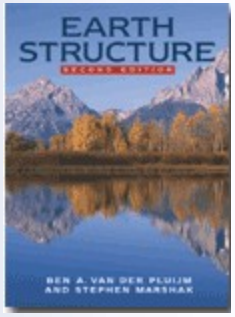
Lecture 14

Lithosphere Imaging and Contraction Tectonics

Chapters 15 & 17



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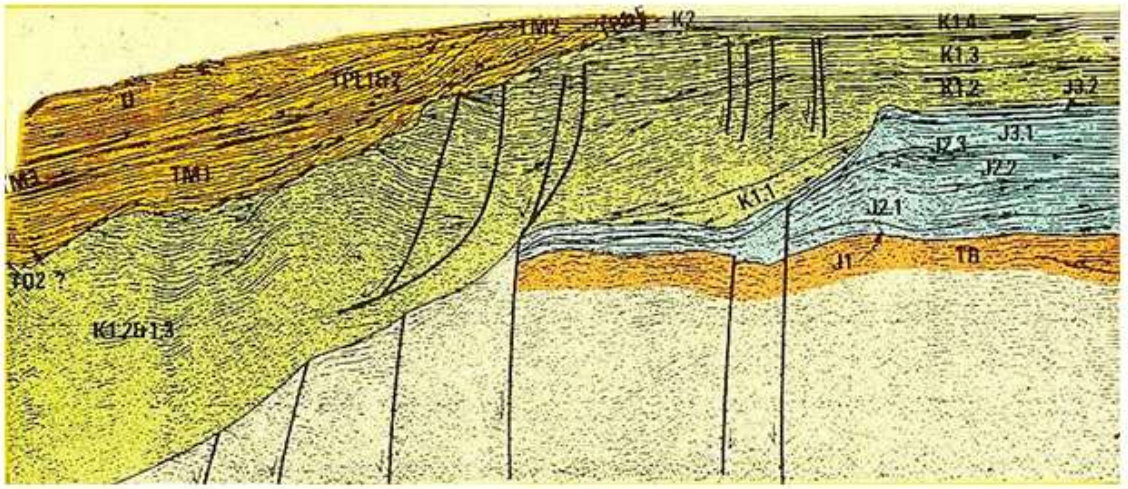
The Seismic Reflection Method

Courtesy of ExxonMobil



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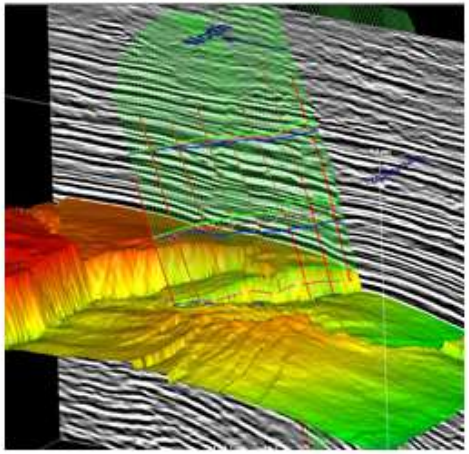
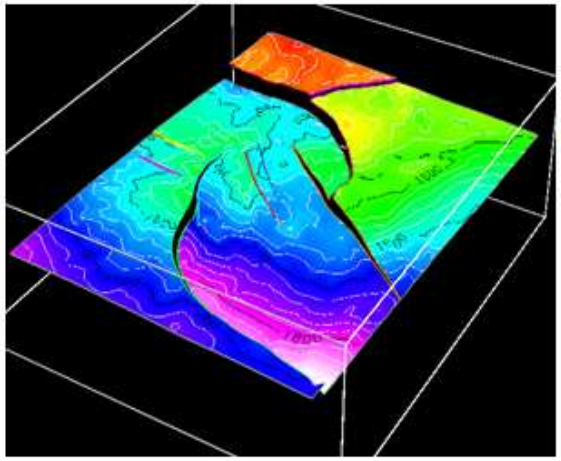
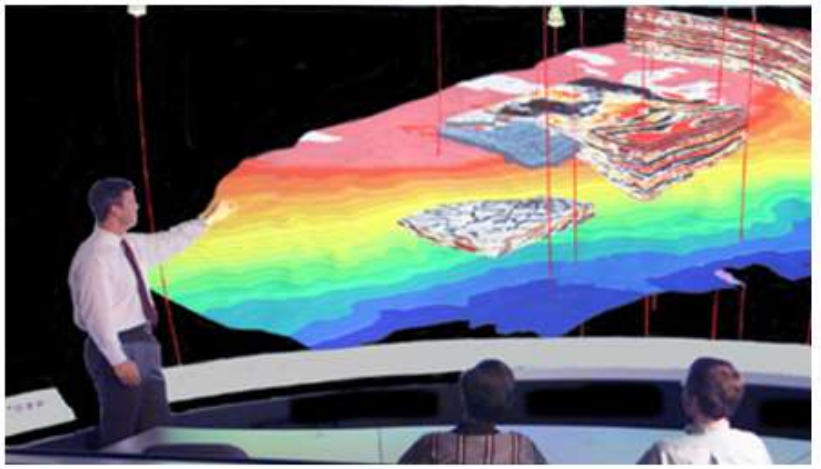
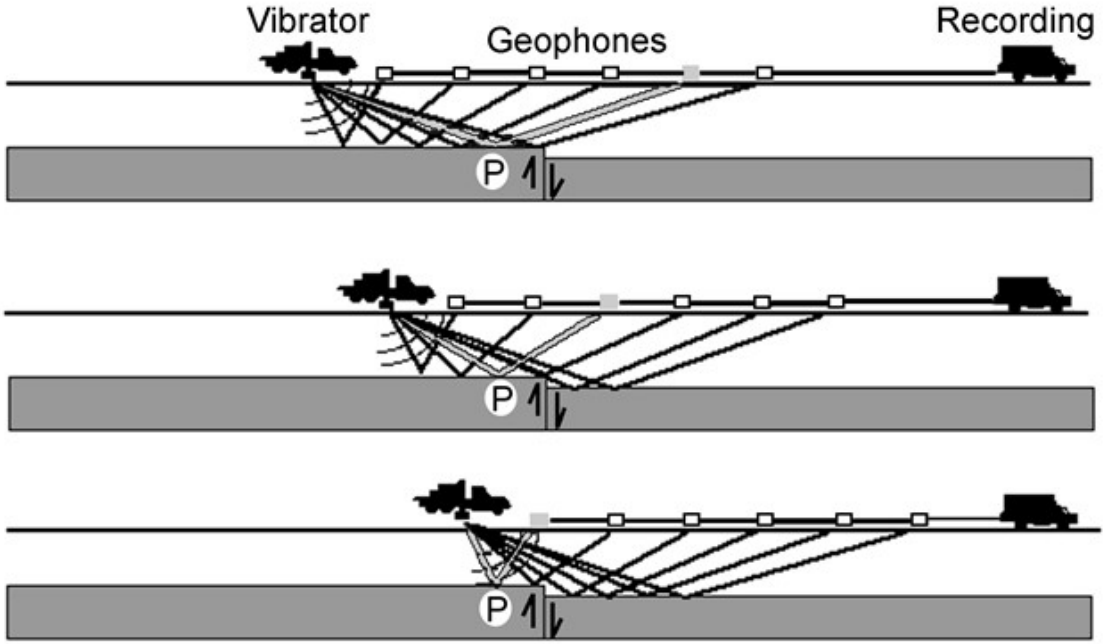
Mitchum et al., 1977b





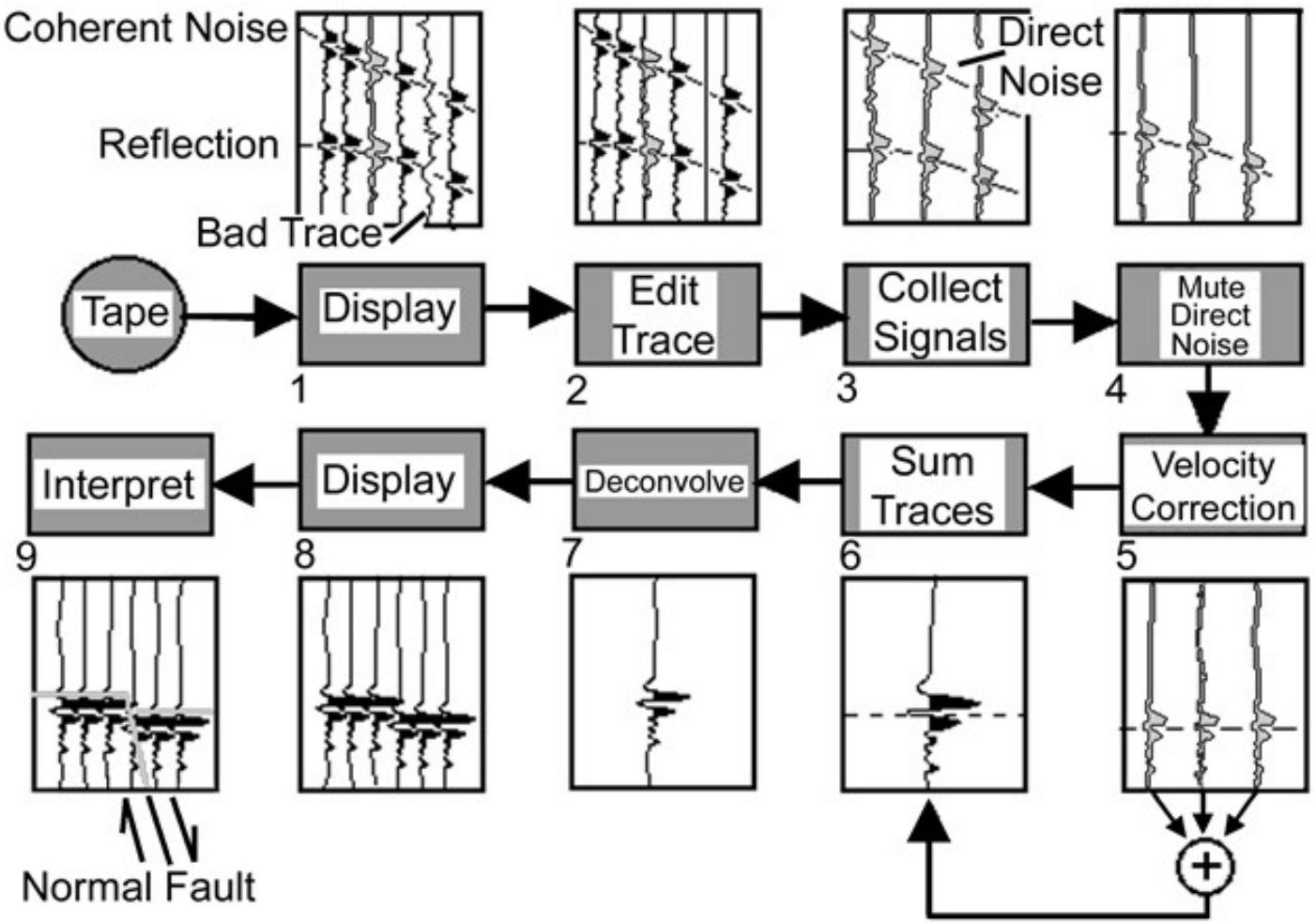


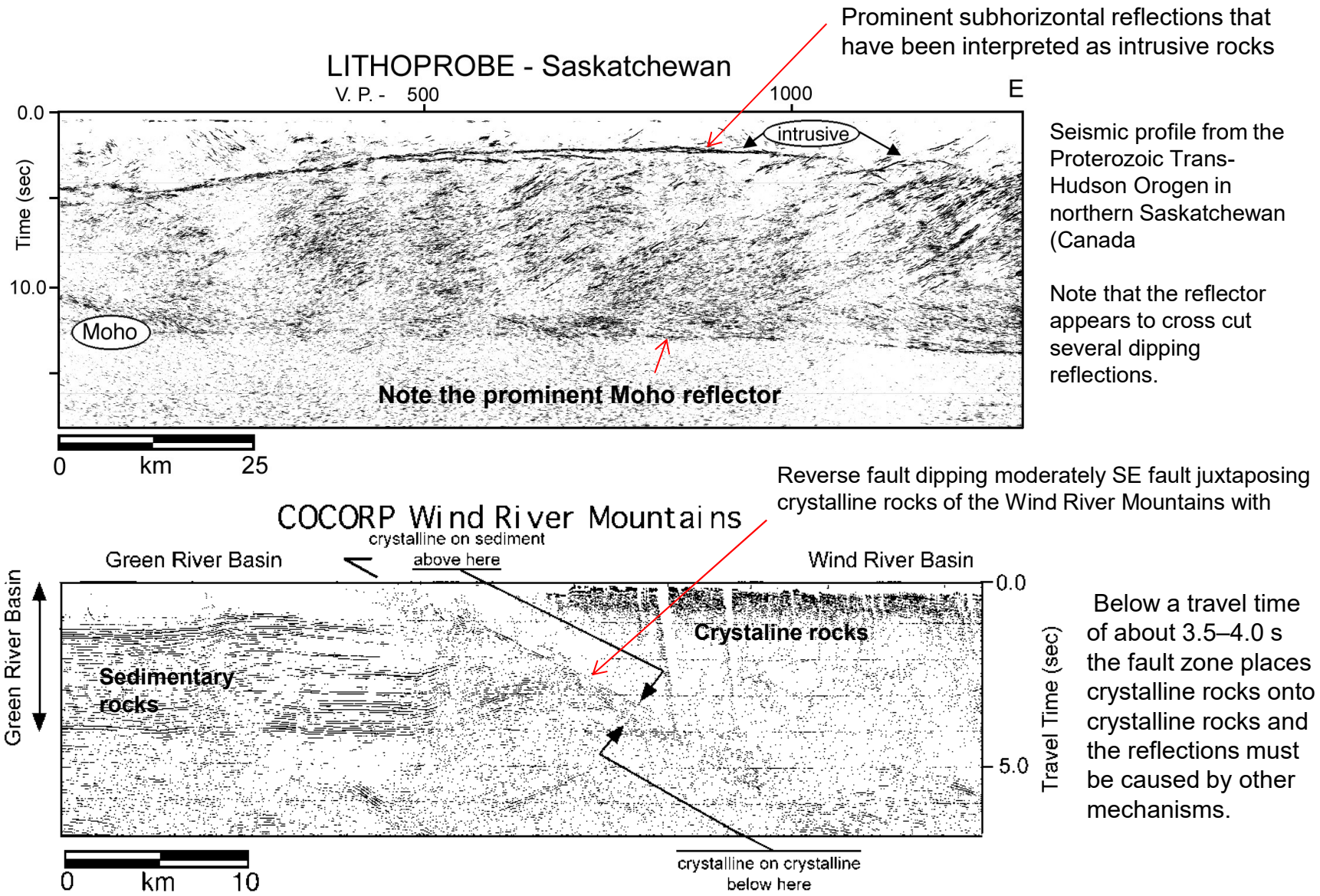
- Conversion to depth requires knowledge of the **seismic wave velocities** in the rocks.
- The more accurately the variations in wave velocity are known, the greater will be the accuracy of the image.
- Average velocities can be estimated for developing a cross section since seismic waves generally travel faster in crystalline rocks than in sedimentary rocks
- A good rule-of-thumb estimate for average seismic velocities in crystalline rocks of the crust is about 6.0 km/s; hence the depth in kilometers may be estimated by multiplying one-half of the transit time by a factor of 6.0
- A transit time of 5.0 s corresponds to a depth of about 15.0 km.



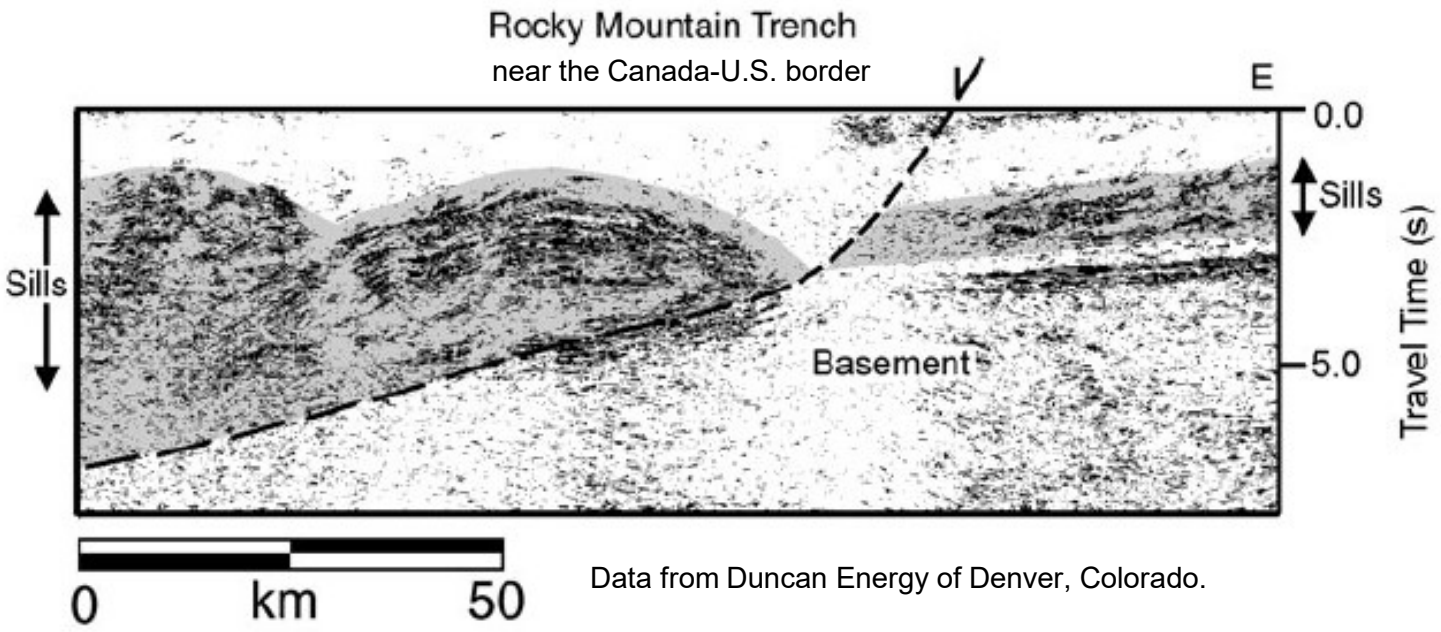
- Below the Moho, the seismic wave velocity increases to about 8.0 km/s.

The Seismic-Reflection Method





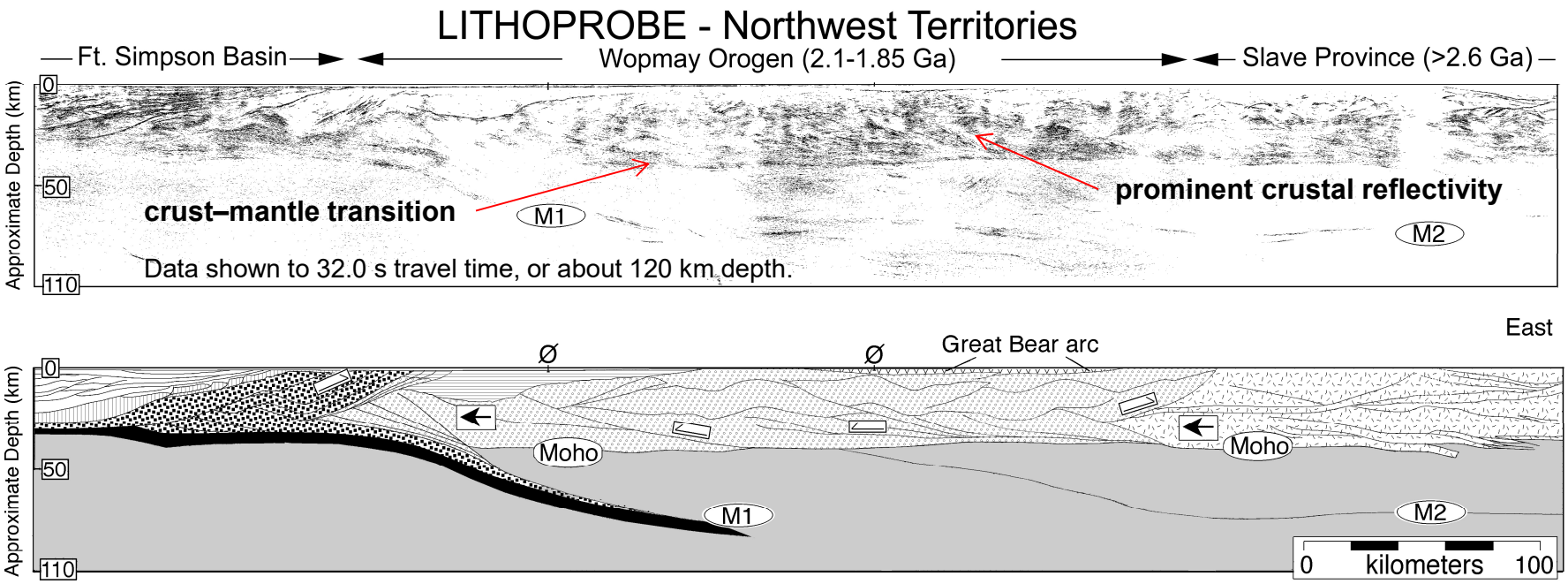
COCORP (Consortium for Continental Reflection Profiling) 1977 data



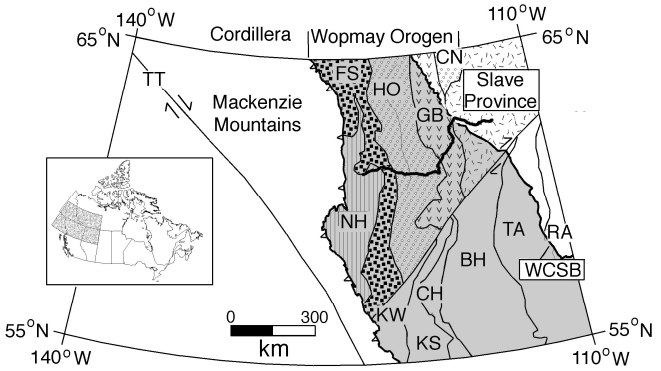
Data from Duncan Energy of Denver, Colorado.

- Note that the prominent layering, which is drilled on the west and is known to be dominantly Proterozoic sills, is offset along a west-dipping listric normal fault that has about 10 km of dip-slip displacement.

Regional seismic profile from ancient rocks of the Slave Province (>2.6 Ga) on the east, across the Proterozoic Wopmay Orogen (2.1–1.85 Ga) in the center, and then the younger Proterozoic (~ 1.74–0.55 Ga) Fort Simpson Basin on the west.



- A general interpretation illustrate how the accretion of the Proterozoic rocks to the Slave Province probably resulted from subduction, the remnants of which are probably the dipping mantle reflections.



Seismic-reflection studies combining other geophysical methods

Example from the New York Recess

- Check-shot velocity survey
- Bouger gravity
- Aeromagnetics

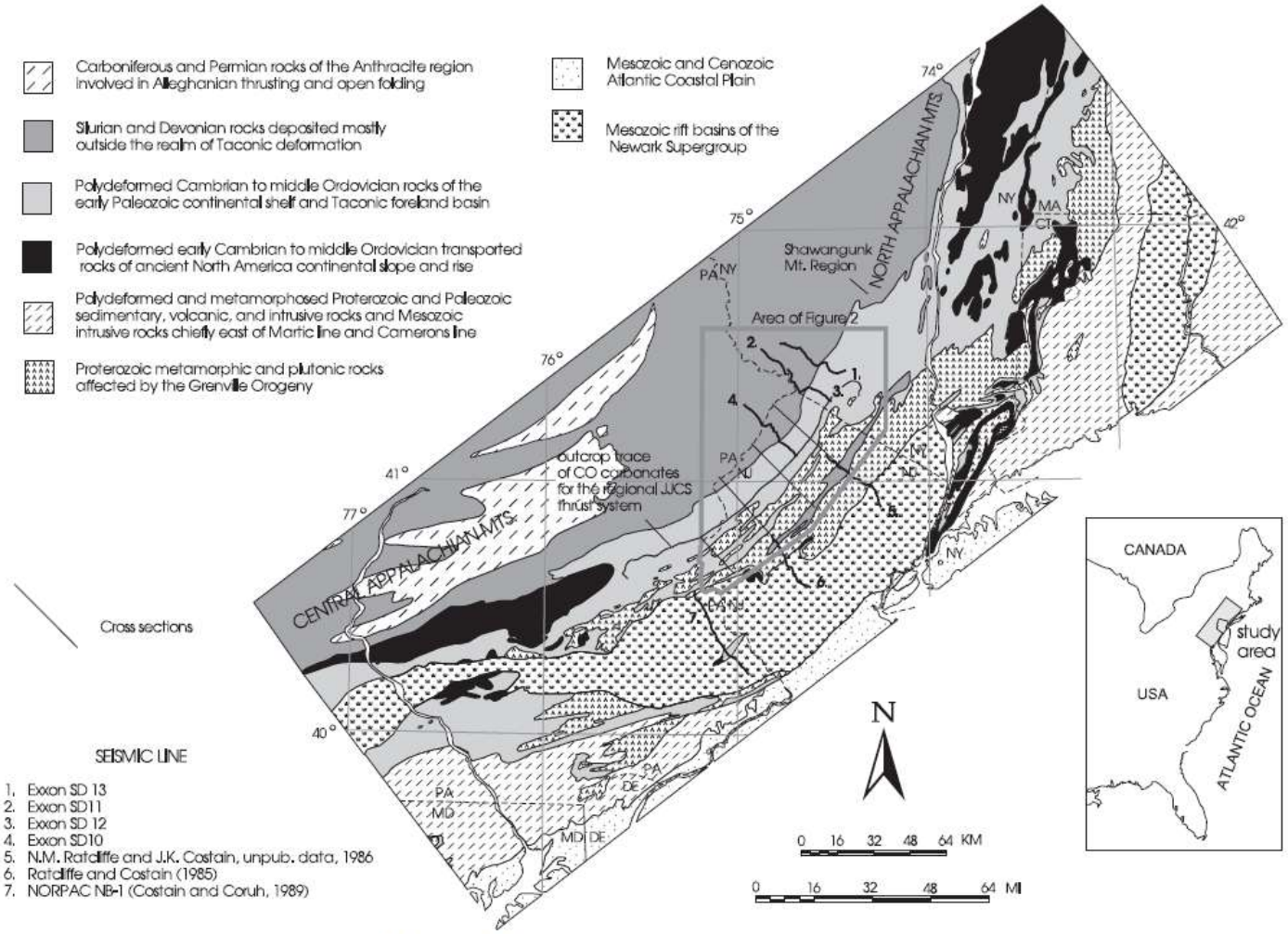
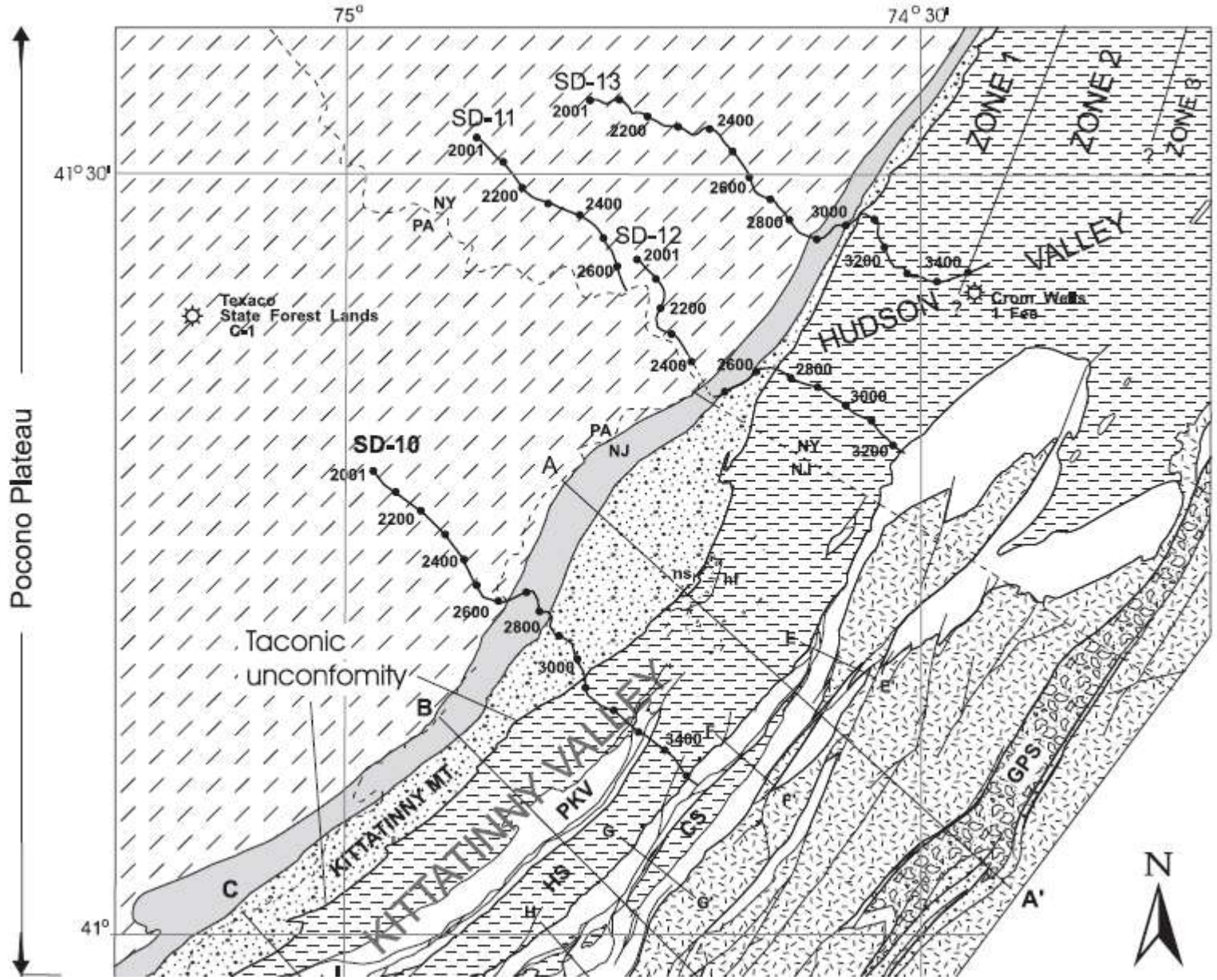


Figure 1. Generalized bedrock geology of the New York recess showing the locations of the study area, regional cross sections, and nearby seismic reflection data. Modified from Williams (1978). The distribution of Cambrian–Ordovician (CO) rocks at the Jenny Jump–Crooked Swamp (JJCS) thrust belt serves to approximate the fault length when calculating a length-displacement scaling ratio.

Foreland crustal structure of the New York recess, northeastern United States *GSA Bulletin*; August 1997; v. 109; no. 8; p. 955–977; 18 figures; 2 tables.


75°
74° 30'
41° 30'
41°
Pocono Plateau
SD-13
SD-11
SD-12
SD-10
2001
2200
2400
2600
2800
3000
3200
3400
NY
PA
NJ
Texaco
State Forest Lands
C-1
Crom Wells
1 Fee
ZONE 1
ZONE 2
ZONE 3
HUDSON VALLEY
KITTATINNY VALLEY
KITTATINNY MT.
PKV
HS
CS
GPS
Taconic
unconfomity
A
A'
B
C
N

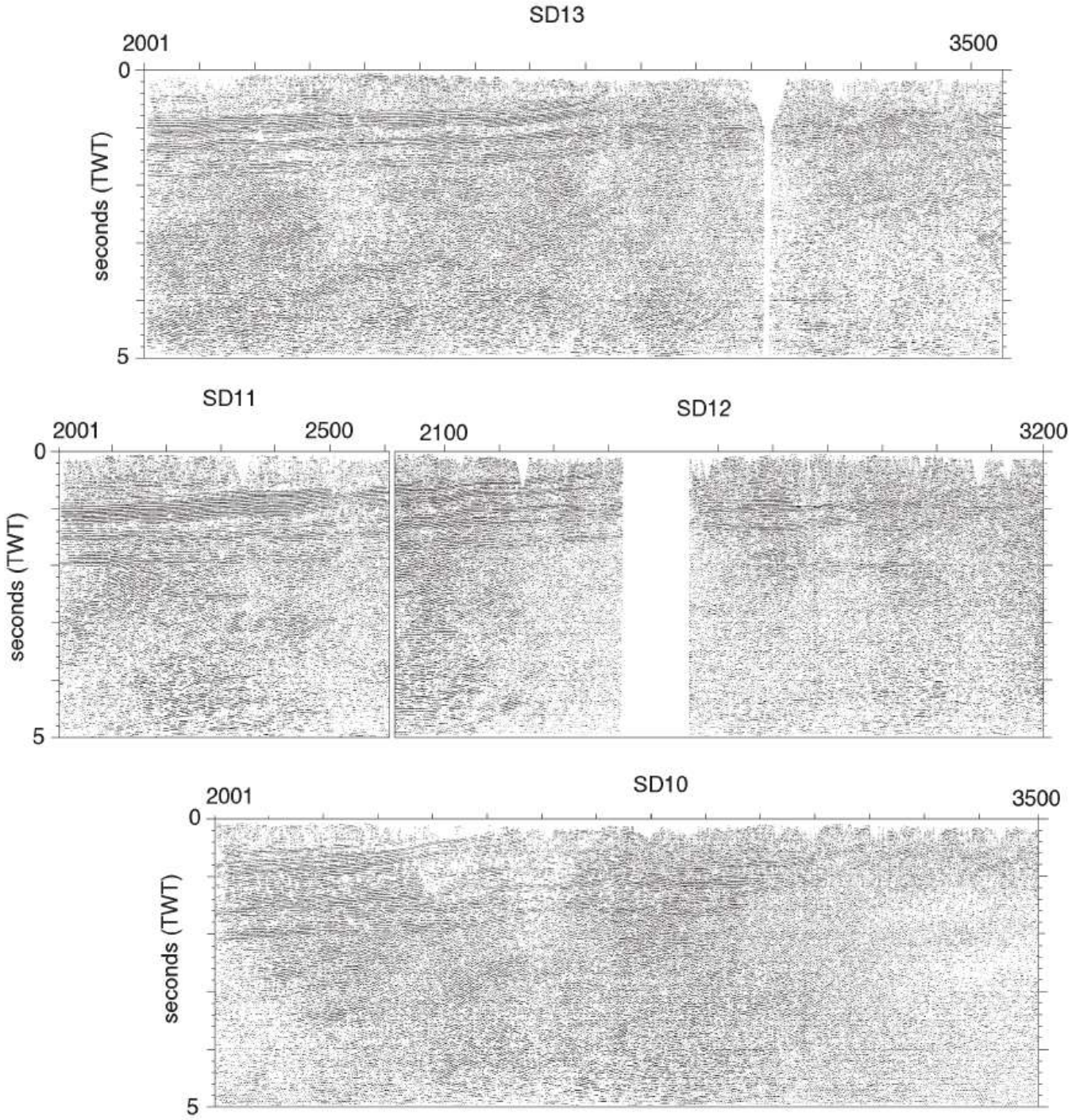


Figure 5. Exxon seismic-reflection profiles SD-10, SD-11, SD-12, and SD-13. Profiles show maximum 64 fold common depth point migrated data on the central foreland of the New York recess in New Jersey, Pennsylvania, and New York. The shot point locations are shown in Figure 2. TWT—two-way traveltime.

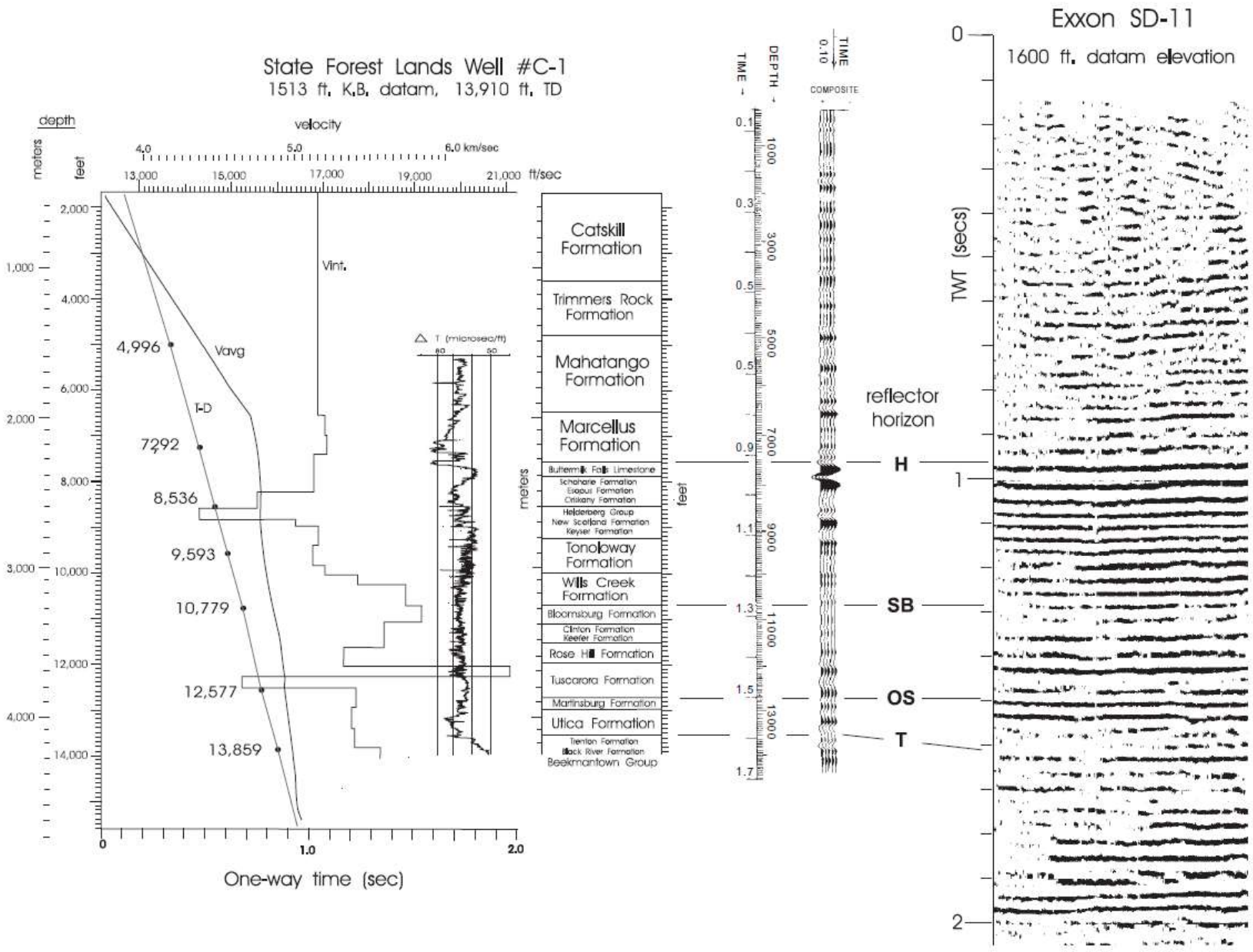
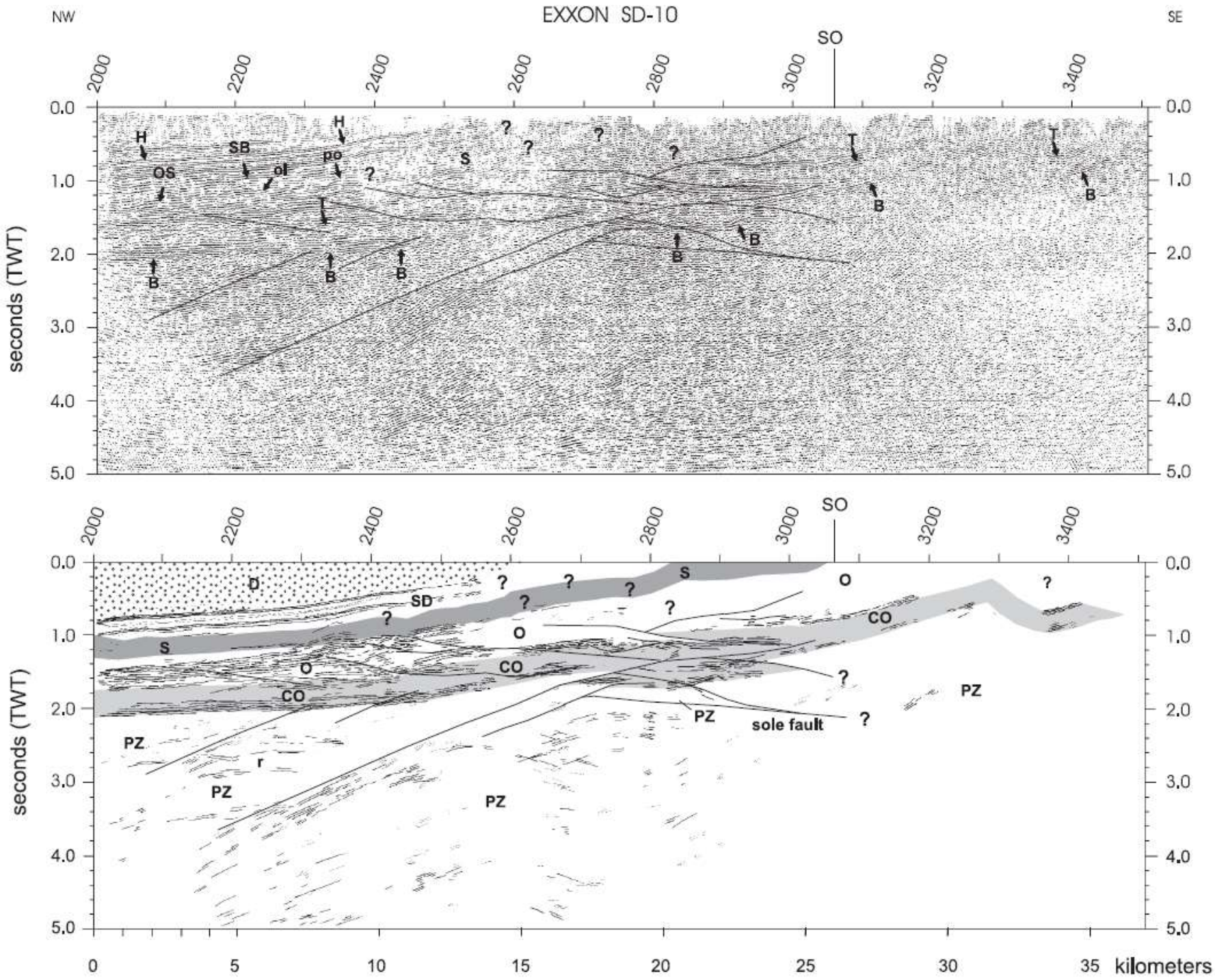


Figure 6. Borehole data for the Texaco well C-1 showing a stratigraphic correlation to the northwest end of Exxon profile SD-11. The bore-hole compensated sonic log and conventional velocity analysis are by Texaco. The synthetic seismogram was generated by Exxon. See text for further discussion.


EXXON SD-10
NW
SE
SO
2000
2200
2400
2600
2800
3000
3200
3400
0.0
1.0
2.0
3.0
4.0
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seconds (TWT)
H
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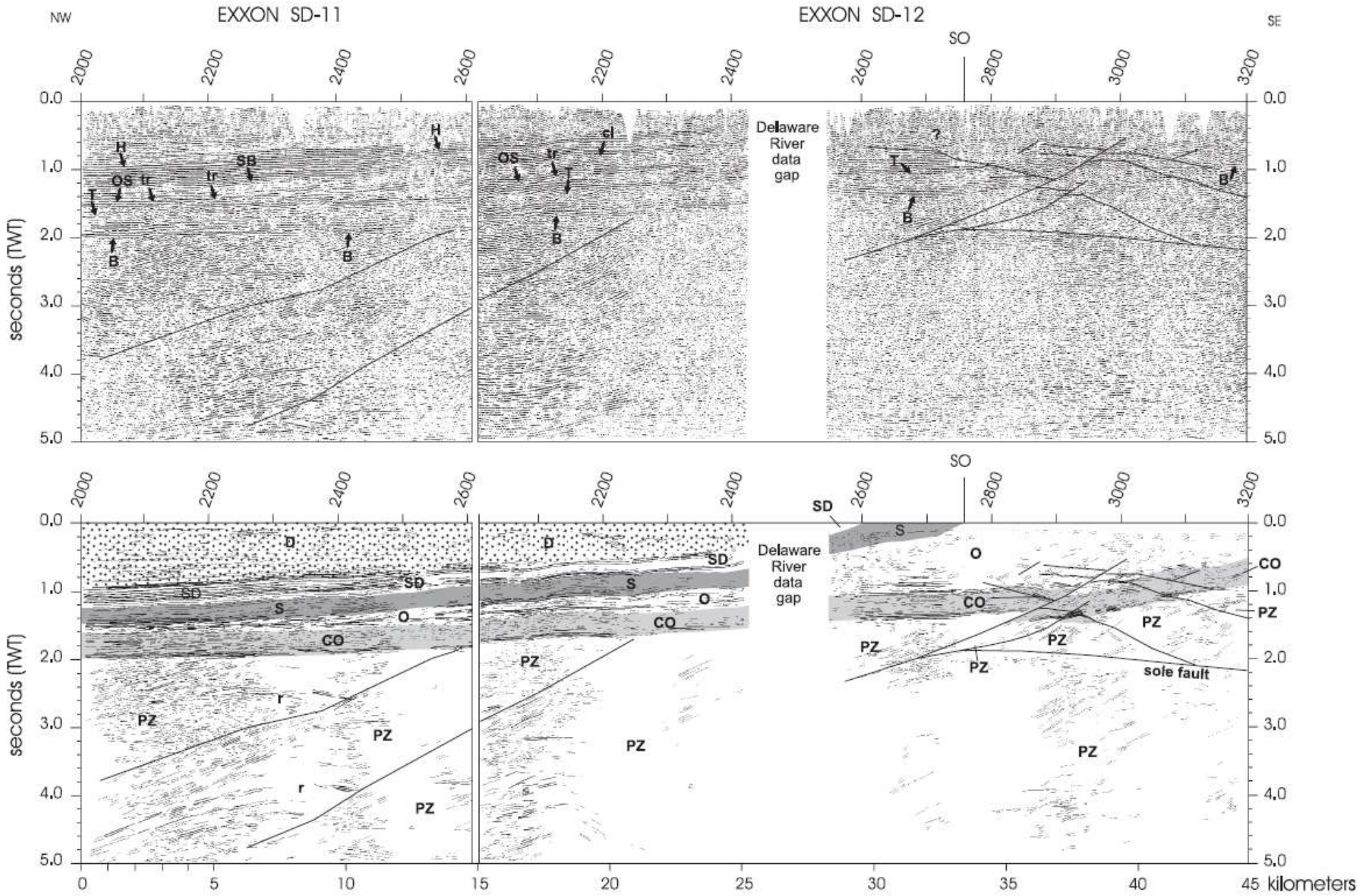
kilometers


NW
EXXON SD-11
EXXON SD-12
SE
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2000
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2400
2600
2800
3000
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1.0
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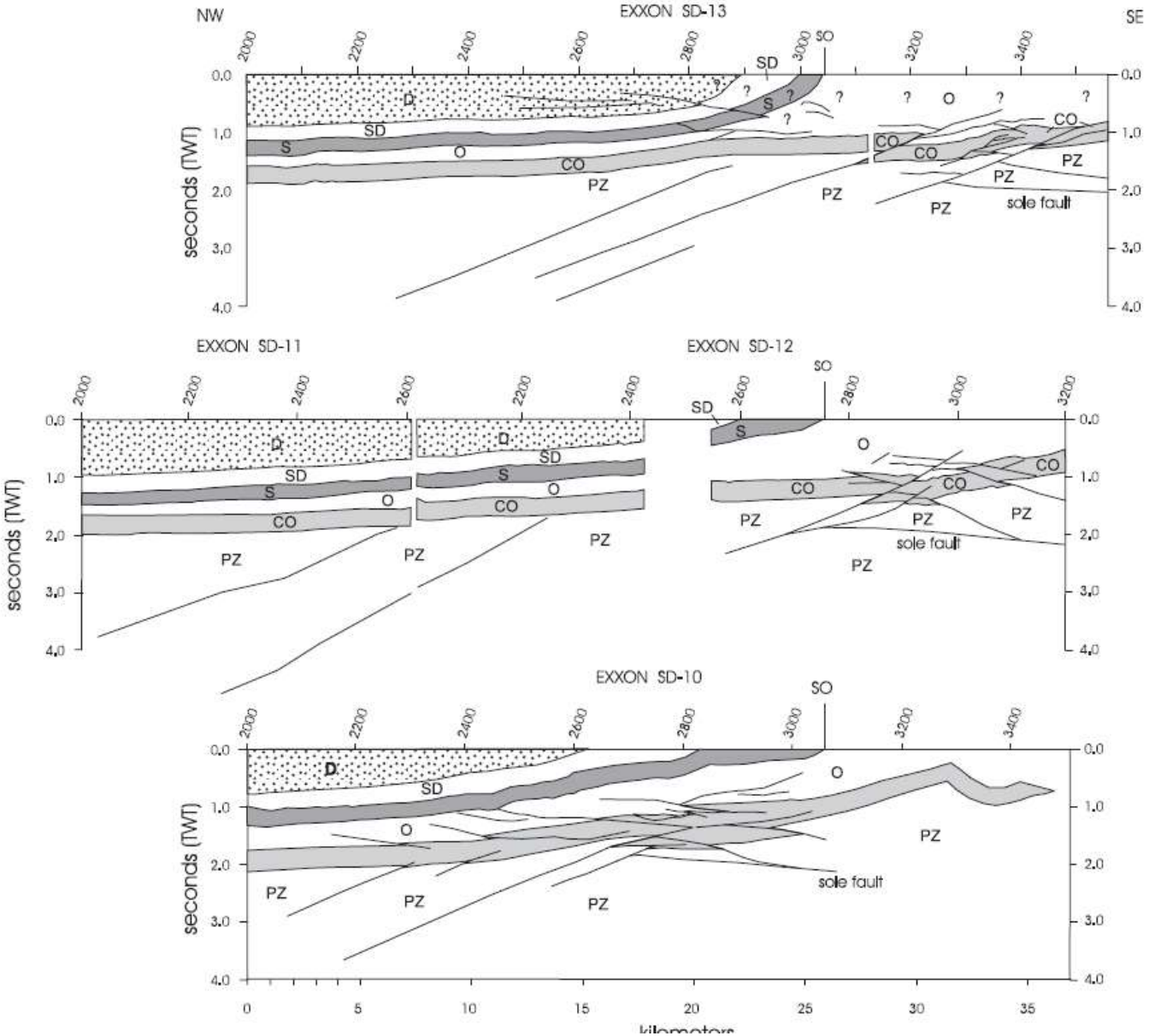
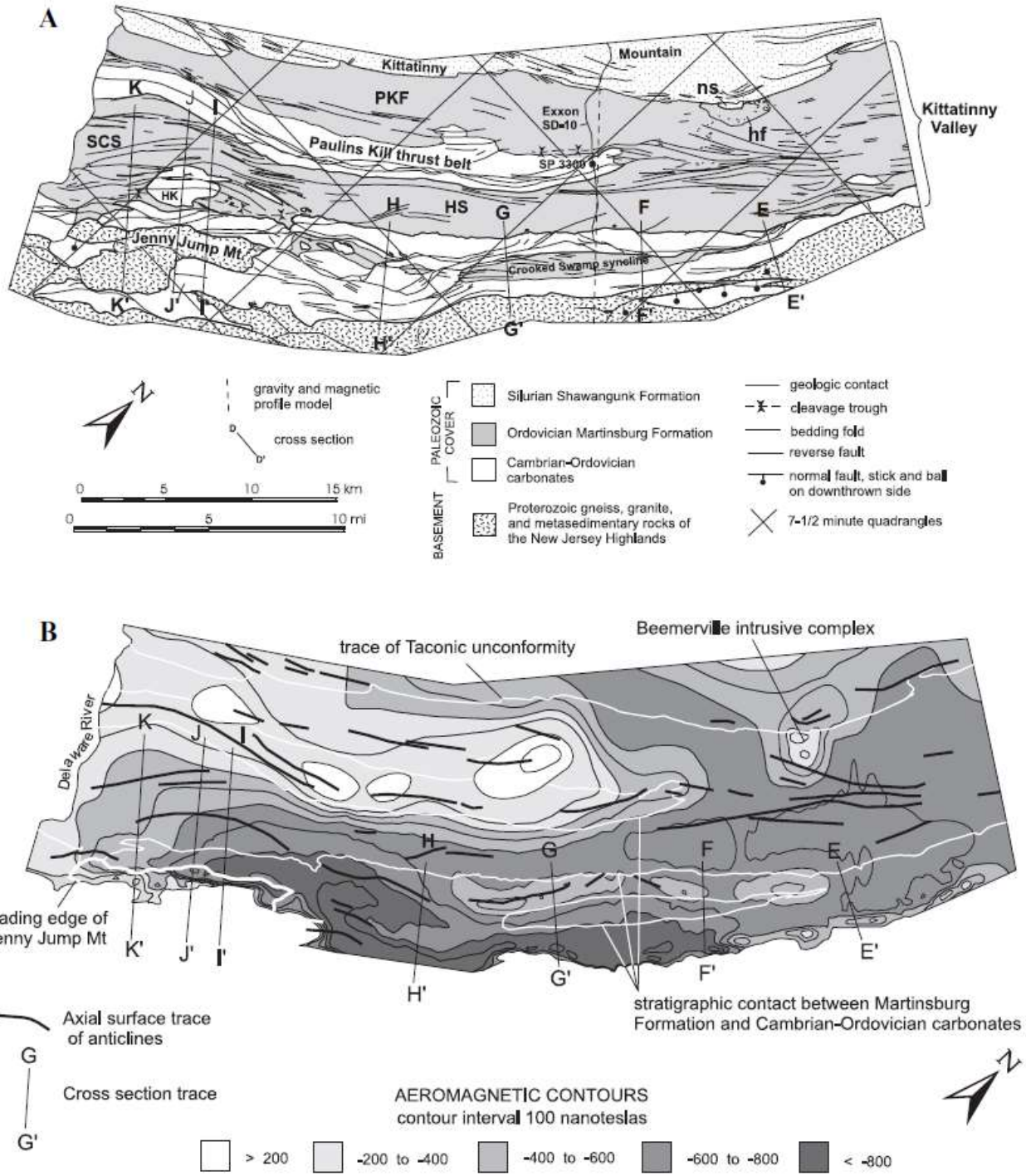


Figure 10. Geologic interpretations of the Exxon seismic-reflection profiles shown in serial arrangement. TWT—two-way traveltime. Profiles are aligned to the map trace of the Taconic unconformity (SO). Abbreviations and symbols as in Figure 7.

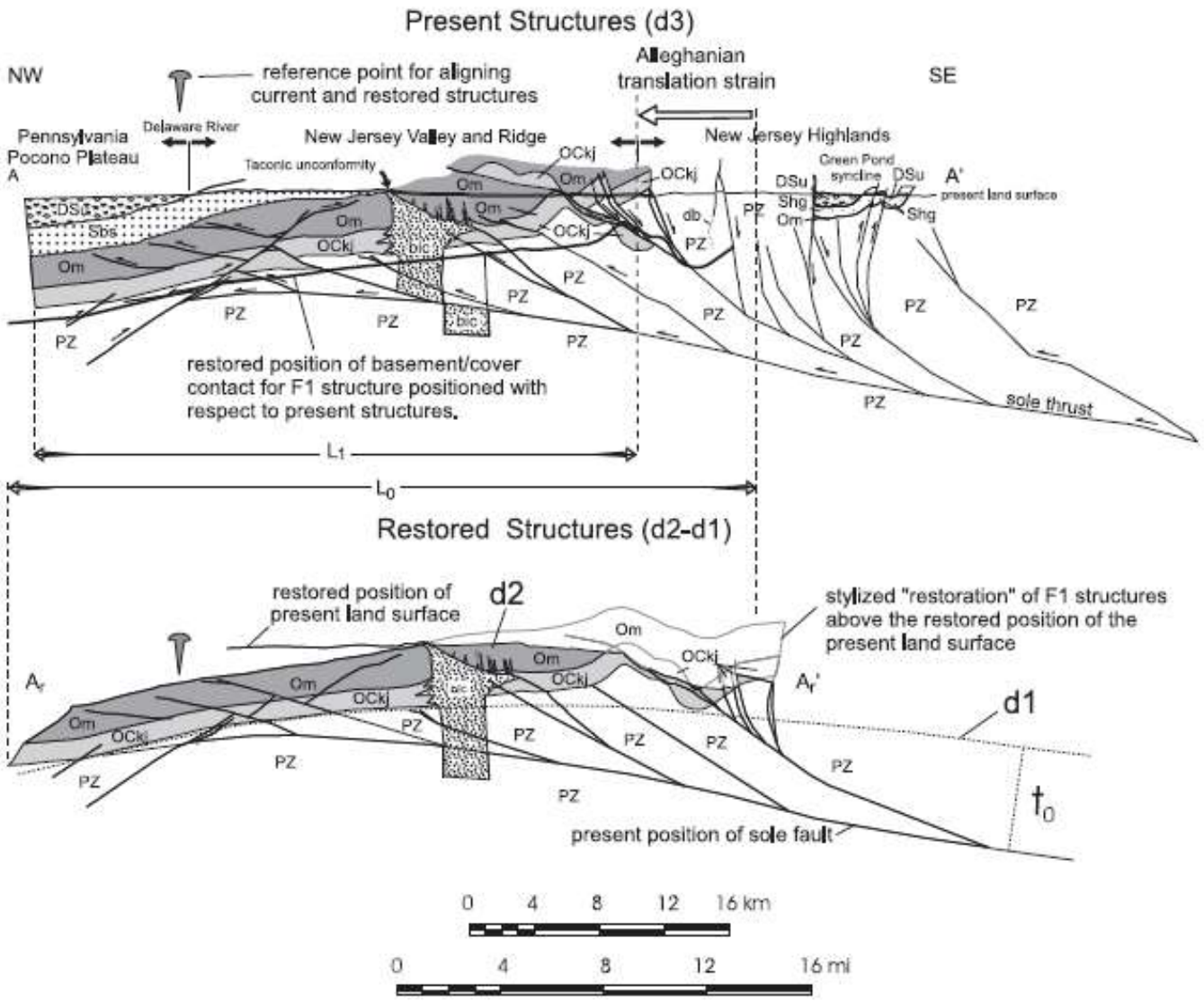


Tectonic map of the Kittatinny Valley, New Jersey.

PKF—Paulins Kill foreland, ns—nepheline syenite, hf—Martinsburg Formation hornfels, HK—Hope klippe, SCS—Stone Church syncline, HS—Halsey syncline.

Aeromagnetic map of the Kittatinny Valley, New Jersey.

Aeromagnetic data are modified from Snyder (1997).

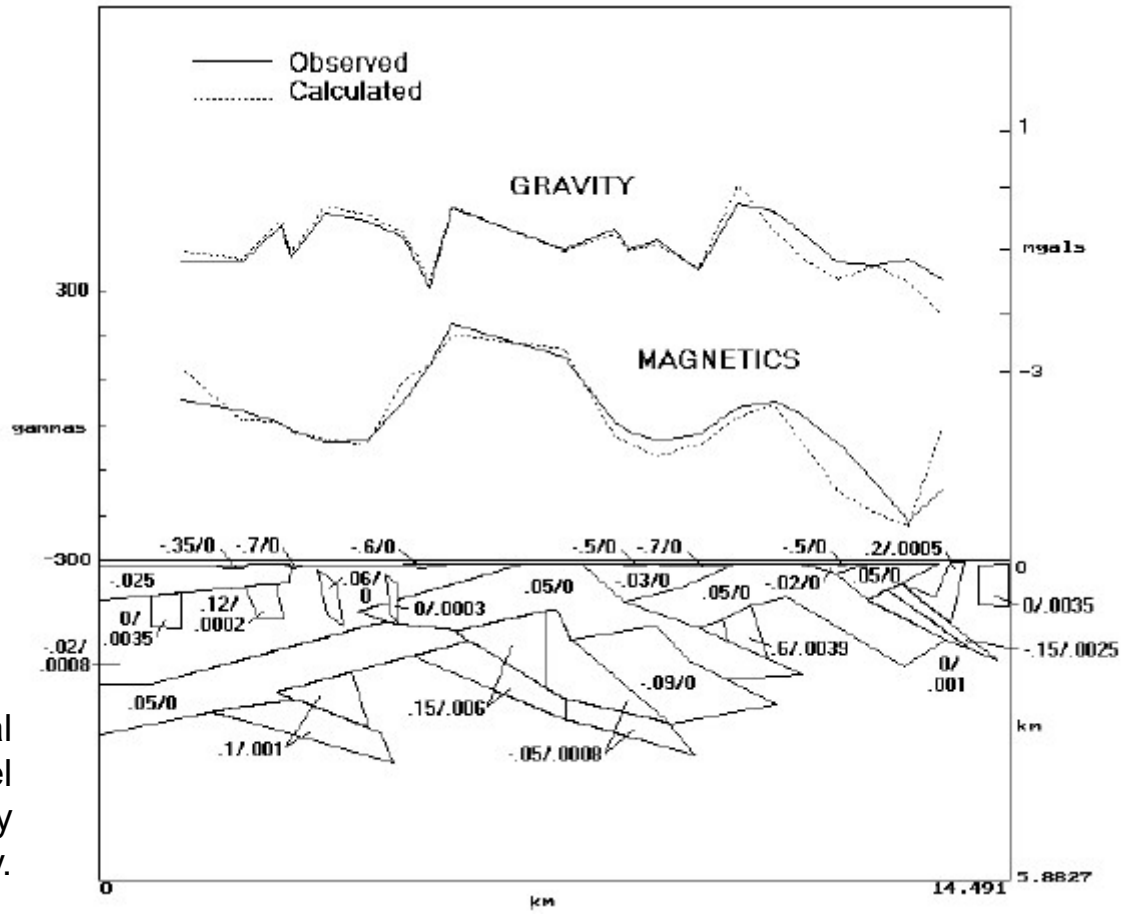


Retrodeformed cross sections structures (d2 and d1) in the foreland region of the New York recess.

The d2 structures reconstruct d3 (Alleghanian) thrust-fault trajectories and related F2 fold and S2 cleavage strains

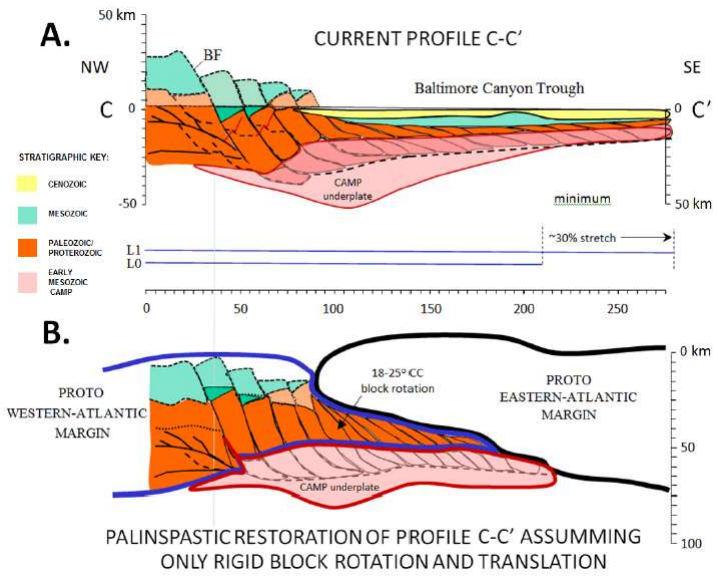
Gravity and magnetic anomalies result from variations in rock mass, from variations in the magnetic susceptibility of rocks (% Iron)

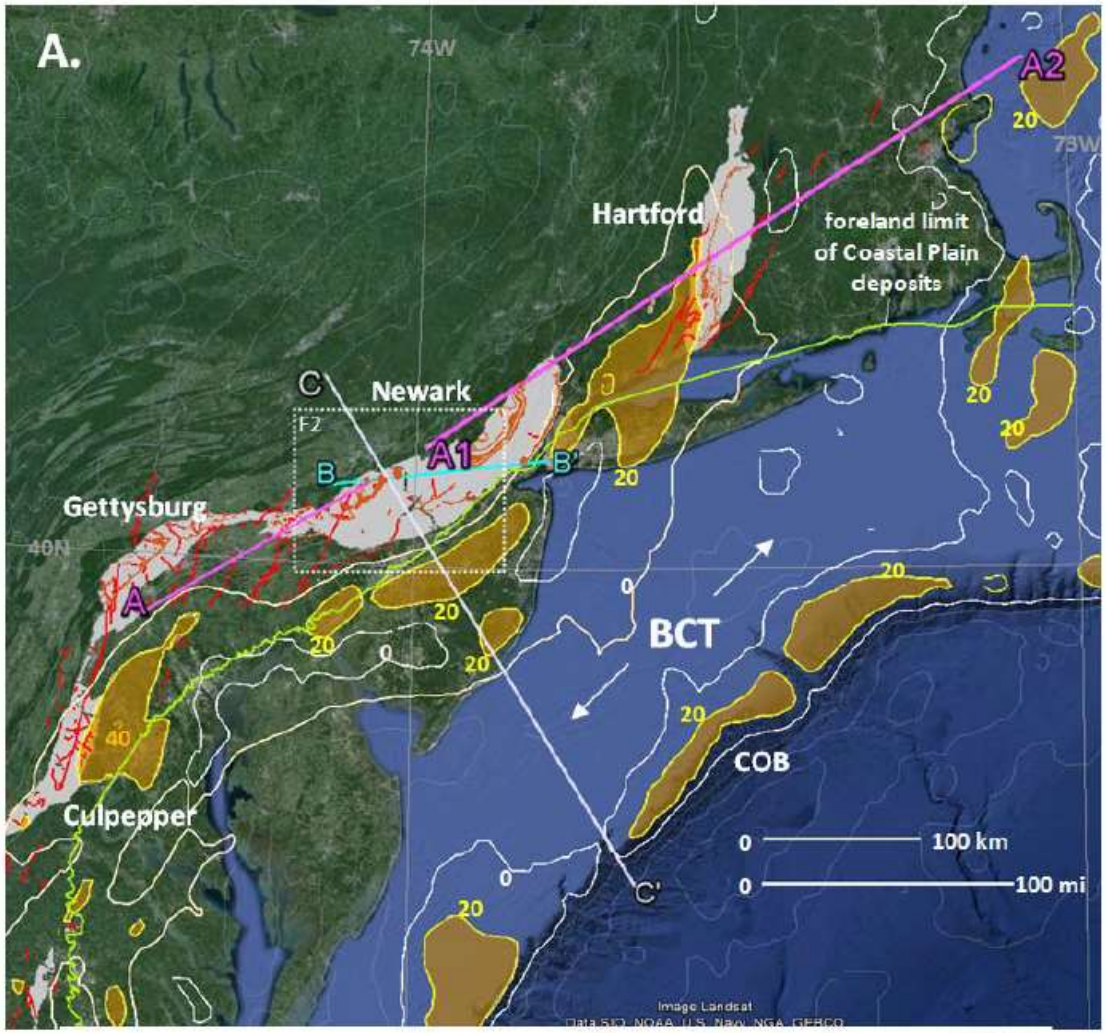
- After accounting for the shape of the Earth, surface elevations, and regional trends, residual values, or anomalies, are contoured on maps that represent variations in density and magnetism in crustal rocks near the surface.

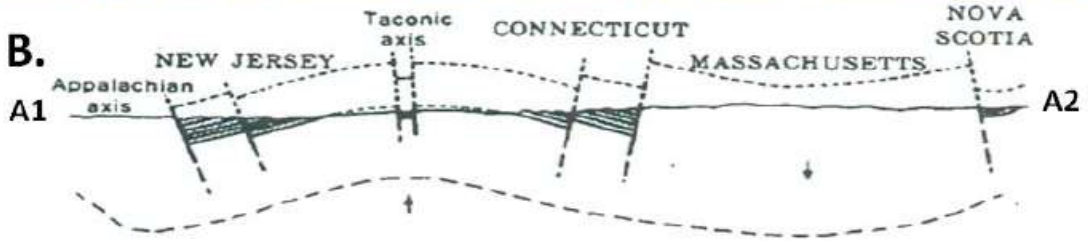


Bouguer gravity anomaly and total intensity magnetic anomaly model cross-section across the Kittatinny Valley, New Jersey.

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







Contraction Tectonics

Chapter 17

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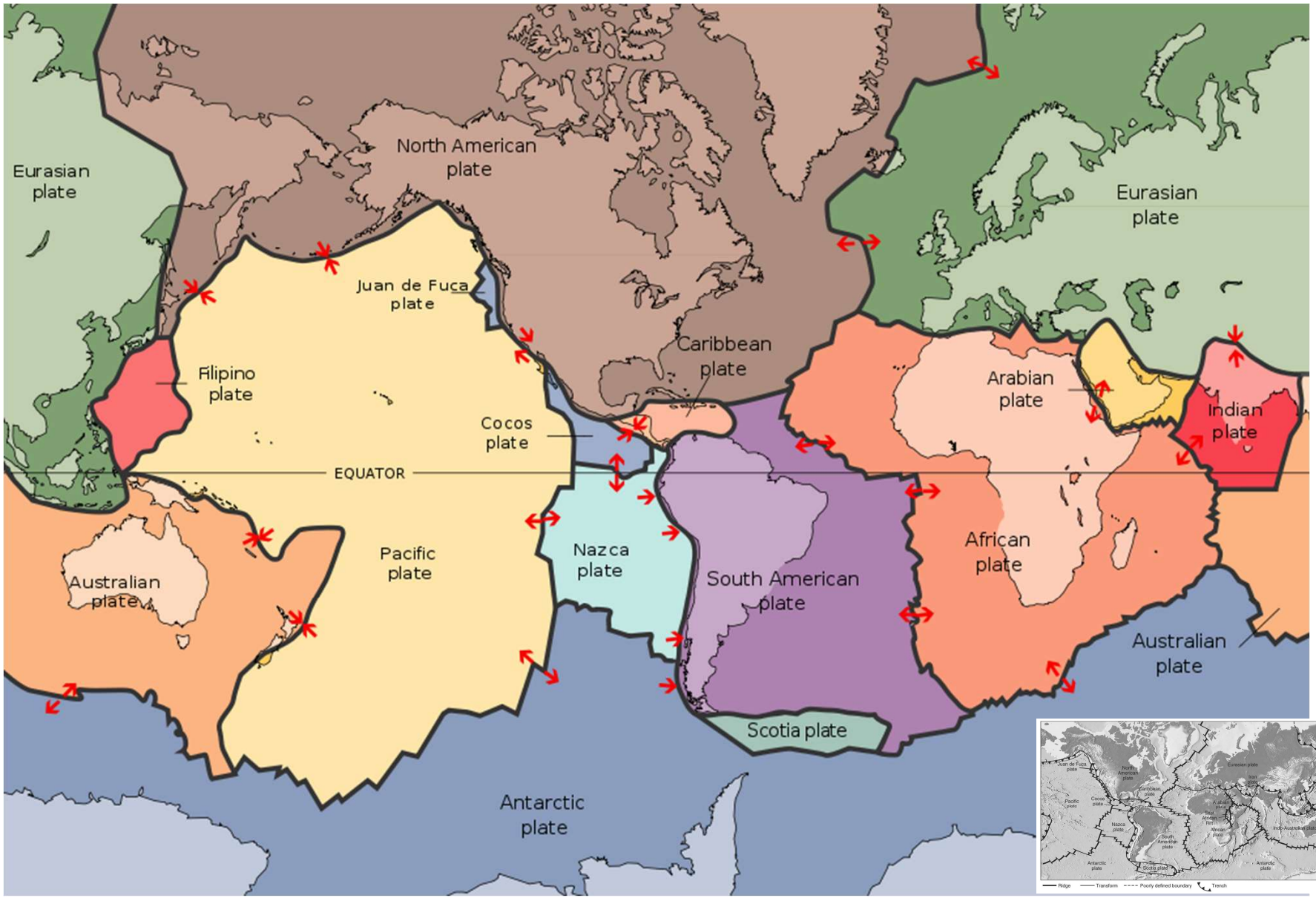
Today's Major (8) and Minor Plates



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Collision Belts

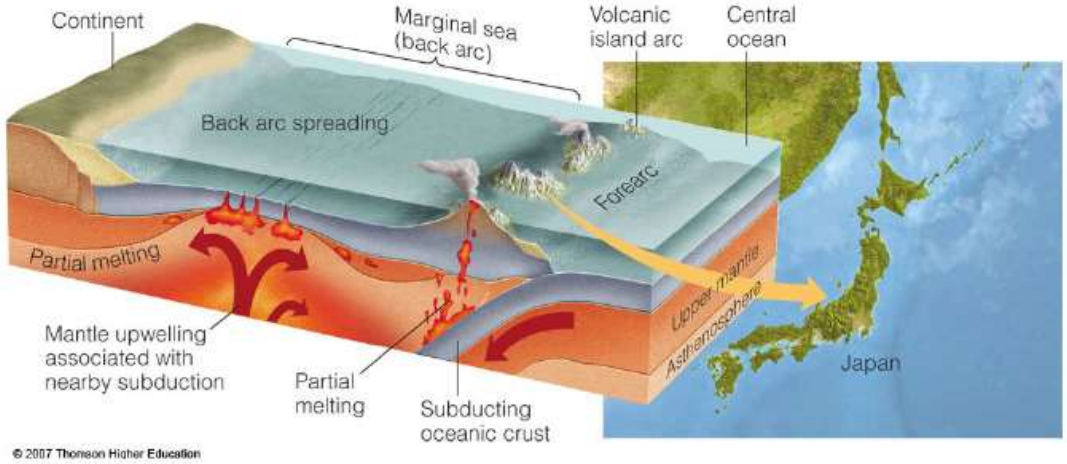
Southern Andes Mountains of Chile include old accretionary prisms and granitic intrusions of a continental volcanic arc.

Collision Belts

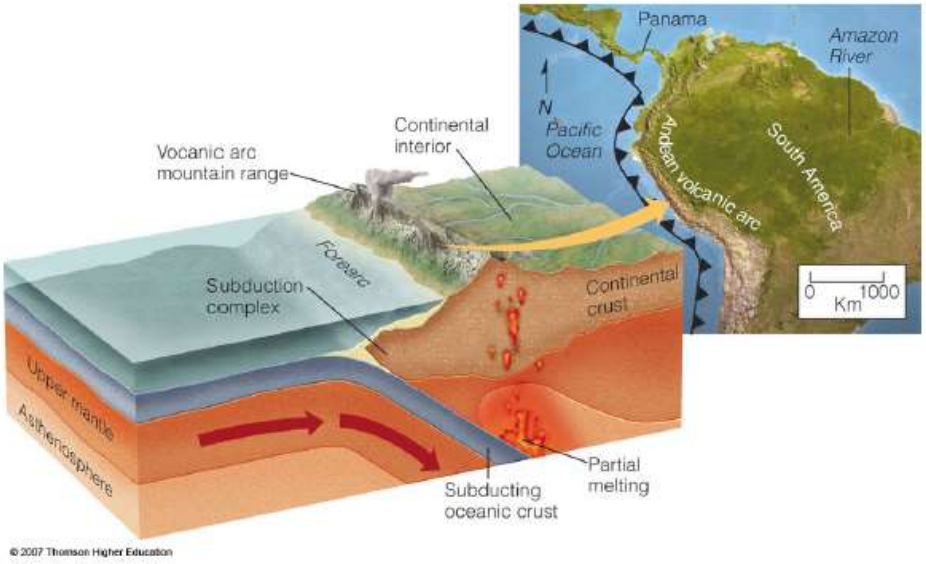
Central Himalaya Mountains, Nepal.

Mt Everest and the Himalayan collision zone

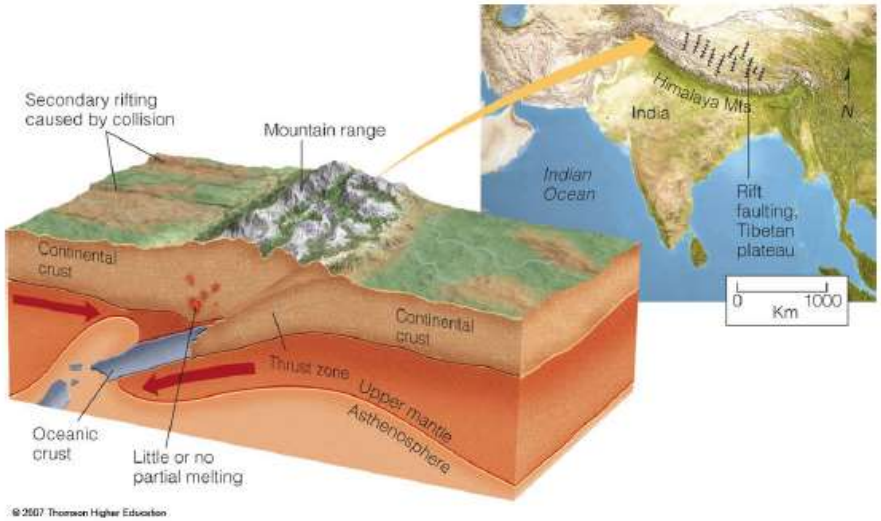
Convergent boundaries exist where one plate is *subducted* beneath another and crust is destroyed, and/or two plates with continental crust on their leading edges collide, and mountains are formed



Type 1 ocean – ocean



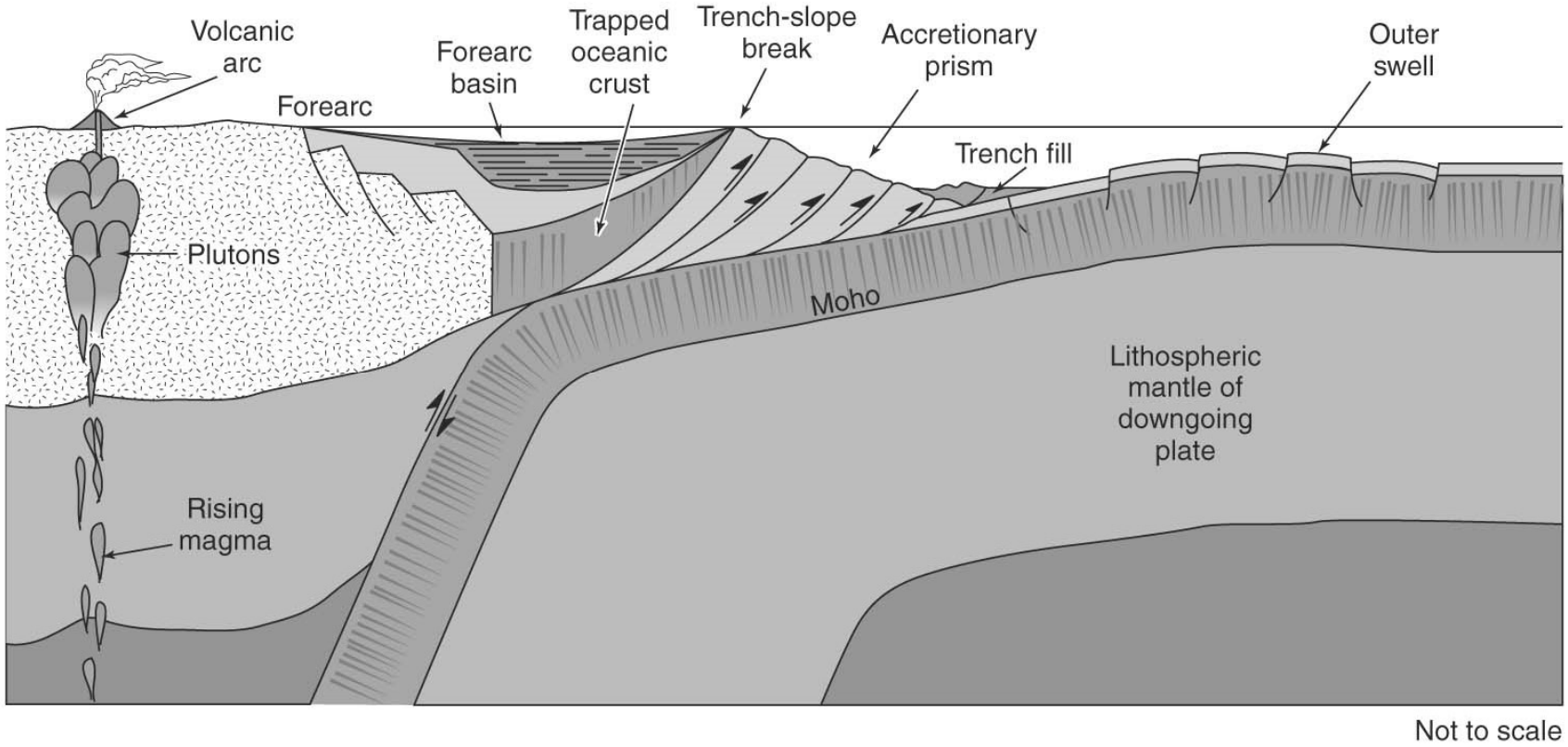
Type 2 ocean – continent



Type 3 continent – continent

Generalized Cross-Section Fig. 17.4

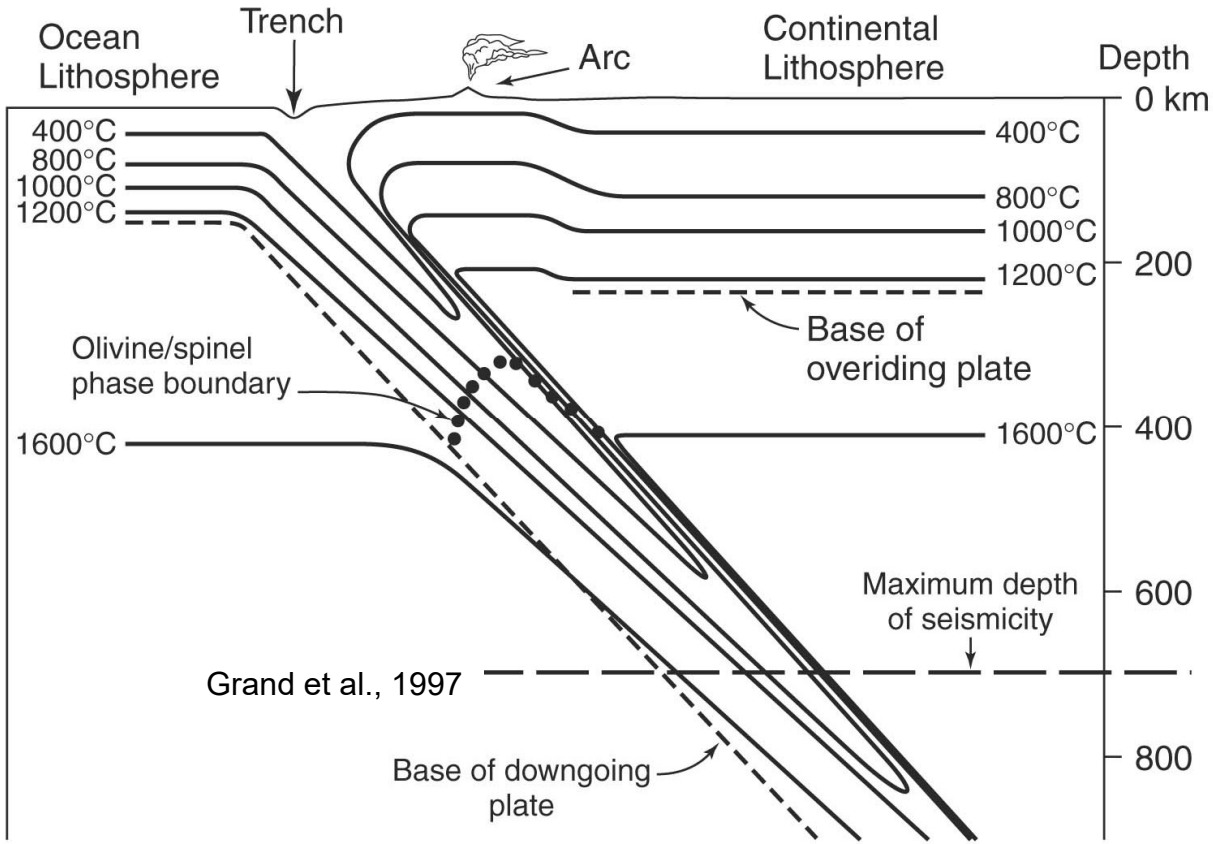
Idealized cross section of a convergent plate margin and related terminology.



In this case, the margin occurs along the edge of a continent, bordered by a sliver of trapped oceanic crust.

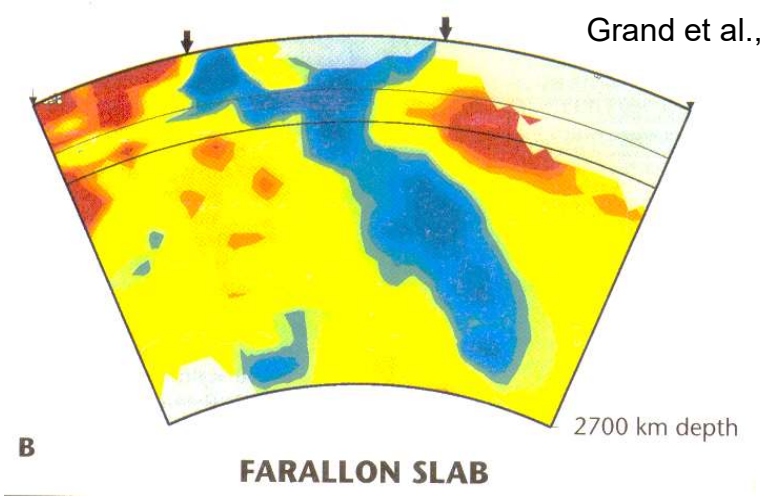
Thermal Structure and Slab Evolution Fig. 17.7

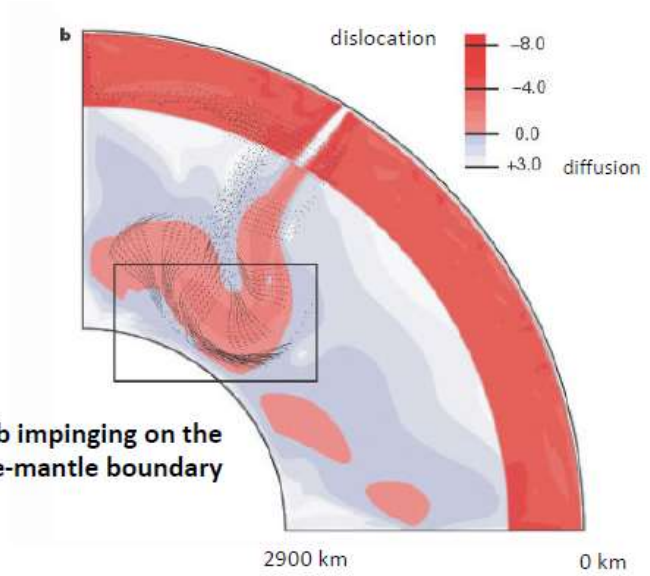
A simplified model of the thermal structure of the down-going plate.
(The thermal effects of mineral phase changes are not shown.)

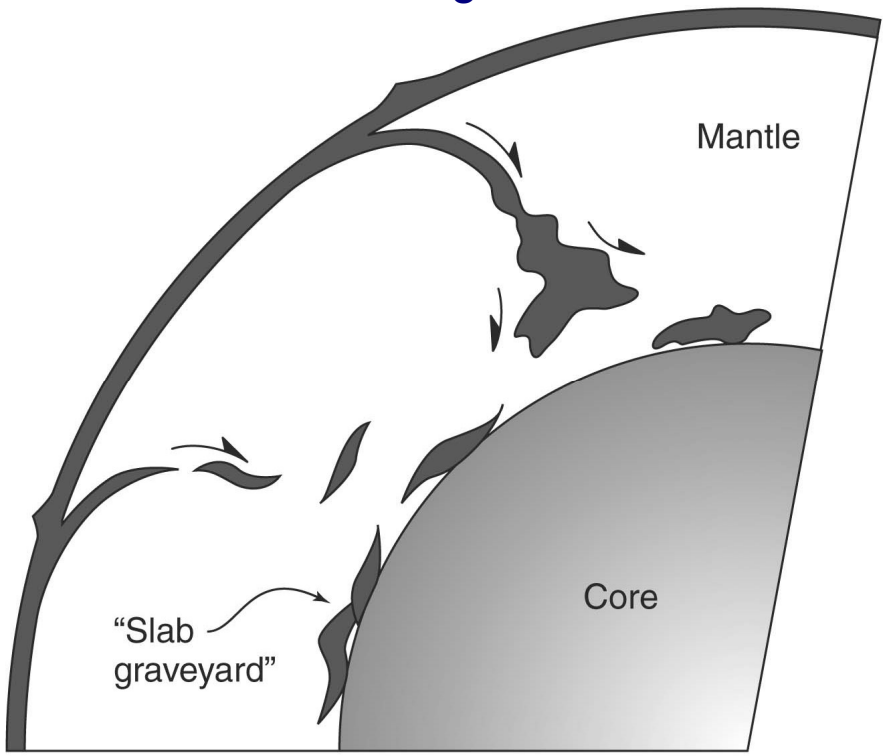


- Note that within the down-going plate, relatively low temperatures are maintained to great depth.
- For example at a depth of 400 km, the asthenosphere is at about 1600°C, while the interior of the downgoing plate may be as cool as 750°C.

Thermal Structure and Slab Evolution Fig. 17.9

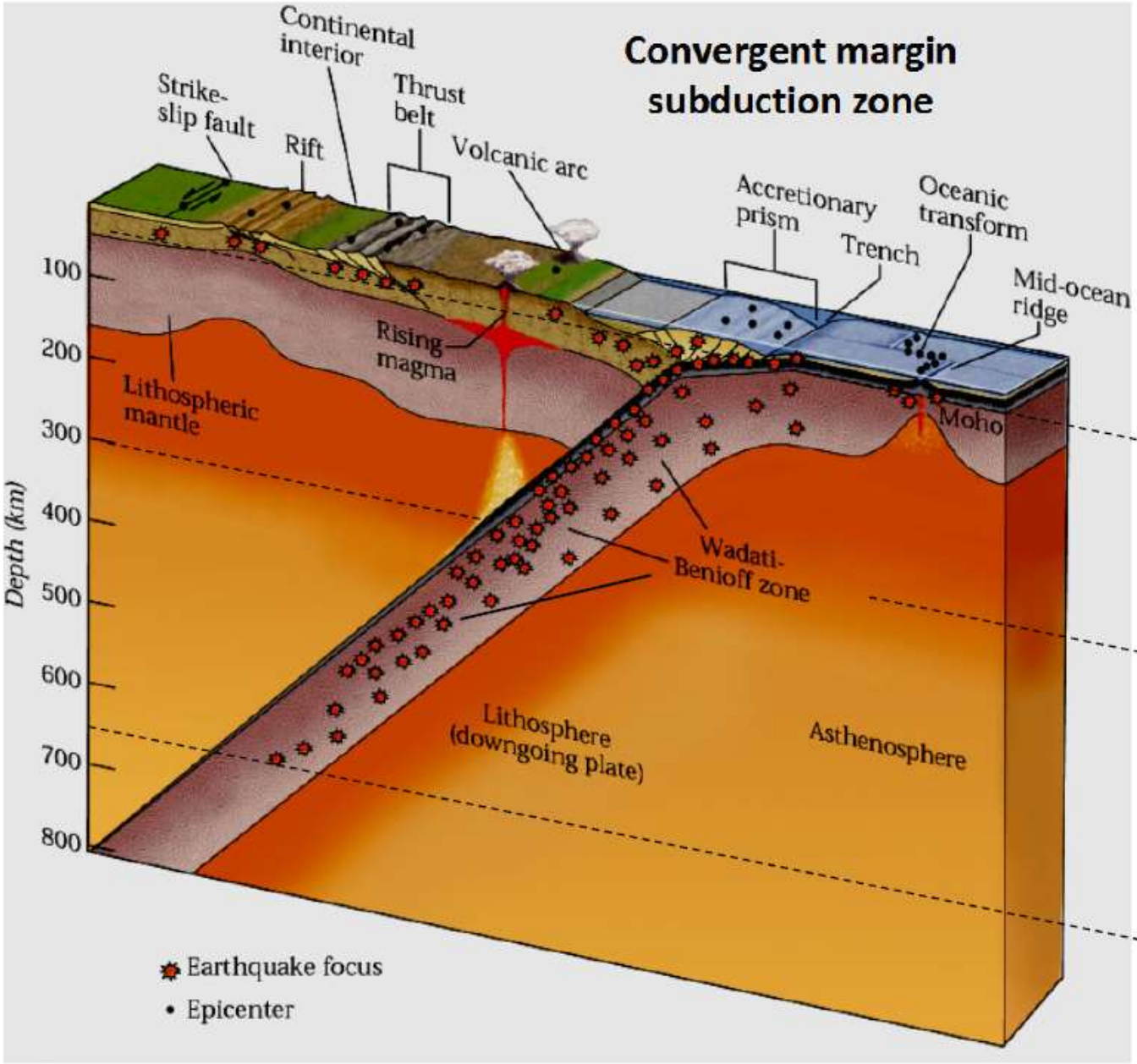




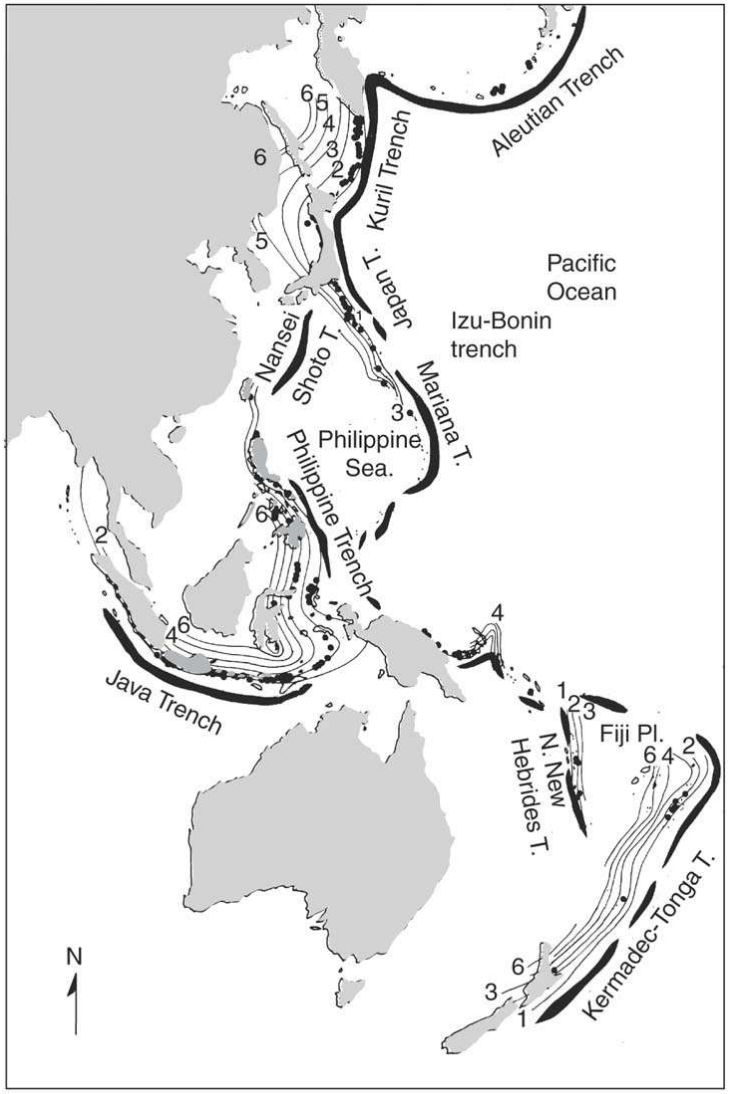


Schematic cross section of the Earth illustrating the concept of a slab graveyard in which masses of subducted oceanic lithosphere may accumulate near the base of the mantle.

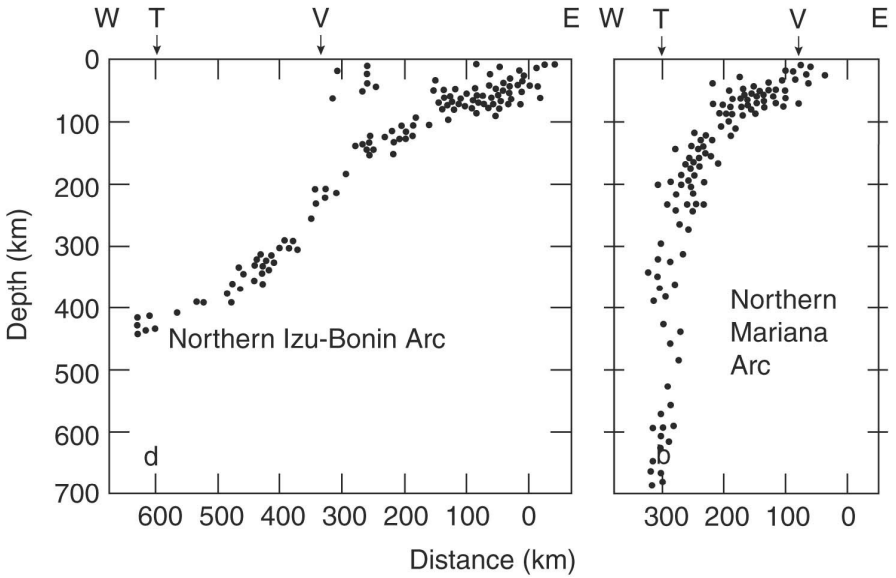
EARTHQUAKES AND SEISMOLOGY



Subduction Zones and Earthquakes Fig. 17.6



- Map of the western Pacific, showing trenches (heavy lines), and volcanoes (black dots) related to subduction in the western Pacific.
- The depth to *Wadati-Benioff zones* is shown by contour lines. The contours are given in multiples of 50 km (e.g., “2” means 2 × 50 = 100 km depth below the surface.)



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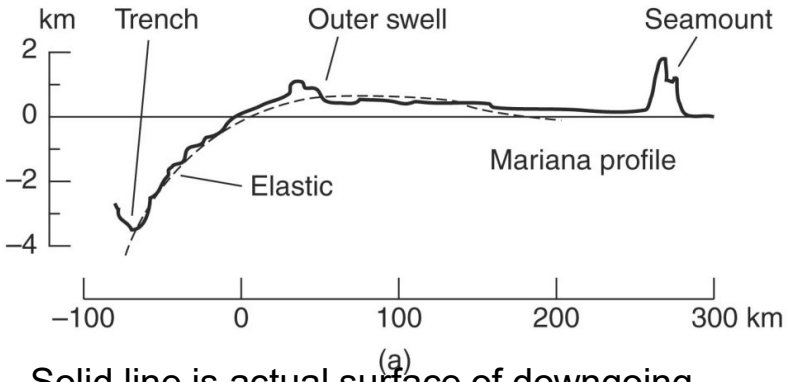
The Peripheral Bulge of the Downgoing Plate Fig. 17.5

Example of peripheral bulge just east of Mariana Trench in western Pacific.



Solid line is actual surface of downgoing slab; dashed line is calculated profile assuming plate behaves like a sheet with flexural rigidity.

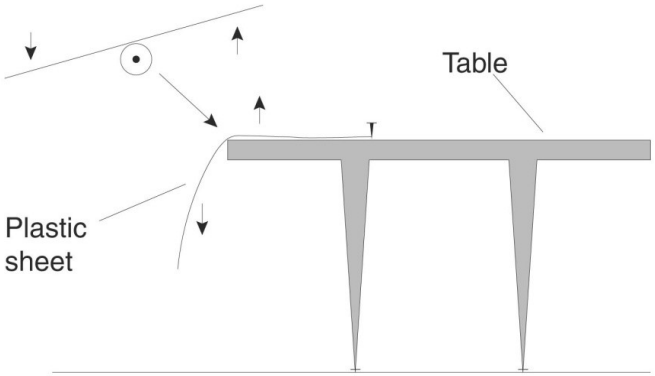
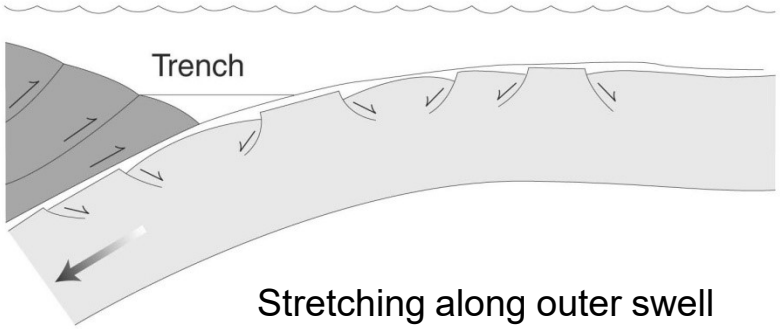


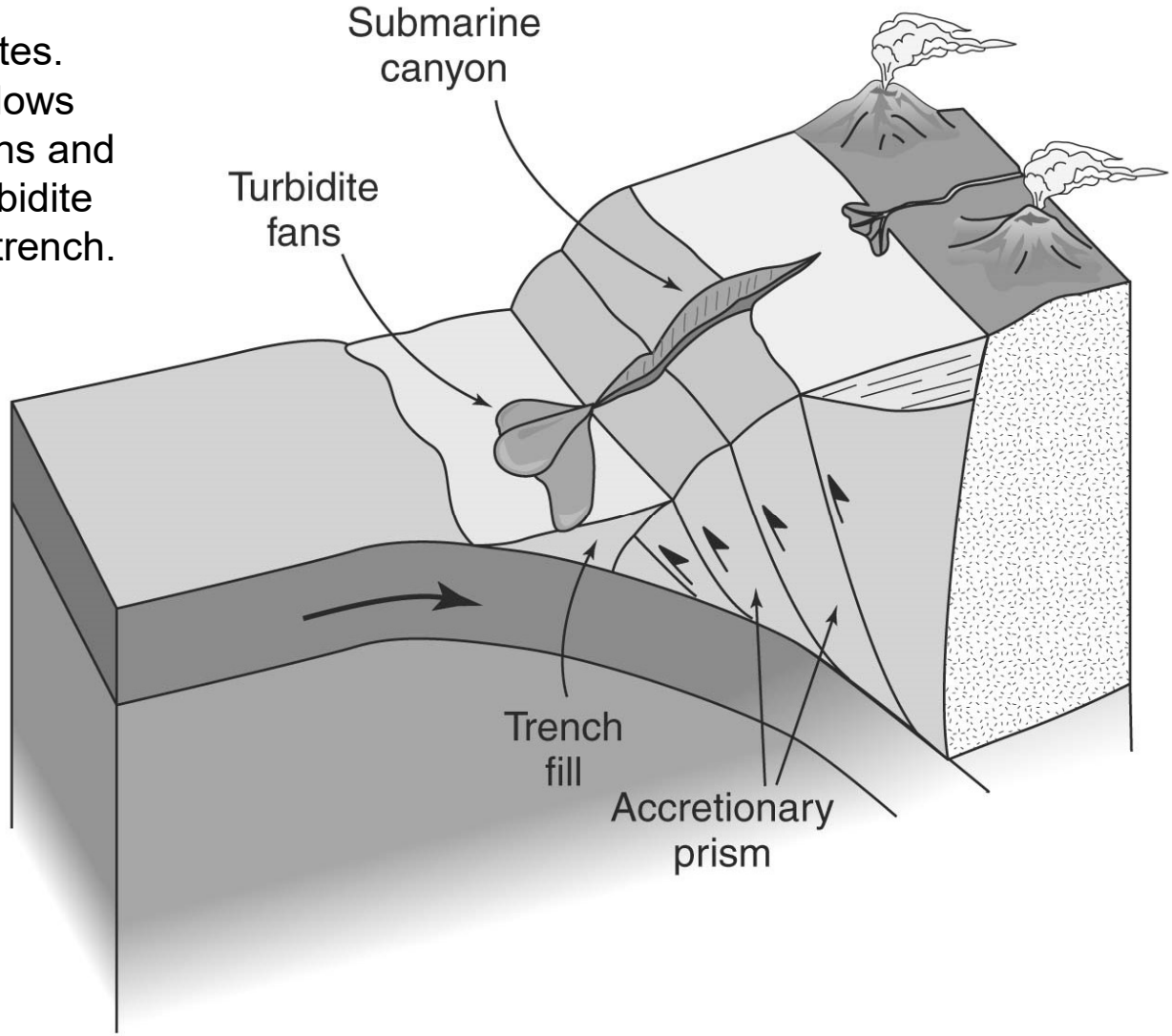
Table-top model of peripheral bulge, with inset showing lever concept.



Stretching along outer swell produces horsts and grabens at surface of downgoing slab.

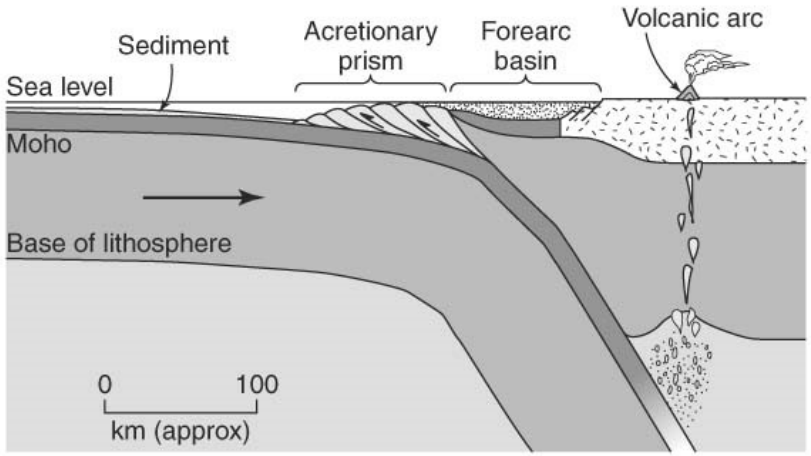
Trench Fill and Tectonic Mélange Figs. 17.10

- Trenches fill with turbidites. Much of this sediment flows down submarine canyons and then accumulates in turbidite fans on the floor of the trench.



Two possible configurations of accretionary prisms (or wedge) Fig. 17.11

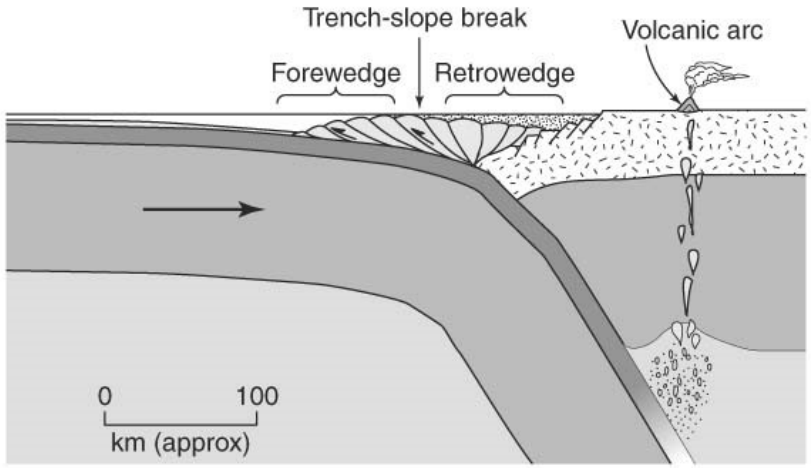
An accretionary prism caught beneath the lip of trapped ocean lithosphere



(a)

An accretionary prism being scraped off the edge of a continent.

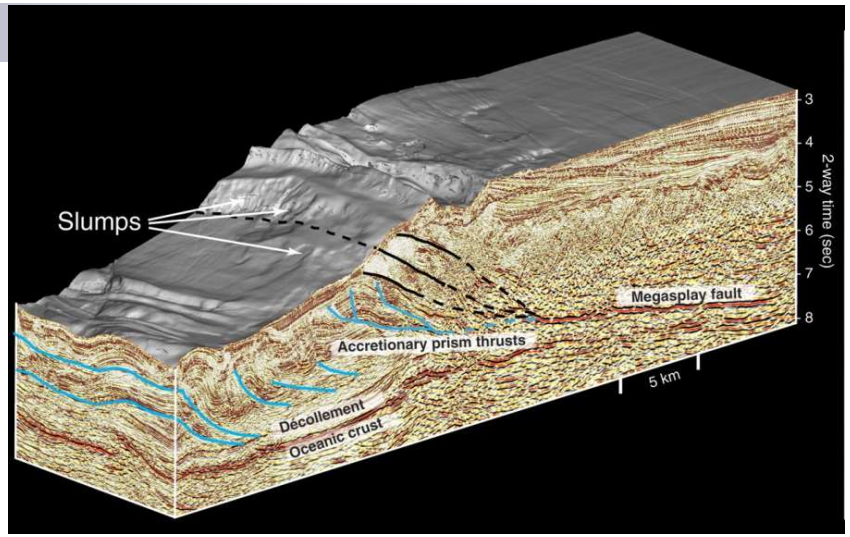
Note that the prism, in this case, is bivergent.



(b)

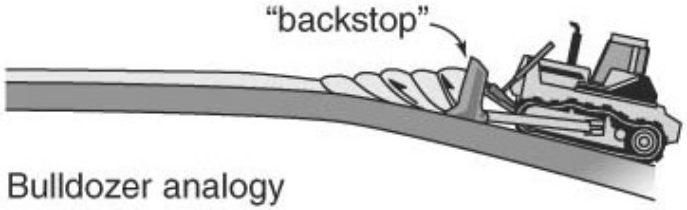
Accretionary prism (or wedge)

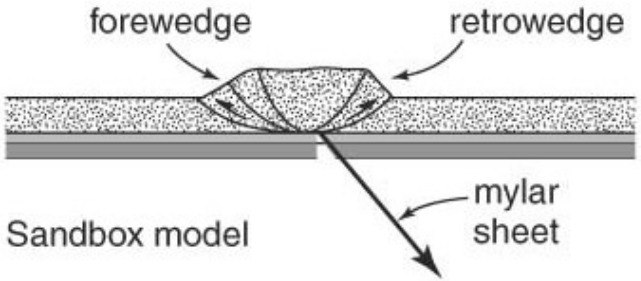
Fig. 17.11



The bulldozer analogy for the formation of an accretionary prism.

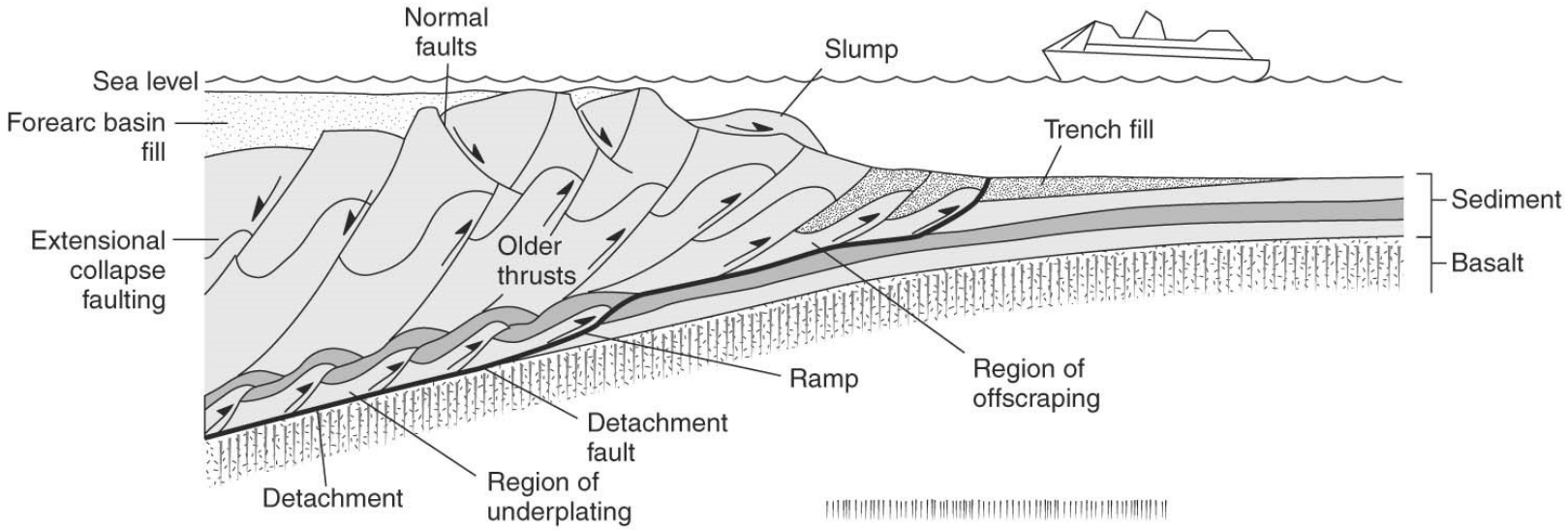
The blade acts as the backstop.

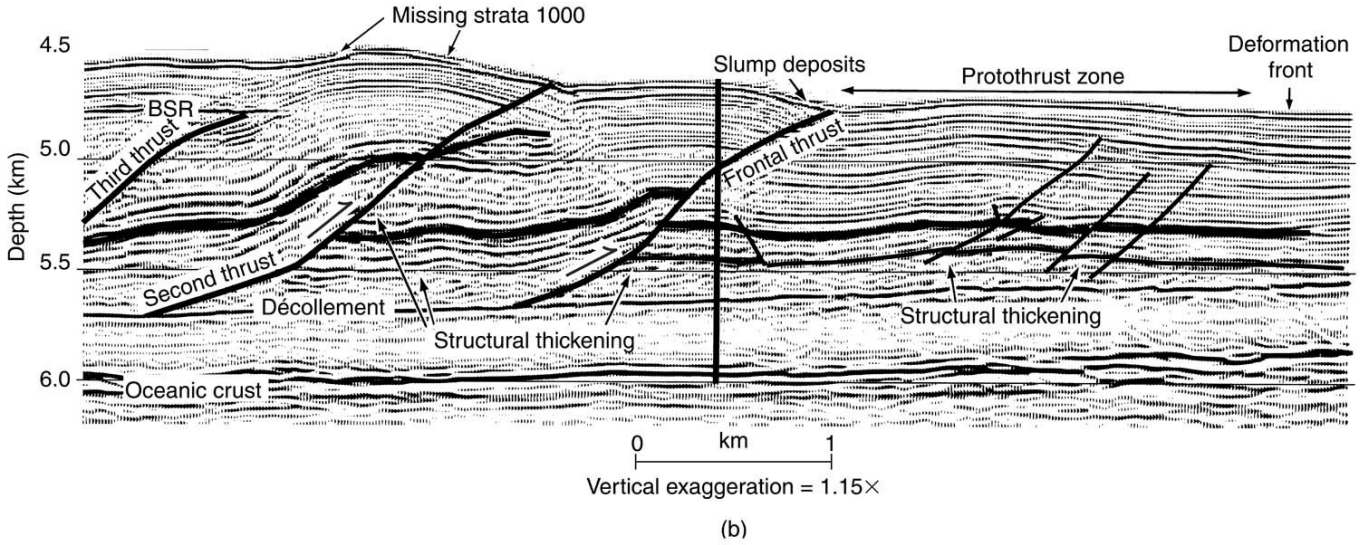




Sandbox model showing the formation of a bivergent wedge.

Accretionary Wedge





(b)

Paleozoic mélange exposed in an outcrop in north-central Newfoundland and 17.15

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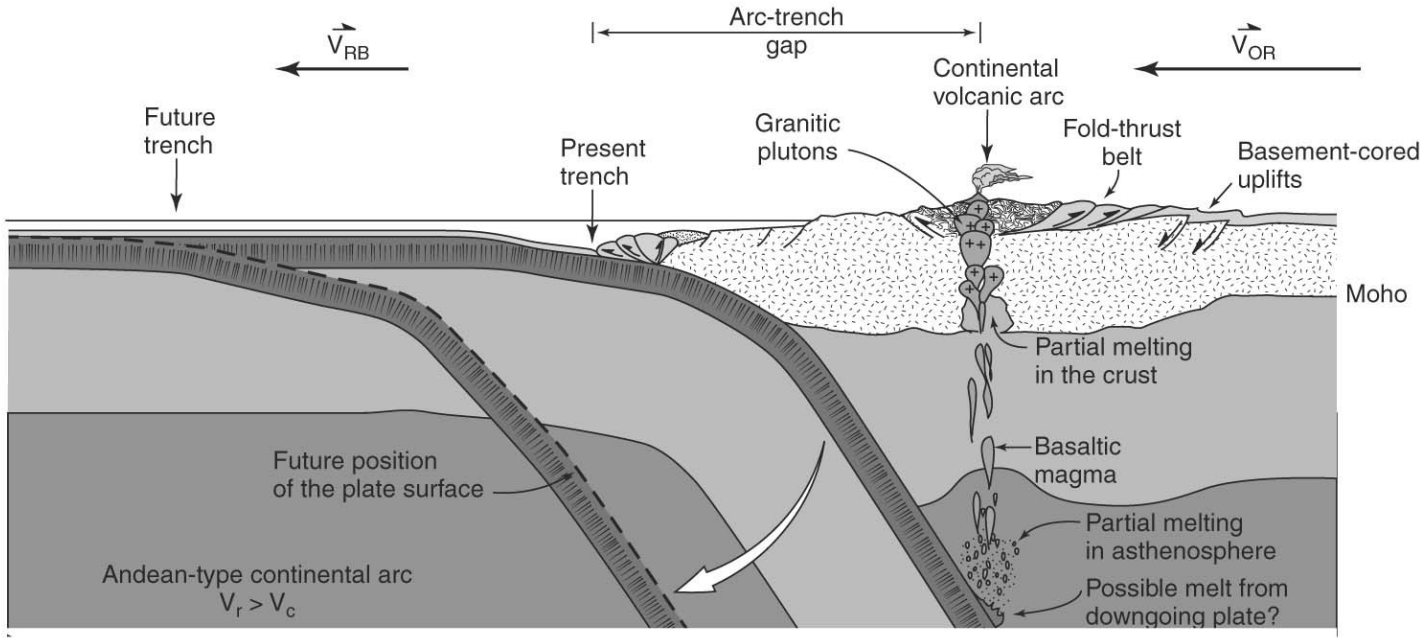
Note how layers are disrupted, strongly cleaved, and complexly folded, and that a variety of different rock types are visible.

An Andean-type continental arc, with a compressional backarc region
Fig. 17.16

- As the volcanic arc grows on continental crust compression has generated a fold-thrust belt and “Laramide-style” basement-cored uplifts.

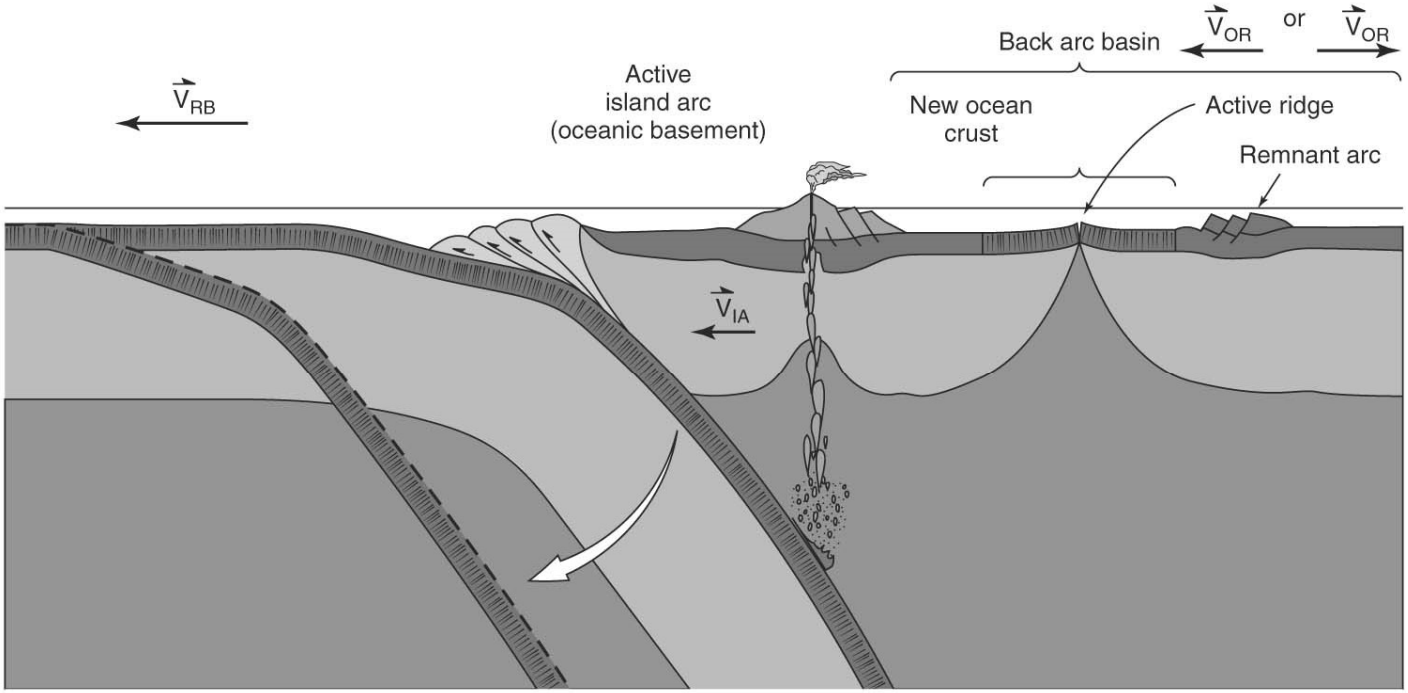


Large granitic plutons develop.

This situation develops where the velocity of the overriding plate (v_{OR}) is in the same direction and exceeds the rollback velocity (v_{RB}).

A Mariana-type island arc, with extensional backarc region Fig. 17.16

- The volcanic arc grows on oceanic crust, and a backarc basin develops in which there is seafloor spreading.

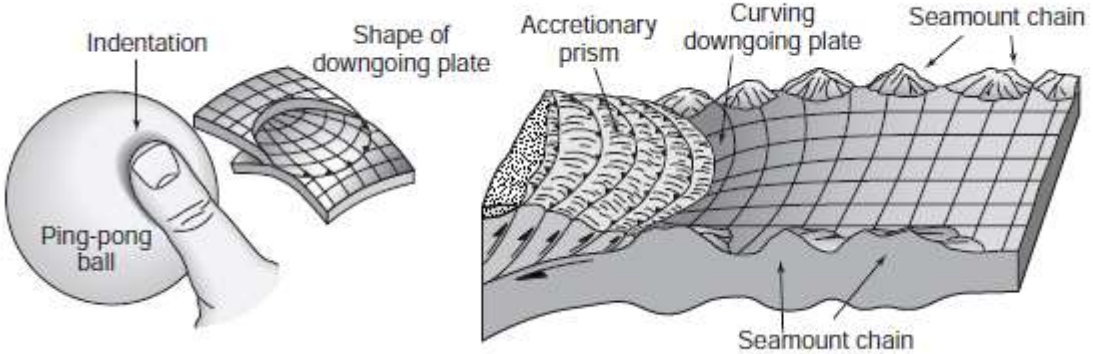


A remnant arc, composed of a rifted off fragment of the arc may occur in the basin.

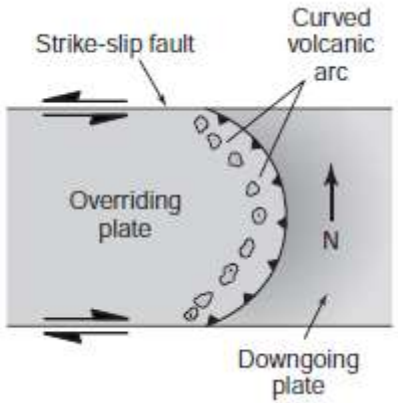
- This situation develops when $v_{OR} < v_{RB}$, or is in the opposite direction to v_{RB}.
- The island arc must move to keep up with the rollback.

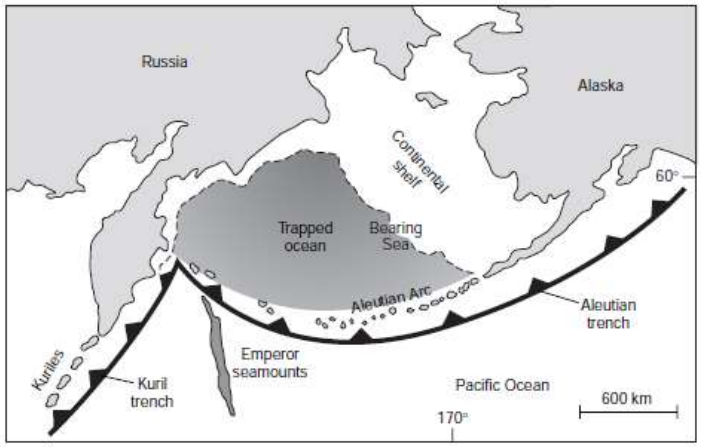
Reasons for the curvature of volcanic arcs Fig. 17.18

Seamounts chains can collide with an arc and cause indentations because the lithosphere of the seamount is more buoyant and subducts at a shallow angle, and the seamounts act as an obstacle to growth of the accretionary prism.



Strike-slip and drag origin for island-arc curvature



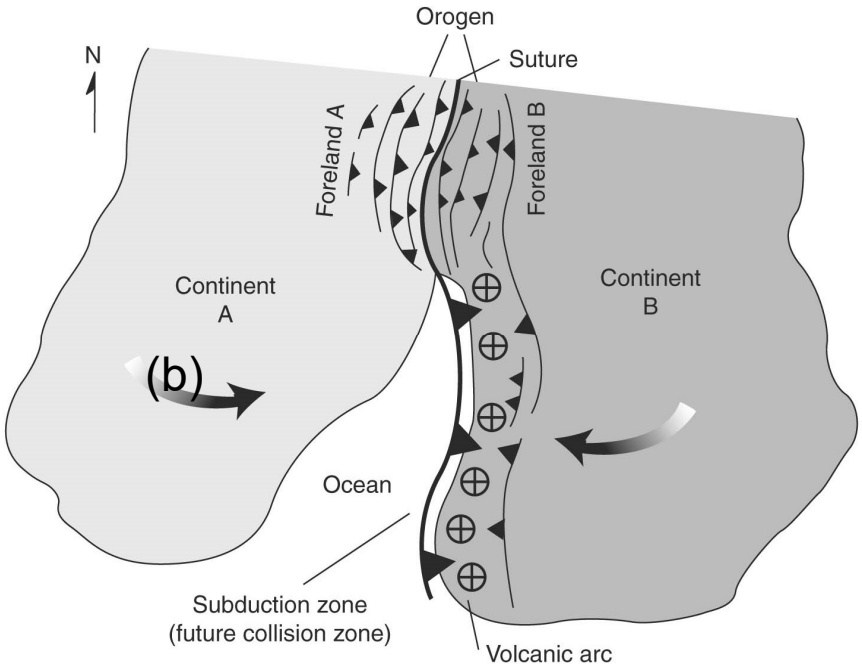


The Bering Sea is an example of a backarc region behind a volcanic arc formed from trapped ocean.

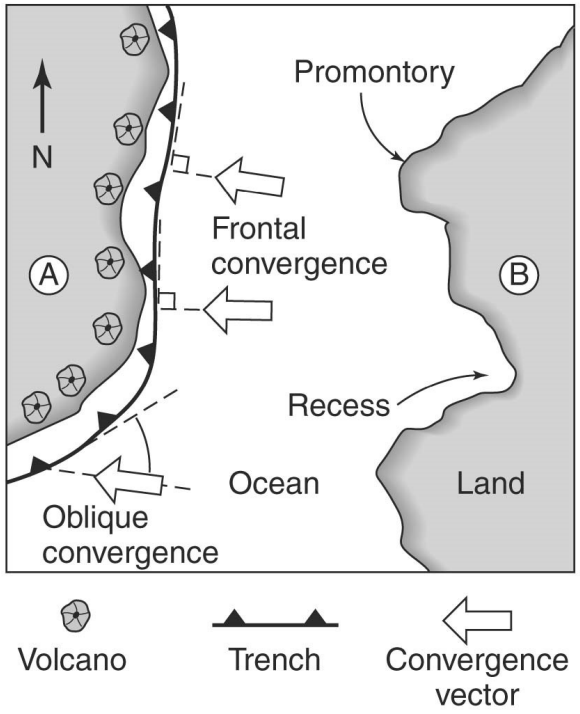
The oceanic lithosphere that now lies behind the arc formed in the Mesozoic and is not a consequence of Cenozoic backarc spreading.

Zipper-like collision between two continents FIG. 17.20

- The ocean between the two continents is closing progressively from north to south. In the collision zone, the boundary between what had originally been two separate continents.

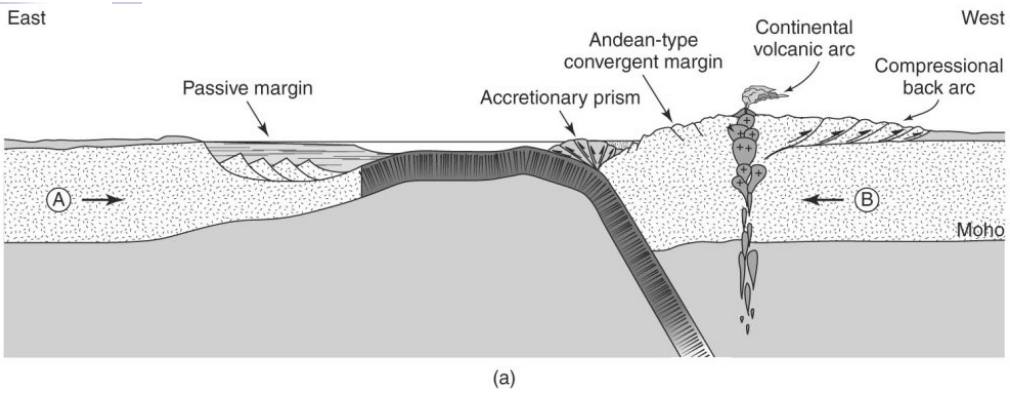


Promontories and recesses make the west coast of Continent B irregular.

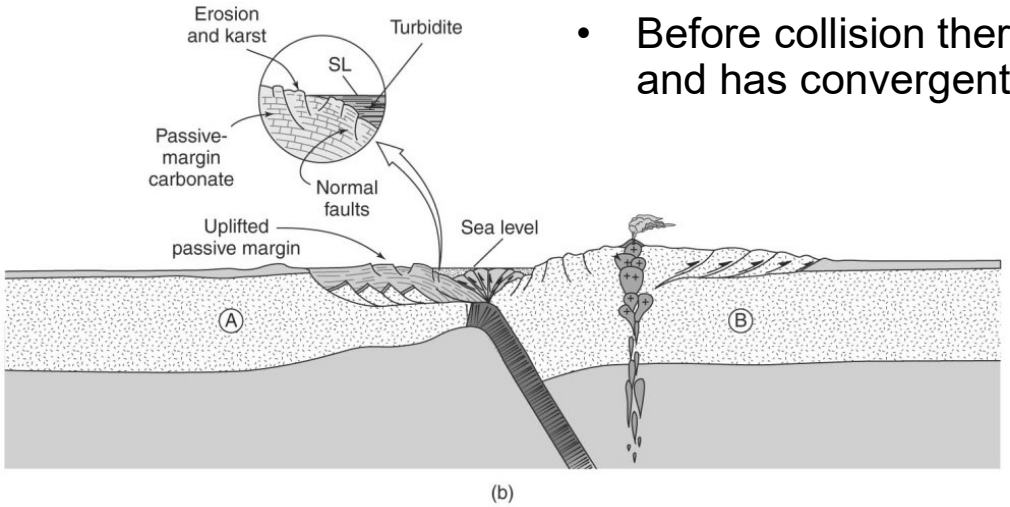


- The subduction zone along Continent from frontal convergence and eventual frontal collision will occur to the north, while oblique convergence (and, eventually, oblique collision) will occur to the south.

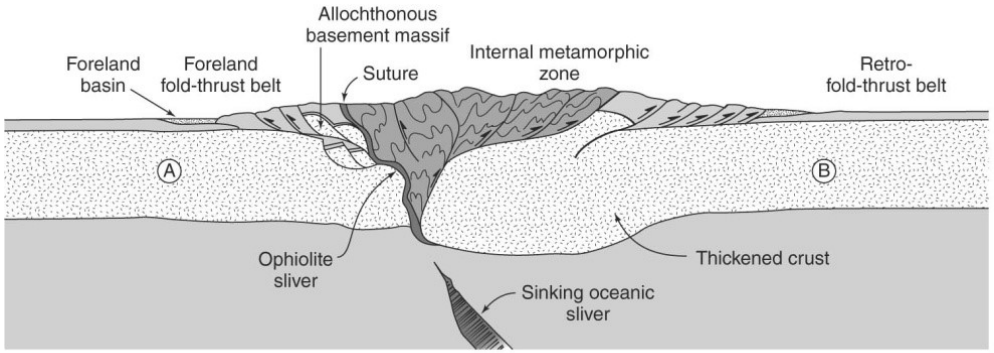
Stages in an idealized continent–continent collision Fig. 17.21



(a)



(b)



(c)

- Before collision there is a passive-margin basin on east coast and has convergent margin on west coast.
- Onset of collision the passive margin is uplifted, an unconformity develops, turbidites derived from B bury unconformity (inset).
- Normal faults break up strata of passive-margin basin, due to stretching. Thrusts develop, transporting deeper parts of basin over shallower parts.
- In mature collision orogen, subducting slab has broken off, a suture has formed, and metamorphic rocks are uplifted and exhumed in orogen interior.

TERMINOLOGY OF COLLISION Table 17.2

- Exotic terrane - An independent block of buoyant crust that has been brought into a convergent margin during subduction, where it collides and docks against the continent (also called accreted terrane). The adjective “exotic” in this context is used simply to emphasize that the block in question did not originate as part of the continent to which it is now attached, but rather came from somewhere else.

- Accreted terrane - A piece of exotic crust that has been attached to the margin of a larger continent. (Note the spelling of *terrane,* which differs from that of the geographic term for a tract of land, spelled *terrain.*)

- Suspect terrane A crustal block in an orogen whose tectonic origin is unclear. The block does not appear to correlate with adjacent crust in the orogen where it now resides and thus may be exotic. A block remains “suspect” only until its origin (i.e., whether it’s exotic or not) has been determined.

- **Basin inversion** - The process whereby a region that had undergone crustal extension during basin formation subsequently undergoes crustal shortening during collisional tectonics; in the process, faults that began as normal faults are reactivated as reverse faults, and the strata of the basin thrusts up and over the former basin margin.

TERMINOLOGY OF COLLISION Table 17.2

- Delamination - In the context of collisional tectonics, the separation of the basal portion of the thickened lithospheric mantle beneath a collisional orogen; this delaminated lithospheric mantle then sinks downward through the asthenosphere.

- Lateral escape - The process, accompanying collision, during which crustal blocks of the overriding plate slide along strike-slip faults in a direction roughly perpendicular to the regional convergence direction

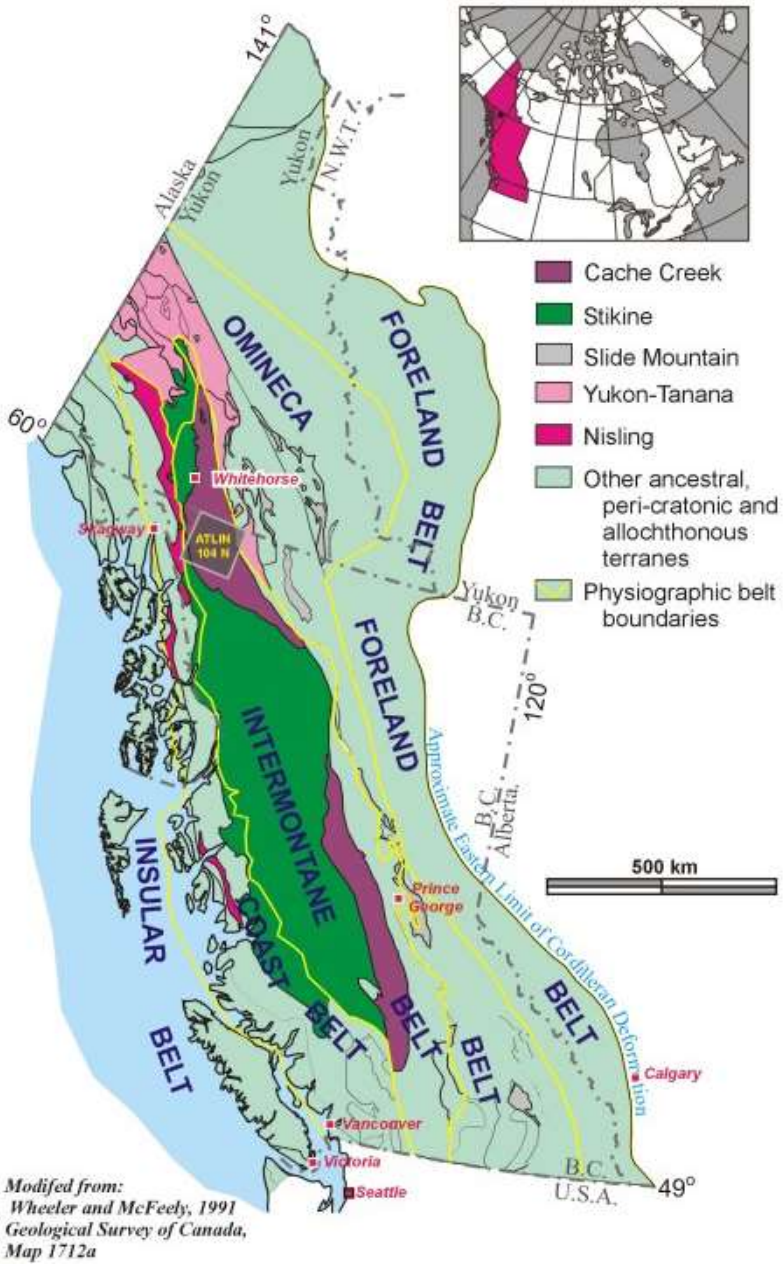
- **Orogenic collapse** - Occurs when thickened crust in a collisional orogen weakens and starts to sink under its own weight. Effectively, gravitational loads cause horizontal extensional strain to develop. In some cases, extension is coeval with thrusting (synorogenic collapse), in other cases it occurs after thrusting has ceased (postorogenic collapse). (Also called *extensional collapse.*)

- Suture - The shear surface within an orogen that marks the boundary between once-separate continents; commonly, slivers of ophiolites occur along a suture.

Terranes and Superterranes

Terranes: Exotic, relatively buoyant blocks that are accreted to a continent during subduction (many collisions)

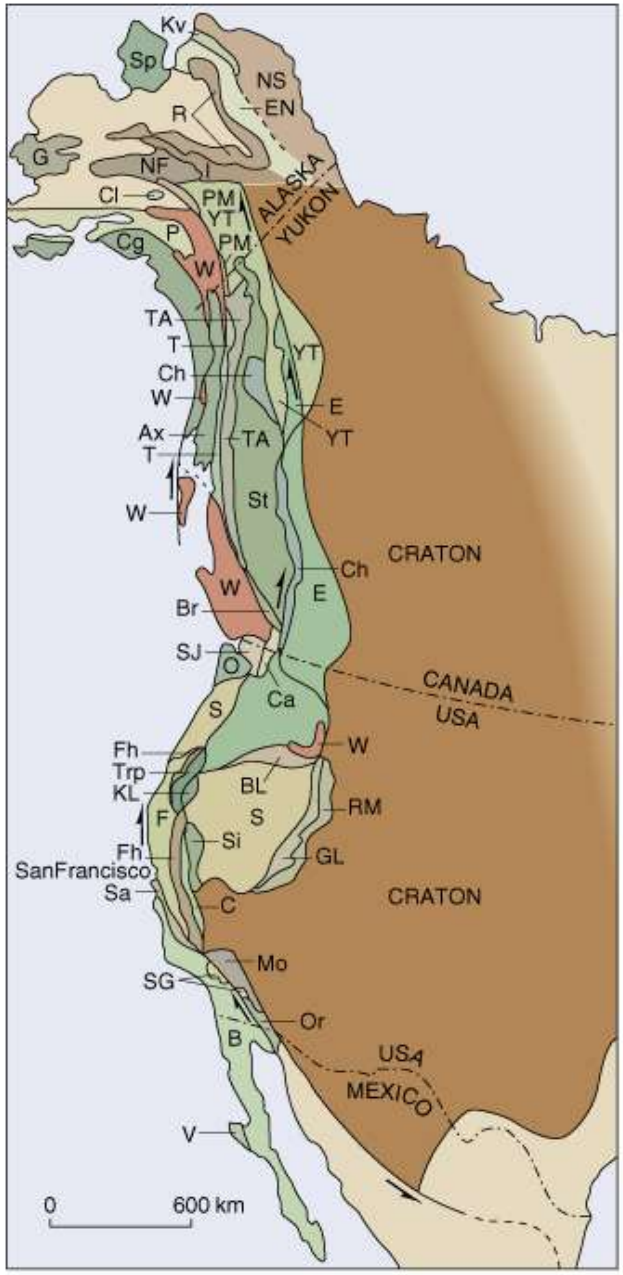
Superterranes: Amalgamation of exotic blocks into a larger terrane prior to accretion to a larger continent (main collision pulses)



Cordilleran (suspect) terranes Fig. 17.29

Map of the North American Cordillera, showing the regions that consist of accreted crust.

This crust can be divided into numerous exotic terranes.



Symbol	Name
Ax	Alexander
B	Baja
BL	Blue Mountains
BR	Bridge River
C	Calaveras
Cg	Chugach
Ch	Cache Creek
Cl	Chulitna
E	Eastern assemblages
En	Endicott
F	Franciscan and Great Valley
Fh	Foothills Belt
Gl	Golconda
I	Innoko
Kl	Klamath Mountains
Kv	Kagvik
Mo	Mohave
NF	Nixon Fork
NS	North Slope
O	Olympic
P	Peninsular
PM	Pingston and McKinley
R	Ruby
RM	Roberts Mountains
S	Siletzia
Sa	Salinian
SG	San Gabriel
Si	Northern Sierra
SJ	San Juan
Sp	Seward Peninsula
St	Stikine
T	Taku
TA	Tracy Arm
Trp	Western Triassic and Paleozoic of Klamath Mountains
V	Vizcaino
W	Wrangelia
YT	Yukon-Tanana

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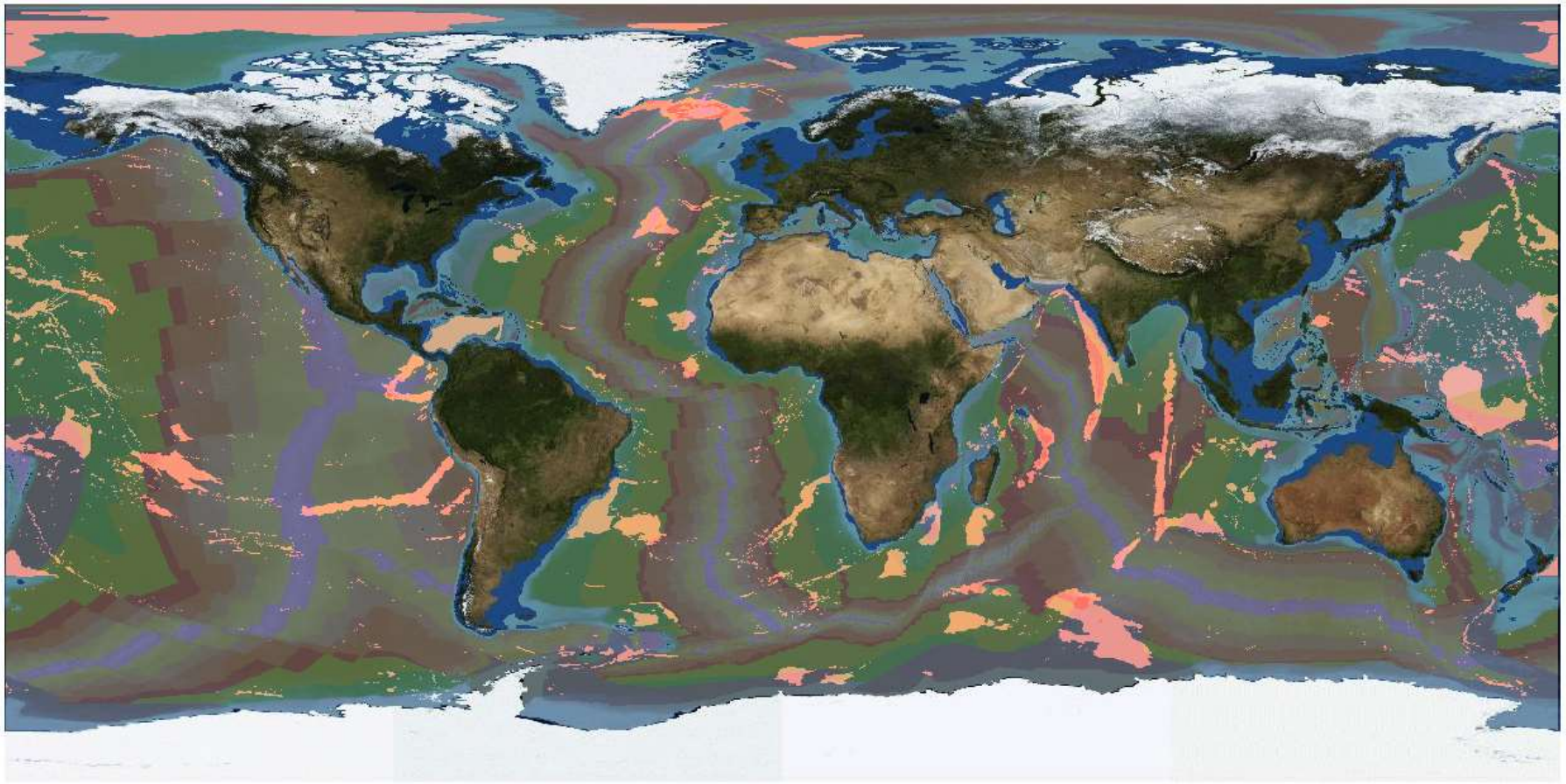
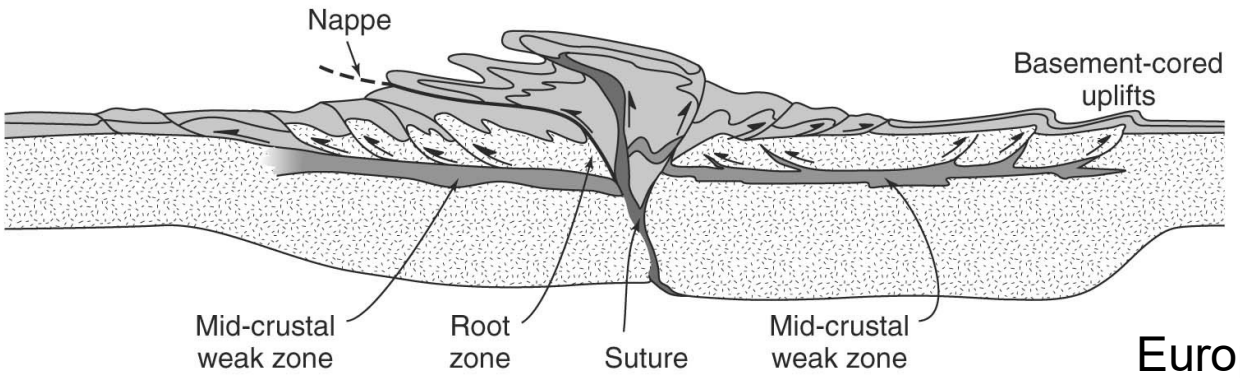
Future Terranes: Oceanic Plateaus Fig. 17.19



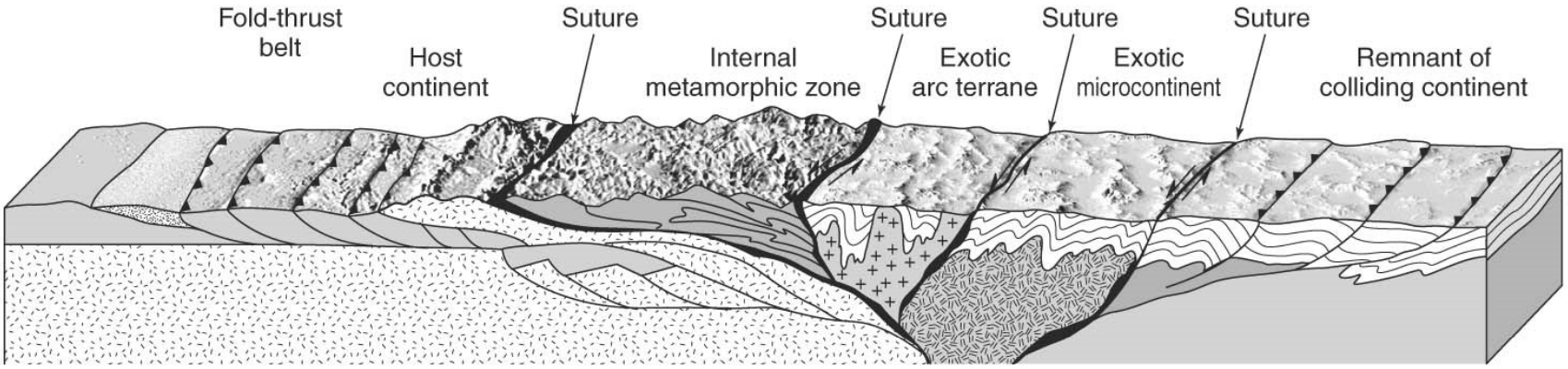
A map showing blocks of buoyant crust including volcanic arcs, oceanic plateaus, and continental fragments. Blocks that have darker shading rise above today's sea level. Blocks that have lighter shading are presently submerged. Convergence between any two blocks could cause collisional tectonics.

Schematic Sections of Collisional Orogens (Suturing) Fig. 17.23

(erosional land surface isn't shown)



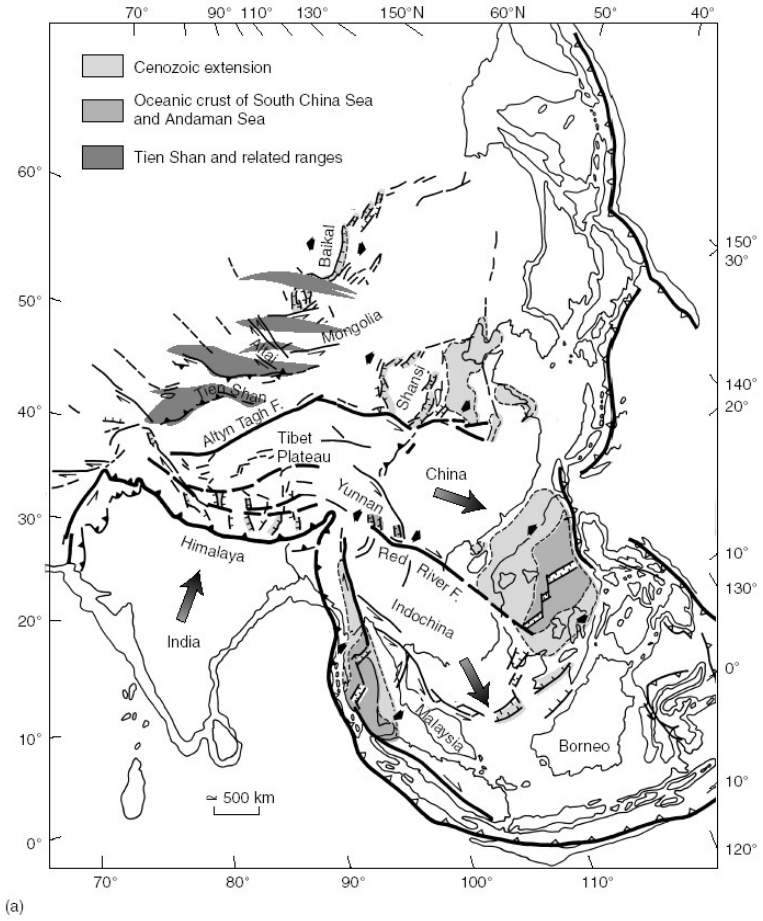
European Alps



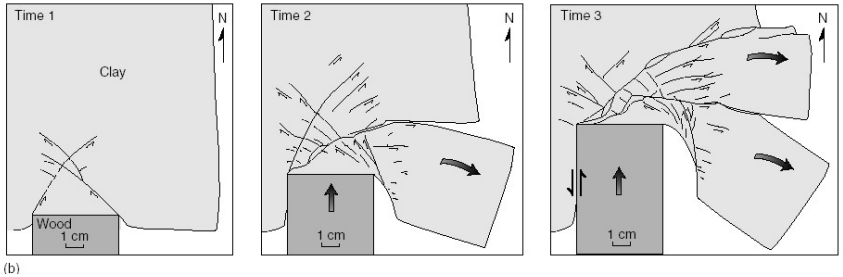
Block diagram with DEM

US Appalachians

Syn- and Post Orogenic Processes: Indentation and Extrusion Fig. 17.26

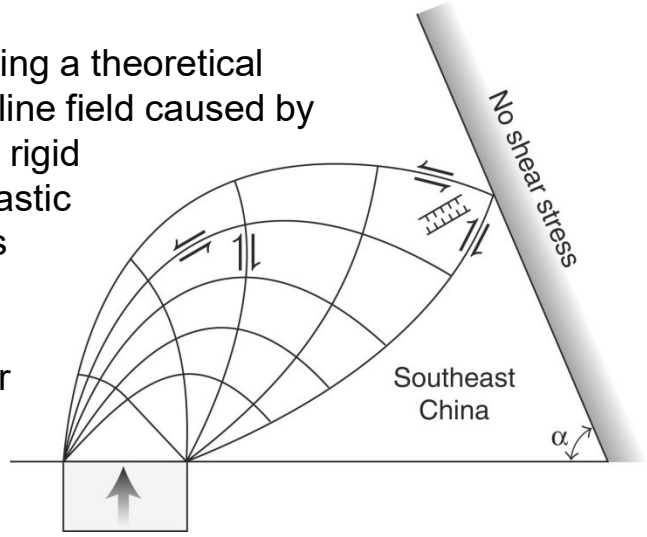


Map of major structures in southeastern Asia



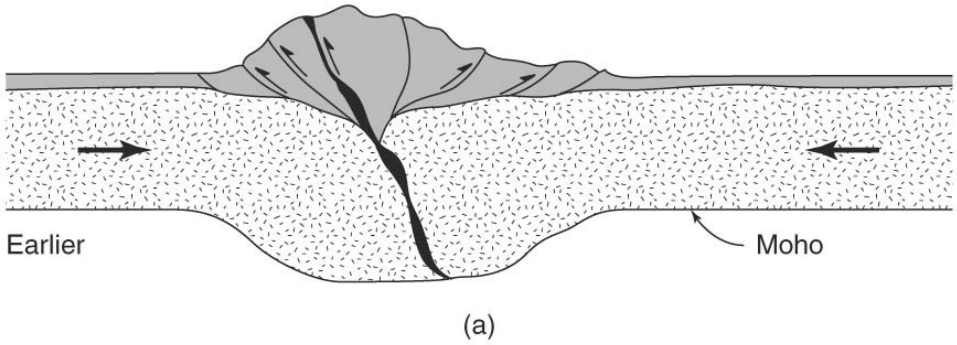
Map-view sketch of a laboratory experiment to simulate lateral-escape tectonics.

Map view showing a theoretical model of a slip-line field caused by indentation of a rigid block into an elastic sheet. The lines represent the trajectories of maximum shear stress.

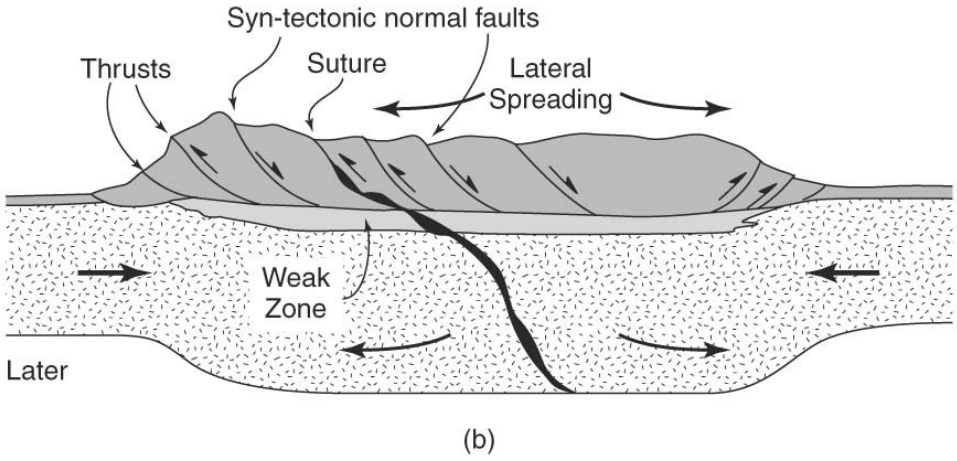


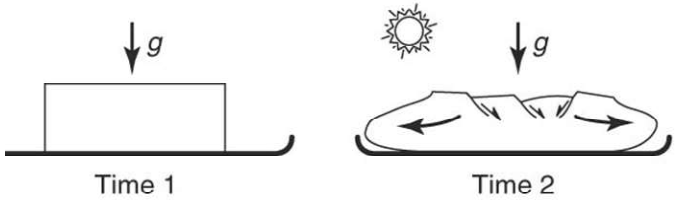
The Concept of Orogenic Collapse Fig. 17.24

During an early stage in a collision, the crust thickens by thrusting.



Not to scale



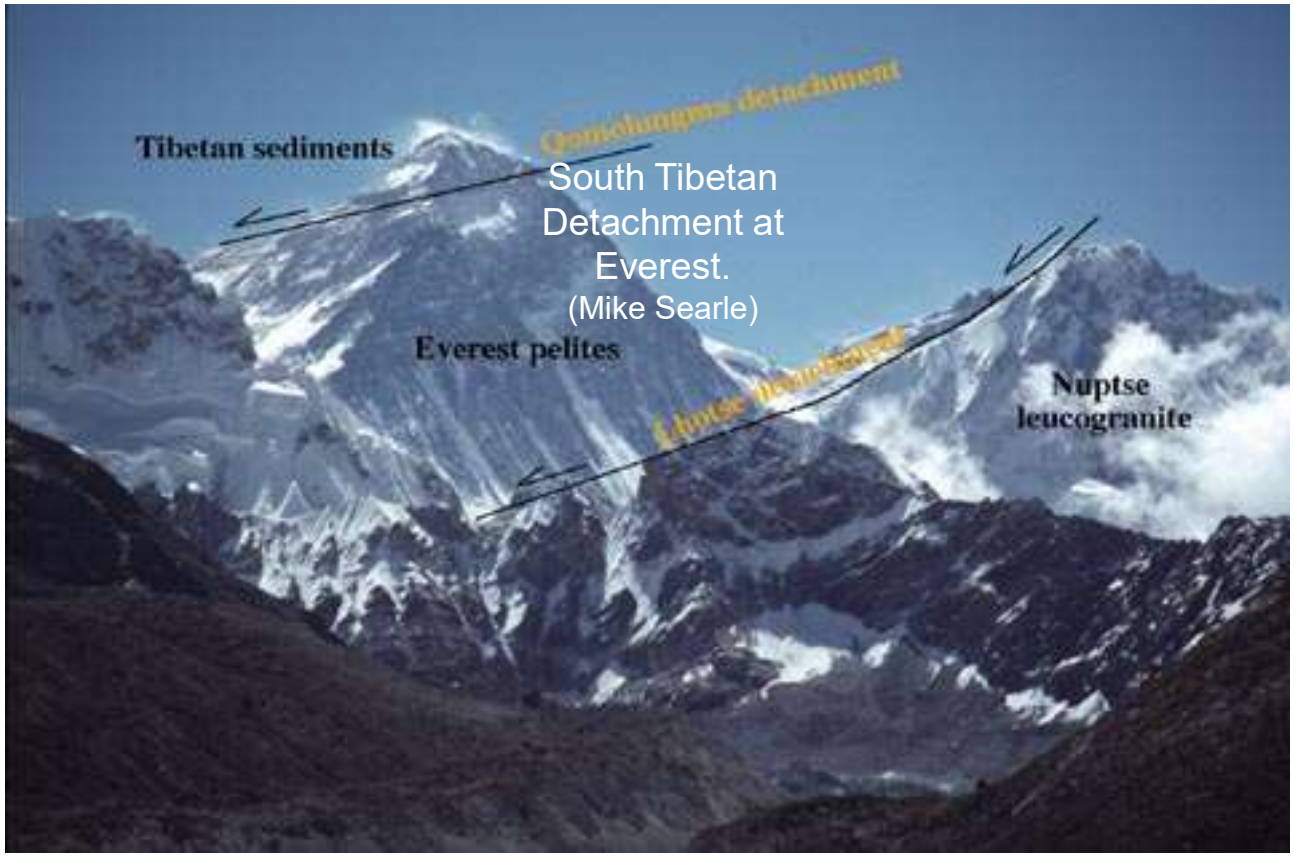


The soft-cheese analogy for extensional collapse. A block of cold cheese can maintain its thickness. If the cheese warms up in the sun, it loses strength and spreads laterally. The rind of the cheese ruptures, and small faults develop.

Later, as collapse occurs, extensional faults develop in the upper crust, while plastic flow occurs at depth. This process may contribute to development of a broad plateau.

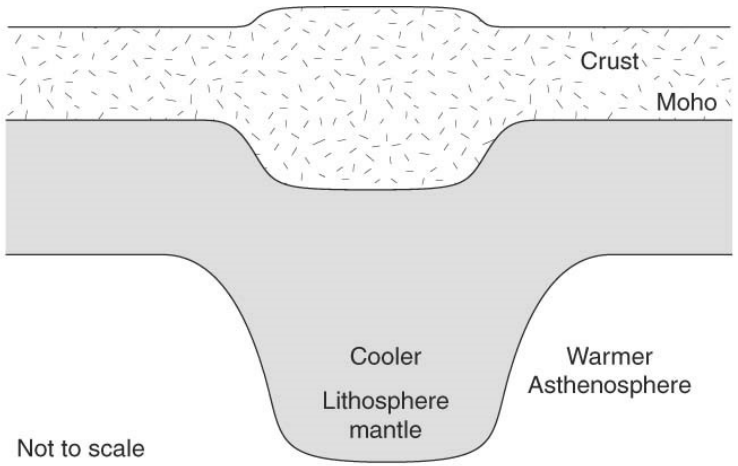
The Concept of Orogenic Collapse Fig. 17.24

A thick slab of metamorphic rock runs the full length of the Himalayan chain that formed in the mid-crust at an earlier stage of the evolving collision between India and Asia.



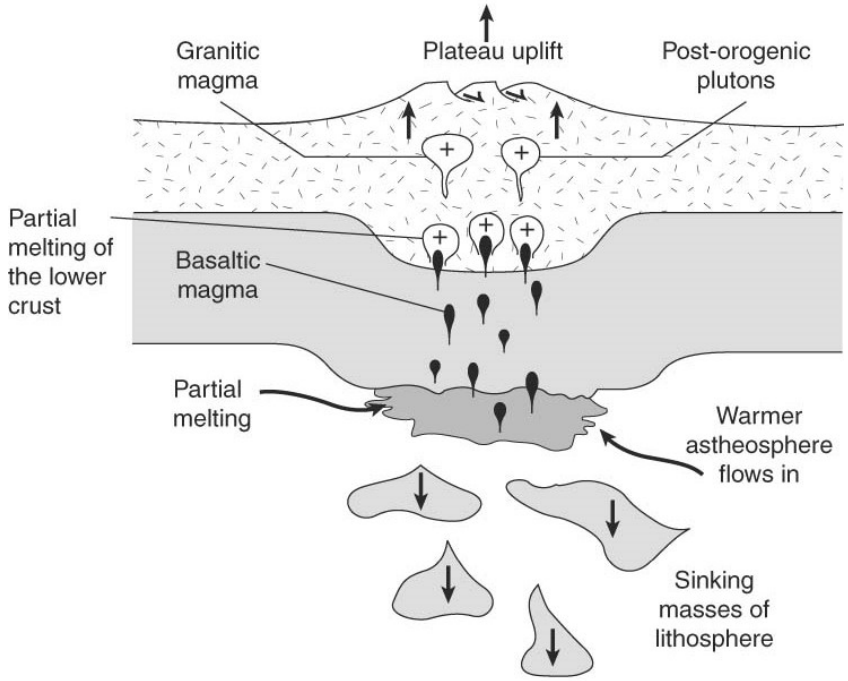
Two shallow-dipping detachments near the base of the slab reflect orogenic collapse by juxtaposing units of varying metamorphjic grade

Syn- and Post Orogenic Plutons: Delamination Fig. 17.25



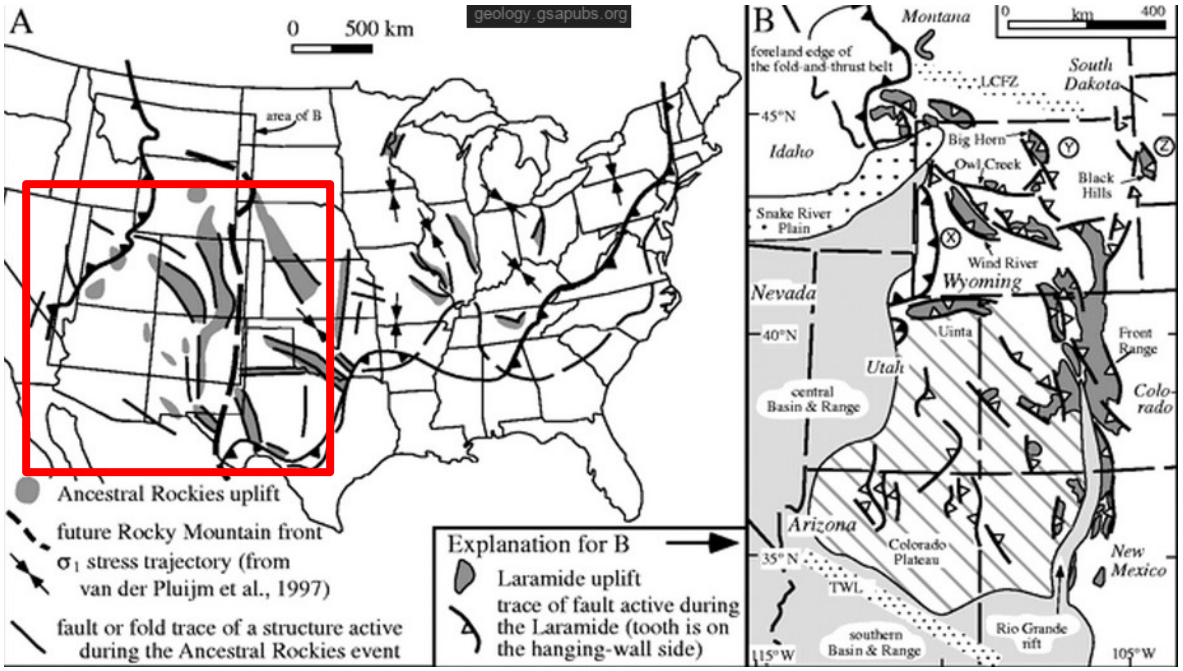
Thickening of lithosphere forms a keel-shaped mass of cool lithosphere to protrude down into the asthenosphere.

"mantle drip"

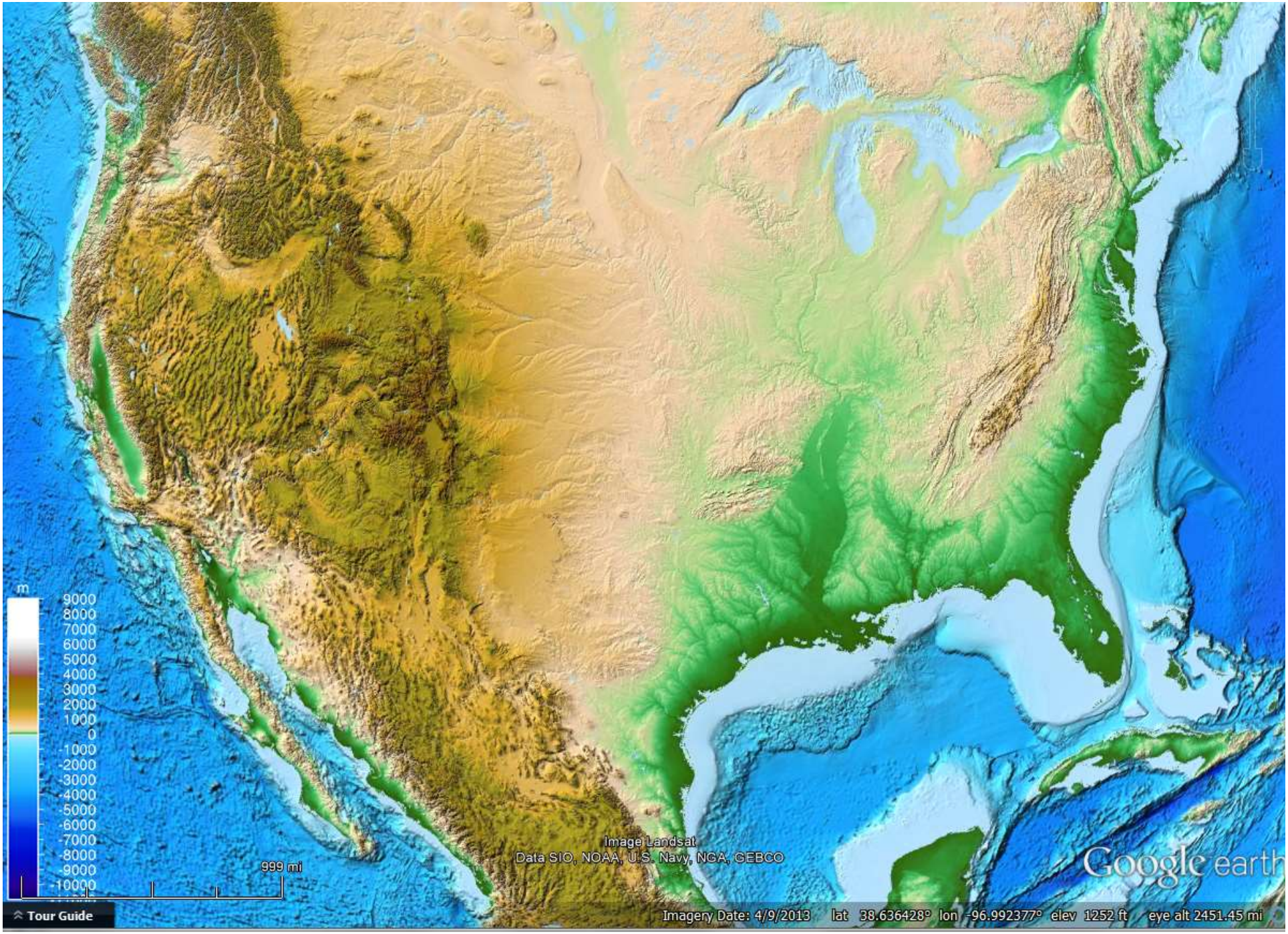


- The keel drops off and is replaced by warm asthenosphere, causing partial melting and formation of anorogenic (postorogenic) plutons.
- The surface of the crust may rise as a consequence.

Map of the Ancestral Rockies and equivalent that were active during the Alleghanian Orogeny when Africa collided with North America.



Geologists refer to the region in the western United States in which Late Paleozoic faults, folds, uplifts, and basins formed as the **Ancestral Rockies,** because it occurs in the region now occupied by the present-day Rocky Mountains (a Cenozoic feature) but existed long before the present mountains formed.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Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Tour Guide
Imagery Date: 4/9/2013 lat 38.636428° lon -96.992377° elev 1252 ft eye alt 2451.45 mi

USA Midcontinent fault-and fold zones within the interior of the Illinois basin

Fig. 17.28

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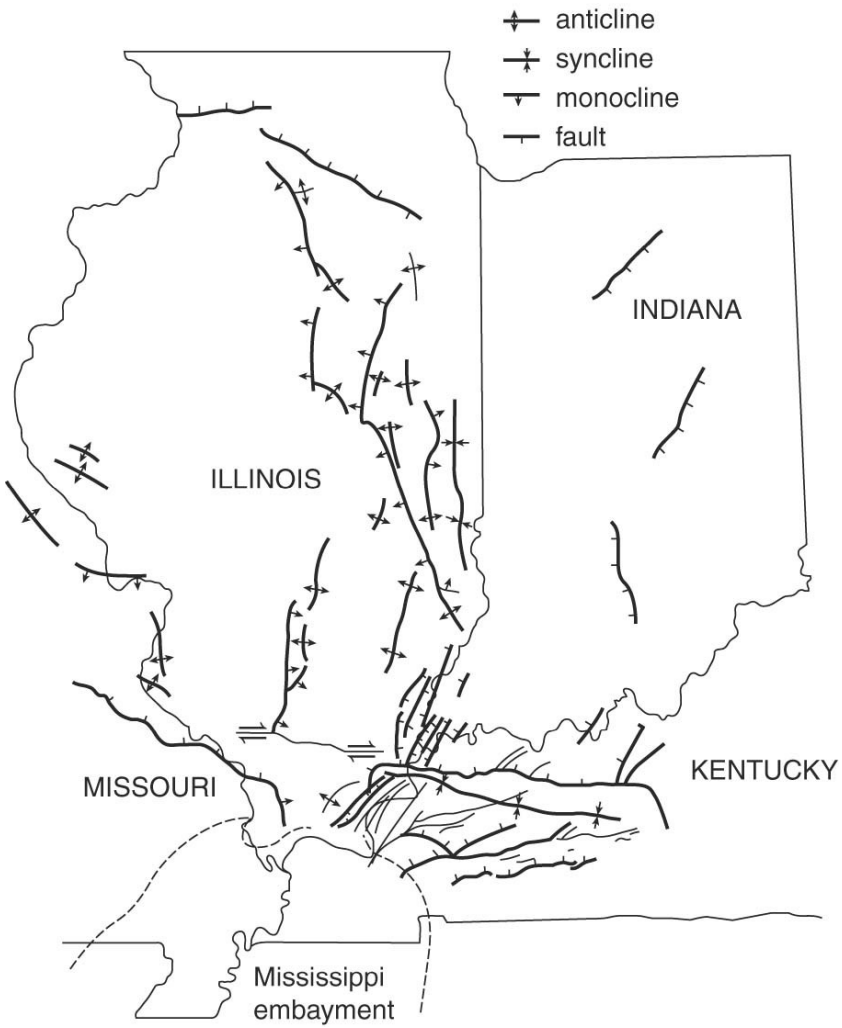
- Structures similar to those of the traditional Ancestral Rockies lie beneath the corn and wheat fields of the Midcontinent Region—these structures are called **Midcontinent fault-and-fold zones** .

- Though they are not as well exposed as those of the west, and typically do not display as much displacement, they probably formed in much the same way, in that their movement probably occurred in response to far-field stresses generated during Paleozoic orogeny along the eastern and southern margins of North America.