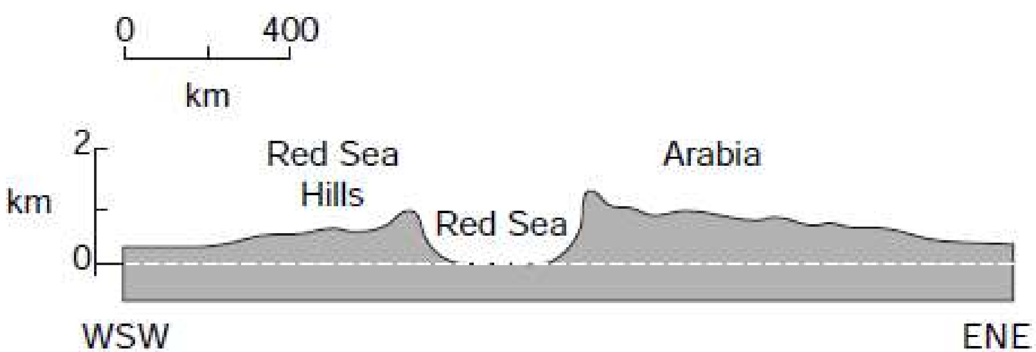
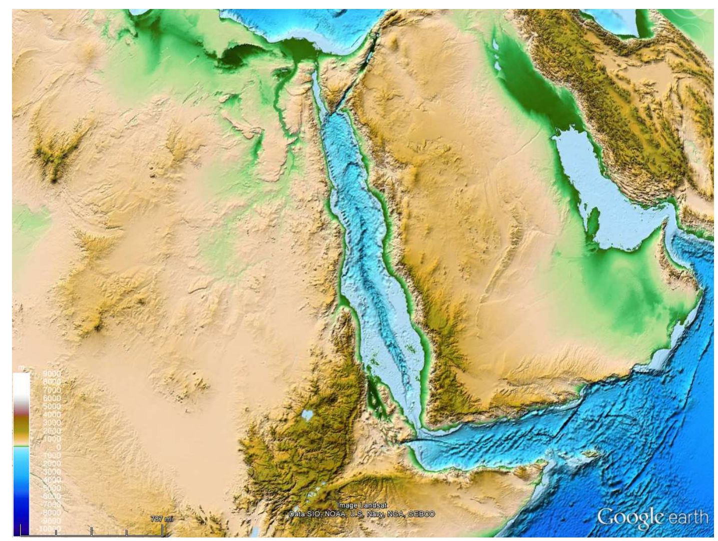




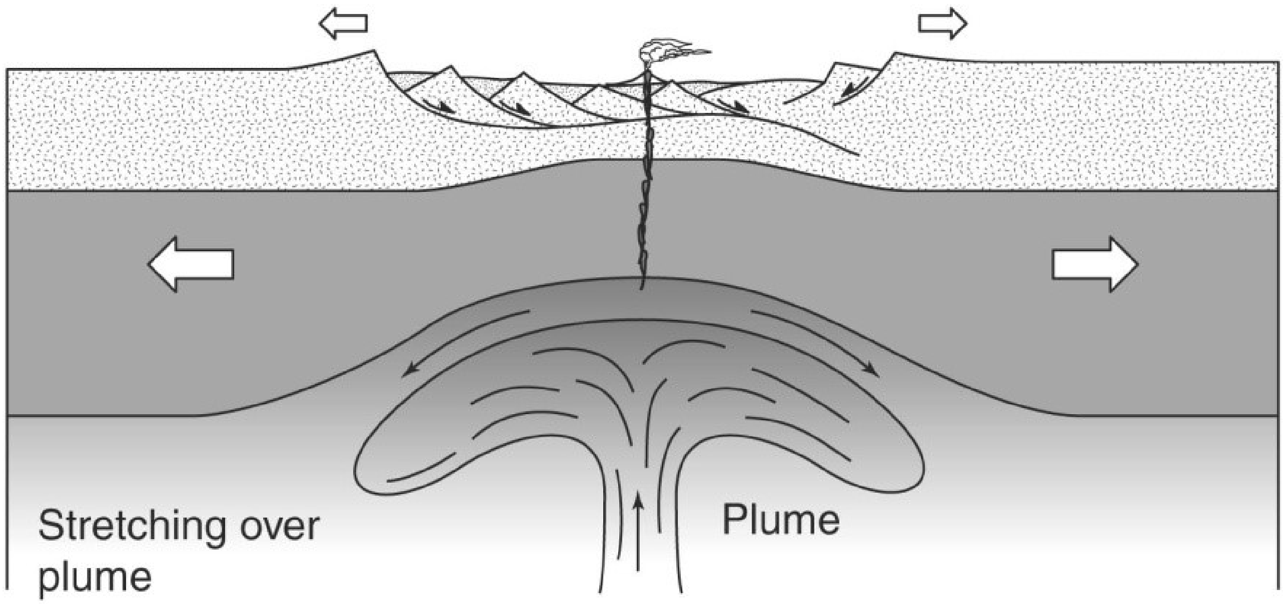
(b)

Red Sea Rift of northeastern Africa



Six Causes of Rifting Fig. 16.29

1. Thermally activated rifts

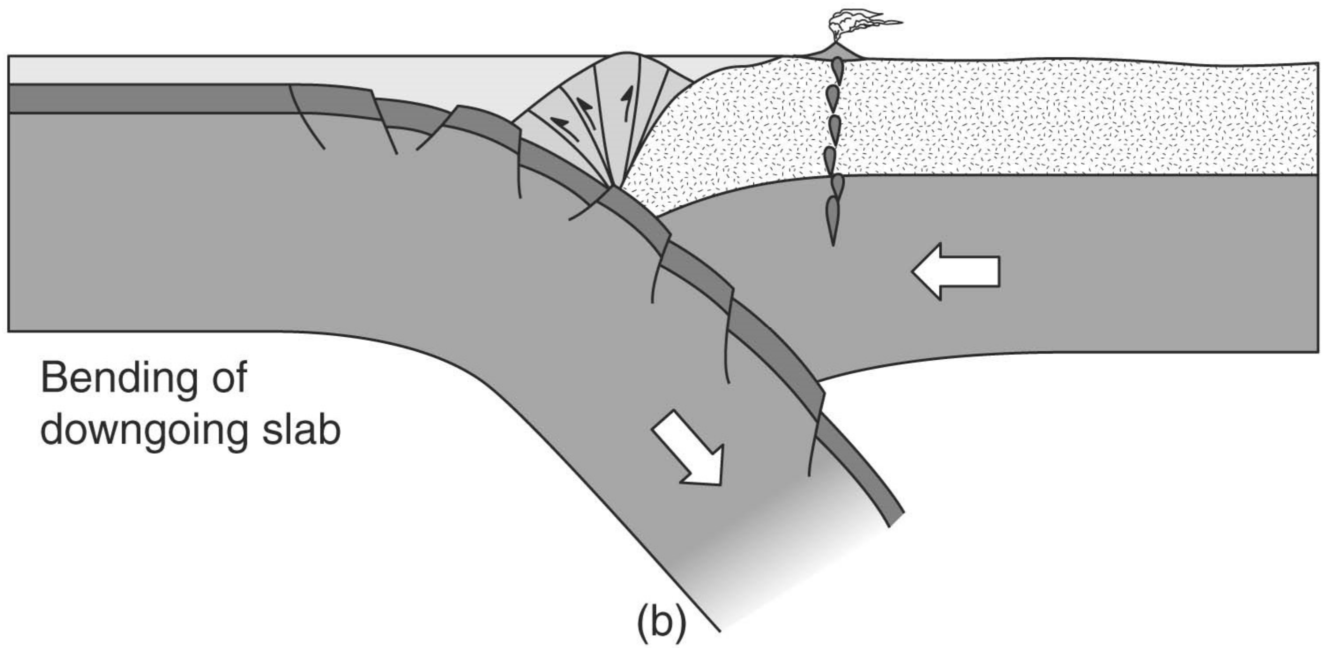


(a)

A thermal mantle plume rises, uplifting the lithosphere, doming and stretching the crust

Causes of Rifting Fig. 16.29

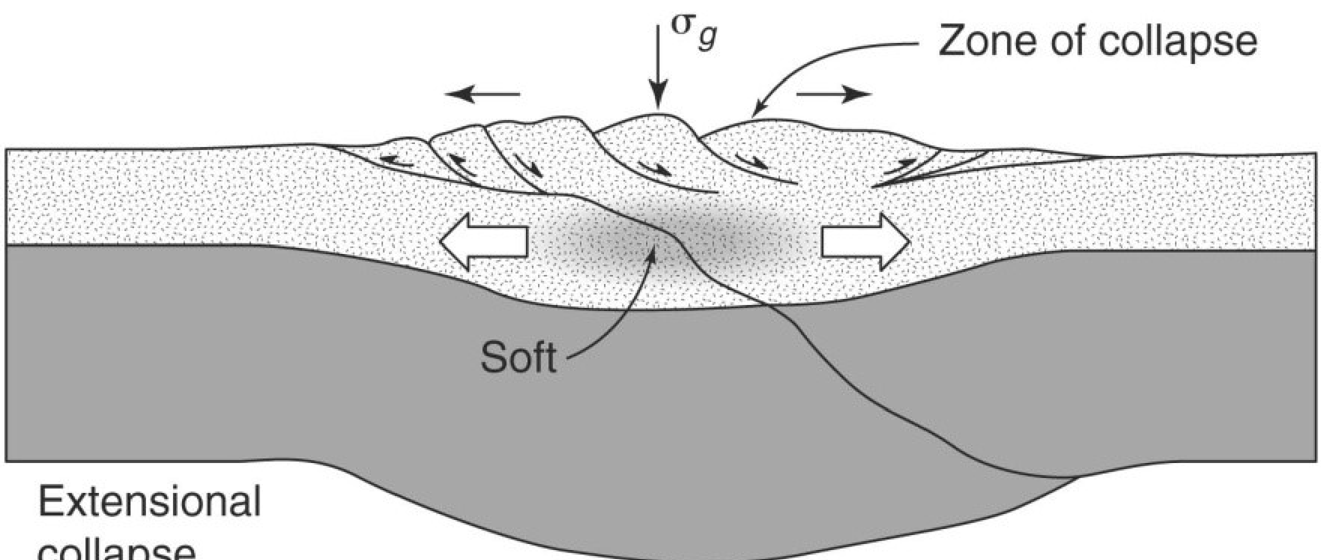
2. Flexure-related rifts



Outer-arc extension of a bending slab at a subduction zone; as the down-going (subducting) plate bends to descend into the mantle, the top surface of the plate stretches to form a series of grabens.

Causes of Rifting Fig. 16.29

3. Extensional, gravitational, or orogenic collapse

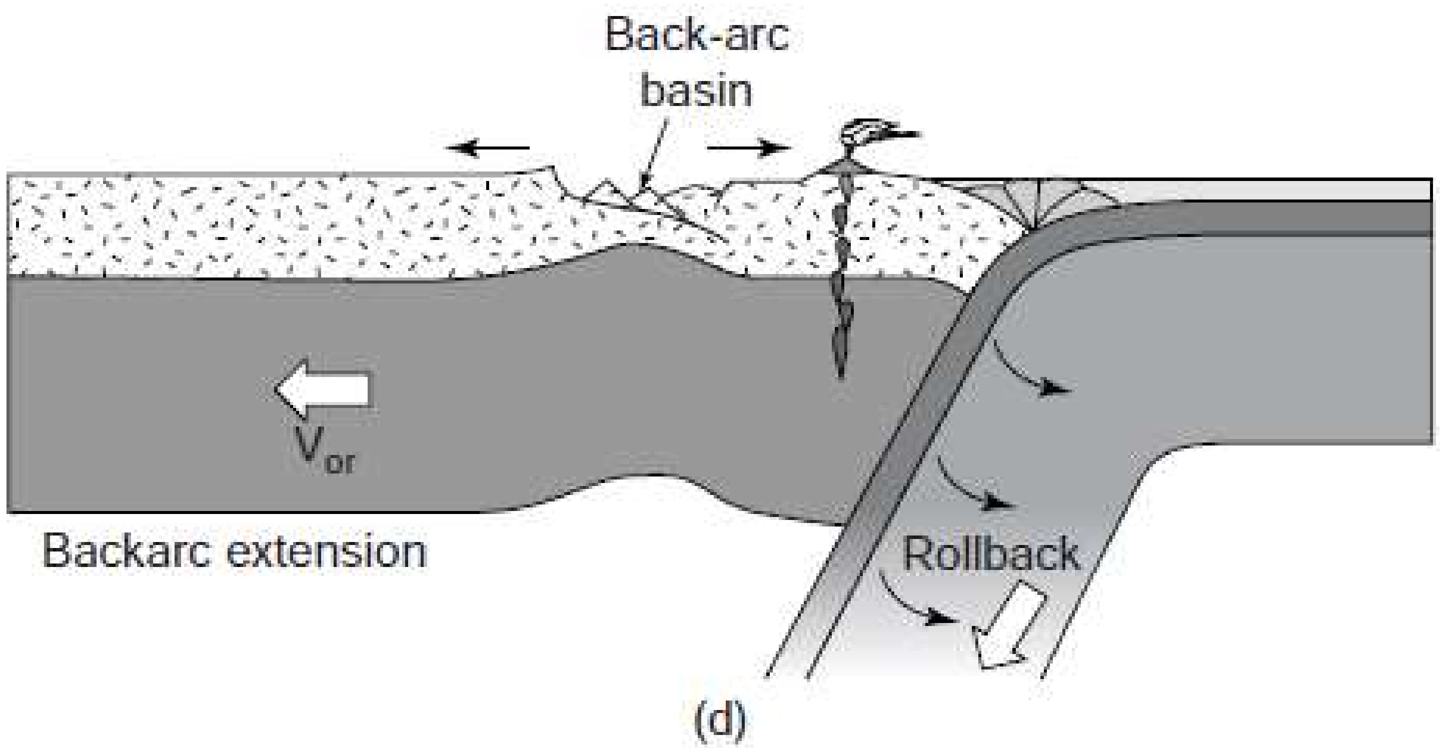


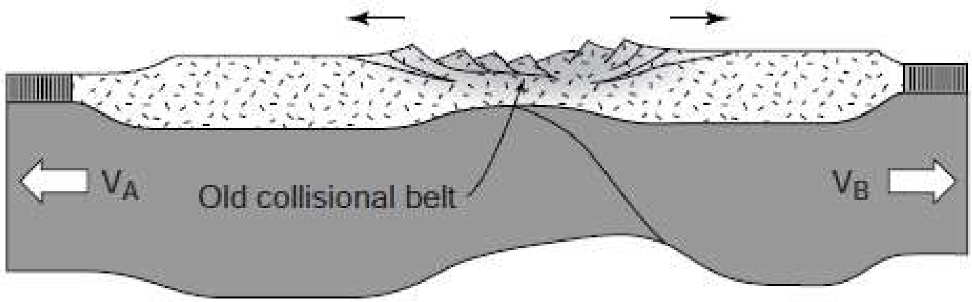
(c)

Gravitationally driven extensional collapse of thickened crust at an orogen; the crust becomes soft at depth, and gravitational potential energy causes it to spread laterally, even if convergence is continuing. The upper crust breaks up by normal faulting.

Causes of Rifting Fig. 16.29

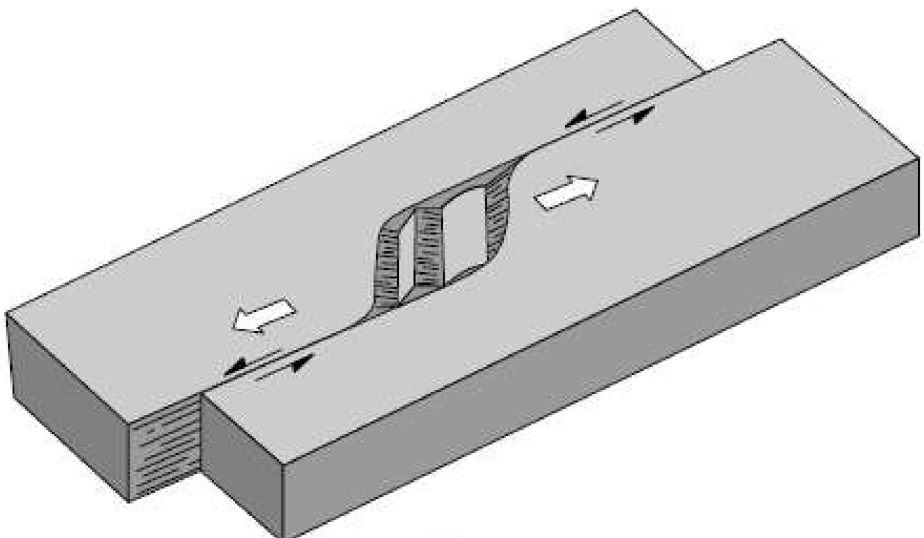
4. Back-arc extension resulting form convergence





(e)

5. Back-arc extension resulting form convergence

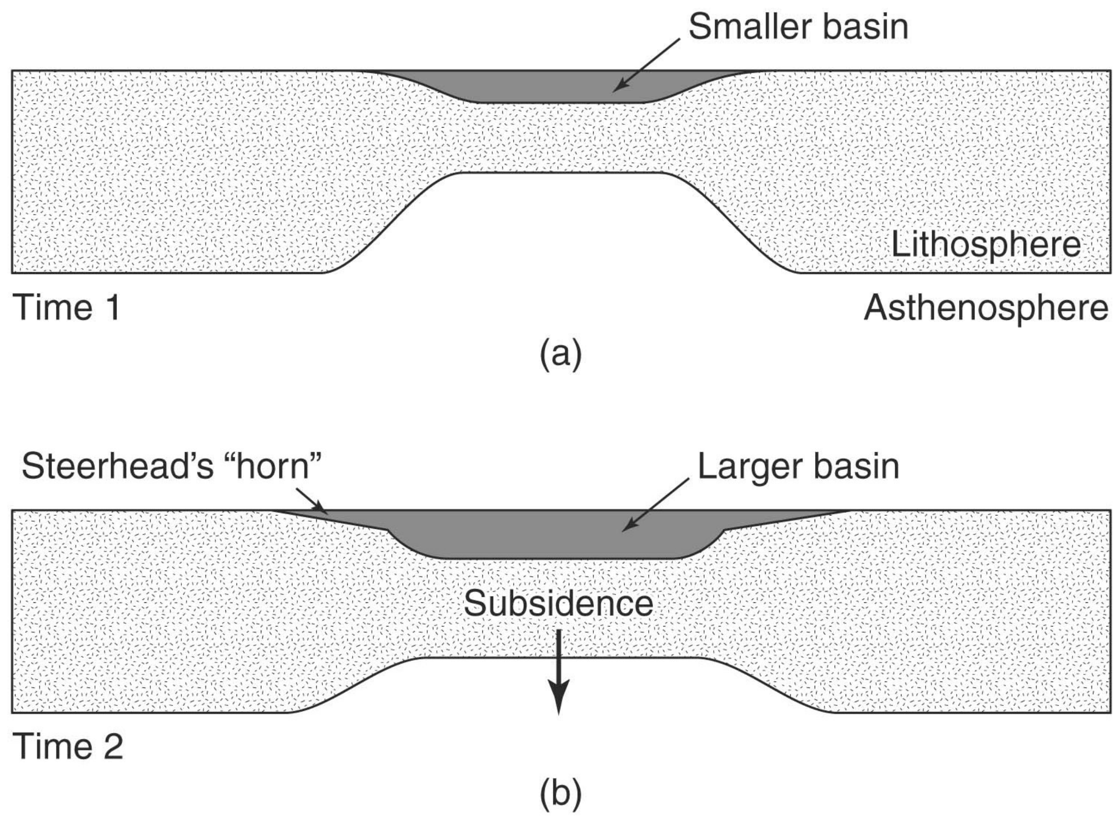


(f)

6. Extensional grabens formed in strike-slip fault zones

Thermal subsidence of a rift basin Fig. 16.29

- Upon rifting, the lithosphere is very thin, and the surface of the lithosphere has sunk to form a rift basin that rapidly fills with sediment.

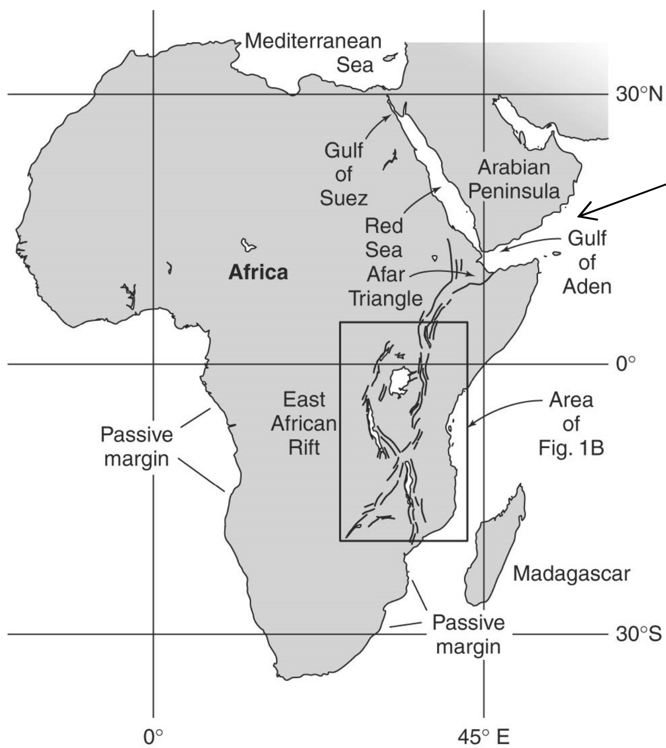


- After time, the lithosphere cools and thickens, and therefore sinks to maintain isostasy.
- The basin therefore gets deeper with time.
- The margins of the basin may warp down, so that sediments lap onto the unthinned lithosphere , resulting in 'steerhead ' basin geometry (as in bull with horns).

East African Continental Rift Fig. 16.1

As we see in East Africa*, a continental rift consists of a belt of normal faults, bounding deep troughs*.

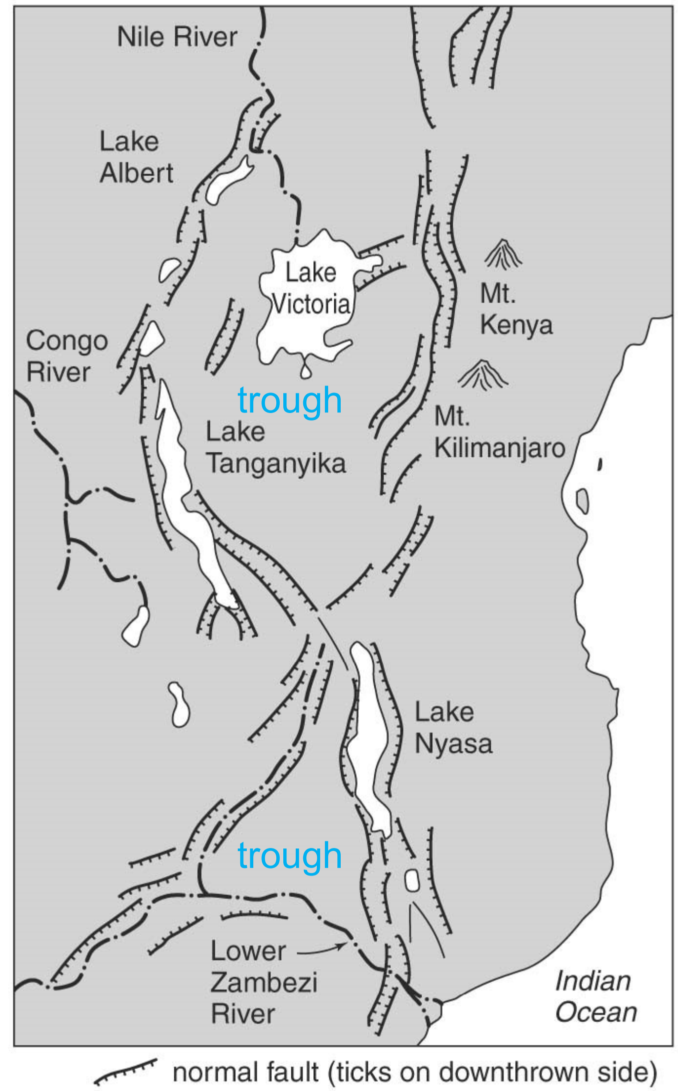
- Some of the troughs may fill with water to become lakes. If the rift is “successful,” a narrow ocean basin, like the Red Sea or Gulf of Aden, develops.



Map of Africa, showing the East African Rift, the Red Sea, and the Gulf of Aden.

The Afar Triangle lies at the triple junction between the Red Sea, the Gulf of Aden, and the East African Rift.

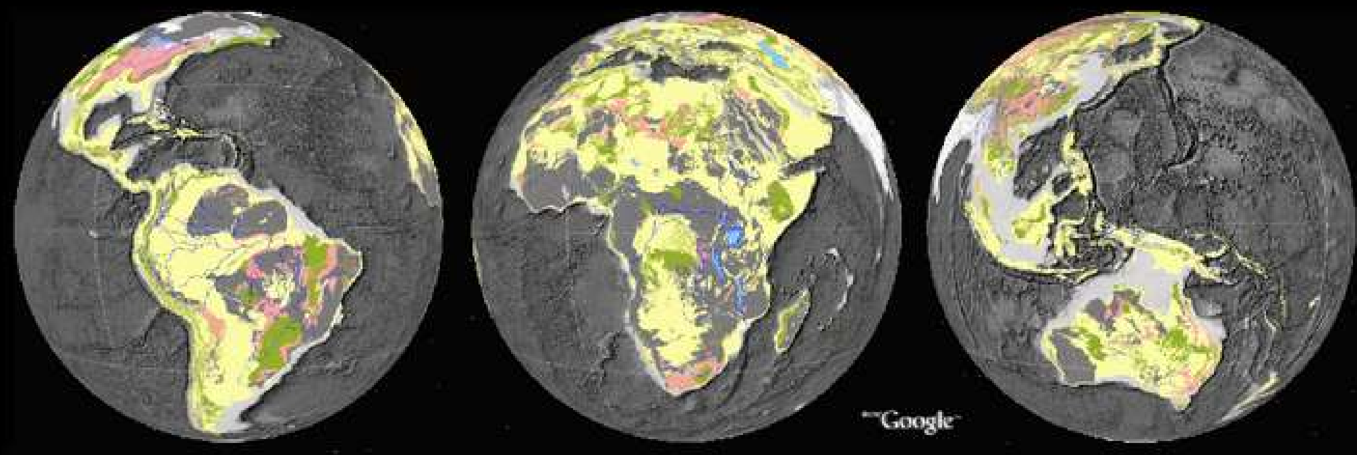
- If seafloor spreading continues for a long time, the narrow ocean could grow to become a large ocean, like the Atlantic.



- *The passive continental margins bordering the ocean basin are underlain by stretched continental crust*

Earth Continental Geology by Era and Sea-Floor Physiography for Google Earth

The Earth_continental geology by Era 032014.kmz file (288KB) references a set of tiled GIF imagery representing Earths continental geology colored by geological era and grayshade sea-floor imagery compiled by the US Geological Survey. The KMZ file loads 12 images (shown below) into Google Earth to produce a seamless, world coverage of continental geology by Era *(except for those few areas lacking coverage)*. The set of images totals 5.53 MB.



EXPLANATION OF COLORS USED FOR CONTINENTAL AREAS ONLY

CENOZOIC	MESOZOIC & CENOZOIC
MESOZOIC	PALEOZOIC & MESOZOIC
PALEOZOIC	PRECAMBRIAN TO MESOZOIC
PRECAMBRIAN	PRECAMBRIAN & PALEOZOIC
ICE	WATER
UNKNOWN	

Yellow- Cretaceous, Green - Mesozoic, Pink - Paleozoic, Dark Gray - Precambrian
Orange - unknown age, including undated intrusive and volcanic igneous rocks.

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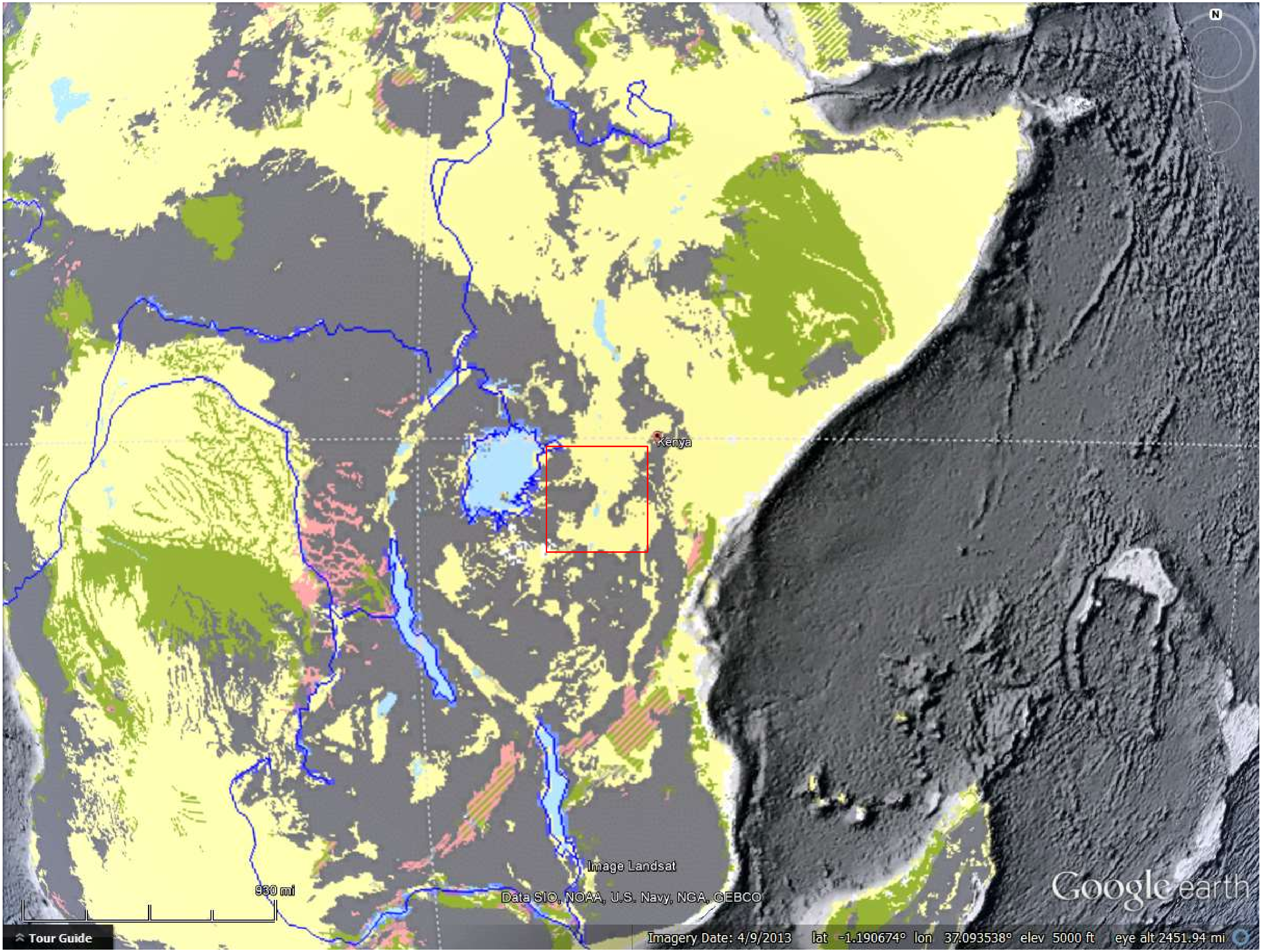
www.impacttectonics.org/Earth/Geology_KML.html

N
Kenya
Image Landsat
930 mi
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Tour Guide
Imagery Date: 4/9/2013 lat 14.479095° lon 15.558581° elev 879 ft eye alt 2451.94 mi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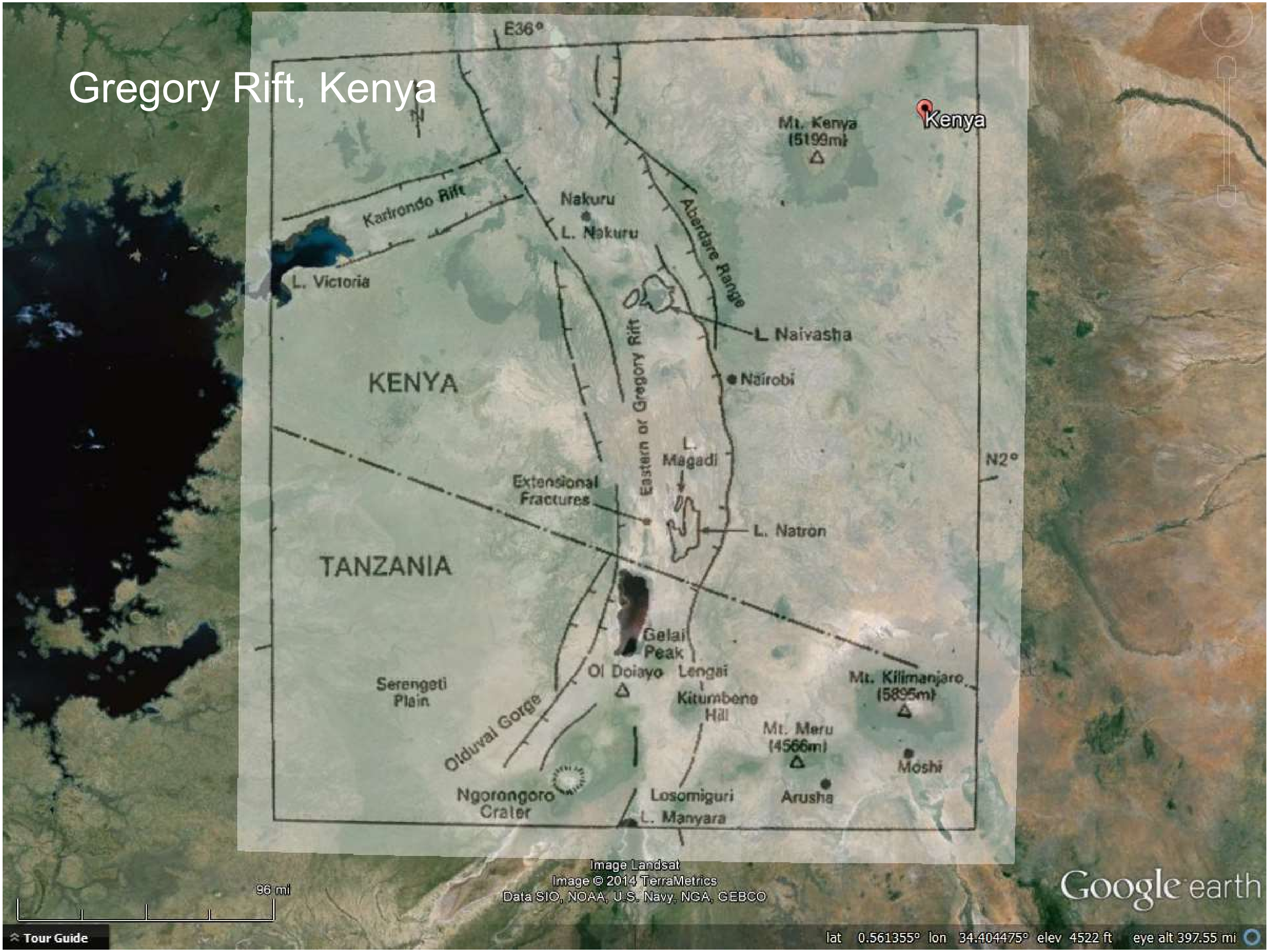
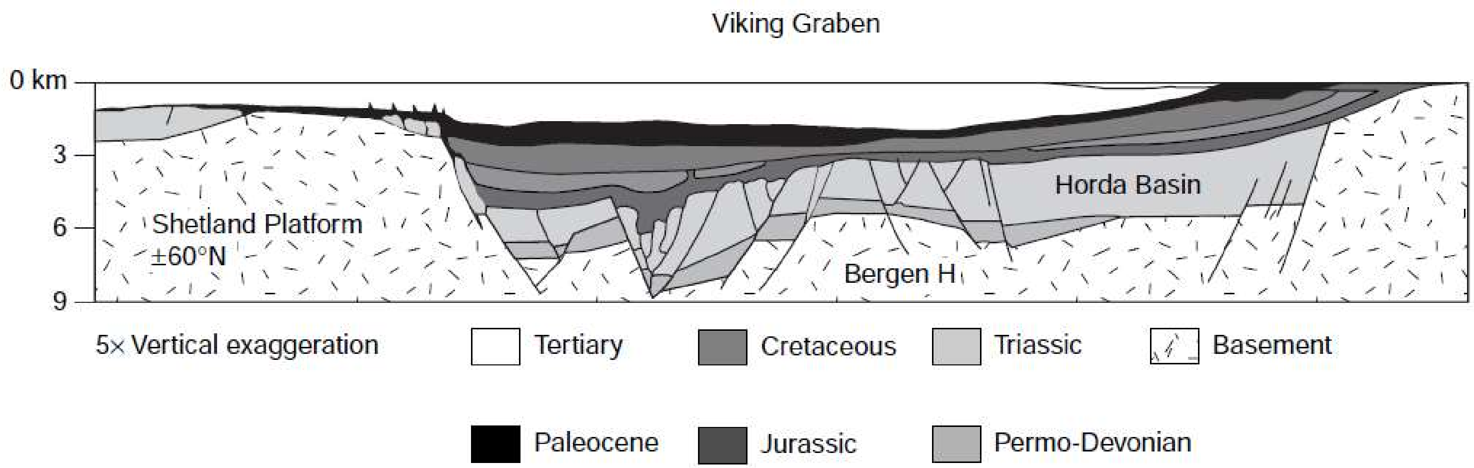
Gregory Rift, Kenya



Gregory Rift

Classic Graben details Fig. 16.11



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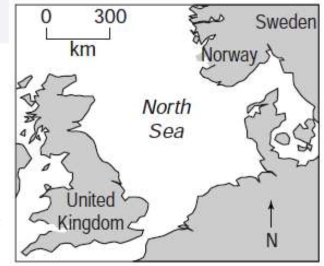

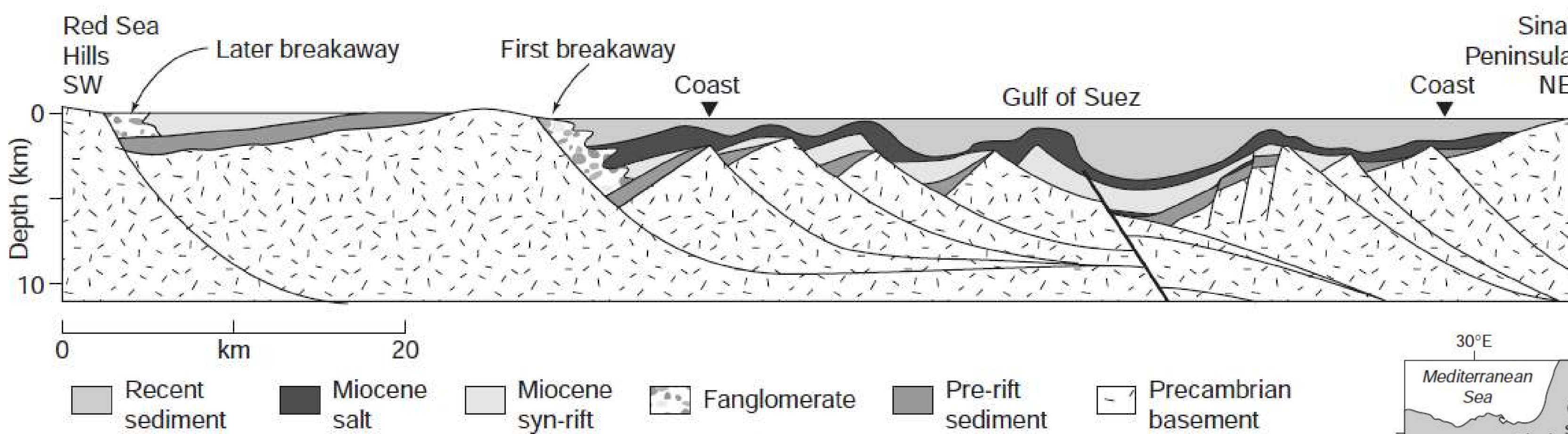

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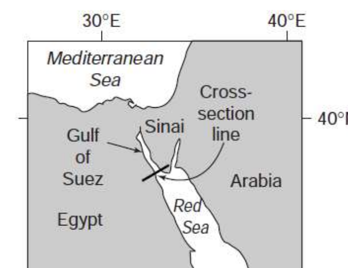
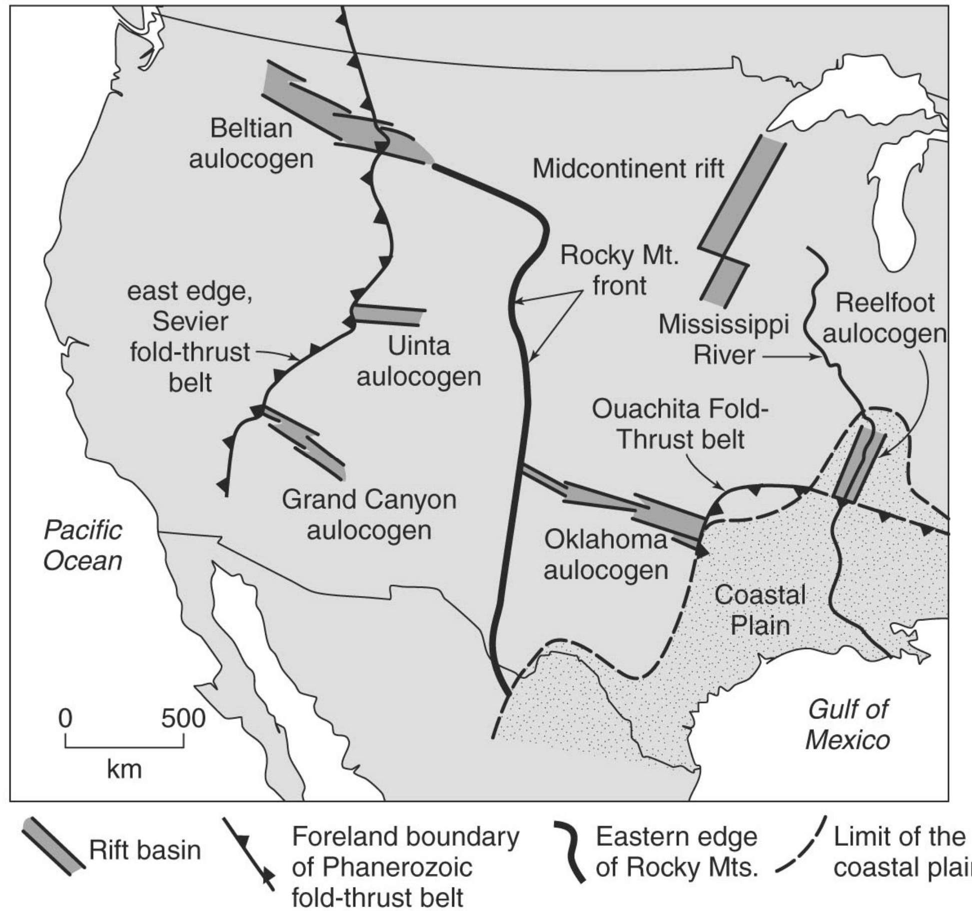


Continental Rifting and rift systems Fig. 16.3

- *Successful rift results when crustal plates are split whereas unsuccessful rifts stopped before succeeding.*

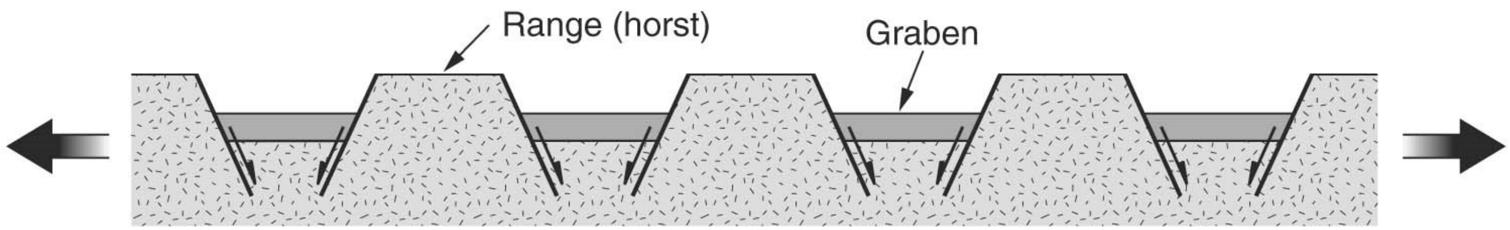
- **Aulocogens** are unsuccessful rifts that cut into cratonic areas of continents at high angles to the continental margin

- Maybe relicts of unsuccessful rifting events that occurred prior to the successful rifting that generated the margins of North America at the beginning of the Phanerozoic.

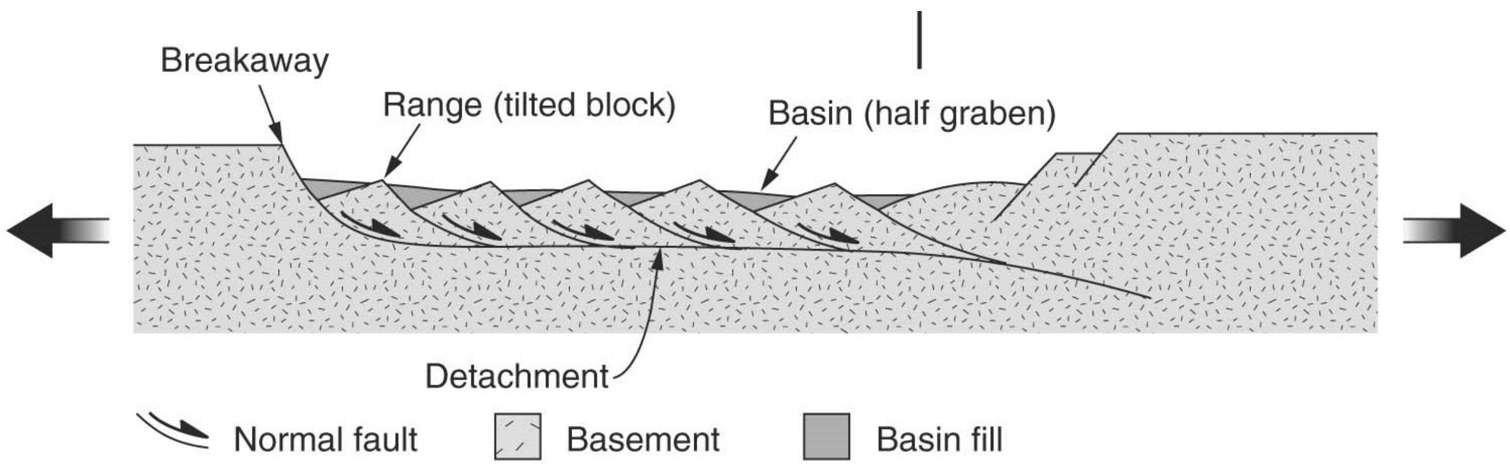


Inactive Proterozoic aulocogens of the western US

Old and current views of rifting Fig. 16.5



Old concept of symmetric horsts and grabens.

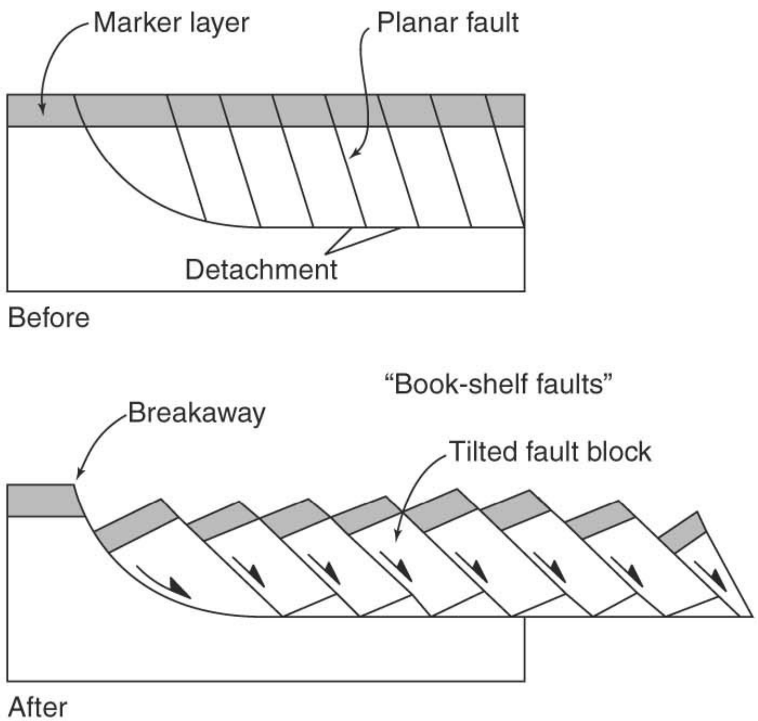


Current concept of fault blocks and half grabens above a detachment.

Rifts contain both *parallel* and *listric* normal faults Fig. 16.6

Parallel rotational faults.

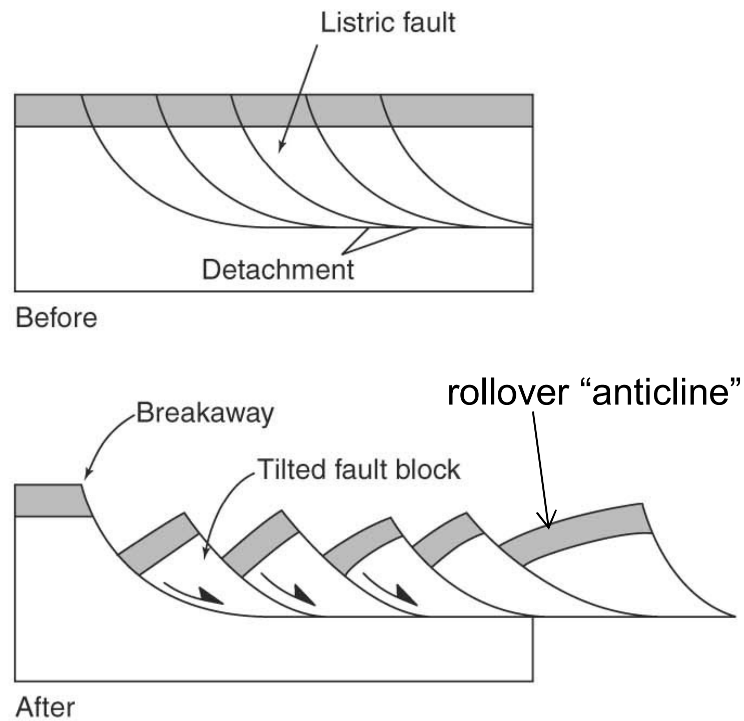
The faults are parallel and not curved before faulting



After faulting (bottom), fault blocks are tilted. In reality, crushing and small-scale faulting at the base of the blocks fill the gaps.

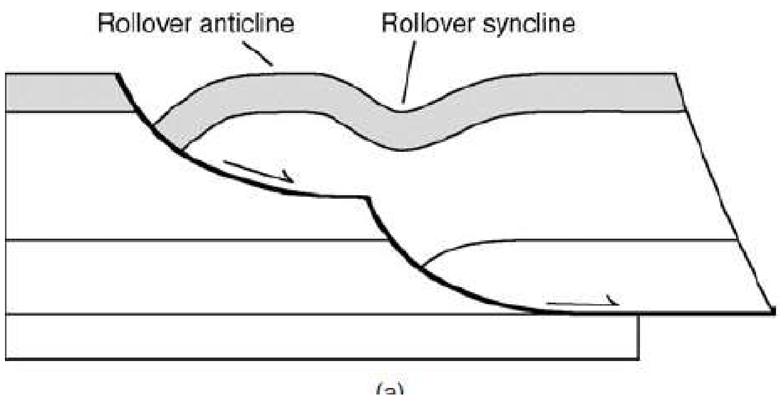
Listric faults and unfaulted rollover.

The faults shallow with depth and merge with a detachment



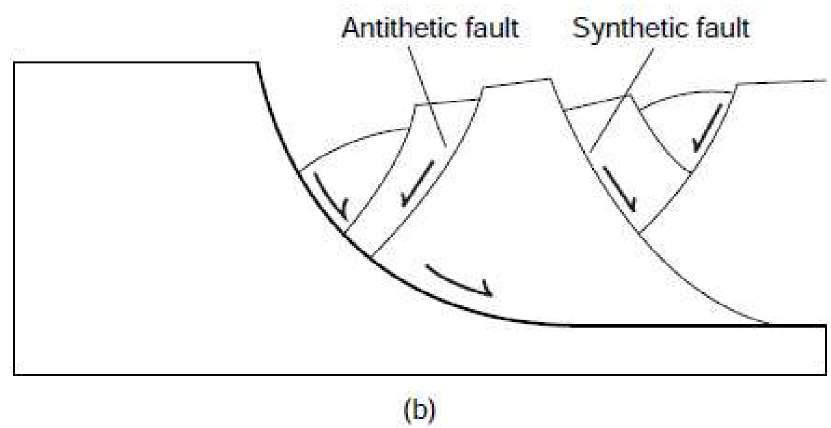
After faulting, the blocks have moved. The block to the right curves down to maintain contact with the footwall, forming a rollover anticline.

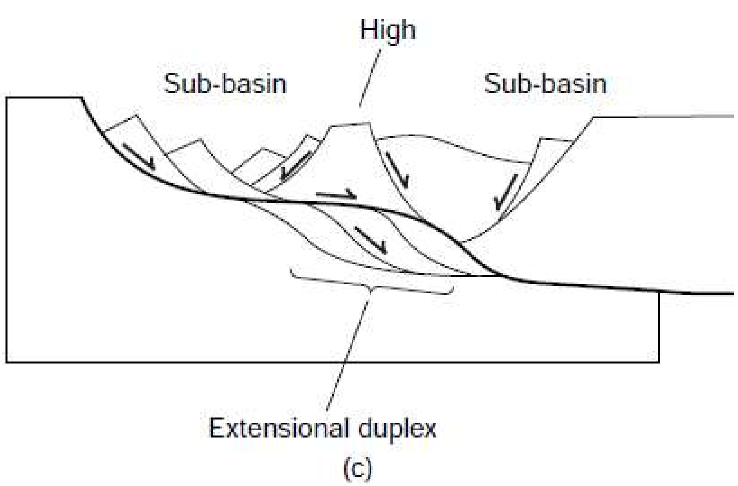
Complex fault systems and related folds found in rifts Fig. 16.8



Cross section showing a rollover anticline above a listric normal fault, and a rollover syncline forming at the intersection of a ramp and flat.

Antithetic faults dip toward the main fault and *synthetic faults* dip in the same direction as the main fault to break up the hanging-wall block.





Complex fault system underlain by an *extensional duplex*. Note the sub-basins and the high block between them.

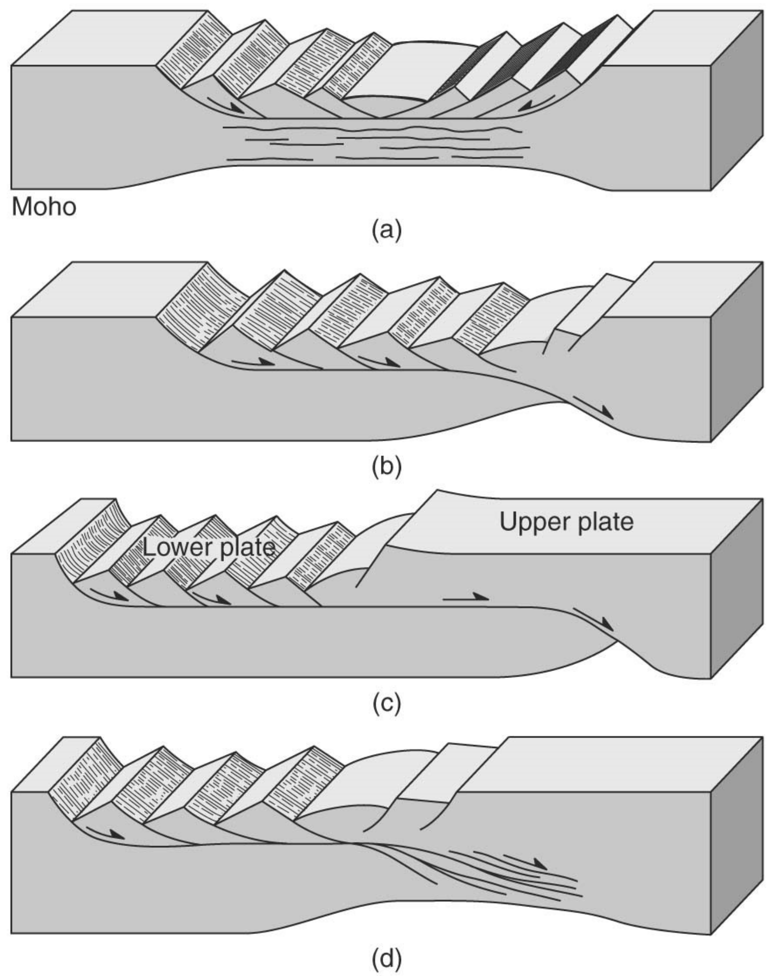
Models of crustal-scale rifting Fig. 16.9 What do faults do at depth?

Pure-shear model

Simple-shear model

Delamination model

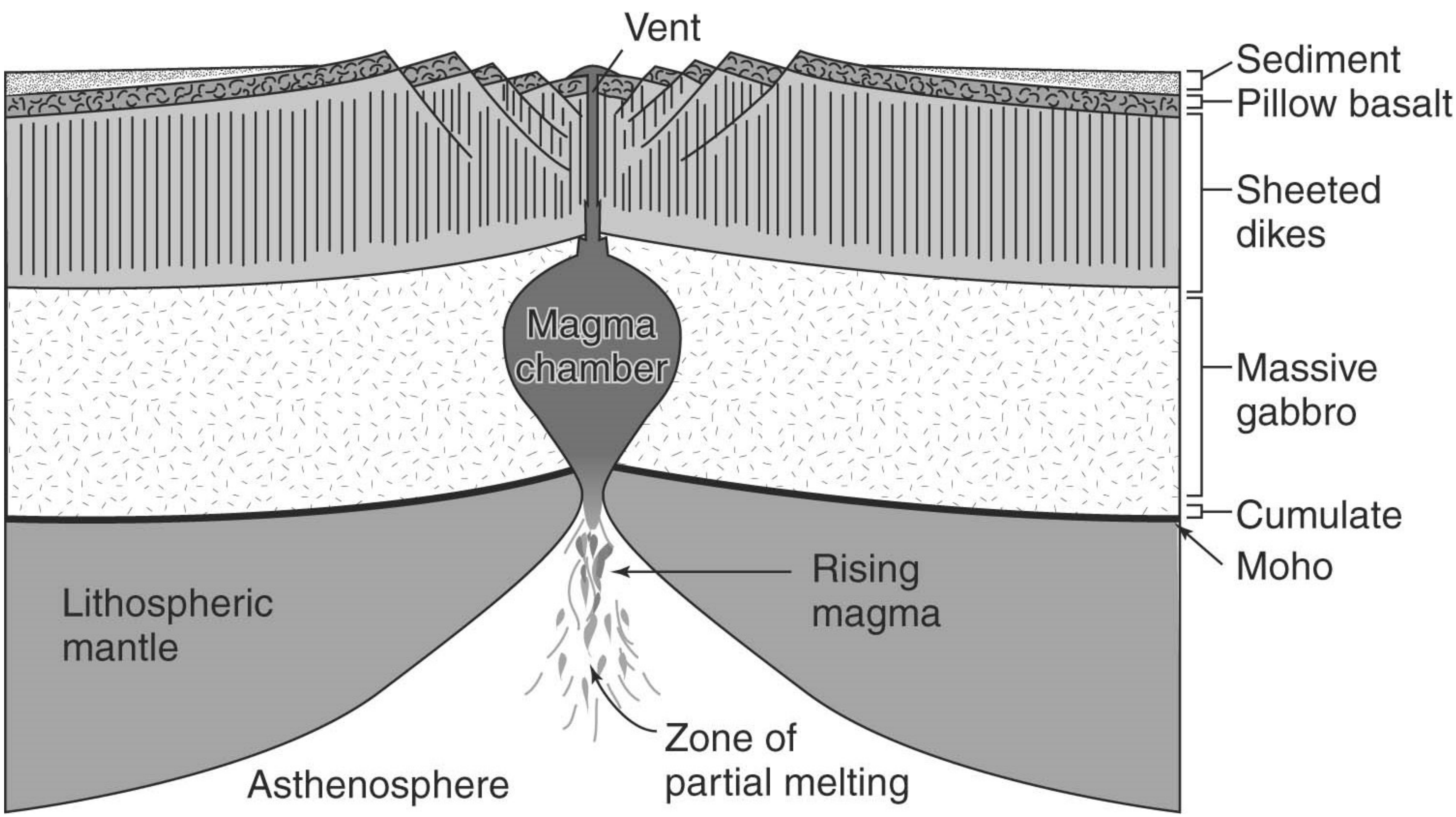
Hybrid model (simple shear plus broad zone of distributed shear at depth).



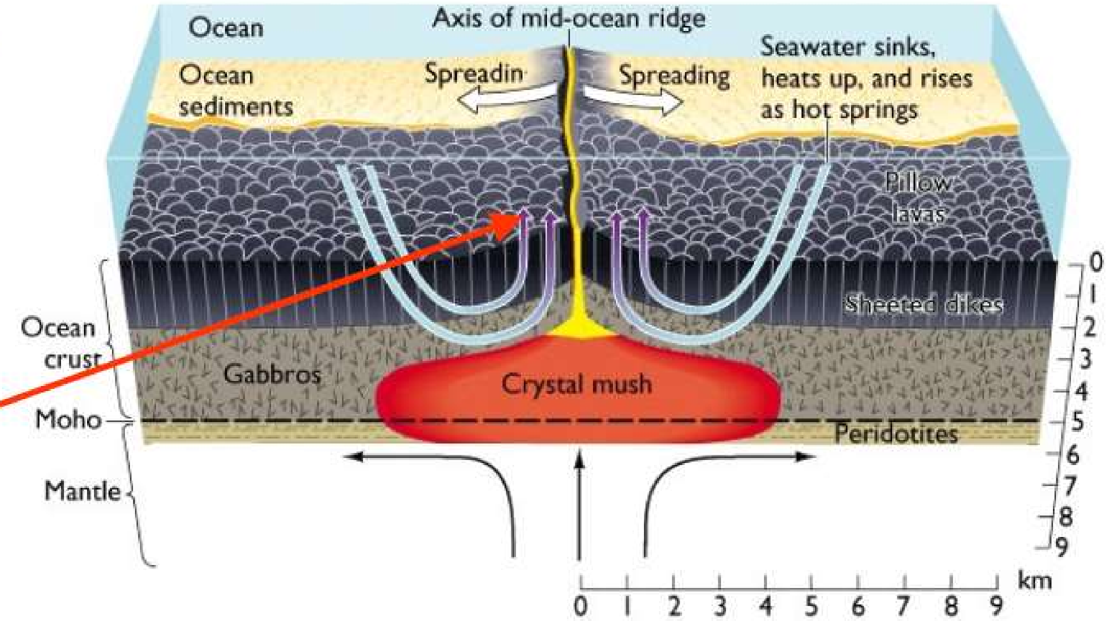
Tectonics of Mid-Ocean Ridges (Divergent plate boundary)

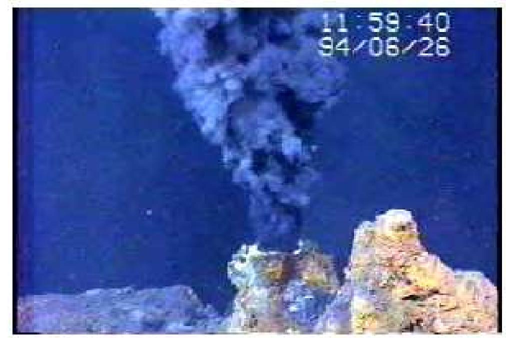
North Atlantic Mid-Oceanic Ridge

Cross Section of Ocean Ridge Fig. 16.25



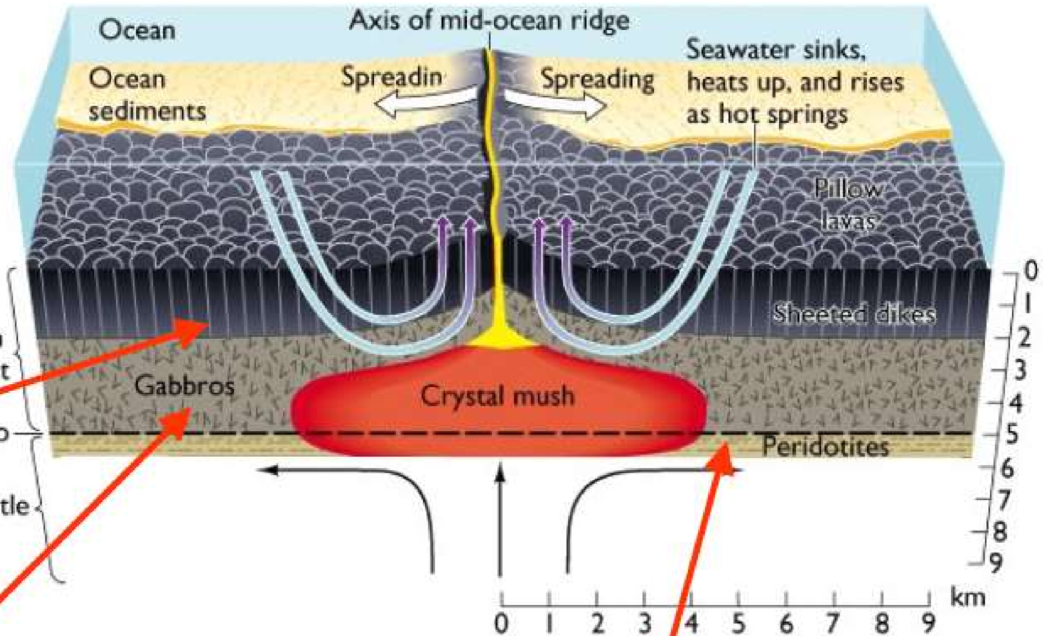
Oceanic divergent boundaries

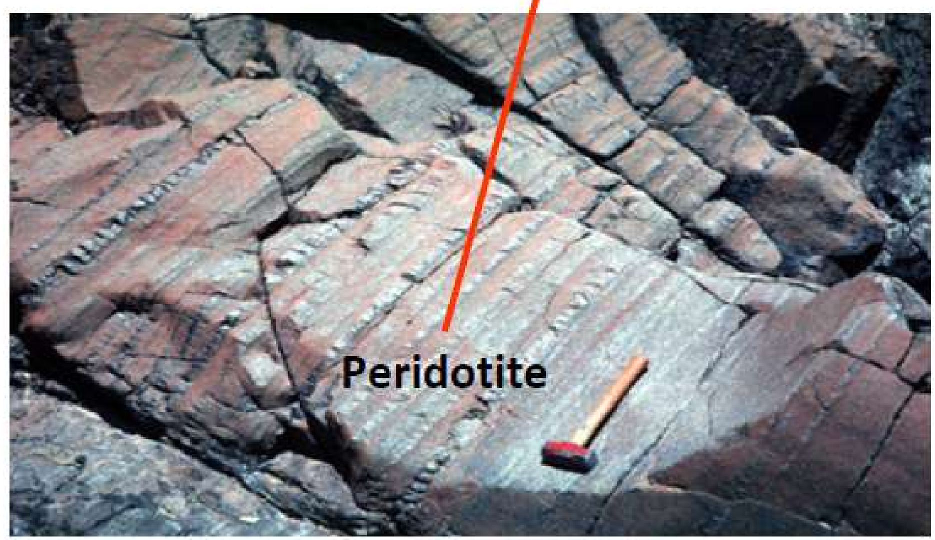




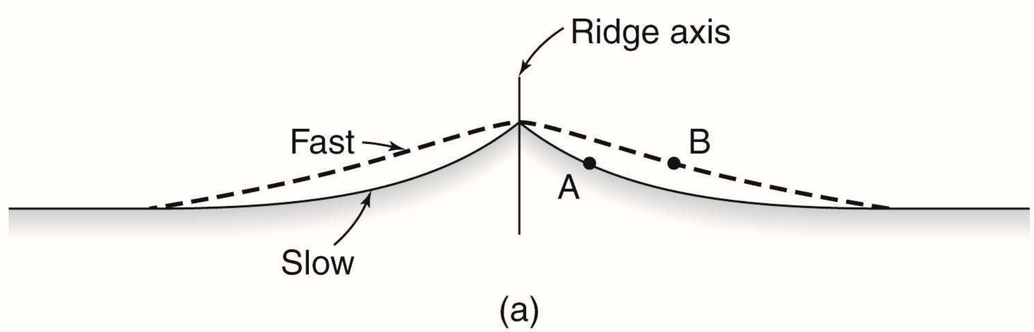
Precambrian basalt from 2-billion-year-old slice of seafloor, Quebec, Canada

Oceanic divergent boundaries



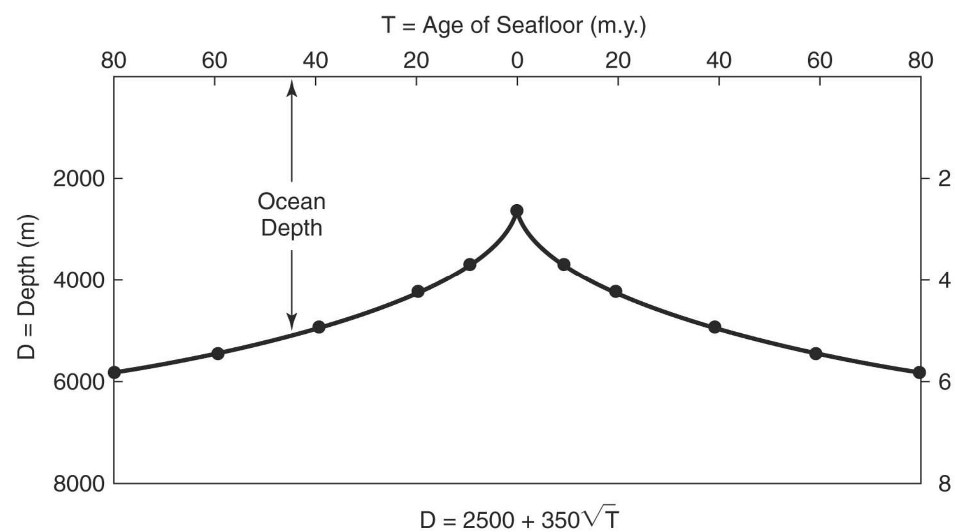


Morphology of Oceanic Ridges Fig. 16.26



- Simplified profiles of a fast ridge versus a slow ridge.
- Notice that fast ridges are wider. That's because the depth to which the seafloor sinks depends on its age.
- The slow plate at point *A* is the same age as the fast plate at point *B,* but both are at the same depth.

The age versus depth curve for seafloor.

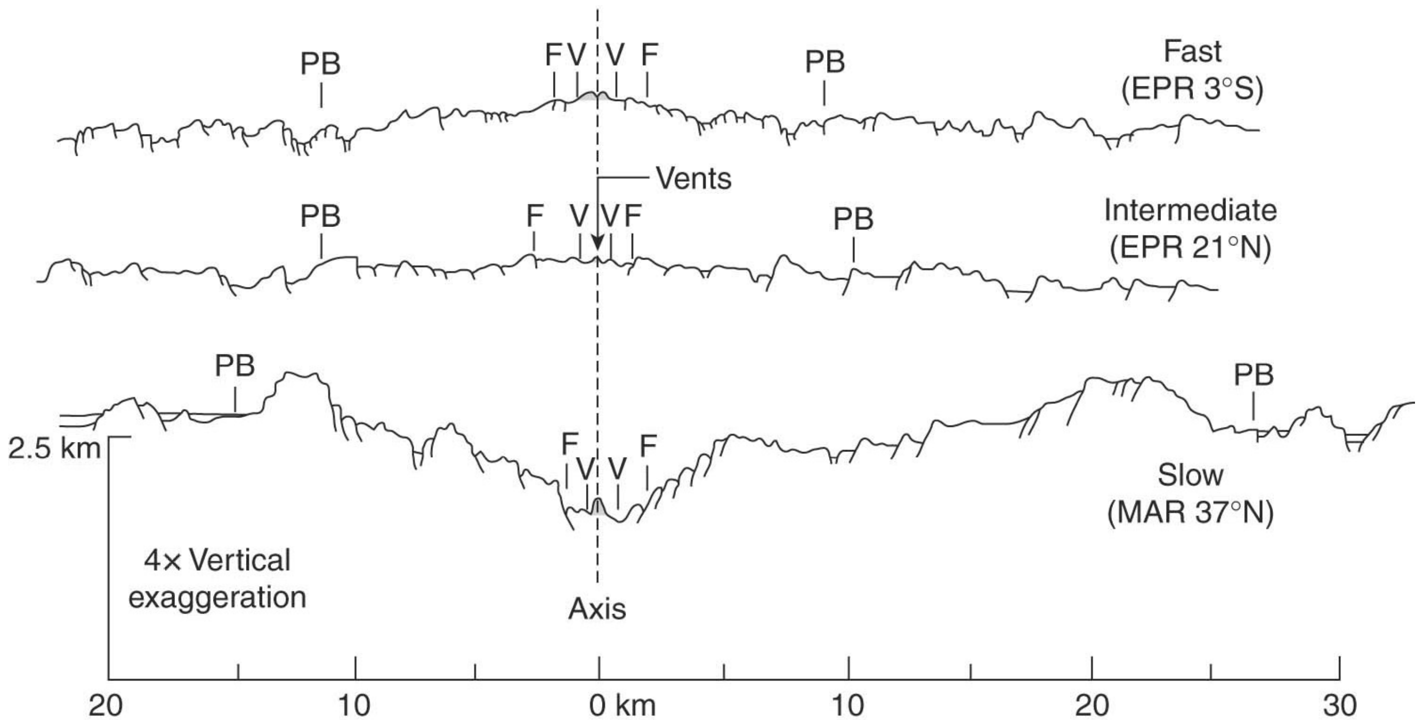


Morphology of Oceanic Ridges Fig. 16.26

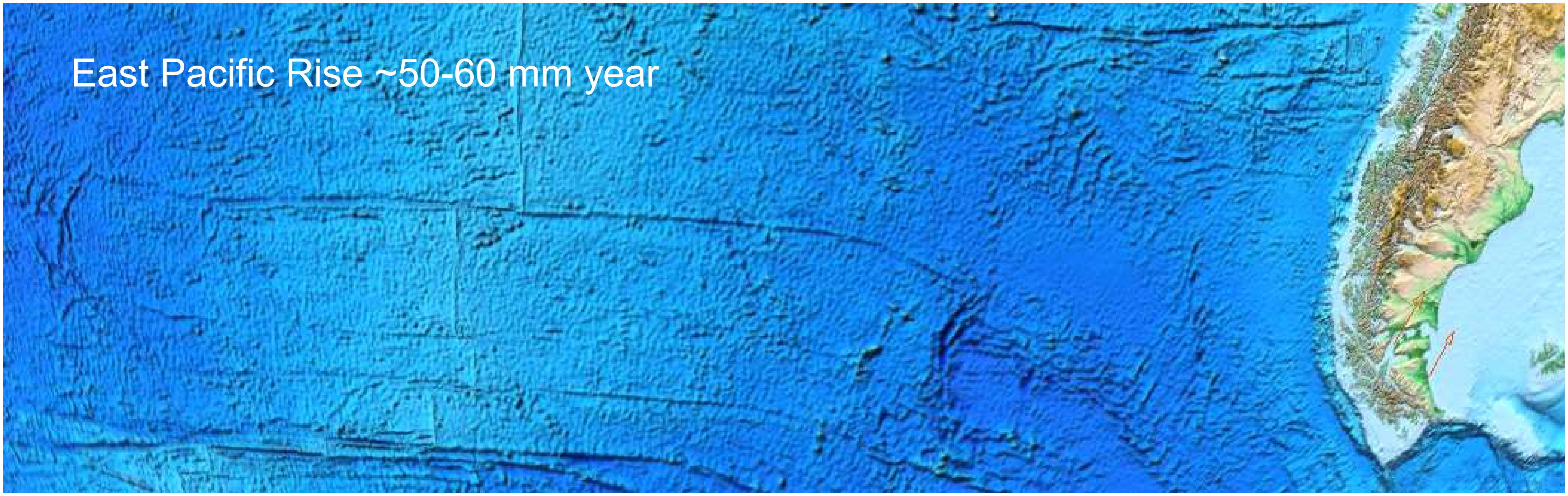
Profiles contrasting fast and slow ridge axes.

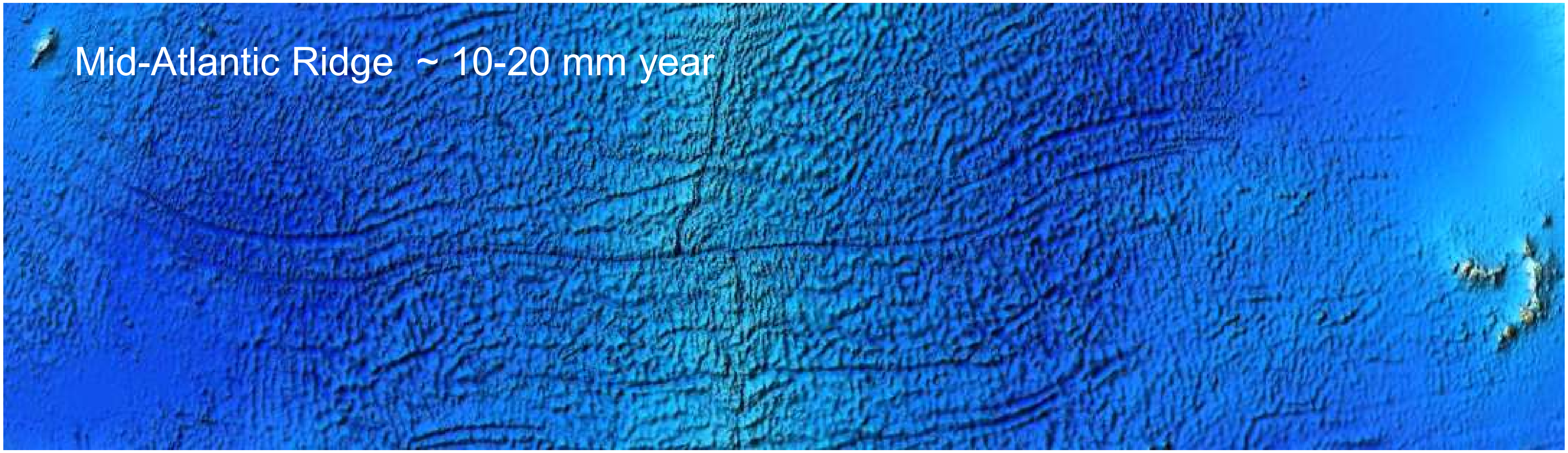
East Pacific Rise

Mid-Atlantic Ridge



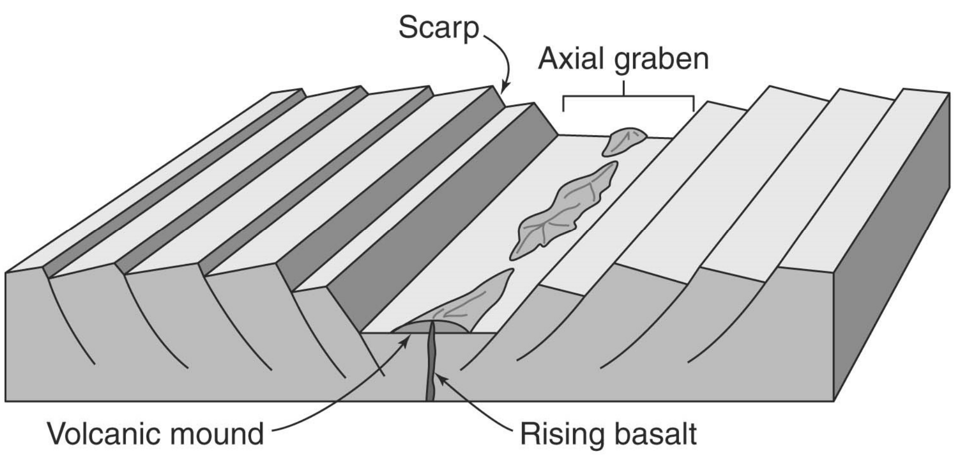
- Note that an axial trough only occurs at slow ridges, not at fast ridges. “V” marks the position of volcanic vents, PB – pillow basalts, F - Fractures


East Pacific Rise ~50-60 mm year

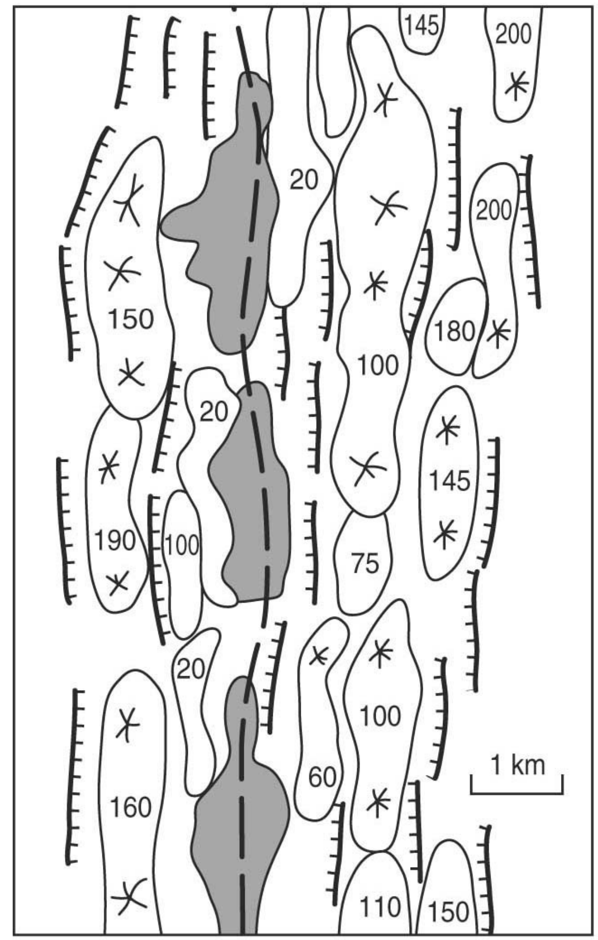

Mid-Atlantic Ridge ~ 10-20 mm year

Morphology of Oceanic Ridges Fig. 16.26

- Three-dimensional block diagram emphasizing the axial graben of a ridge.
- Mounds of pillow basalt build up over individual vents. Fault scarps border the graben.



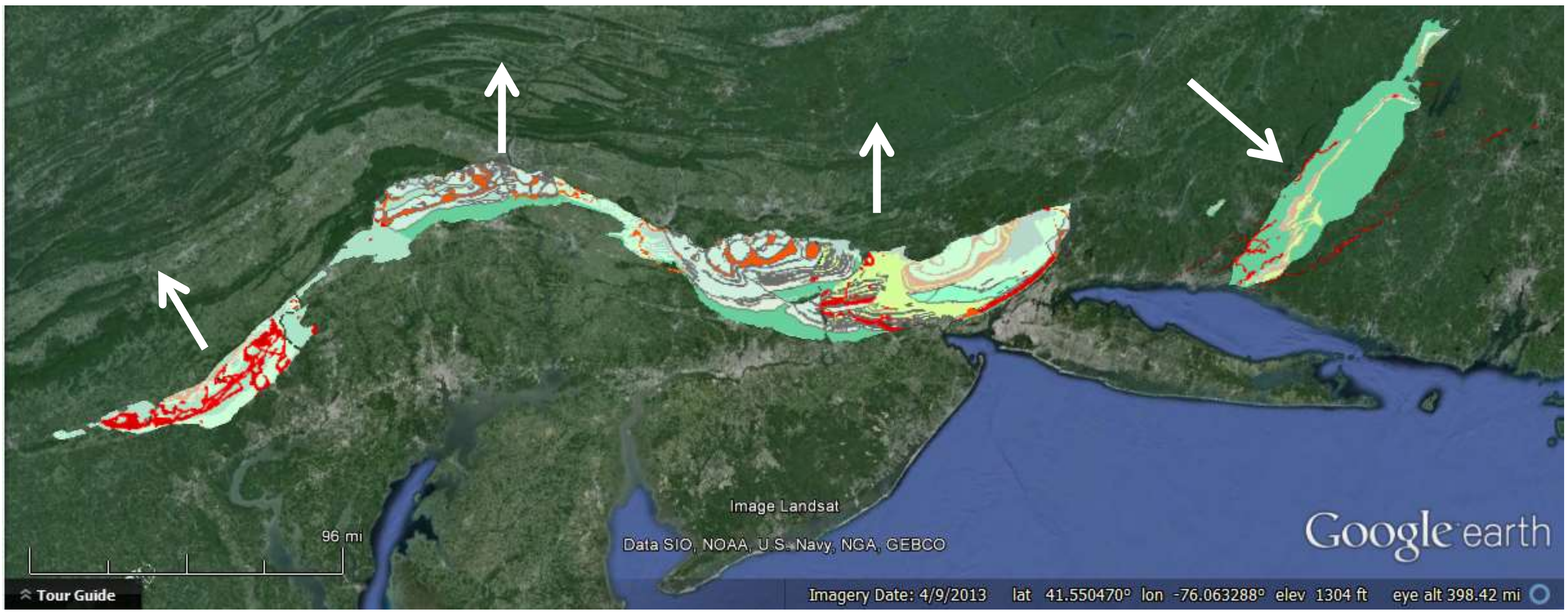
(d) Detailed map of the axial graben of the Mid-Atlantic Ridge, showing dated mounds of basalt. Note that the entire ridge is not active at any given time. The barbed lines are faults, and the stars are vents. The heavy dashed line is the plate boundary. Ages are in hundreds of thousands of years.



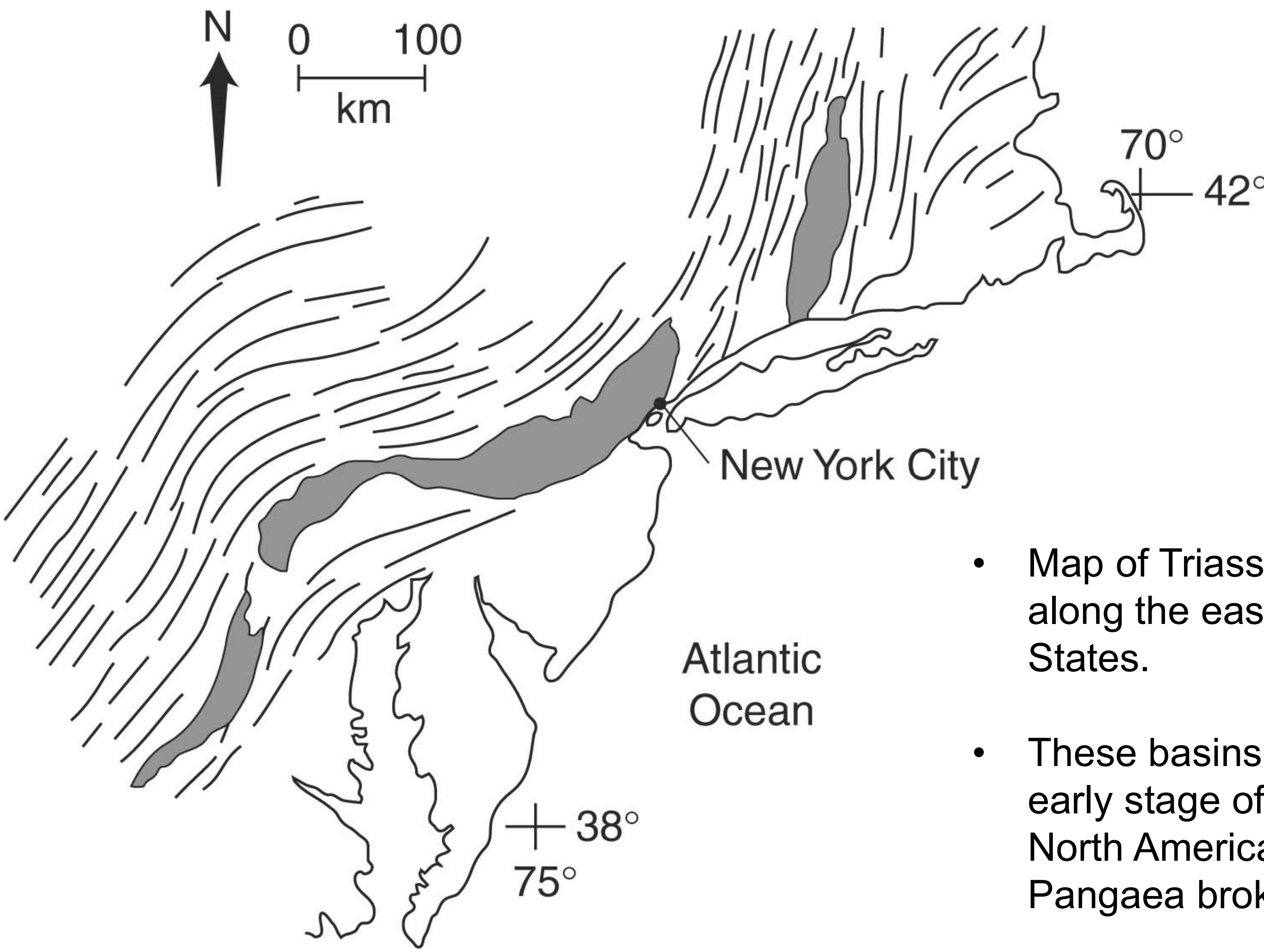
(d)

Formation of a Rift System Sec. 16.4

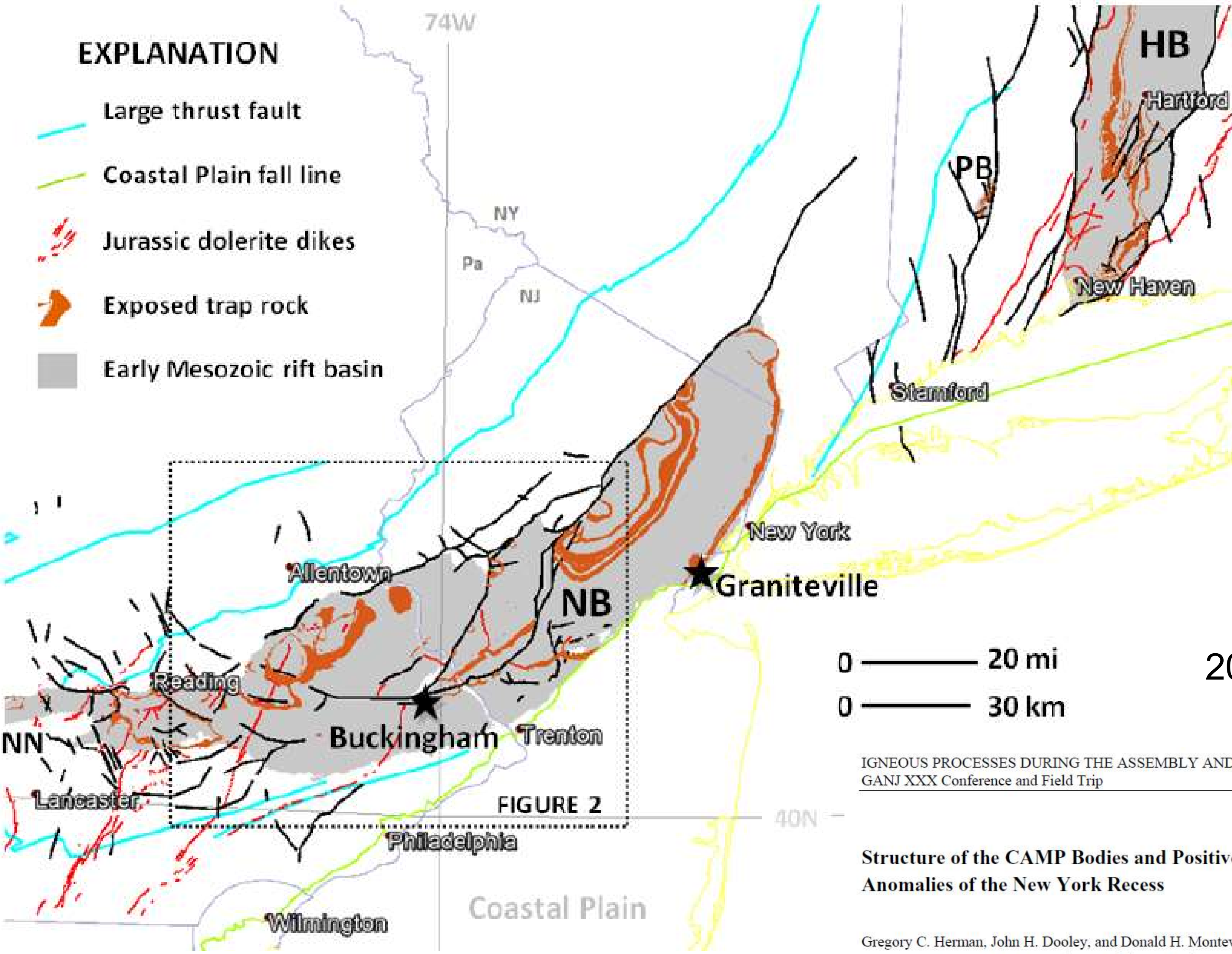
- Extension along the entire length of a continent-scale rift system does not begin everywhere at the same time.
- In a given region, the rift system begins as a series of unconnected **rift segments**, 100–700 km long, each containing a set of normal faults, which die out along their length.
- The numerous normal faults that comprise an individual rift segment dip dominantly in the same direction.



Early Mesozoic Rift Basins of Eastern US Fig. 16.17



- Map of Triassic/Jurassic rift basins along the east coast of the United States.
- These basins formed during the early stage of rifting that separated North America from Africa, as Pangaea broke up.

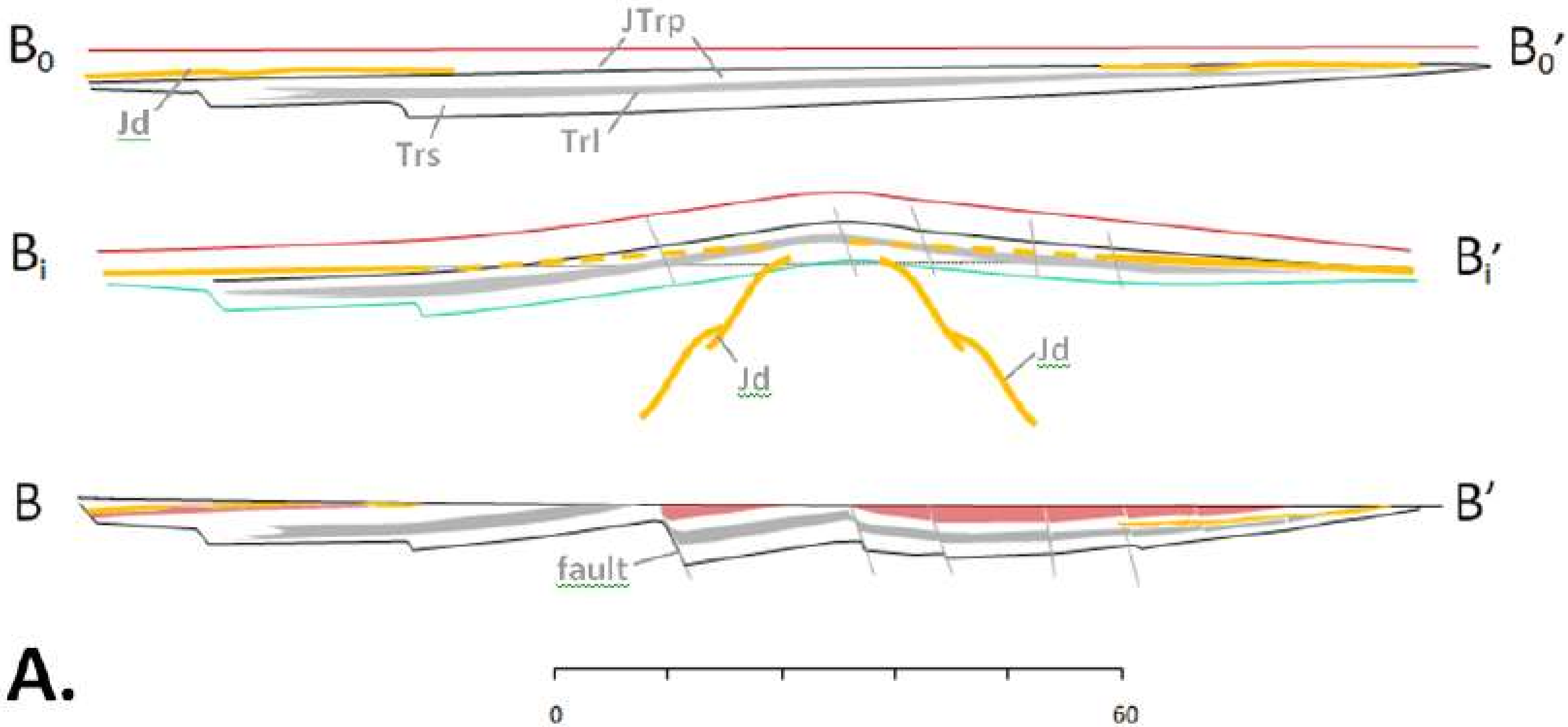


2013

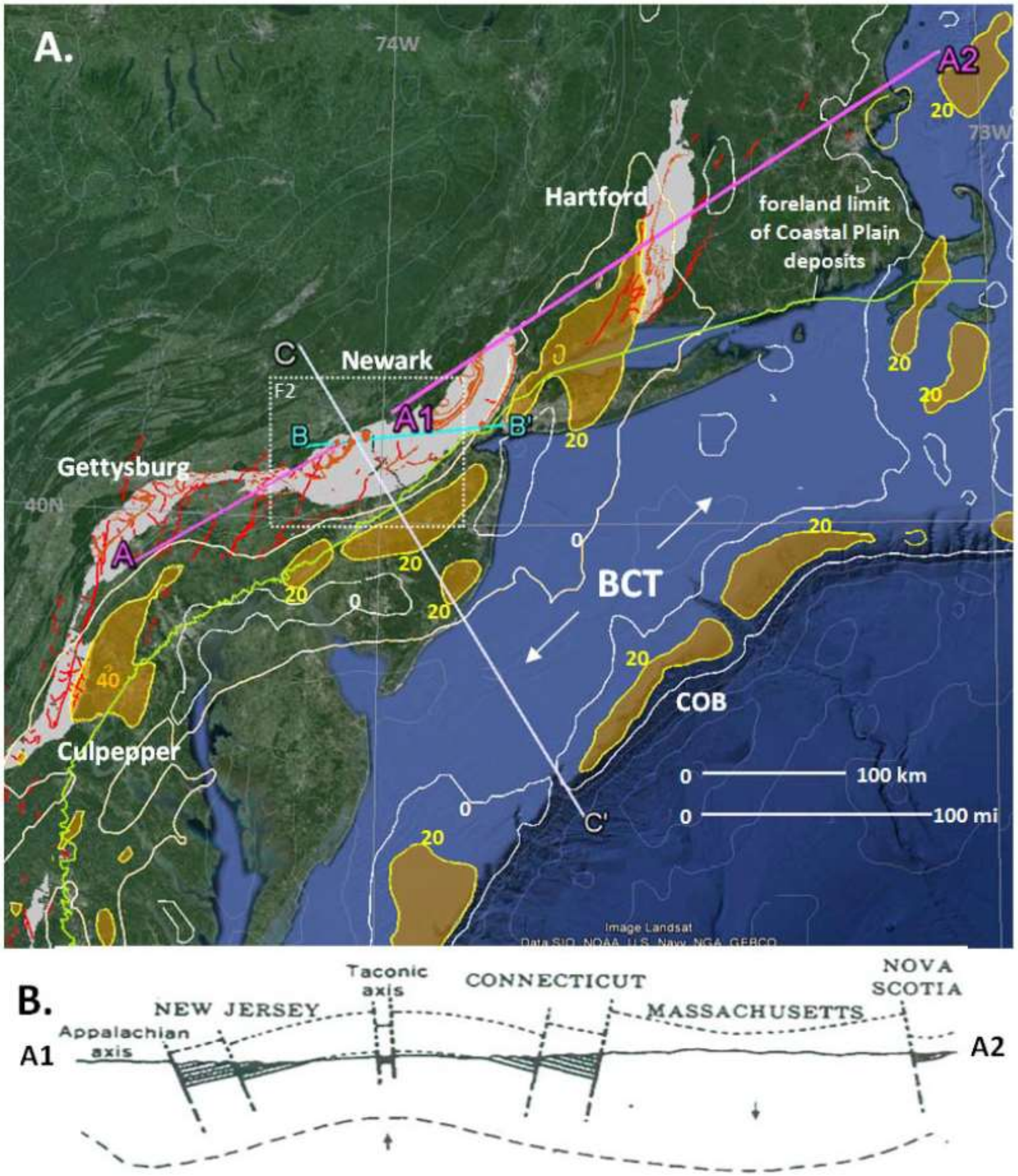
IGNEOUS PROCESSES DURING THE ASSEMBLY AND BREAKUP OF PANGAEA
GANJ XXX Conference and Field Trip

Structure of the CAMP Bodies and Positive Bouger Gravity Anomalies of the New York Recess

Gregory C. Herman, John H. Dooley, and Donald H. Monteverde, NJ Geological and Water Survey, Trenton, NJ greg.herman@dep.state.nj.us



Longitudinal cross sections illustrating dolerite dikes and plutons relative to the Buckingham dome. **A.** The dome in Bi-Bi' is an intermediate-phase of crustal strain that's inserted between an adapted version of Olsen's (1980) current (B-B') and restored (B0 -B0') sections (map trace shown on fig. 15).



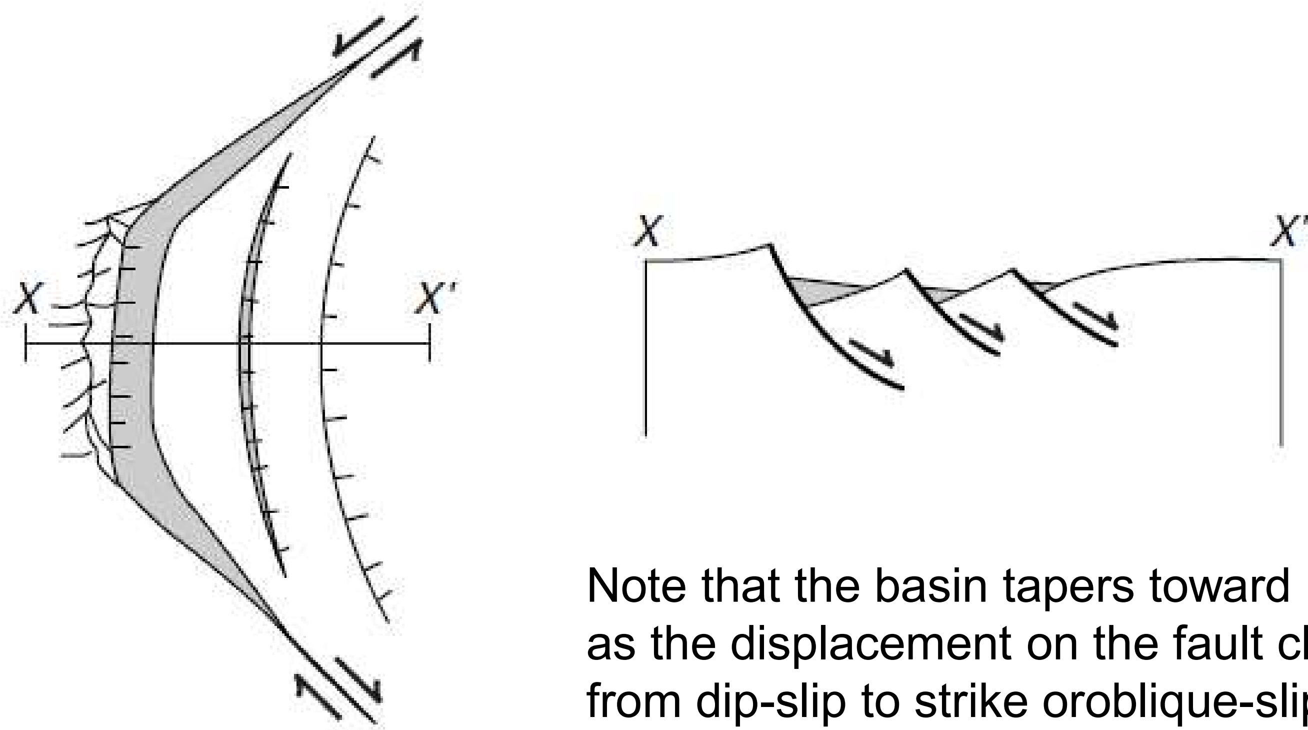
A. Map of the New York Recess showing exposed Early Mesozoic rift basins (gray polygons), and CAMP dikes (red lines) and exposed dolerite bodies (small, solid orange polygons in rift basins) in relationship to positive Bouger gravity anomalies. Positive anomalies are highlighted using white (0 mGal) and yellow (20 mGal) polylines.

The broad-wavelength, >20 mGal anomalies are emphasized using semi-transparent orange polygons that probably indicate the locations of thick remnants of deep CAMP plutons.

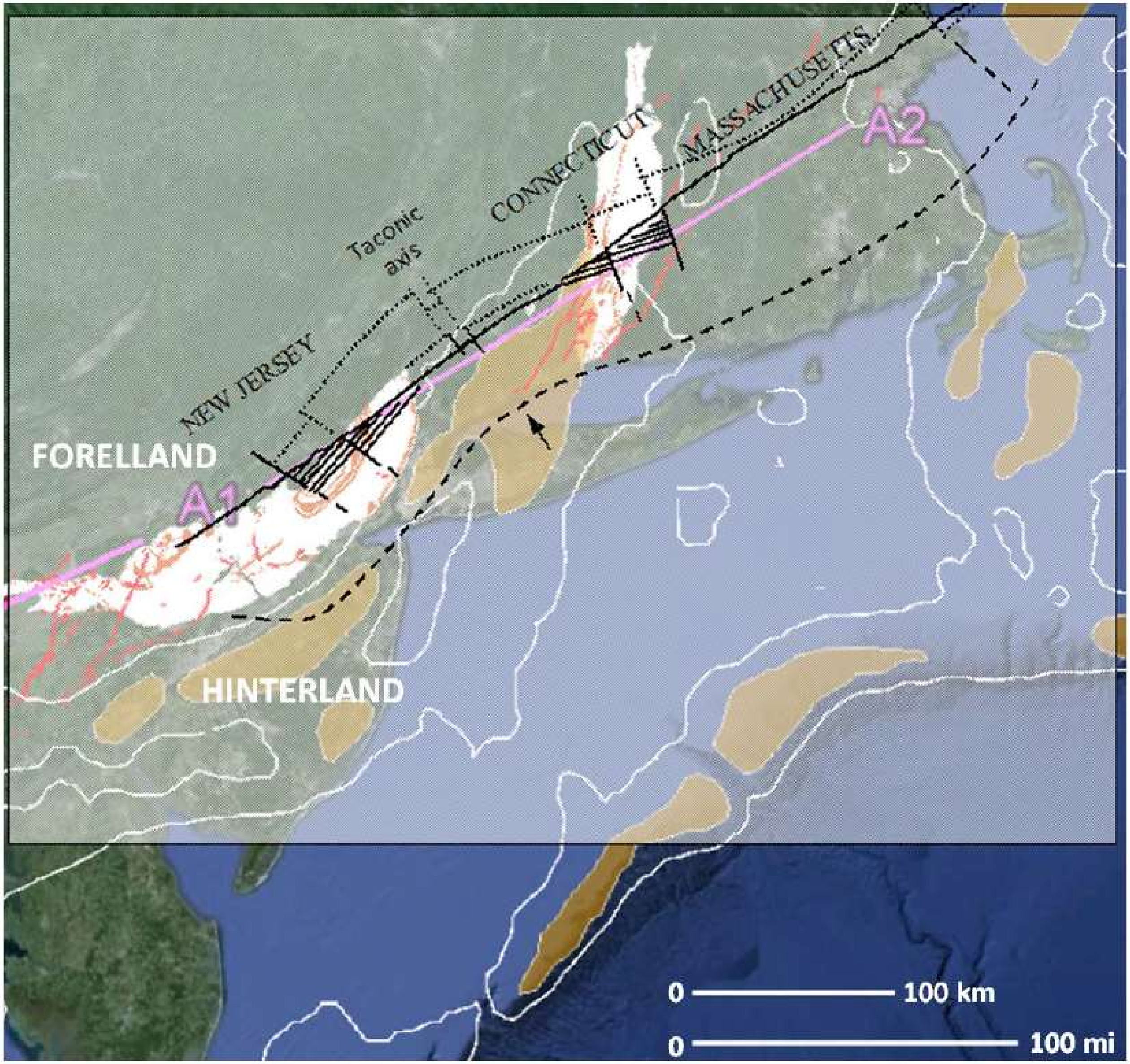
B. Longitudinal cross-section A1-A2 from Woodworth (1932) showing arching of the Taconic axis relative to rift basins and a Massachusetts trough. BCT - Baltimore Canyon Trough.

Half Graben Fig. 16.14

Map view and cross section of a "C-shaped" half graben.

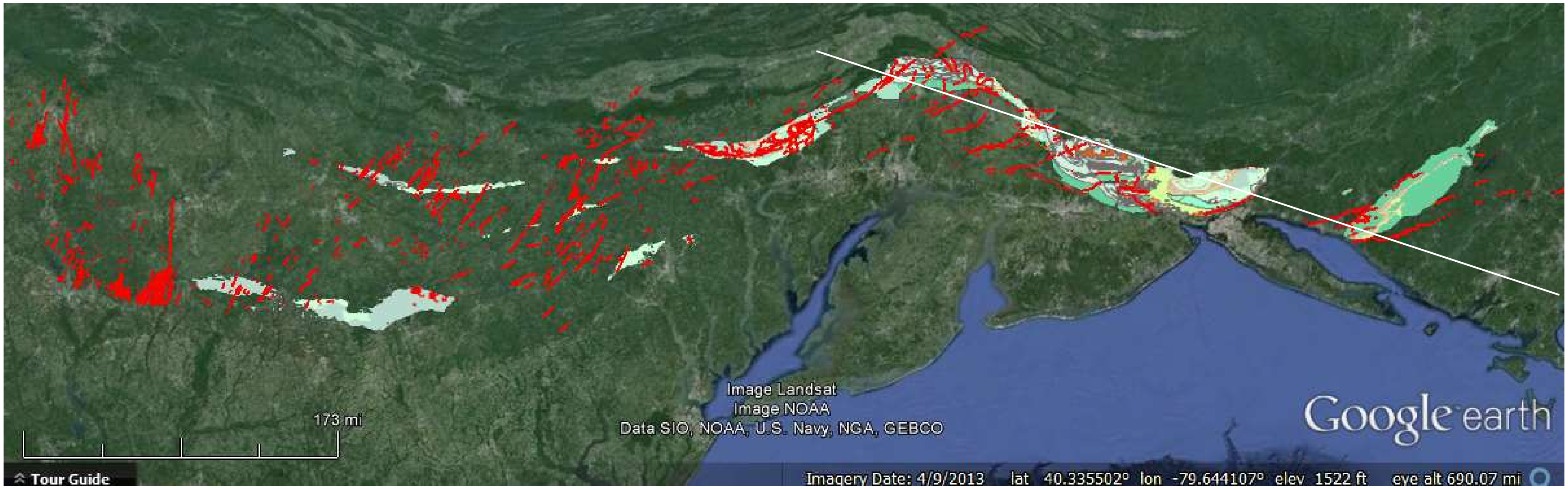


Note that the basin tapers toward its ends as the displacement on the fault changes from dip-slip to strike oroblique-slip.



Woodworth's (1932) cross section image that is rotated, rendered semi-transparent, and placed on top of a non-annotated version of the GE compilation.

This shows the crustal arch overlying a 20mGal Bouger anomaly located between the Newark and Hartford basins.



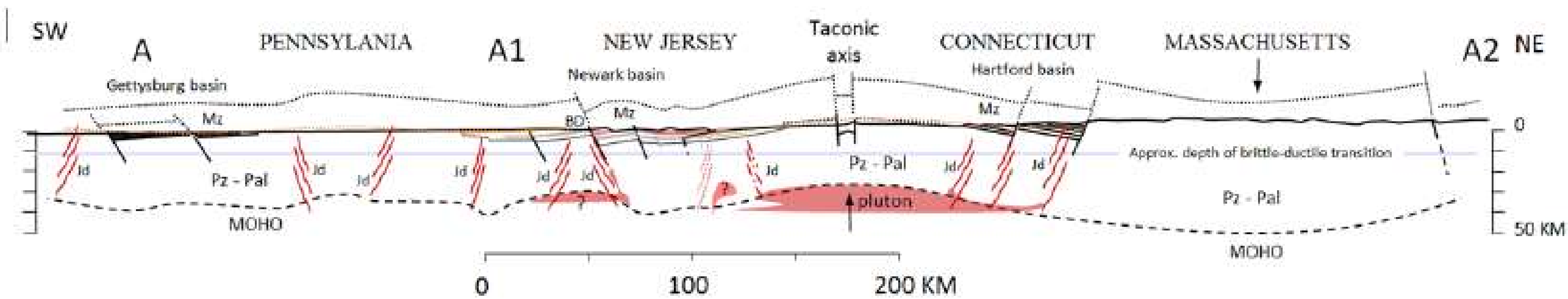
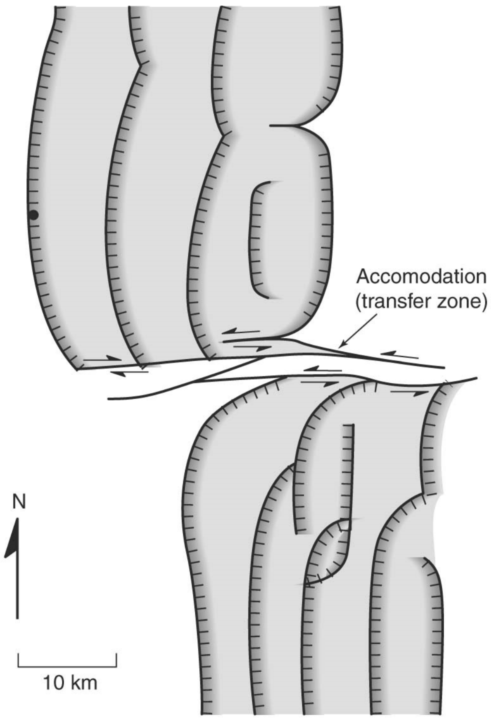
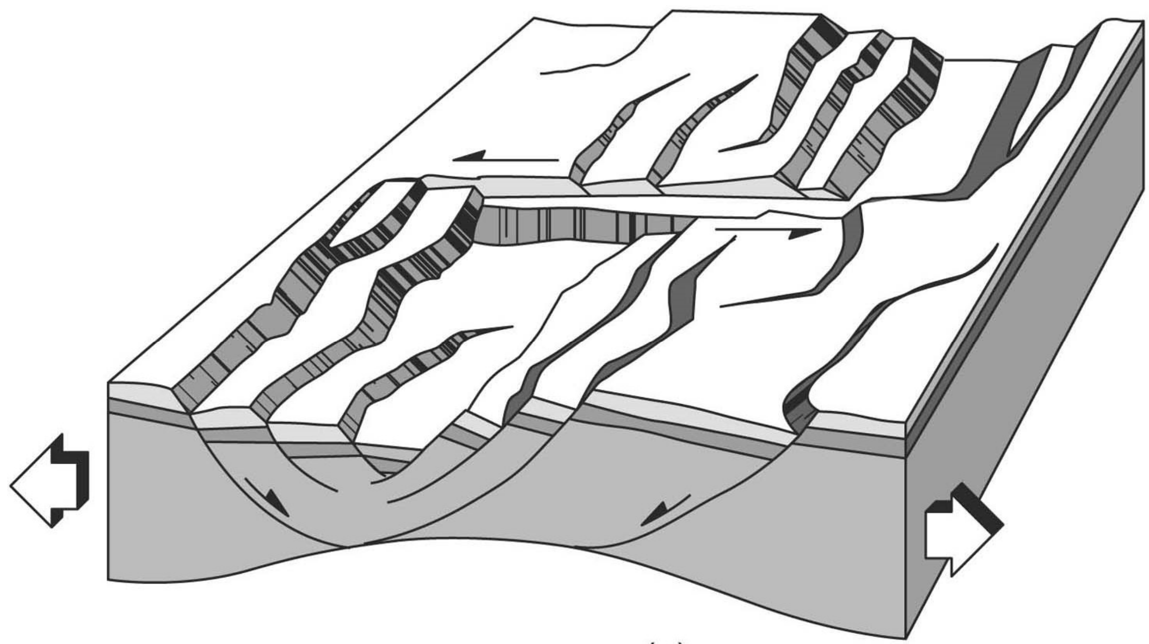


Figure 17. Regional, longitudinal profile across the New York Recess incorporating Olsen's (1980) and Woodworth's (1932) cross sections and depicting Early Mesozoic (Mz) basins relative to deep dolerite plutons beneath the continental lithosphere and overlying, deeply-penetrating dolerite dike swarms. Pz-Pal – undivided Proterozoic and Paleozoic basement, BD – Buckingham dome. MOHO - Mohorovičić discontinuity

Formation of a Rift System Sec. 16.4

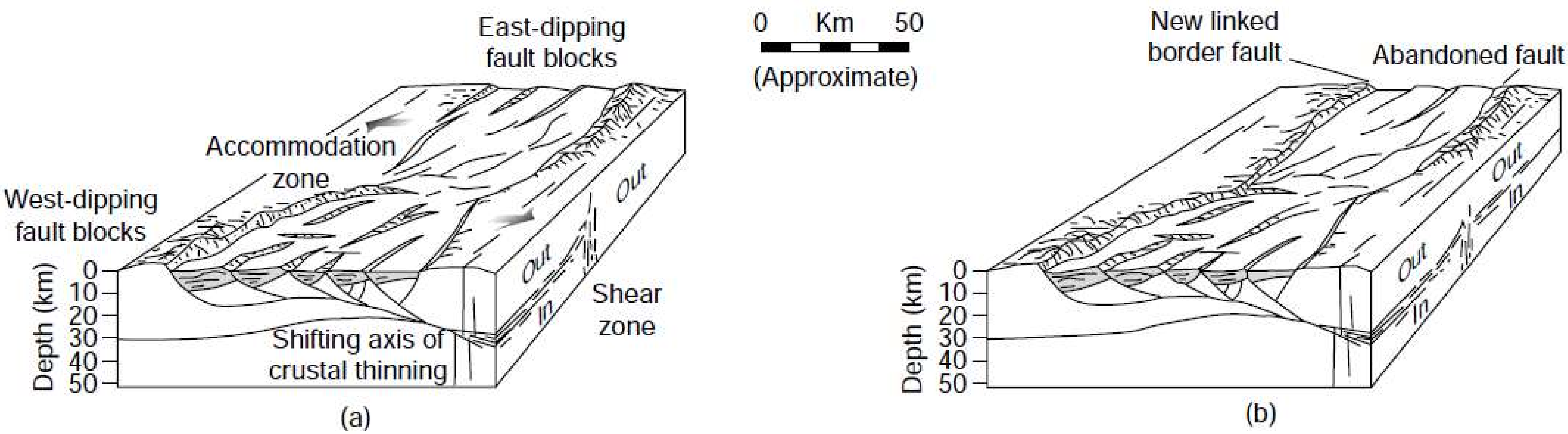
- Regions where two rift segments interact and connect are called **accommodation zones,** and in these zones there is complex deformation involving strike-slip, dip-slip, and oblique-slip faulting





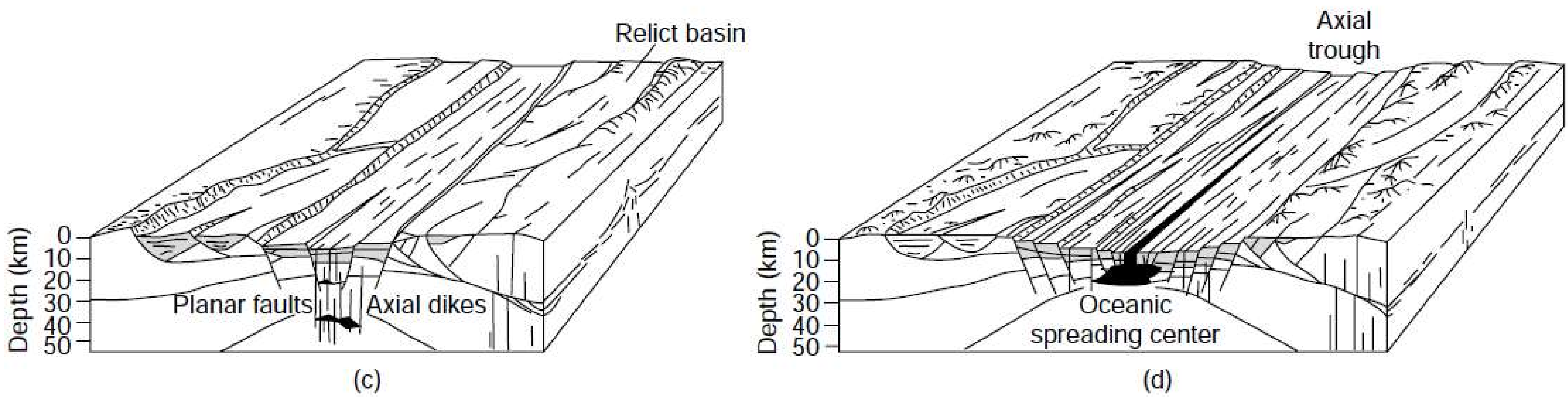
(c)

Rift-to-Drift Evolution Fig. 16.16



- After initial rifting, two north-south-trending rift segments that face in opposite directions or with opposite polarity begin to interact.
- A new linked border faults of one polarity develops at the expense of the other of opposite vergence and the other segment becomes inactive.

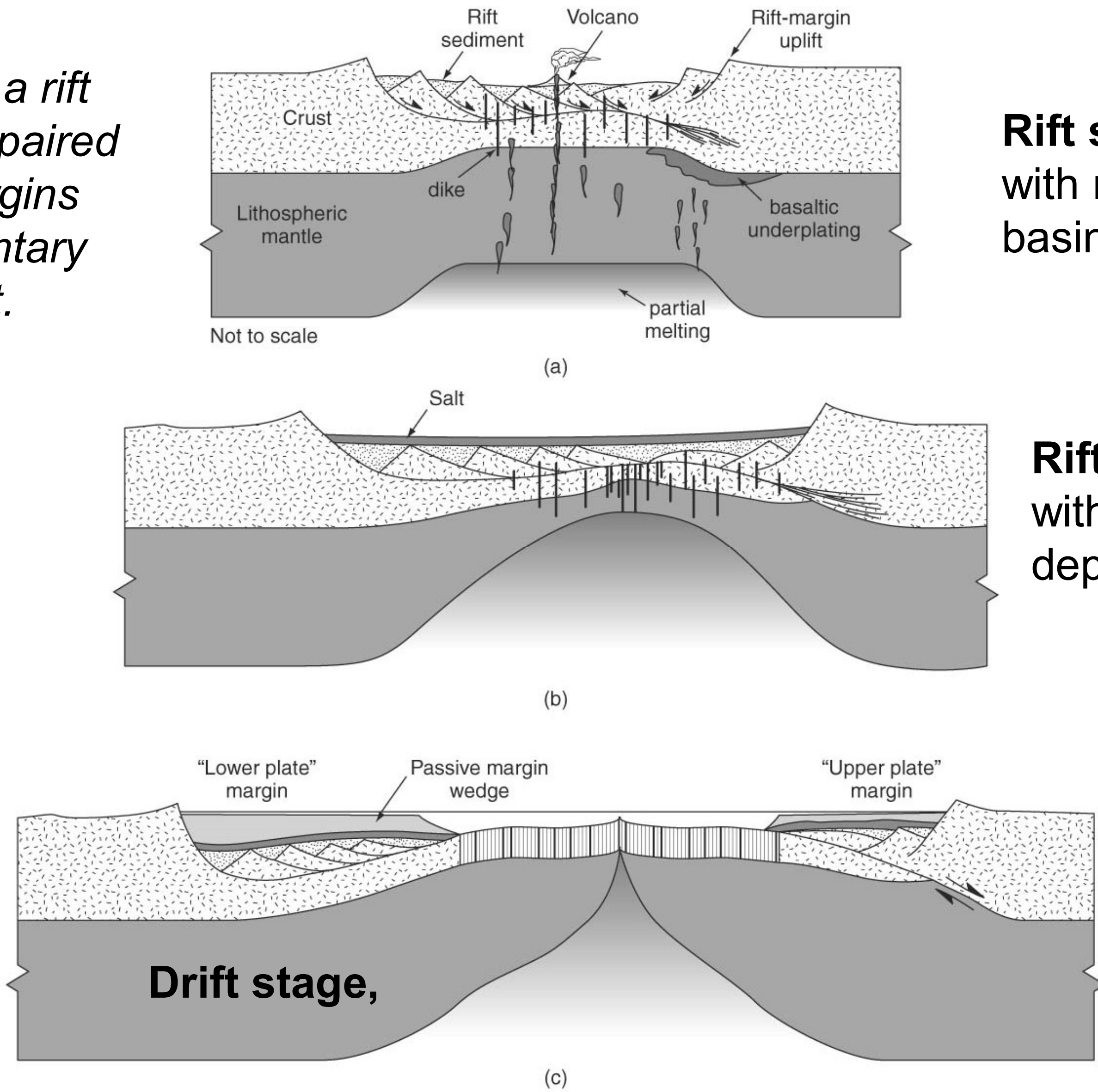
Rift-to-Drift Evolution Fig. 16.16



- A swarm of dikes begins to intrude along the axis of the rift, and the rift–drift transition begins.
- A new midocean ridge initiates, and seafloor spreading begins.

Rift Evolution and Sedimentation Fig. 16.18

Evolution of a rift system into paired passive margins and sedimentary environment.



Rift stage with non-marine basins

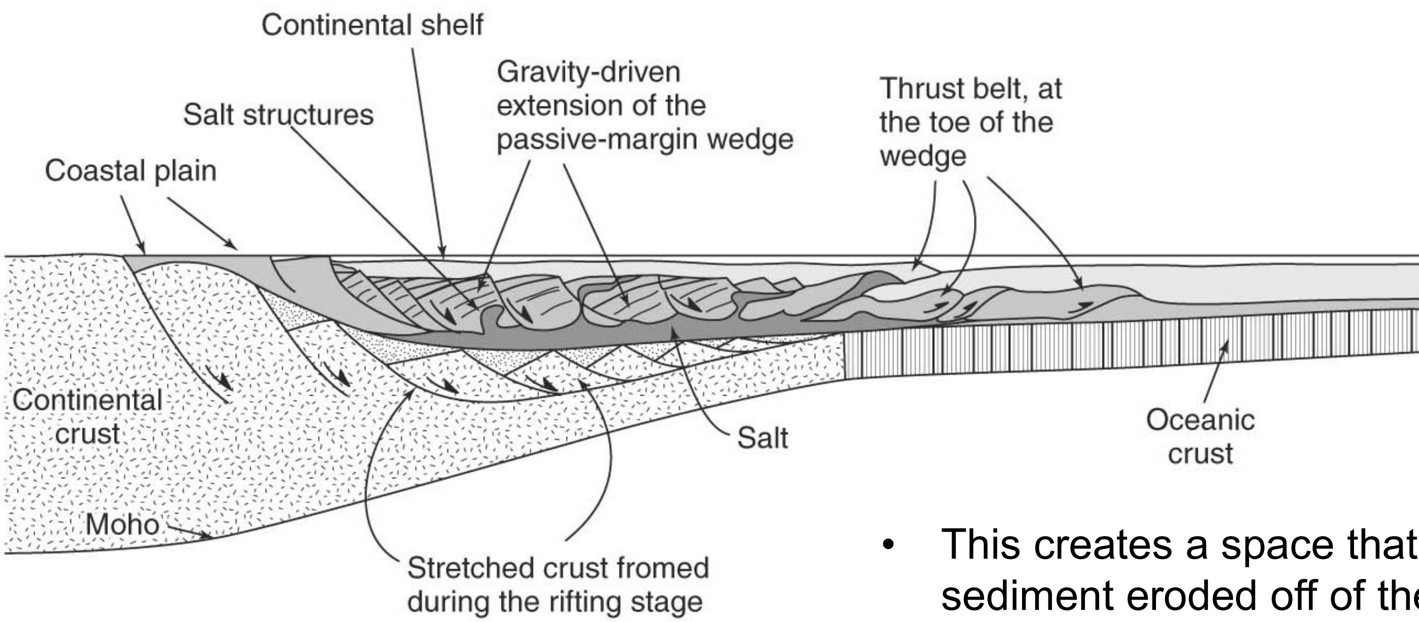
Rift–drift transition with evaporite deposition;

Drift stage,

Sustained sea-floor spreading results in passive-margin evolution

Passive Margins are not considered to be seismically active

- A drifting oceanic-crustal segement loses heat, and **thermally subsides, or sinks** to maintain isostatic equilibrium during cooling.

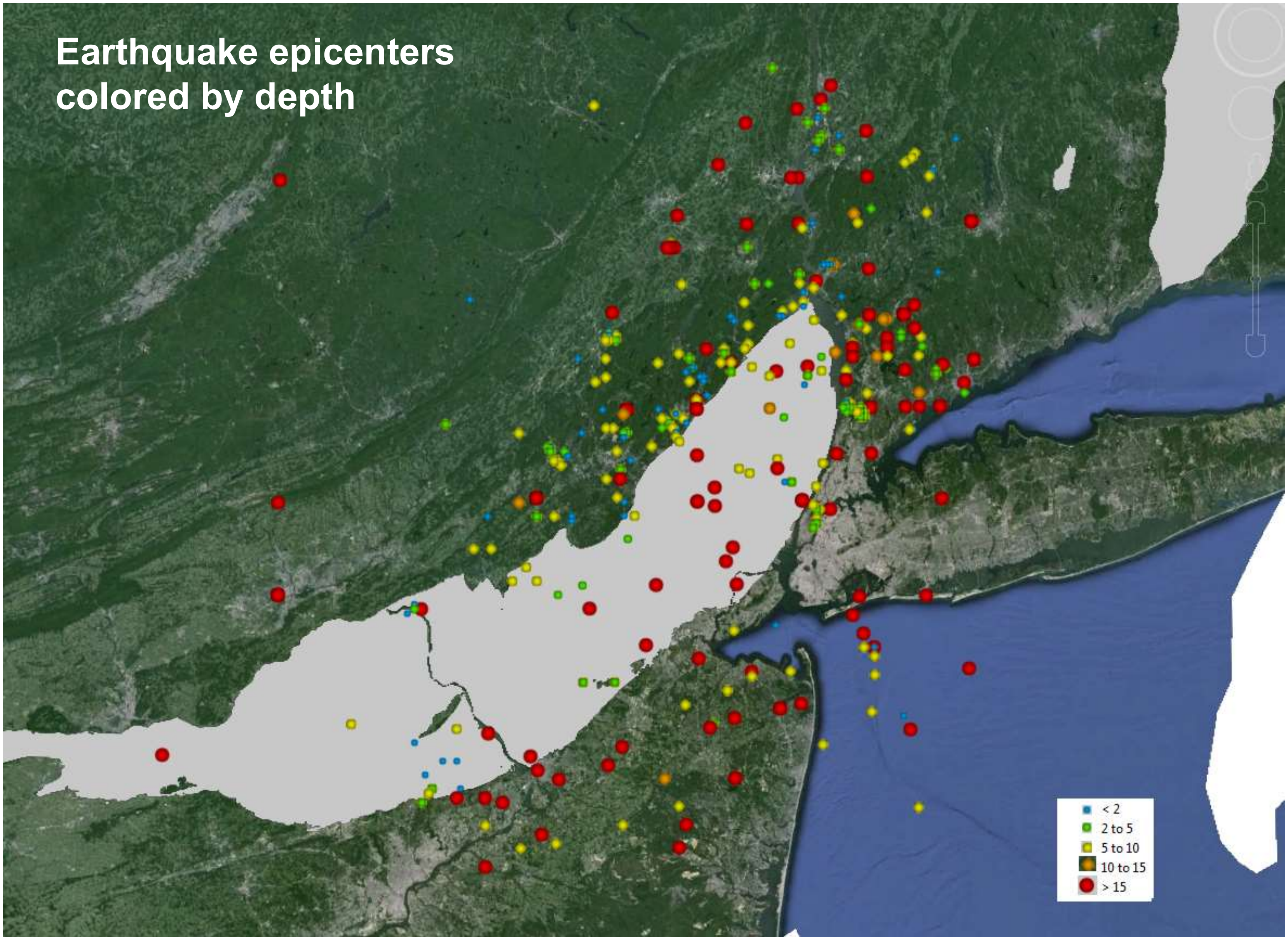


(a)

- This creates a space that fills with sediment eroded off of the adjacent continent and carried into the sea by rivers.

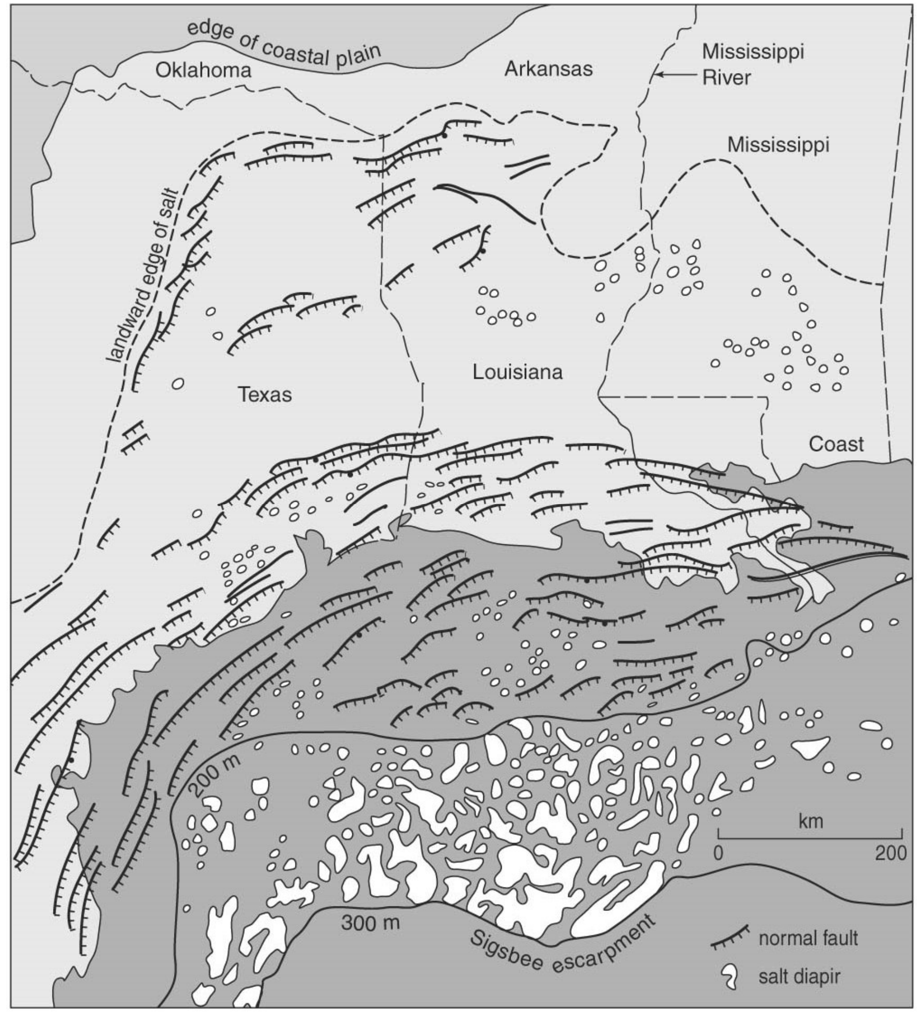
- This “space” is a **passive-margin basin,** and the sediment pile filling the basin is a **passive-margin sedimentary wedge.**

Passive Margins are 'not considered to be seismically active'



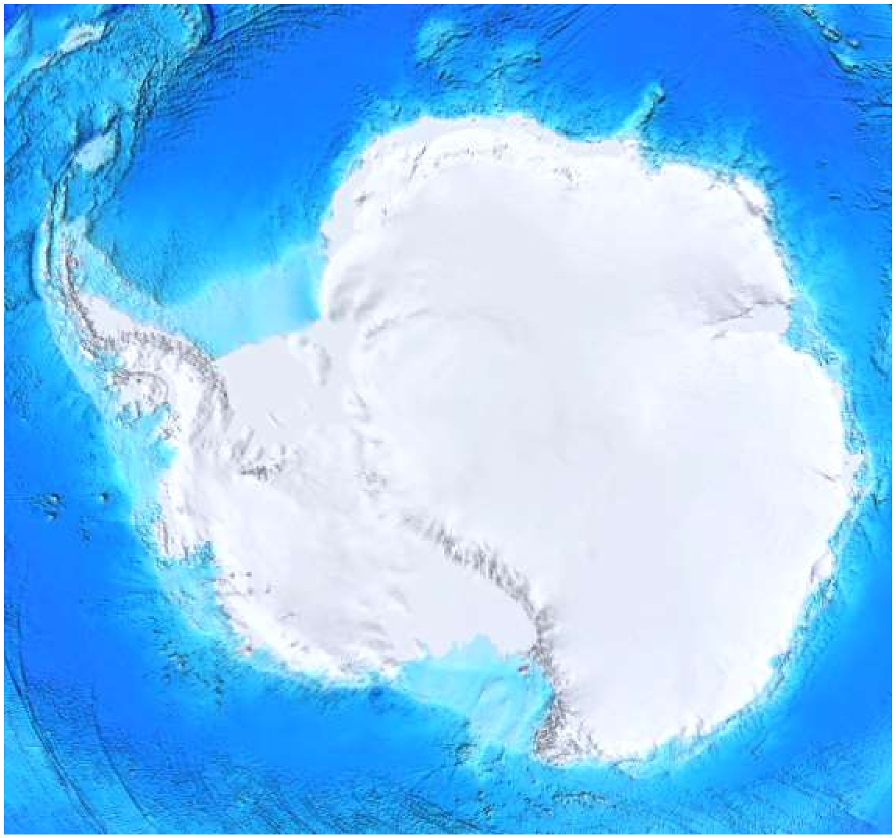
Simplified map of the Gulf Coast region Fig. 16.27

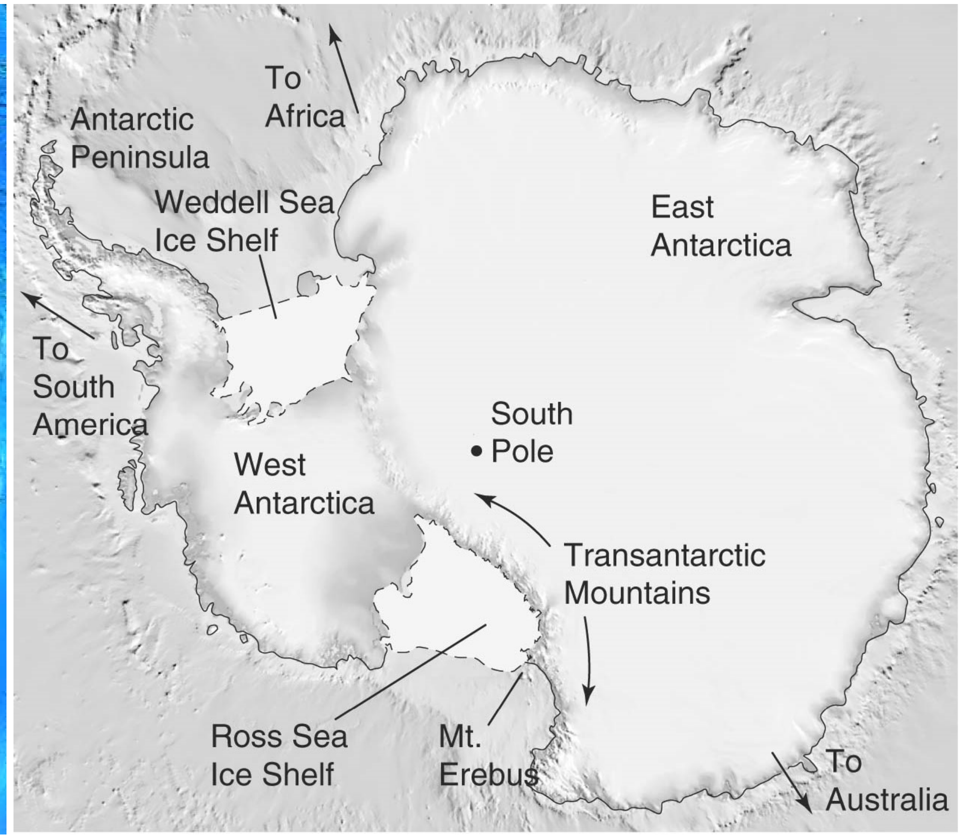
- Normal faults in the passive margin (Gulf of Mexico) with abundant salt diapirs.
- Part of the region lies within the Coastal Plain Province, a region submerged by the sea in the Cretaceous and early Tertiary.
- The edge of the salt (zero isopach) is shown.
- Offshore, we show the 200-m and 300-m bathymetric contours.
- Thrusts at the toe of the passive-margin wedge emerge at the Sigsbee Escarpment.



Shaded relief and topographic map of Antarctica Fig. 16.22

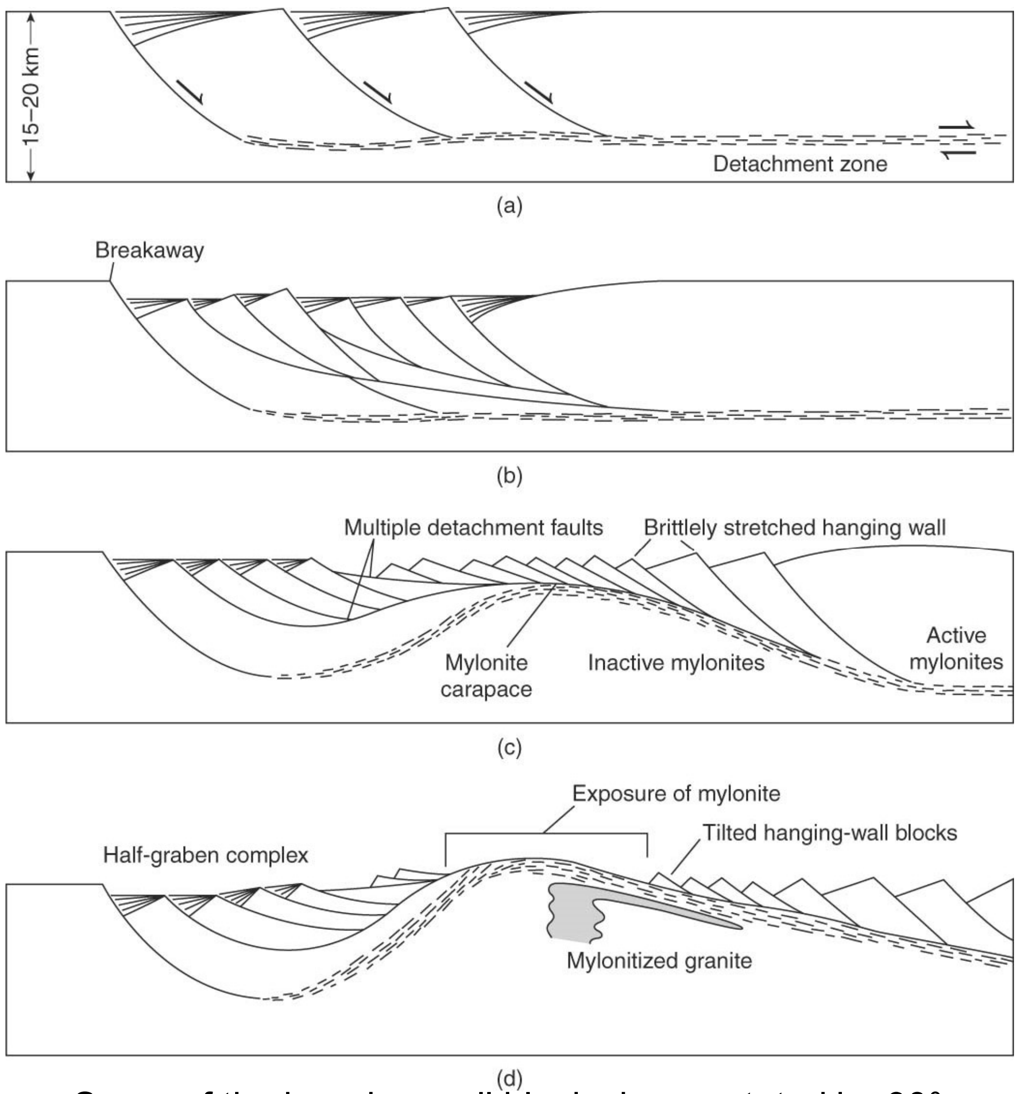
showing passive margins and the Transantarctic Mountains along the edge of the East Antarctic craton.





The Ross Sea and Wedell Sea were formed by Mesozoic rifting.

Evolution of Metamorphic Core Complexes Fig. 16.13



Some of the hanging-wall blocks have rotated by 90°.

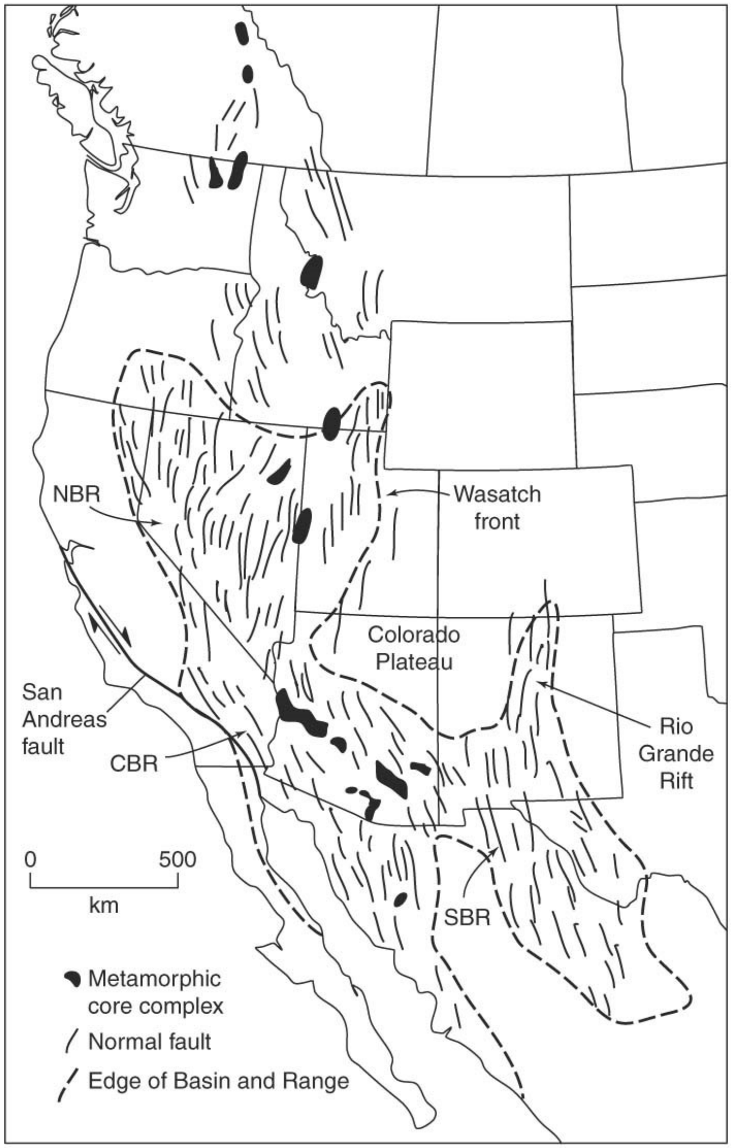
An initially subhorizontal, midcrustal ductile detachment zone is formed beneath an array of steeply dipping normal faults in the upper plate;

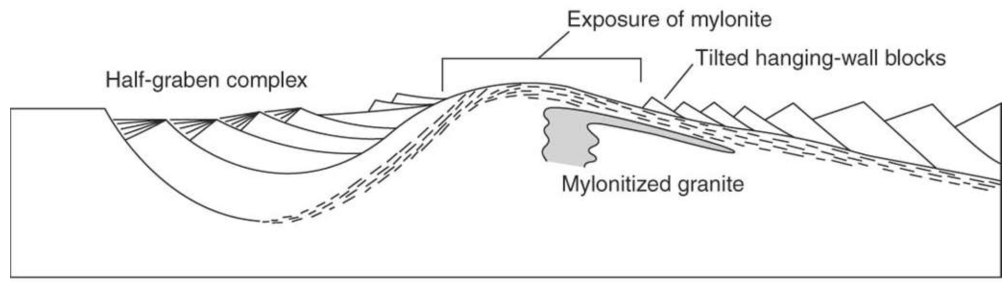
Additional normal faults have formed, increasing the geometric complexity;

As a result of unloading and isostatic compensation, the lower plate bows upward;

Extreme thinning of the hanging wall exposes the “metamorphic core” (an exposure of the mylonitic shear zone of the detachment).

Metamorphic Core Complexes and Detachments





(d)