Basin analysis, Institute of Earth Sciences, Nat. Central Univ.

Instructor: Dr. Andrew T. Lin

Basin analysis is the integrated study of sedimentary basins as geodynamic entities. This course introduces the processes of mantle, lithosphere, oceans, atmosphere, and land surface that coupled together to shape the basin geometry and its infilled stratigraphy. The application of basin analysis to petroleum exploration will be introduced

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SECTION 1 THE FOUNDATIONS OF SEDIMENTARY BASINS
Chapter 1: Basins in their plate tectonic environment
Chapter 2: The physical state of the lithosphere

SECTION 2 THE MECHANICS OF SEDIMENTARY BASIN FORMATION
Chapter 3: Basins due to lithospheric stretching
Chapter 4: Basins due to flexure
Chapter 5: Effects of mantle dynamics
Chapter 6: Basins associated with strike-slip deformation

SECTION 3 THE SEDIMENTARY BASIN-FILL
Chapter 7: The sediment routing system
Chapter 8: Basin stratigraphy
Chapter 9: Subsidence and thermal history

SECTION 5 APPLICATION TO PETROLEUM PLAY ASSESSMENT
Chapter 10: The petroleum play

References

Allen, P. A. & J. R. Allen, 2005, *Basin Analysis: Principles & Applications*: Blackwell Science., Oxford, UK, 549 pp.

Busby, C. J. & R. V. Ingersoll, 1995, *Tectonics of sedimentary basins:* Blackwell Science, Oxford, UK, 579 pp.

Watts, A. B., 2001, *Isostasy and flexure of the lithosphere*: Cambridge University Press, Cambridge, UK, 458 pp.

Course Schedule

Classes: 14 September ~ 3 November 2022
Midterm exam: 2 November 2022
Classes: 9 November 2022 ~ 28 December 2022
Final exam: 4 January 2023

Grading

Midterm exam 45%
Final exam 45%
Assignments 10%

SECTION 1 THE FOUNDATIONS OF SEDIMENTARY BASINS

Chapter 1 Basins in their plate tectonic environment

1.1 Compositional zonation of the Earth

1.1.1 Oceanic crust

1.1.2 Continental crust

1.1.3 Mantle

1.2 Rheological zonation of the Earth

1.2.1 Lithosphere

1.2.2 Sub-lithospheric mantle

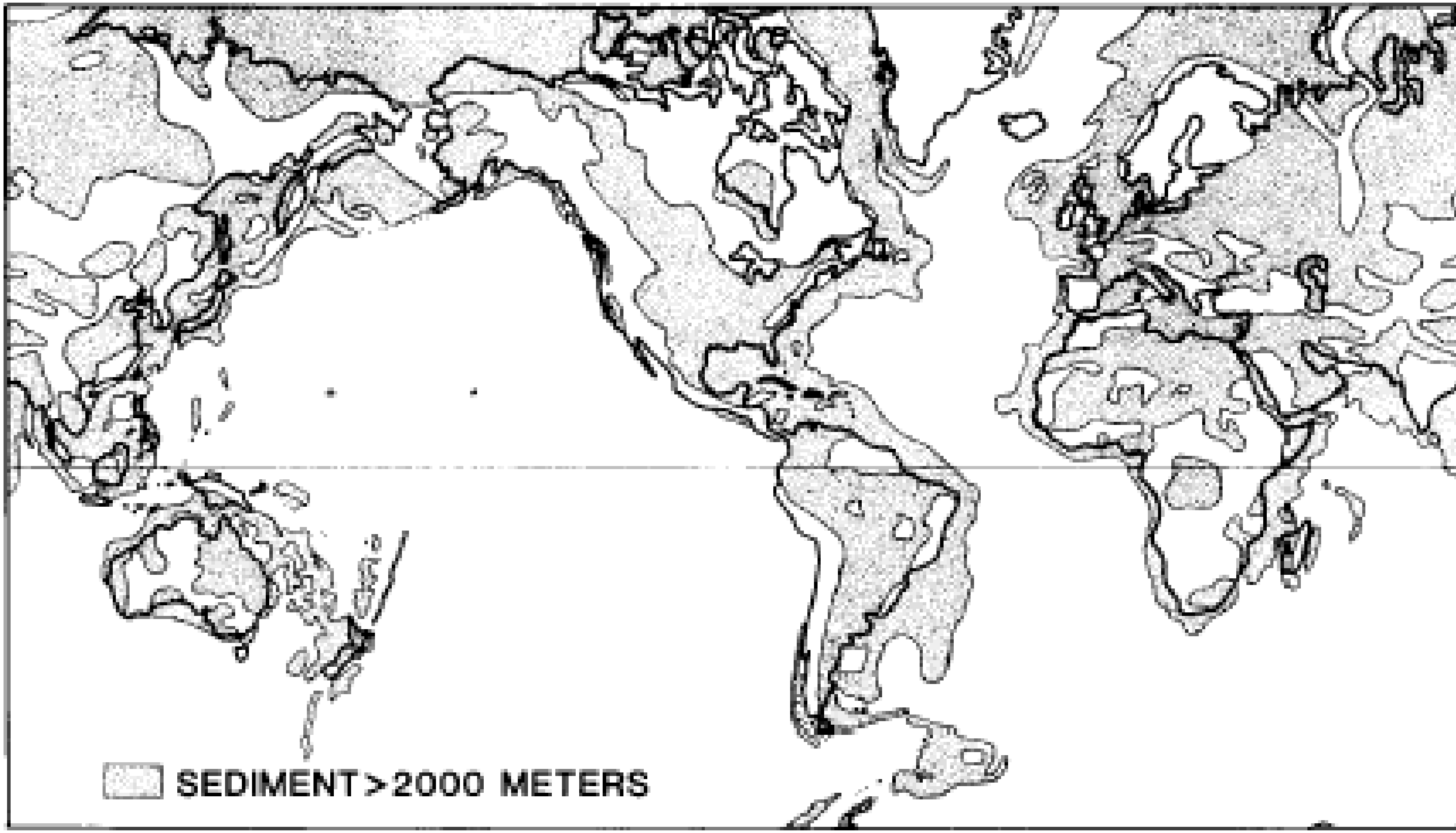
1.3 Plate motion

1.4 Classification schemes of sedimentary basins

1.4.1 Basin-forming mechanisms

What is a sedimentary basin?

A sedimentary basin is an area where long-term basement subsidence and sediment deposition occur.



Approximately 70% of the continental crust is covered by more than 2 km of sediments. The major accumulations occur in sedimentary basins and on continental shelves.

1.1 Compositional zonation of the earth

地球內部分層

以成分分層(chemical)

地殼：海洋(5-15 km; ave. 7 km):成分：玄武岩(以olivine為主，ρ~2950 kg m^{-3}; Vp = 2~7.6 km/s);
大陸地殼(0-40 km; ave. 38 km):成分：花崗岩(quartz，ρ~2650-2950 kg m^{-3} ;Vp = 2~7 km/s)
莫荷不連續面(15-40 km)
地函：
上部地函：15-40~420 km，固態，上部地函低速帶420km處P、S波不連續，橄欖岩(主要礦物為olivine, ρ~3250 kg m^{-3}; mantle immediately beneath Moho @Vp = 8.1 km/s)
過渡帶：420-670km，一連串的固態相變、$MgAl_2O_4$-spinel尖晶石
下部地函：670-2740 km, 固態$MgSiO_3$-perovskite鈣鈦礦
D"過渡層：2740-2889 km固態(可能有液態物)
外地核：2889-5100 km，液態(可能有對流)(Fe,Ni,O)
F過渡層：4570-5153 km，液態(可能有放射物)
內地核： 5153-6371 km ，固態(Fe,Ni)

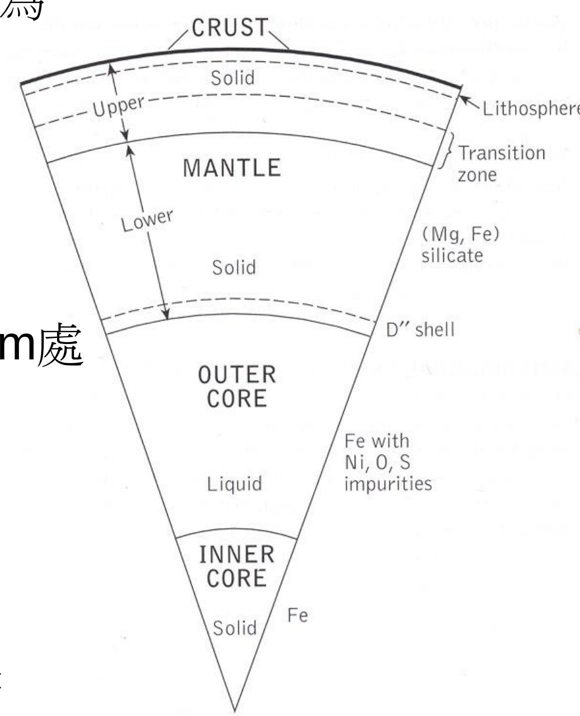


Fig. 1. The major internal divisions of the Earth. The crust and mantle are silicates and the core is predominantly iron. The crust and mantle are solid, the outer core is liquid and the inner core solid.

Hancock et al. (2000)

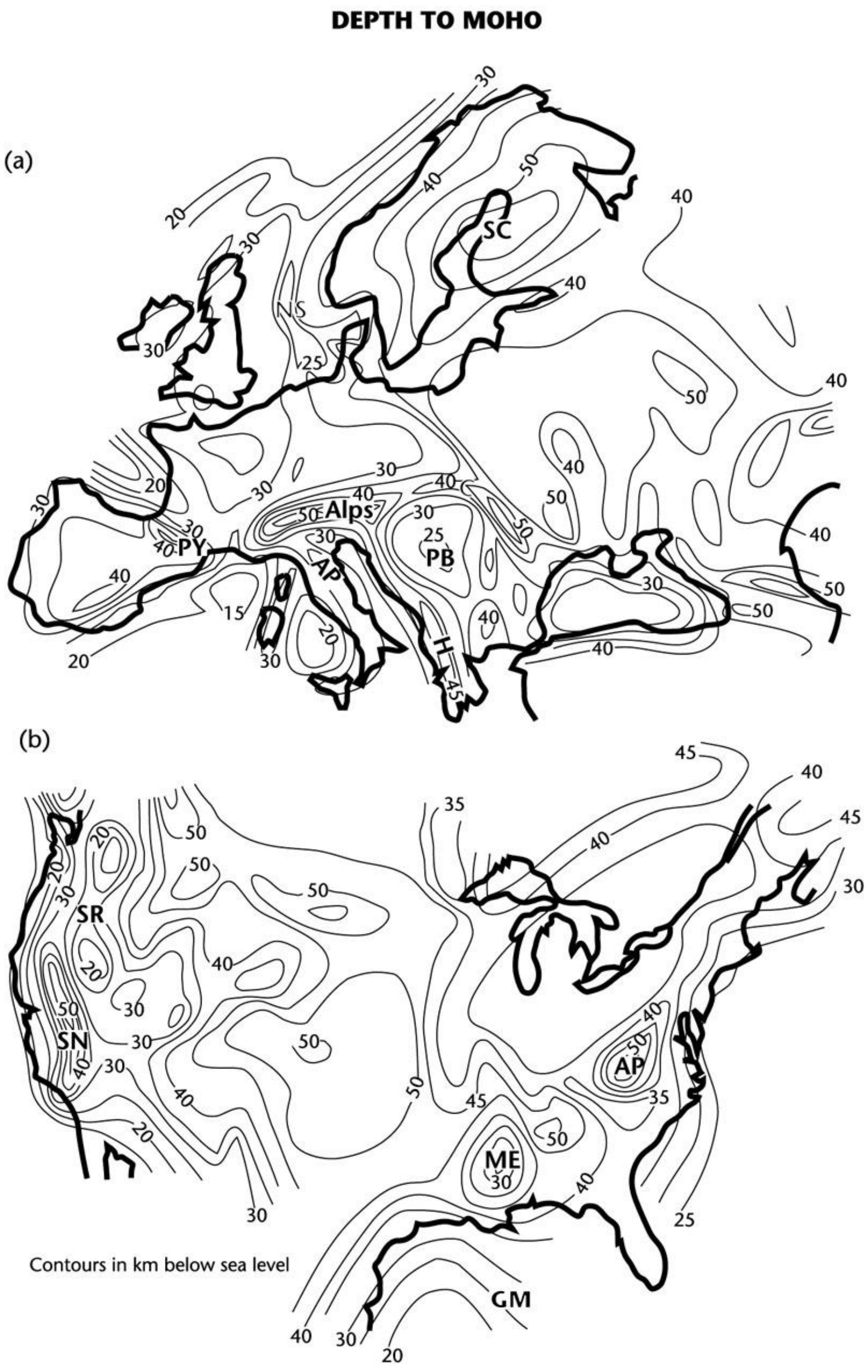


Fig. 1.2 Depth to the Moho below sea-level from (a) Europe and (b) North America, after Allenby and Schnetzler (1983) and Meissner (1986). In Europe, **thick continental crust** occurs in the Pyrenean-Alpine-Carpathian **orogenic belt** and in the Scandinavian Shield. **Thin continental crust** occurs along the **Atlantic margin** and in regions of **continental stretching**, such as the North Sea, western Mediterranean, Pannonian Basin, and Black Sea. In North American, thick continental crust is associated with the batholiths of the Sierra Nevada region, the Appalachian orogenic belt, the American midcontinent and the Canadian-NE USA shield. Thin crust is associated with the plateau basalts of the Snake River area, sites of rifting such as the Mississippi Embayment, and along the western active continental margin, eastern passive continental margin and the Gulf of Mexico. NS, North Sea; SC, Scandinavian Shield; PY, Pyrenees; AP, Apennines; PB, Pannonian Basin; H, Hellenides; SR, Snake River; SN, Sierra Nevada; ME, Mississippi Embayment; AP, Appalachians; GM, Gulf of Mexico.

1.2 Rheological zonation of the earth

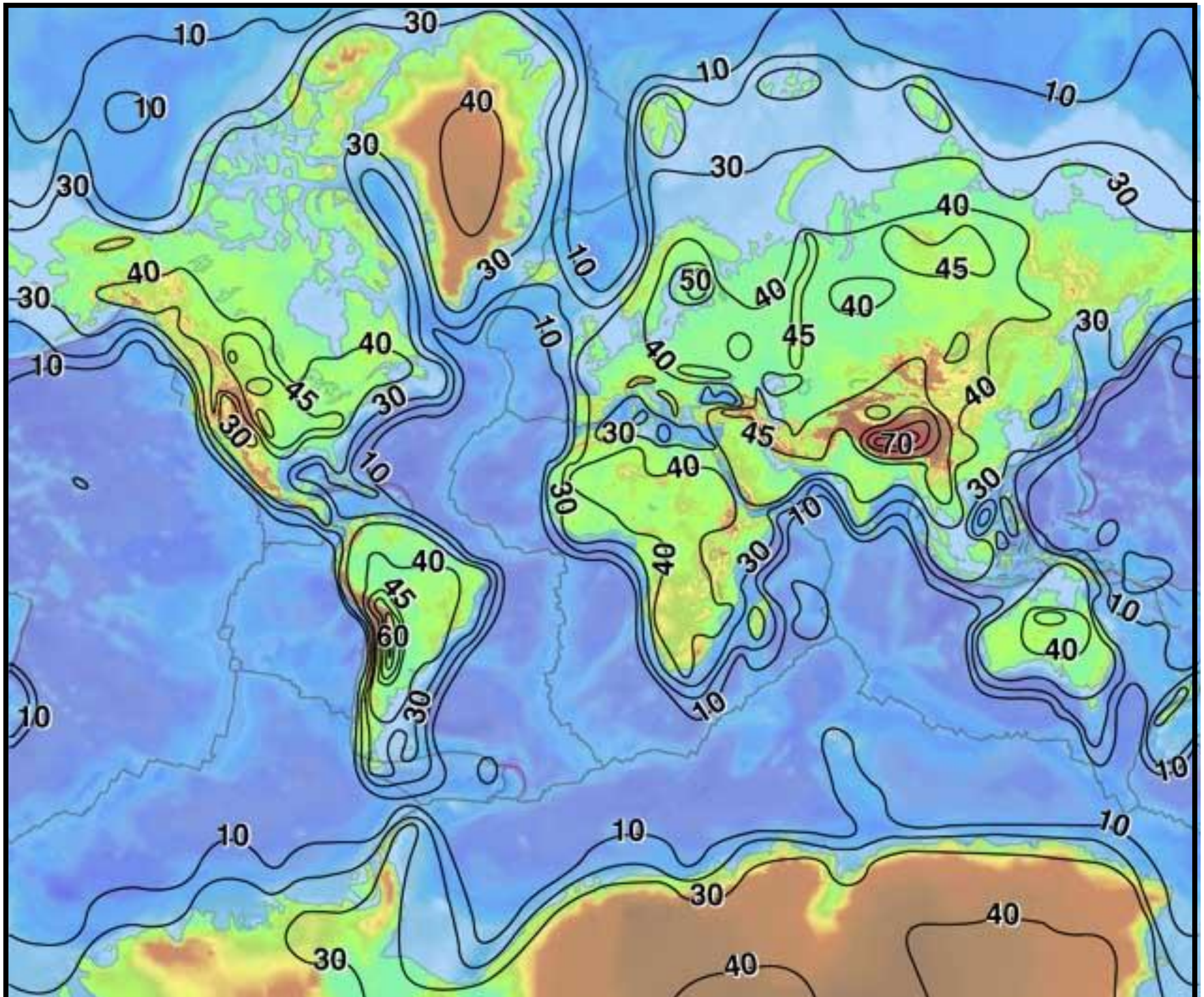
以物理性質分層(Physical)

岩石圈(lithosphere): (4~100-200 km)
地球的最表層，基本上是一個剛性體(essentially a rigid solid)，厚度約100-200公里，位於軟流圈(asthenosphere)的上方。由地殼和地函的最上部(lithospheric mantle，not upper mantle)所組成。

軟流圈(asthenosphere "Greek meaning weak sphere") (100-200km to 670 km) (effective viscosity:10^{19} to 10^{21} Pa s (Pascal second) (Mantle as a whole is of 10^{21} Pa s and 10^{13} Pa s for water. Measurement of the viscosity of asthenosphere by the post-glacial deformation.
位於岩石圈下面的上部地函，受力時呈韌性變形/流動(plastic deformation)，可使上覆的岩石圈達到均衡(isostatic)狀態。

中層圈(mesosphere)(670~2889 km, 現在已很少用)

Thickness of the Earth's crust (in km)



From USGS at : http://earthquake.usgs.gov/research/structure/crust/index.php

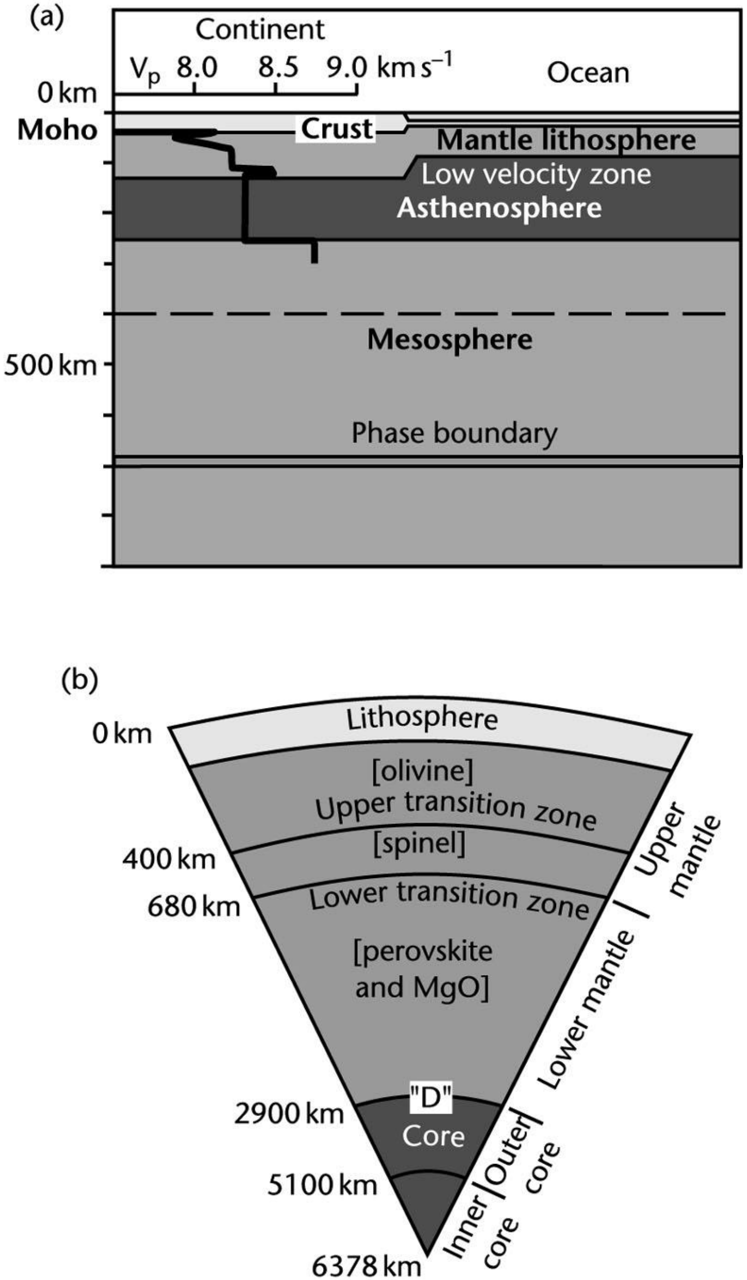


Fig. 1.1 The main compositional (a) and rheological (b) boundaries of the Earth. The most important compositional boundary is between crust, mantle and core, There are strong compositional variations within the continental crust and compositional variations caused by phase changes in the mantle. Vp is velocity of P wave. The main rheological boundary is between the lithosphere and the asthenosphere. P wave velocities increase markedly beneath the Moho, but decrease in a low velocity zone representing the weak asthenosphere. The lithosphere is rigid enough to act as a coherent plate. P wave velocity in (a) from western Europe after Hirn (1976).

Where does the subducted lithosphere go?

The upper/lower mantle boundary or
The core/mantle boundary (“D” layer)?

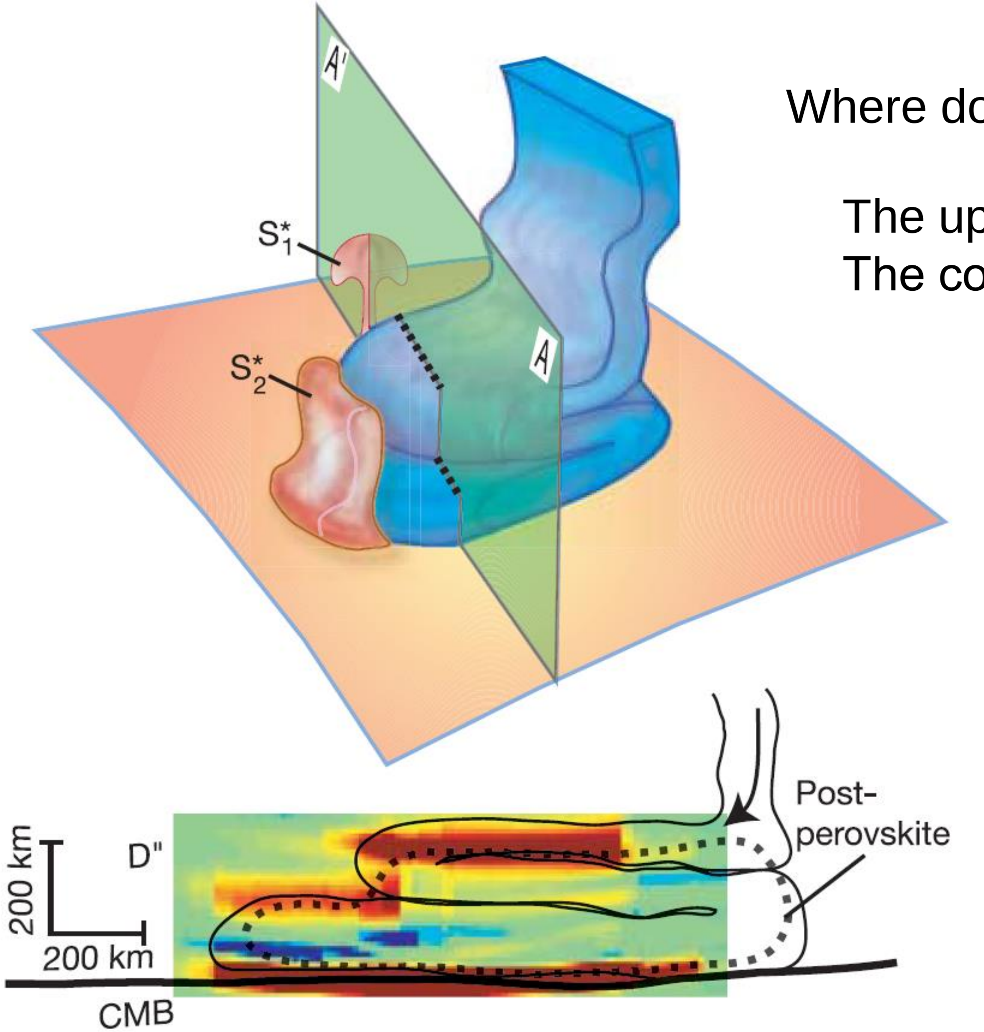
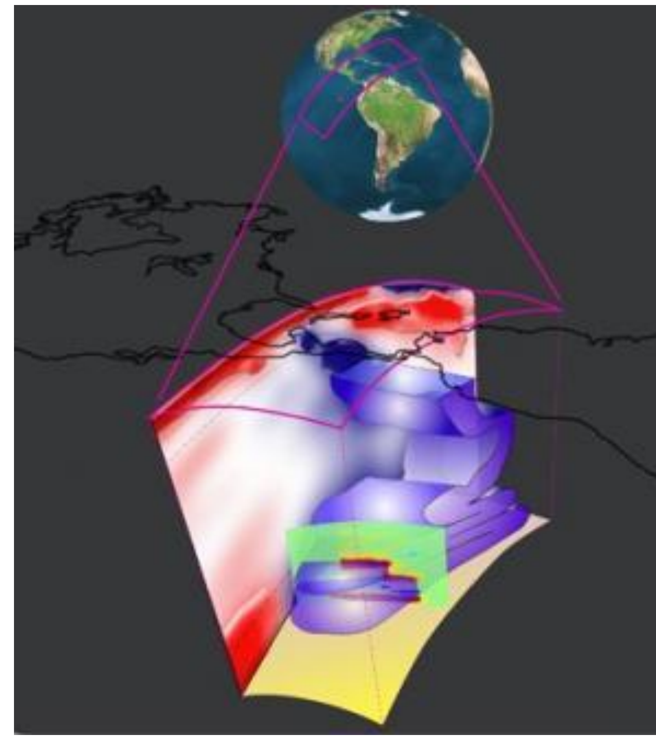


Figure 4 | A cold buckled subducted slab (blue) in the lowermost mantle may account for the thermal structure that results in a step in the perovskite/post-perovskite phase transition.

Hutko et al. (2006) Nature doi:10.1038/nature04757.

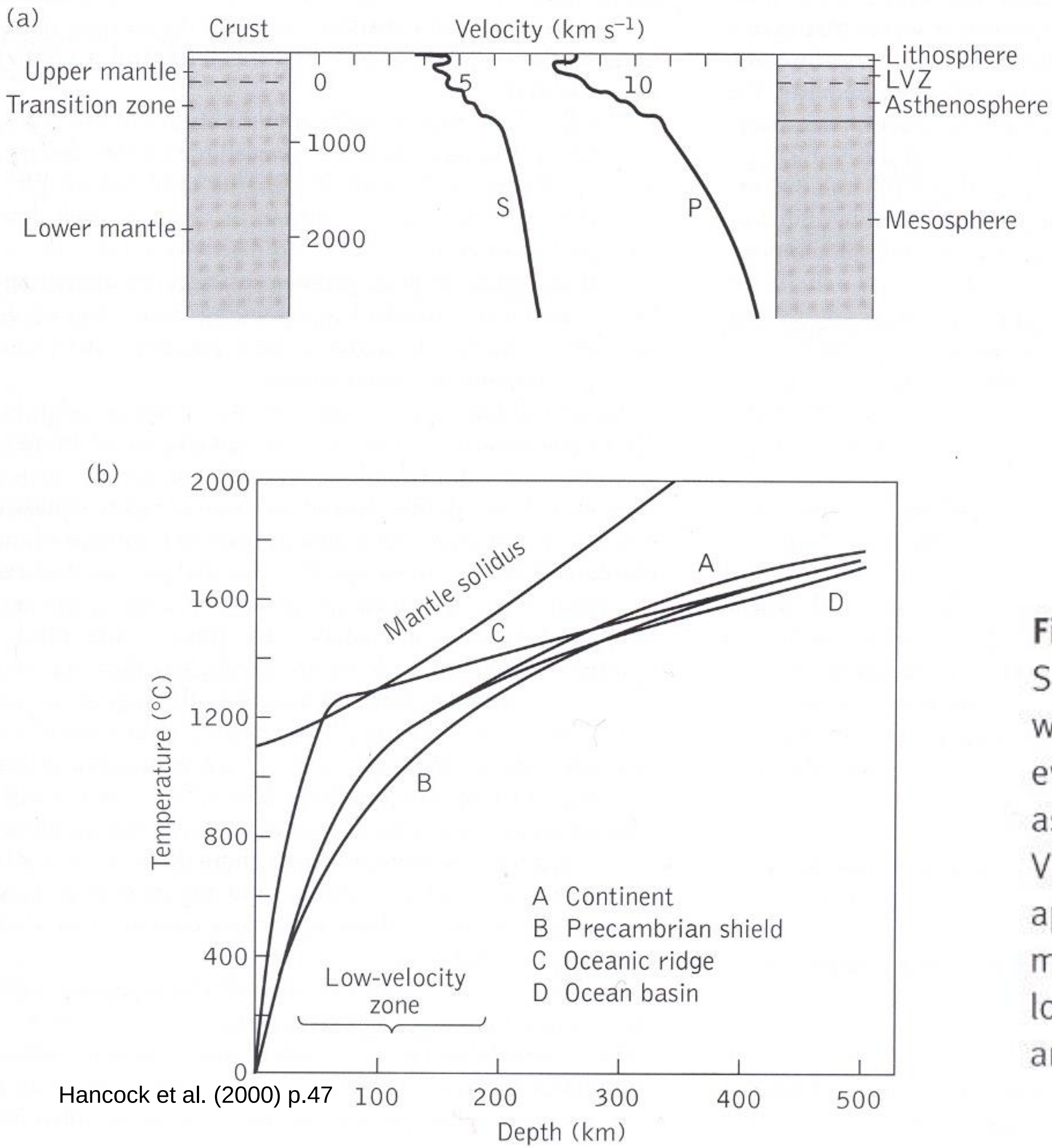


The oceanic lithosphere sunk into the mantle and lies on top of the core-mantle boundary (“D” layer).

↑

http://www.sciencedaily.com/releases/2006/06/060603092903.htm

Low velocity zone(深度約100-300 km) 以海洋岩石圈最清楚；地盾處的大陸岩石圈最不清楚。LVZ可用少量的部份熔融來解釋(如左圖的b) 。Seismic lithosphere的厚度隨岩石圈的年齡增加而增加：以海洋岩石圈為例﹔20 Ma—10 km; 70 Ma—80km



Hancock et al. (2000) p.47

Fig. 1. (a) The P- and S-wave low-velocity zone (LVZ), which provides the primary evidence for a worldwide asthenosphere. (From Kearey and Vine (1996), Fig. 2.16.) (b) Close approach of the geotherm to the mantle solidus at the depth of the low-velocity zone. (After Kearey and Vine (1996), Fig. 2.36.)

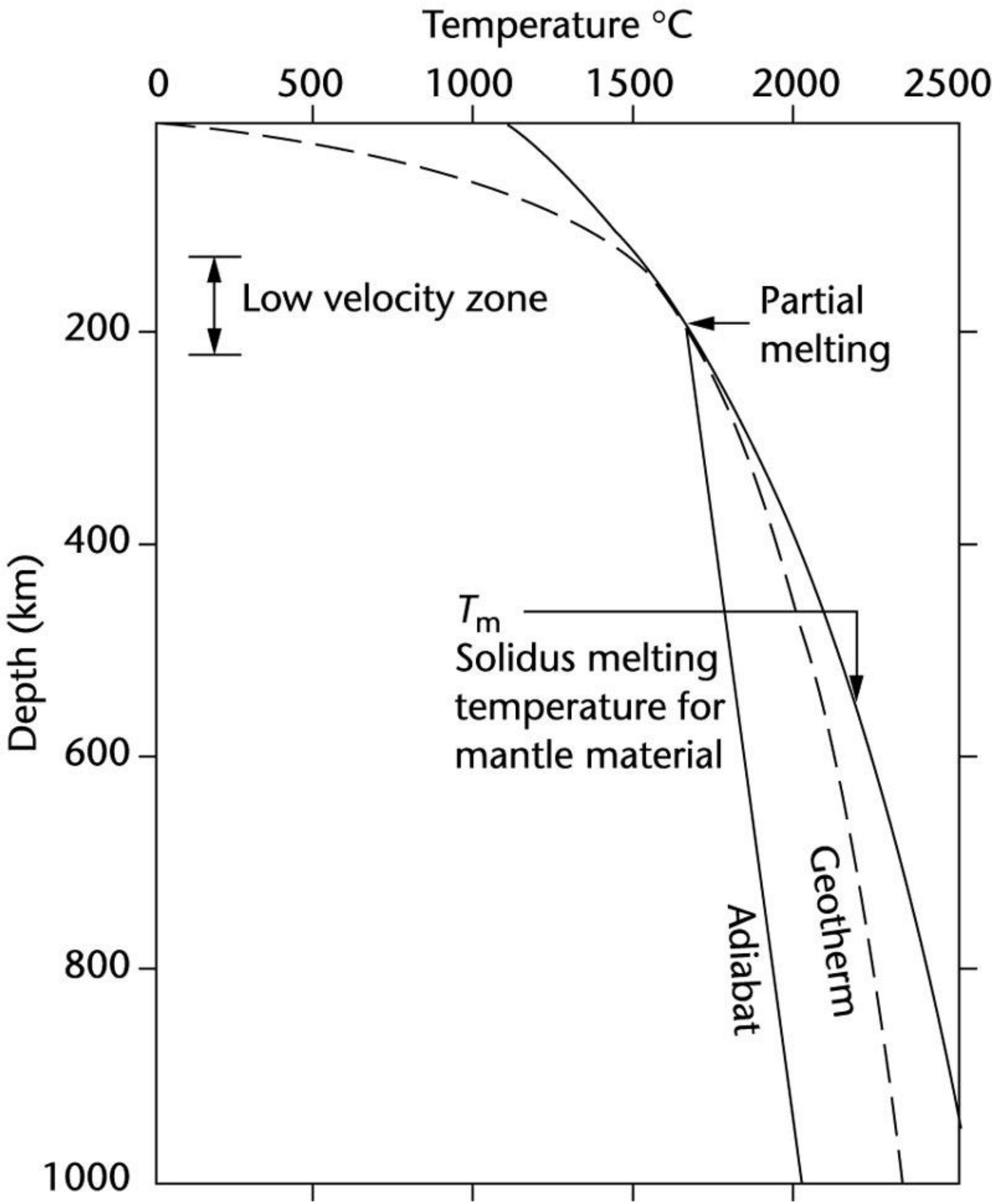


Fig. 1.4 Variation of temperature with depth, or geotherm, and the solidus temperature for mantel material (peridotite). Where the solidus curve (T_m) and the geotherm become tangential, partial melting in the mantle is likely to take place, resulting in a zone of low seismic wave velocities (low velocity zone).

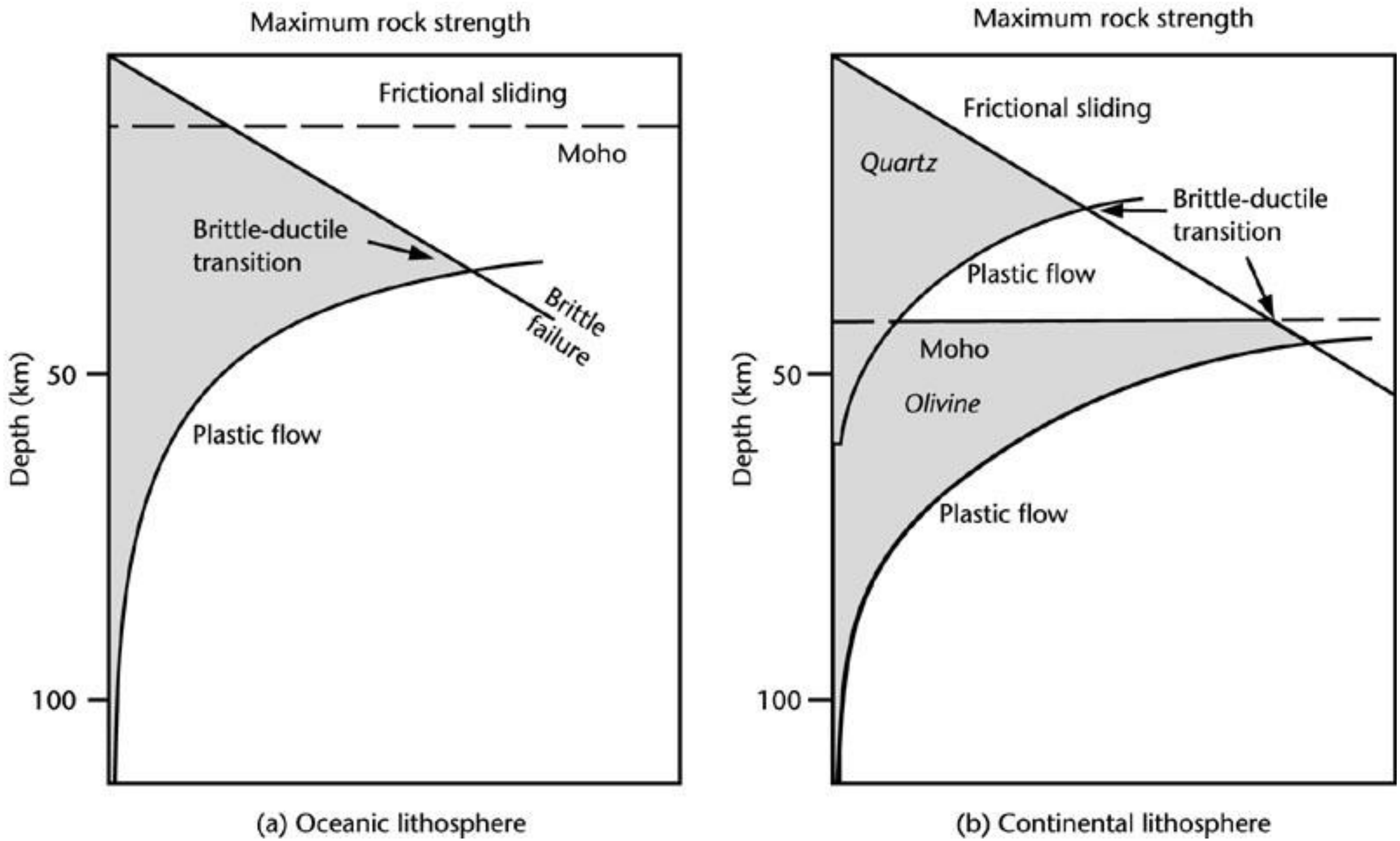


Fig. 1.3 Strength profiles for the oceanic (a) and continental (b) lithosphere, based on Molnar (1988) and Sammonds (1999). The yield strength of the continental and oceanic lithosphere is plotted as a function of depth. The olivine rheology of the oceanic lithosphere provides a strong elastic core extending to depths of over 50km. The quartz or quartz-felspar rheology of the continental lithosphere causes a weak, ductile layer at equivalent depths. A second brittle-ductile transition occurs in the mantle lithosphere because of the compositional change to an olivine rheology. The elastic lithosphere is the upper portion that is able to store elastic stresses over long time periods. The base of the thermal lithosphere is a mechanical boundary separating the relatively strong outer shell of the lithosphere from the very weak asthenosphere.

1.3 Plate motion

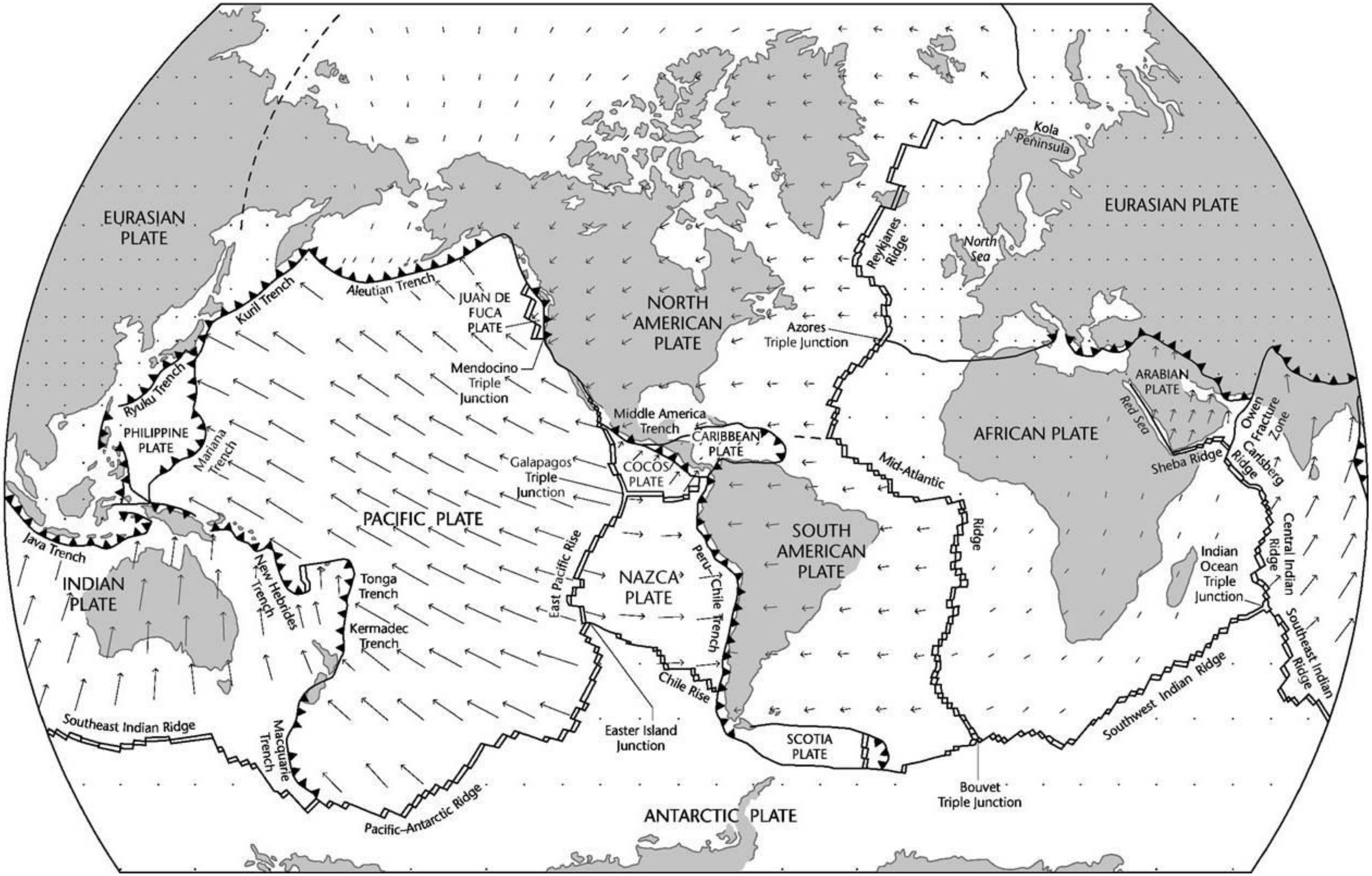


Fig. 1.5 The lithosphere plates, showing mid-ocean ridges, trenches, and transform boundaries (Le Pichon et al. 1973) and absolute motion vectors from Minster and Jordan (1978). Length of arrows is proportional to the plate speed. The fastest plate motion is in the western Pacific and Indian Oceans, whereas Africa, Antarctica, and Eurasia are almost stationary with respect to the mantle reference frame.

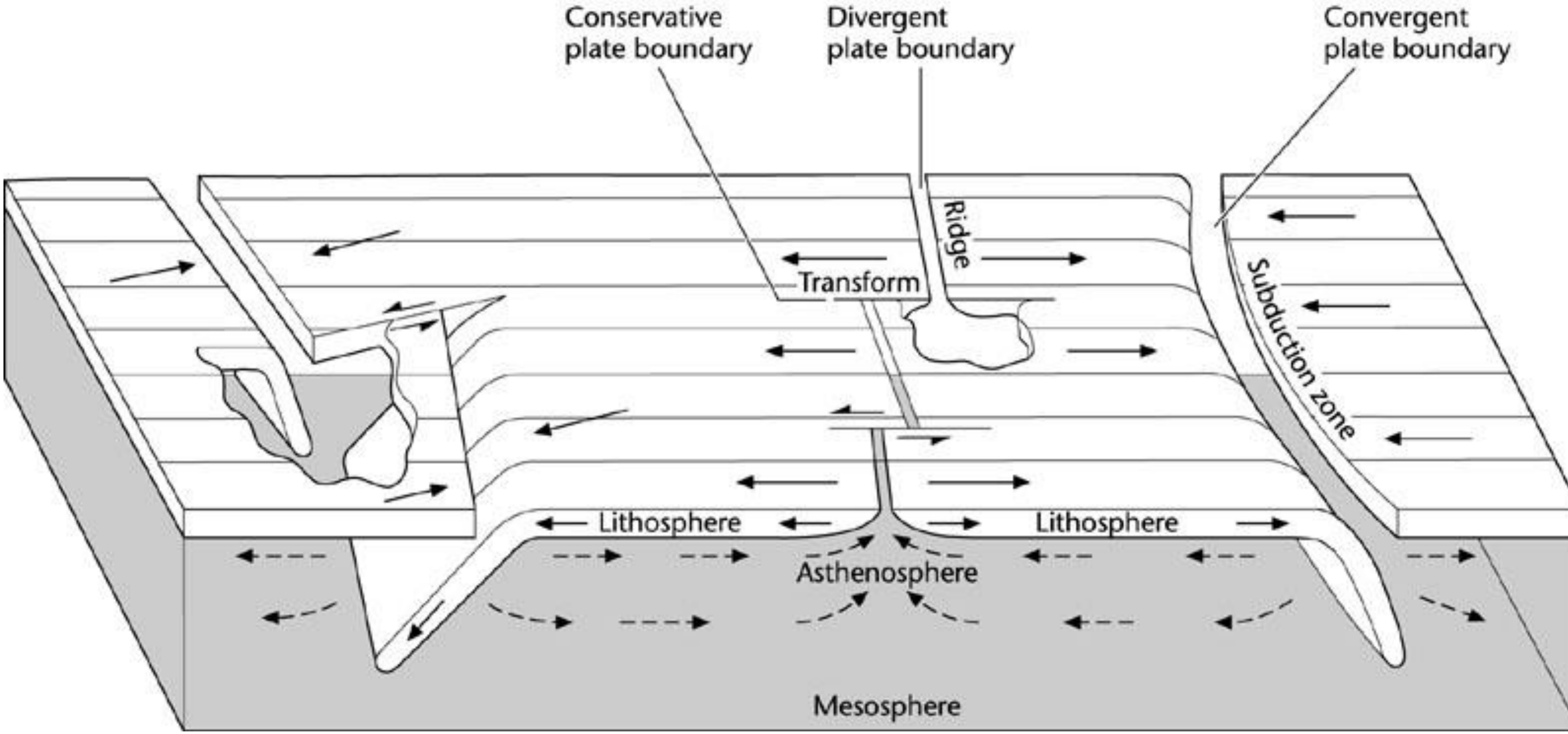


Fig. 1.6 The three types of plate boundary: convergent, divergent, and conservative.

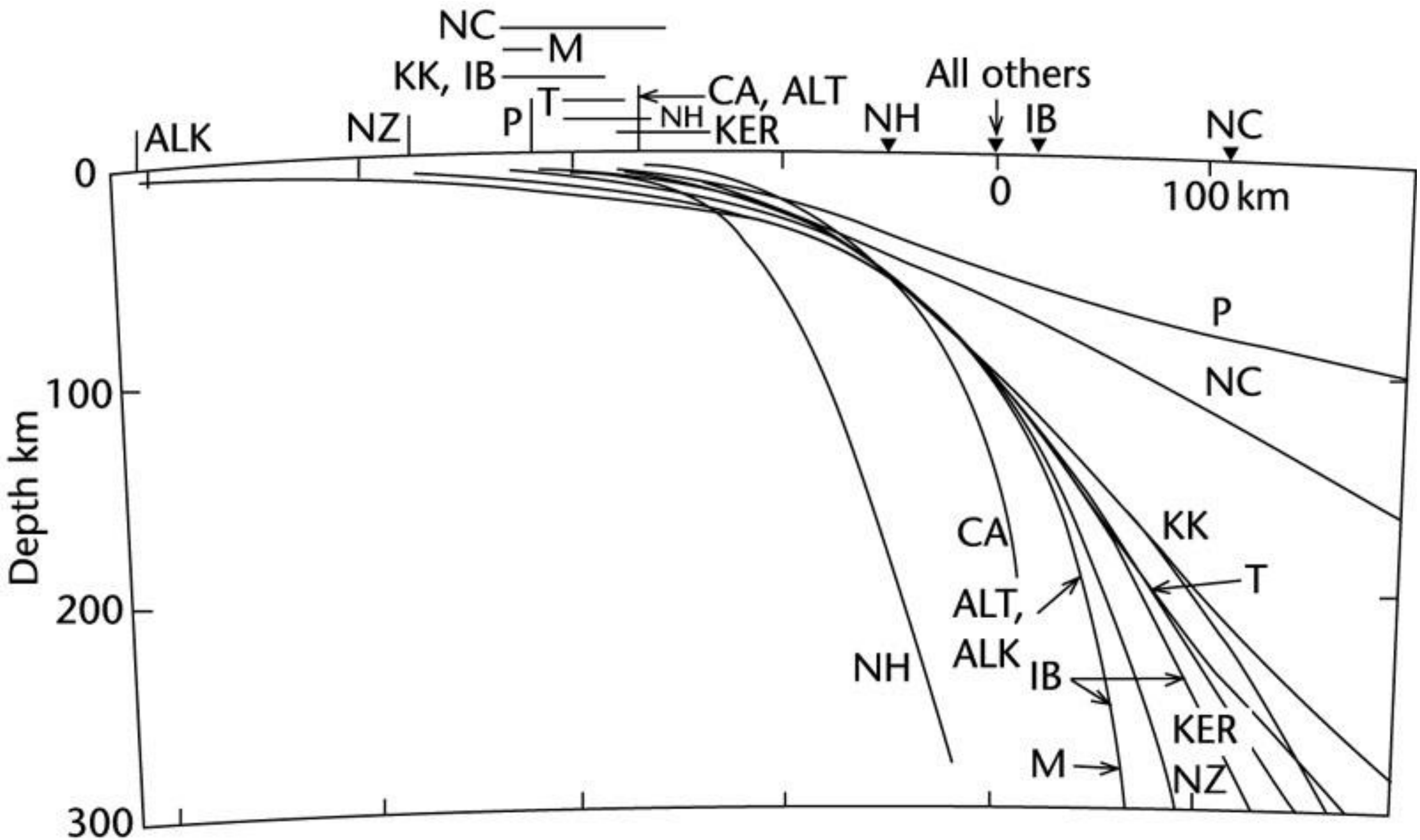


Fig. 1.7 Distribution of earthquake foci along Benioff zones, after Isacks and Barazangi (1977). NH, New Hebrides; CS, Central America; ALT, Aleutians; ALK, Alaska; M, Marianas; IB, Izu-Bonin; NZ, New Zealand; T, Tonga; KK, Kuril-Kamchatka; NC, North Chile; P, Peru.

1.4 Classification schemes of sedimentary basins

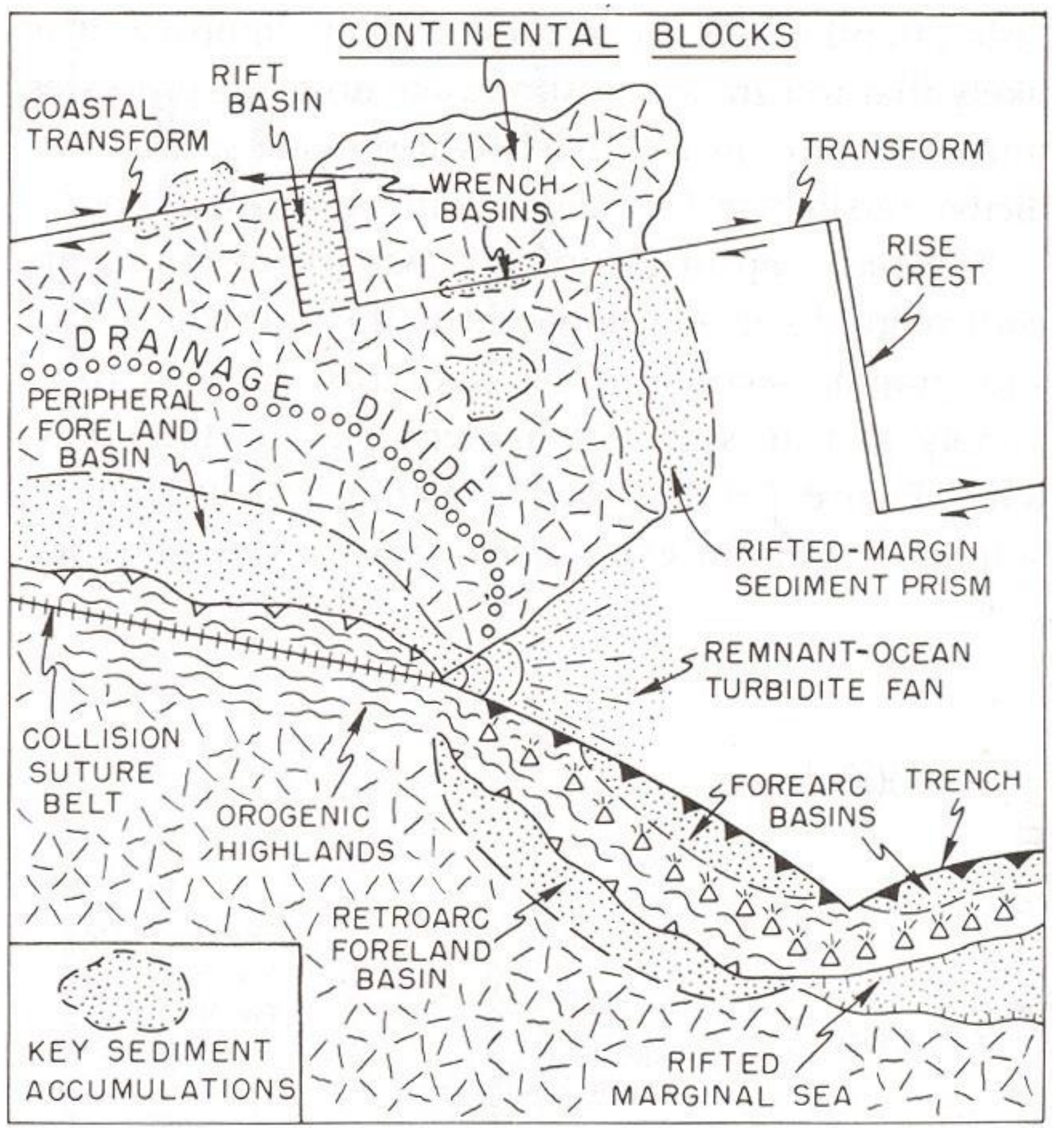
Basin classification based on:

1. Type of basement (continental, oceanic, transitional, anomalous?)

2. Proximity to plate boundary(s)

3. Type of nearest plate boundary(s) (divergent, convergent, transform)

"Classifications are theories about the basis of natural order"



Sites of key basins in relation to plate boundaries, continental margins and associated sources of detrital sediment (Busby & Ingersoll, 1995)

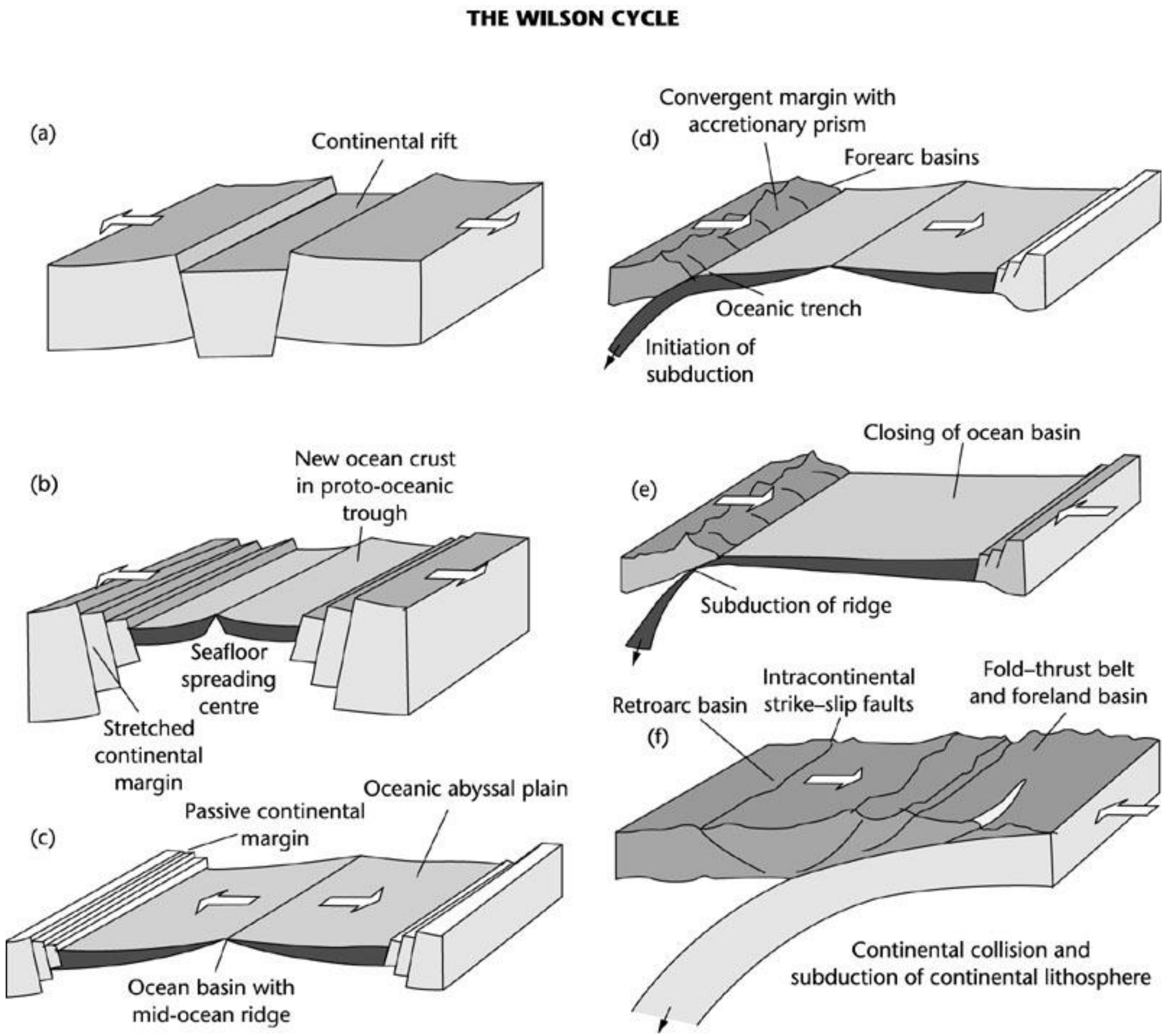
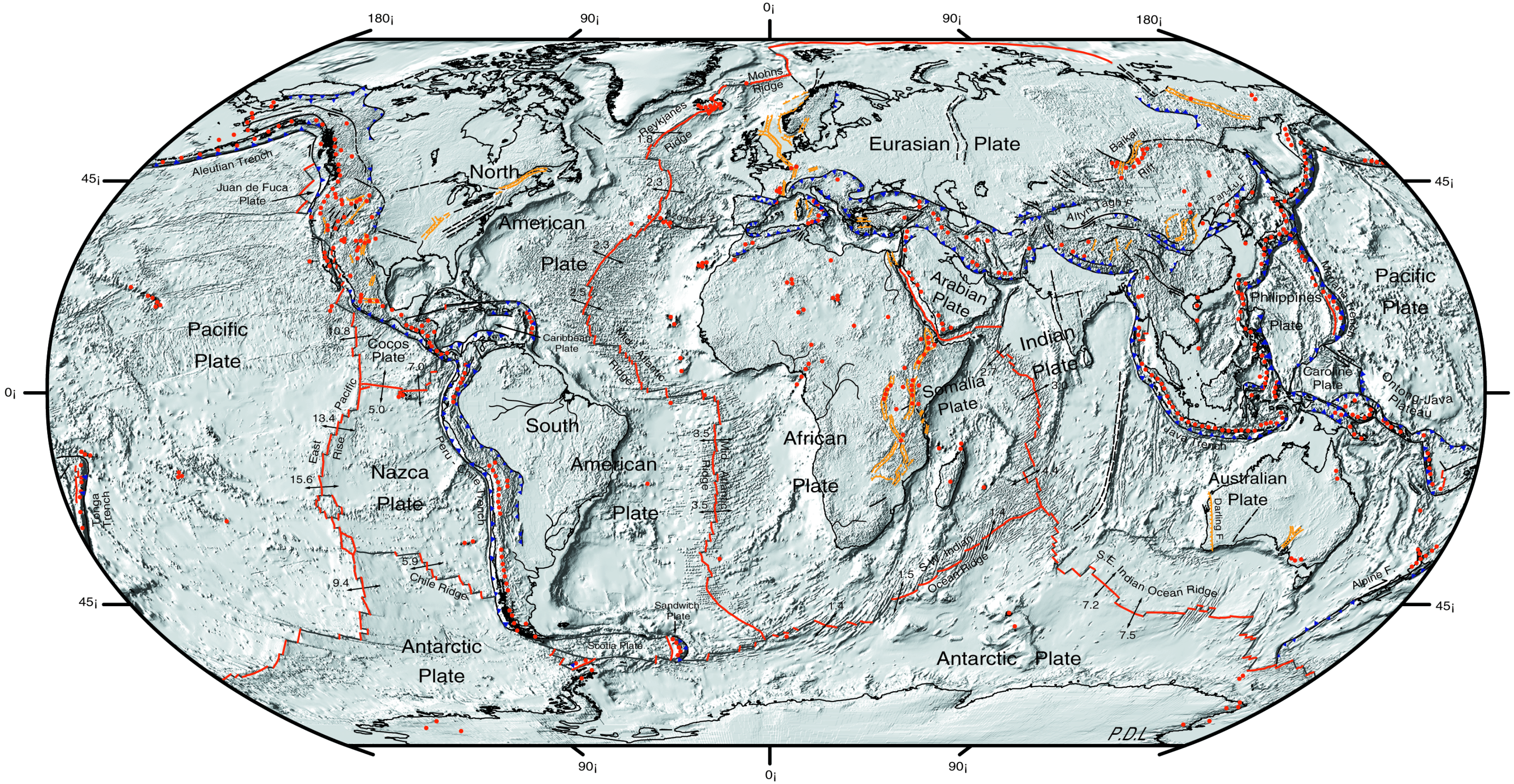


Fig. 1.8 The Wilson cycle of ocean formation and ocean closure. Continental extension (a) is followed by the creation of a new oceanic spreading centre (b) and ocean enlargement (c). Subduction of ocean floor (d) leads to closure of the ocean basin. Subduction of the oceanic ridge (e) takes place before continent-continent collision (f).

Tectonic Activity Map of the Earth



DIGITAL TECTONIC ACTIVITY MAP OF THE EARTH
Tectonism and Volcanism of the Last One Million Years

DTAM

NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

Robinson Projection
October 1998

LEGEND

- Actively-spreading ridges and transform faults
- Total spreading rate, cm/year, NUVEL-1 model (DeMets et al., Geophys. J. International, 101, 425, 1990)
- Major active fault or fault zone; dashed where nature, location, or activity uncertain
- Normal fault or rift; hachures on downthrown side
- Reverse fault (overthrust, subduction zones); generalized; barbs on upthrown side
- Volcanic centers active within the last one million years; generalized. Minor basaltic centers and seamounts omitted.

Divergent to intraplate settings

Terrestrial rift valleys

Proto-oceanic rift troughs

Continental rises and terraces

Continental embankment

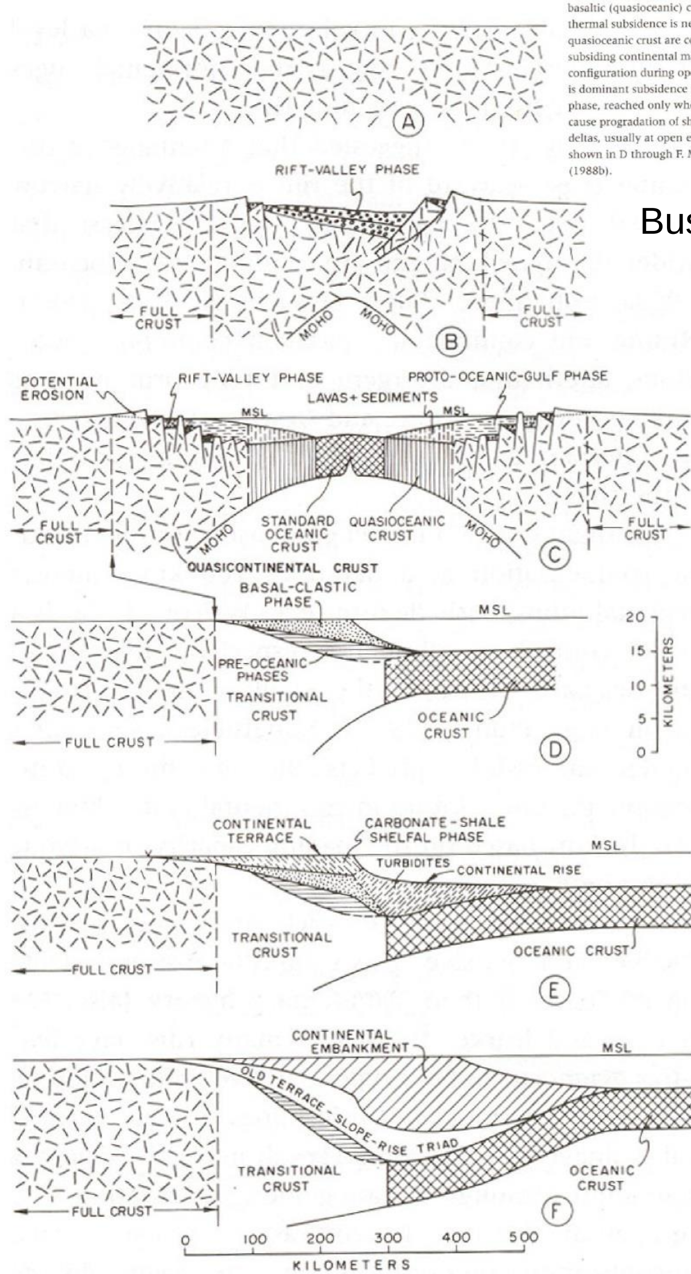


Figure 1.4 Schematic diagrams (vertical exaggeration 10X) to illustrate continental separation (that may "fail" at any time), with evolution from "normal" continental crust (A); to terrestrial-rift-valley phase (B); to proto-oceanic phase, showing terrestrial-rift-valley deposits on top of attenuated continental (quasicontinental) crust, adjacent to thickened basaltic (quasioceanic) crust (C); to end of proto-oceanic phase, when thermal subsidence is nearing completion; quasicontinental and quasioceanic crust are combined into "transitional crust," underlying subsiding continental margin (D); to continental terrace-slope-rise configuration during open-ocean phase, during which sediment loading is dominant subsidence mechanism (E); to continental-embankment phase, reached only where sediment delivery is voluminous enough to cause progradation of shoreline over oceanic crust (in areas of major deltas, usually at open ends of fossil rifts) (F). Only left side of ocean is shown in D through F. Modified from Dickinson (1976a) and Ingersoll (1988b).

Busby & Ingersoll (1995)

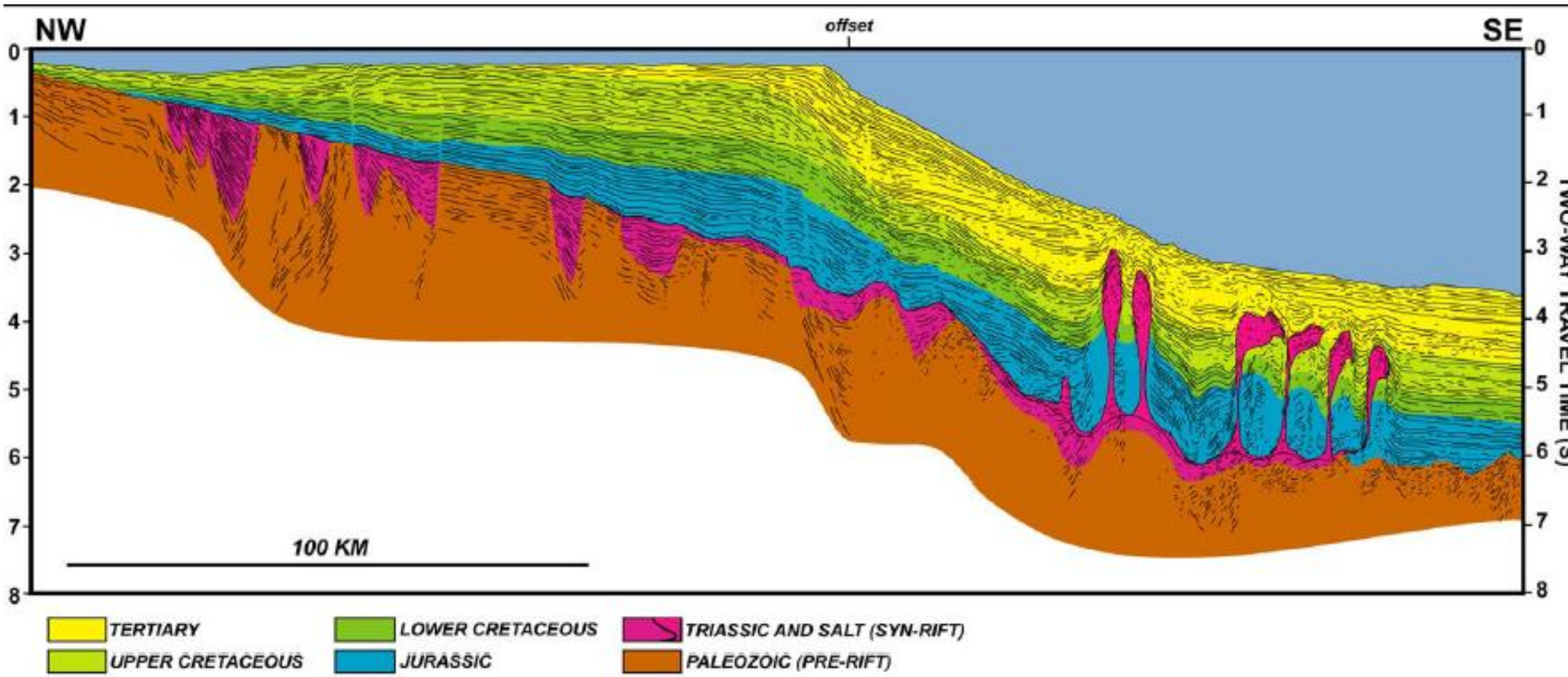
Movie shows the spreading of the oceanic crust, Red Sea.

young

Passive continental margins

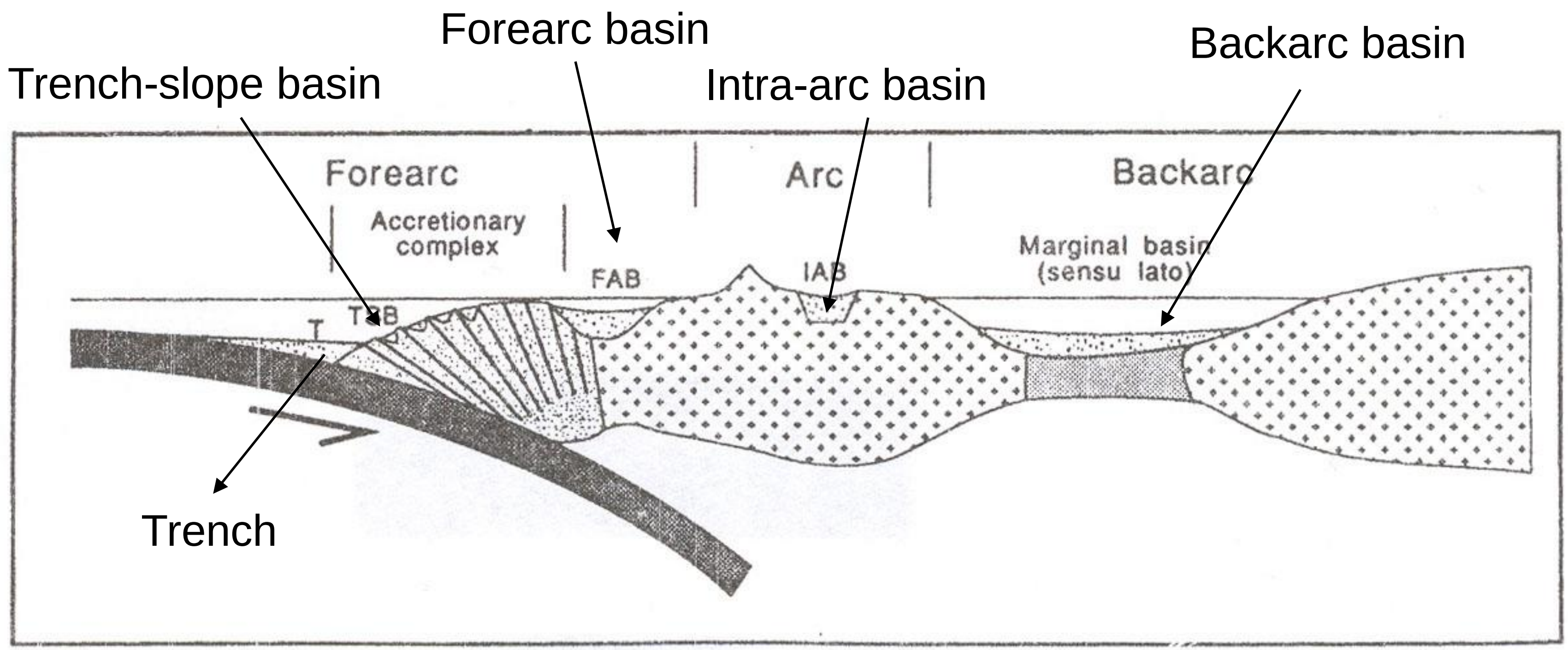
old

Passive margin: Lahave Plateau, Nova Scotia, Canada



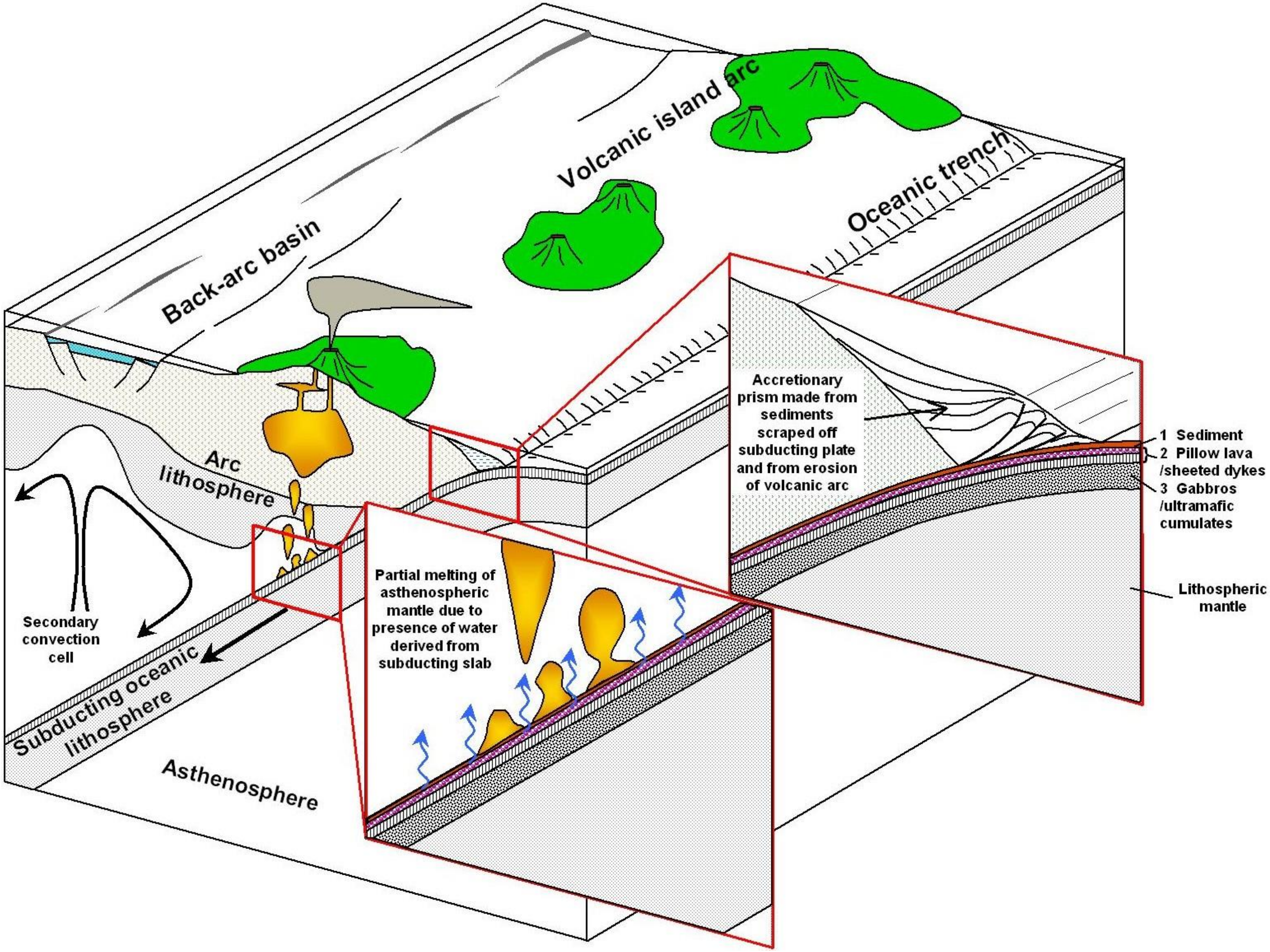
From Dr. Gabor C. Tari at http://www.aapg.org//education/dist_lect/slides/2001_02/tari02.pdf

Convergent setting – arc-trench system



the major sites of sediment accumulation at convergent margins discussed in this paper. T, trench; TSB, trench slope basin; FAB, fore-arc basin; IAB, intra-arc basin; note that an ensialic setting is shown here, but the terminology applies equally to intra-oceanic convergent margins.

Diagram to explain processes associated with subduction

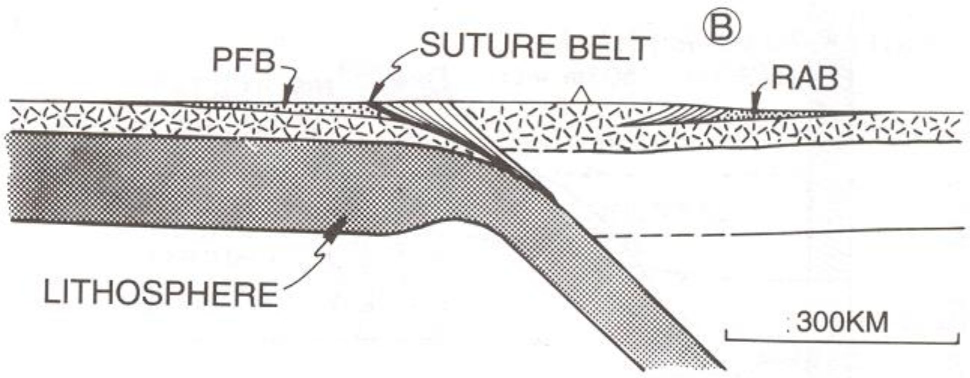


From: http://en.wikipedia.org/wiki/Subduction

Types of foreland basins

Peripheral foreland basin

Retroarc foreland basin



Busby & Ingersoll (1995)

(B) Relationship of peripheral foreland basin (PFB) and retroarc collisional foreland basin (RAB) to suture (reproduced with permission from Dickinson, 1976a). These two types of foreland basin are the subject of this chapter.

Movie shows subduction followed by continent-continent collision

Piggy-back basin

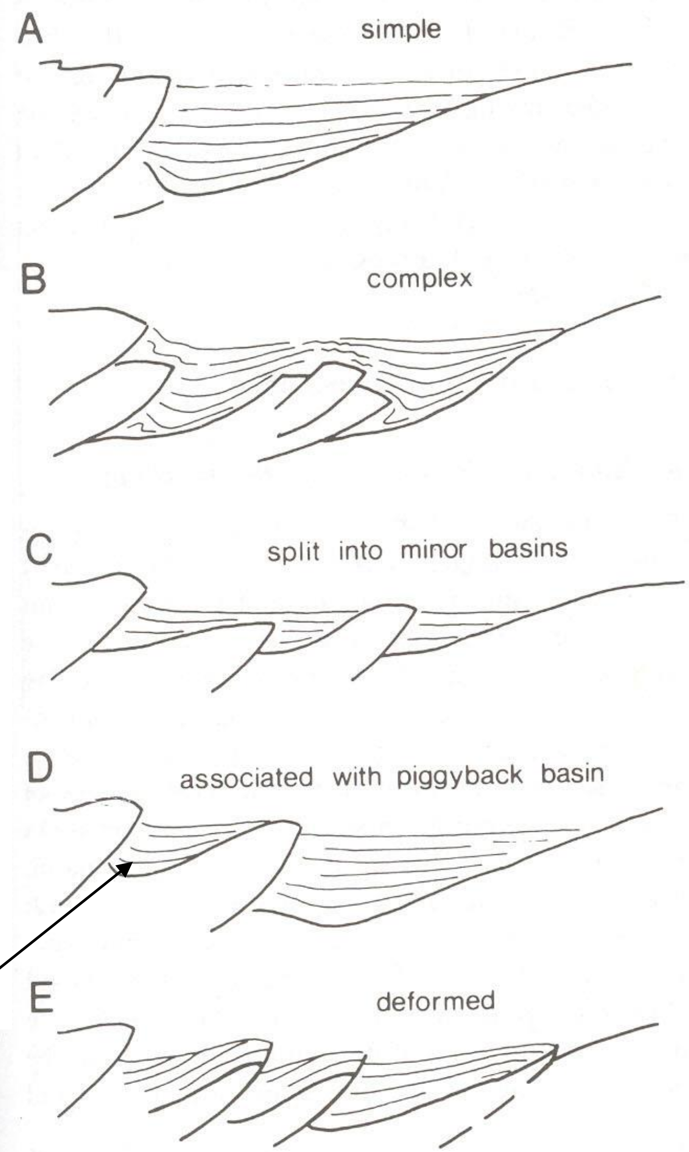


Fig. 11.14 Variations in relationship between fold-thrust belt and foreland basin, based on seismic profiles. Minor basins and piggyback basins are varieties of satellite basins. (Reproduced with permission from Ricci Lucchi, 1986.)

Transform settings (and transcurrent-fault-related basins)

Busby & Ingersoll (1995)

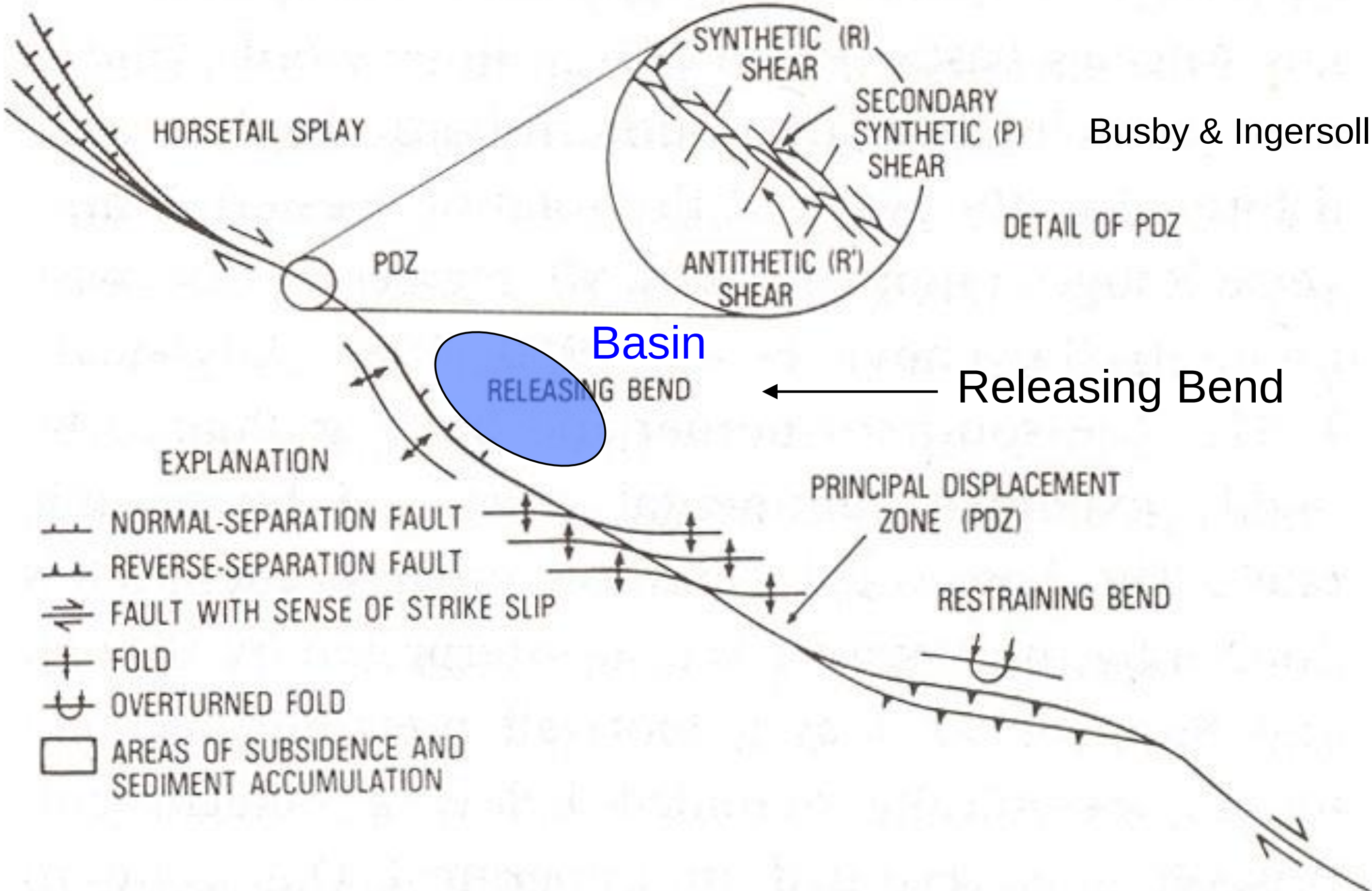
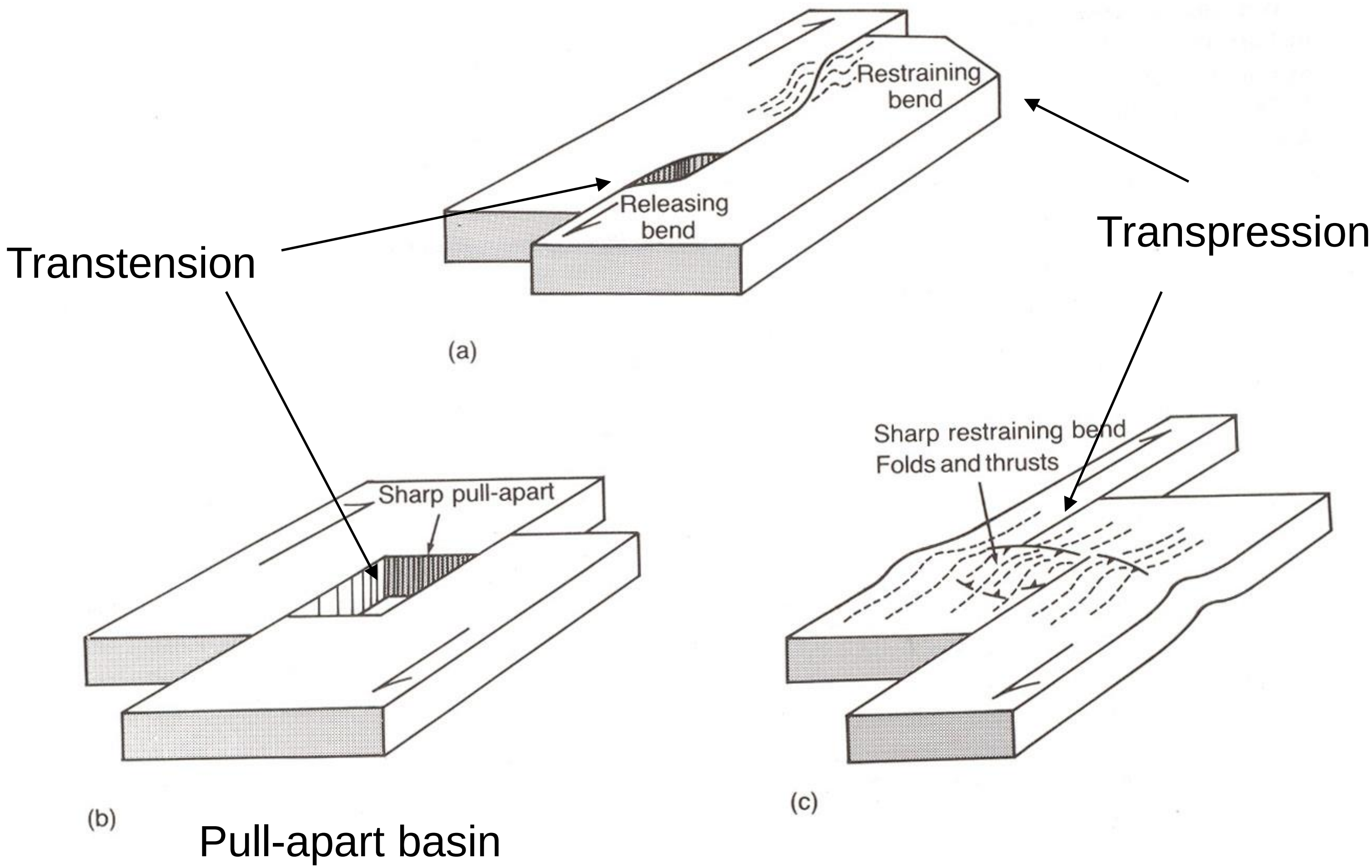


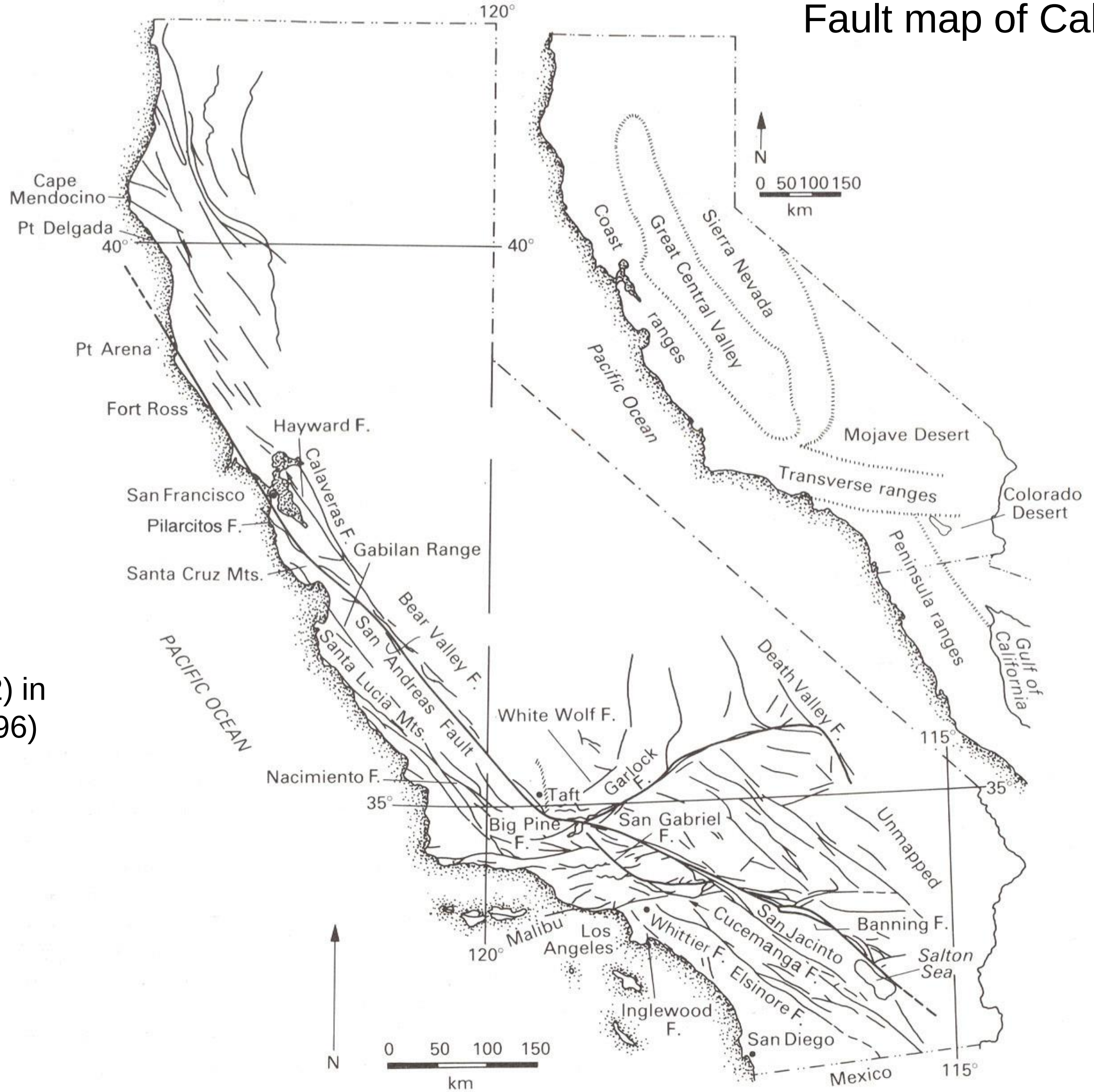
Figure 1.27 Spatial arrangement, in map view, of structures associated with an idealized right-slip fault. From Christie-Blick and Biddle (1985).

Structures developed along continental wrench faults



Fault map of California

Strike-slip faulting in west coast of N. America



from Crowell (1962) in Kearey & Vine (1996)

Transtensional basins in the California Borderland

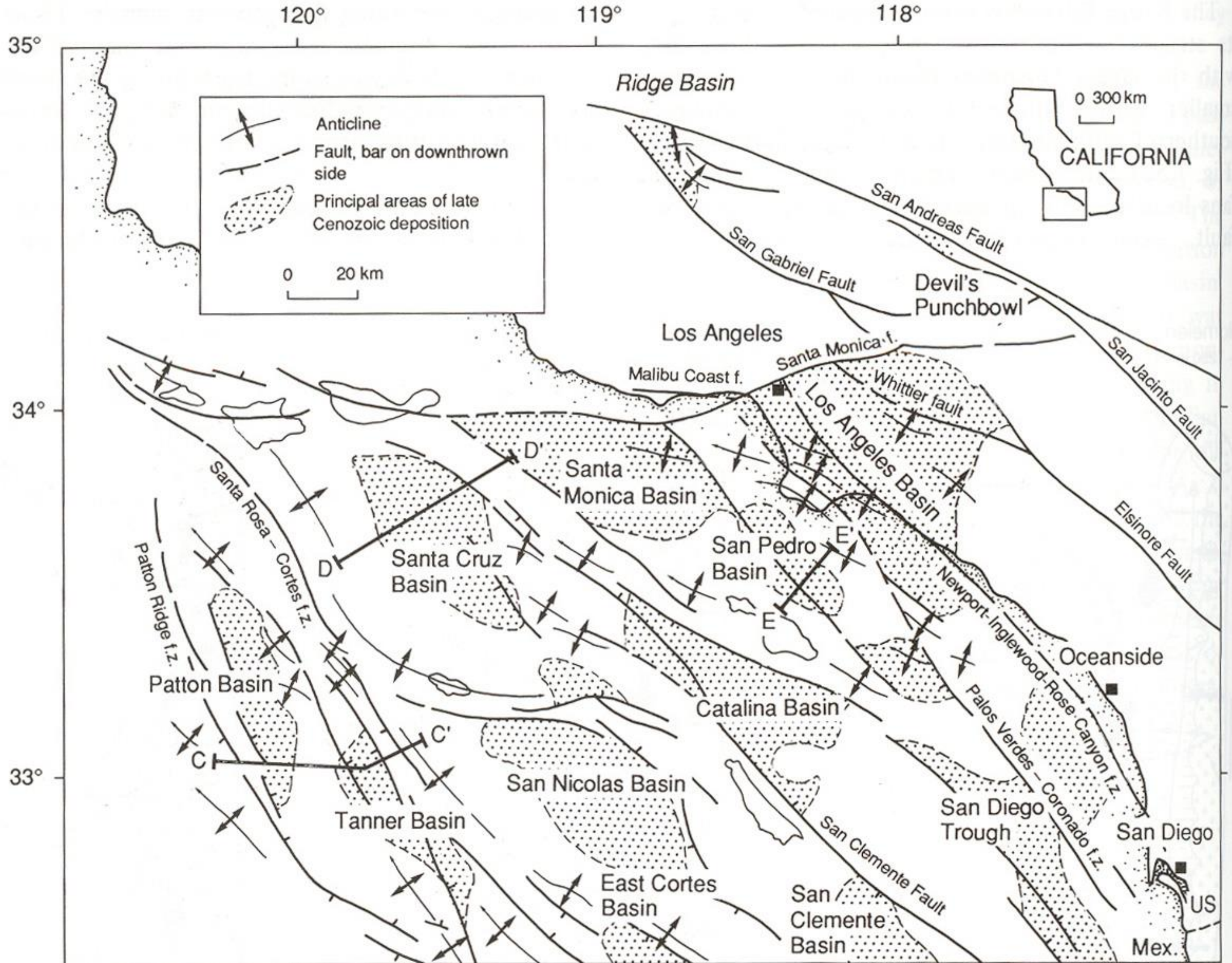


Fig. 7.53. The strike-slip tectonic framework of the California Borderland (Moore 1969, Junger 1976). C–C′, D–D′ and E–E′ are the lines of profiles shown in Fig. 7.54.

Allen & Allen (1990), p.256

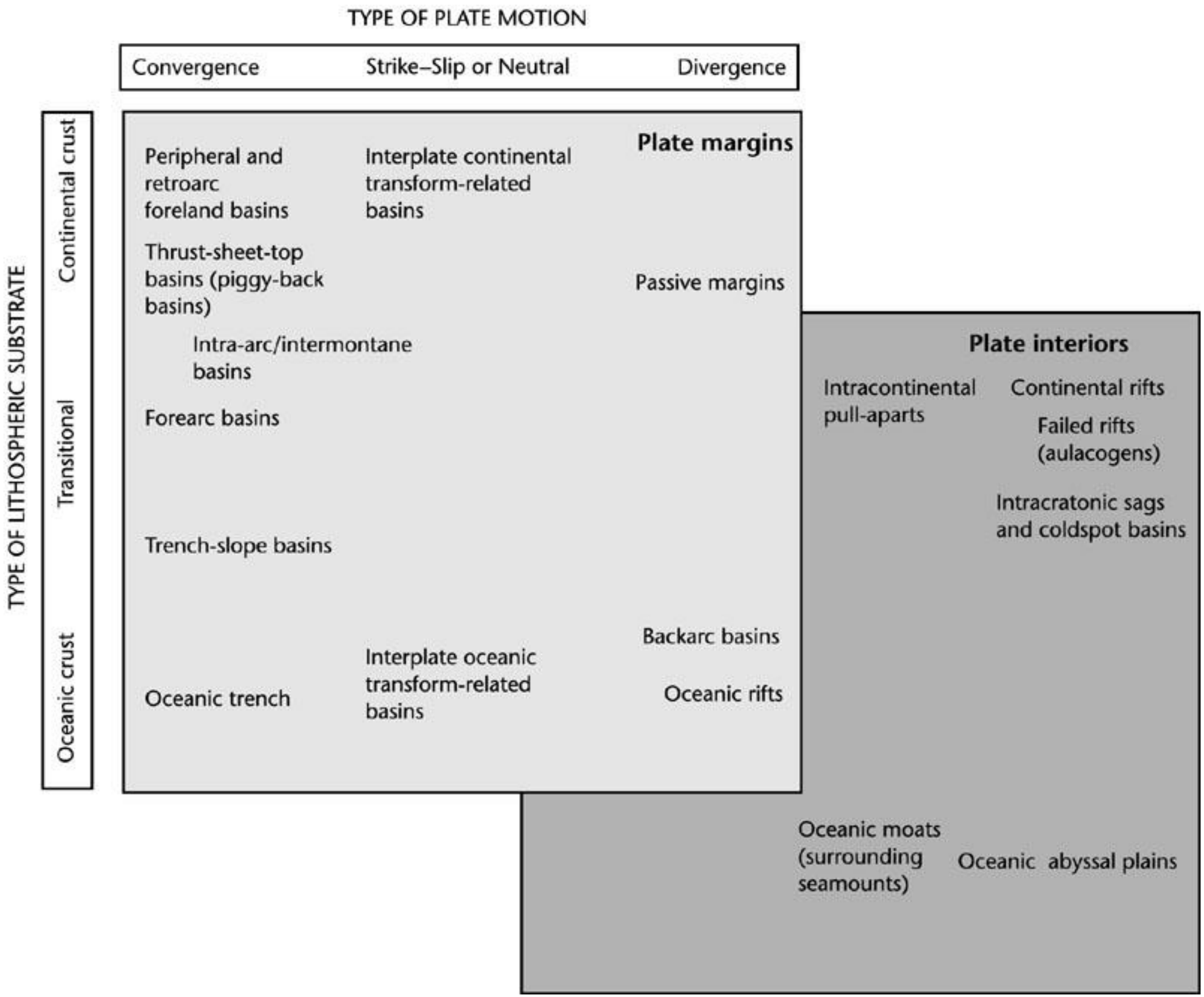


Fig. 1.9 Classification of basins using the type of lithospheric substrate, type of plate motion, and location with respect to the plate boundary.

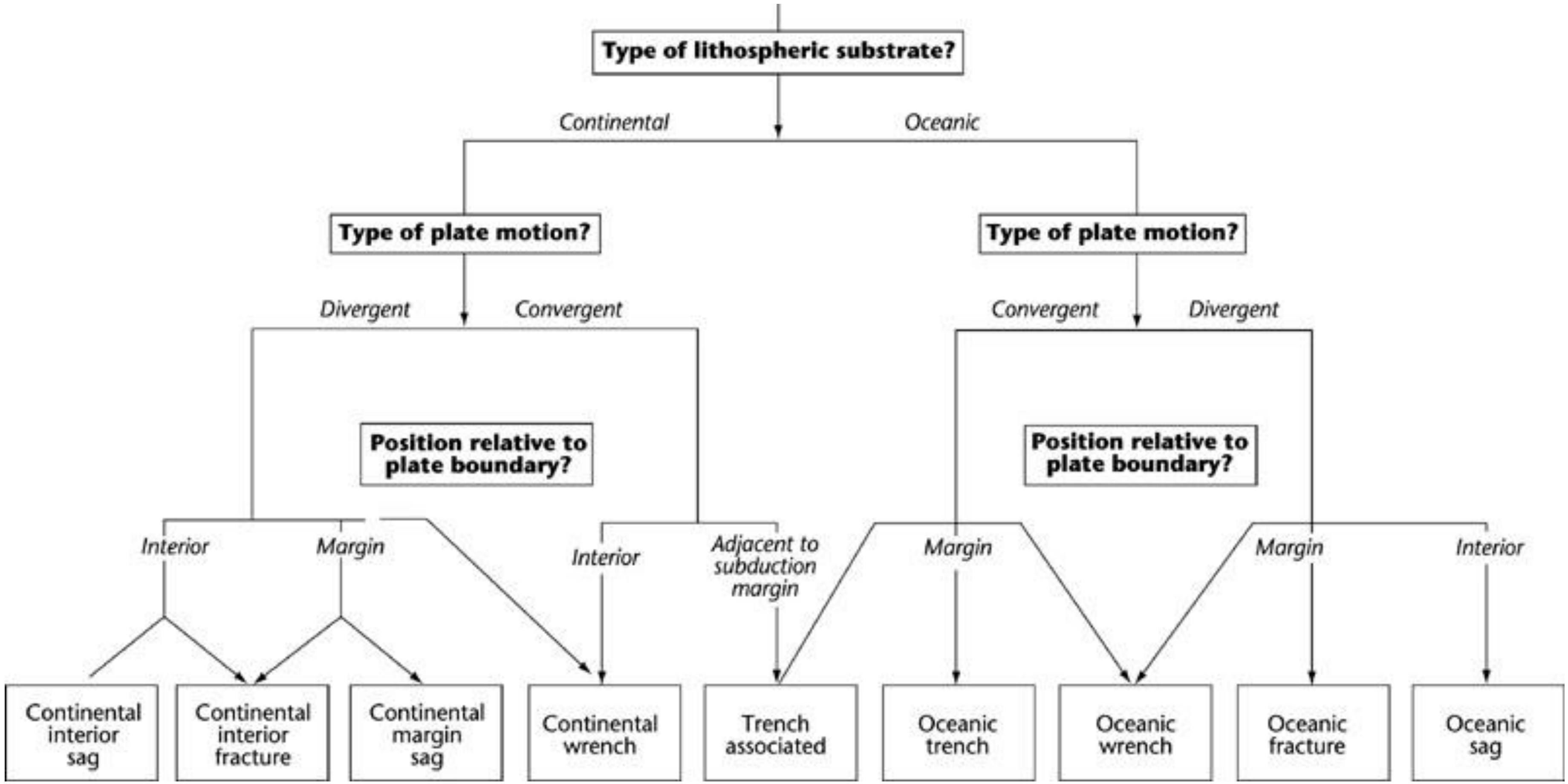


Fig. 1.10 Basin classification scheme based on Kingston et al. (1983a,b). Not all basin types appear in this scheme. Most notably, foreland basins are missing.

Table. 1.1 Basin classification adapted from Ingersoll and Busby (1995), modified from Dickinson (1974, 1976) and Ingersoll (1988), with modern and ancient examples.

Relative plate movement	Basin type	Basin description	Modern example	Ancient example
Divergent settings	Terrestrial rift valleys	Rifts in continental crust, commonly with bimodal volcanism	Rio Grande Baikal Rhine-Bresse Graben	Keeweenawan (Precambrian) Karoo (Jurassic) Viking and Central Grabens (Mesozoic)
	Proto-oceanic rift troughs	Incipient ocean basins floored by new oceanic crust, flanked by young rifted continental margins	Red Sea Gulf of California	East Greenland (Jurassic)
Intraplate settings	Continental rises and terraces	Mature rifted intraplate continental margins at continental–oceanic boundary	East coast, USA	Early Paleozoic of USA and Canadian Cordillera
	Continental embankments	Progradation of sedimentary wedges at edge of rifted continental margins	Mississippi, Gulf Coast, USA	Early Paleozoic Meguma terrane, Canadian Appalachians (?)
	Intracratonic basins	Broad cratonic basins, commonly with underlying rifts	Chad Basin (Cenozoic) Congo Basin	Paleozoic Michigan Basin Illinois Basin Williston Basin (USA)
	Continental platforms	Stable cratons with thin, extensive sedimentary cover	Barents Sea	Middle Paleozoic, North American Midcontinent
	Active ocean basins	Basins floored by oceanic crust at active divergent plate boundaries	Pacific Ocean	Various ophiolite-bearing complexes (Semail, Oman), Neoproterozoic Arabian Shield
	Oceanic islands, aseismic ridges and plateaus	Sedimentary aprons and platforms in intra-oceanic settings	Emperor–Hawaii seamounts	Mesozoic Snow Mountain Volcanic Complex (Franciscan, California)
	Dormant ocean basins	Basins floored by oceanic crust, neither spreading nor subducting	Gulf of Mexico	Phanerozoic Tarim Basin (China)
Convergent settings	Trenches	Deep troughs formed by subduction of oceanic lithosphere	Chile Trench	Cretaceous, Shumagin Island (Alaska)
	Trench–slope basins	Structurally confined basins on subduction complexes	Central America Trench	Cretaceous Cambria slab (California)
	Forearc basins	Basins within arc–trench gaps	Sumatra	Cretaceous Great Valley (California)
	Intra-arc basins	Basins along arc platform, including superimposed and overlapping volcanoes	Lago de Nicaragua	Early Jurassic, Sierra Nevada (California)

Table. 1.1 Continued

Relative plate movement	Basin type	Basin description	Modern example	Ancient example
	Backarc basins	Oceanic basins behind intra-oceanic magmatic arcs, and continental basins behind continental margin magmatic arcs without foreland fold–thrust belts	Marianas	Jurassic Josephine ophiolite (California)
	Retroarc foreland basins	Foreland basins on continental sides of continental margin arc–trench systems	Andes foothills	Cretaceous Sevier foreland (Wyoming-Utah)
	Remnant ocean basins	Shrinking ocean basins between colliding continental margins and/or arc–trench systems (eventually subducted or deformed)	Bay of Bengal	Pennsylvanian-Permian Ouachita Basin
	Peripheral foreland basins	Foreland basins superimposed on rifted continental margins during continental collision	Persian Gulf Indo-Gangetic Plain Po Basin (Italy)	Tertiary North Alpine Foreland Basin (Switzerland)
	Piggy-back (thrust sheet top) basins	Basins carried above moving thrust sheets	Peshawar Basin (Pakistan)	Neogene, Apennines (Italy) Meso-Hellenic Trough (Greece)
	Foreland intermontane basins (broken forelands)	Basins formed among basement cored uplifts in foreland settings	Sierras Pampeanas (Argentina)	Laramide basins (USA)
Transform settings	Transtensional basins	Basins formed by local extension along strike–slip fault systems	Salton Sea, California	Carboniferous Magdalen Basin (Gulf of St Lawrence)
	Transpressional basins	Basins formed by local compression along strike–slip fault systems	Santa Barbara Basin (California)	Miocene Ridge Basin (California)
	Transrotational basins	Basins formed by rotation of crustal blocks about vertical axes within strike–slip fault systems	Western Aleutian forearc	Miocene Los Angeles Basin, California
Hybrid settings	Intracontinental wrench basins	Basins on continental crust associated with strike–slip tectonics caused by distant collisional processes	Qaidam Basin (China)	Pennsylvanian-Permian Taos Trough (New Mexico)
	Aulacogens	Former failed rifts reactivated during convergent tectonics	Mississippi Embayment	Paleozoic Anadarko Basin (Oklahoma)
	Impactogens	Rift basins caused by stresses transmitted from convergent plate margin	Baikal Rift (Siberia)	Rhine Graben (Europe)
	Successor basins	Basins in intermontane settings following cessation of orogenic activity	Southern Basin and Range (Arizona)	Paleogene Sustut Basin (British Columbia)

1.4.1 Basin-forming mechanism

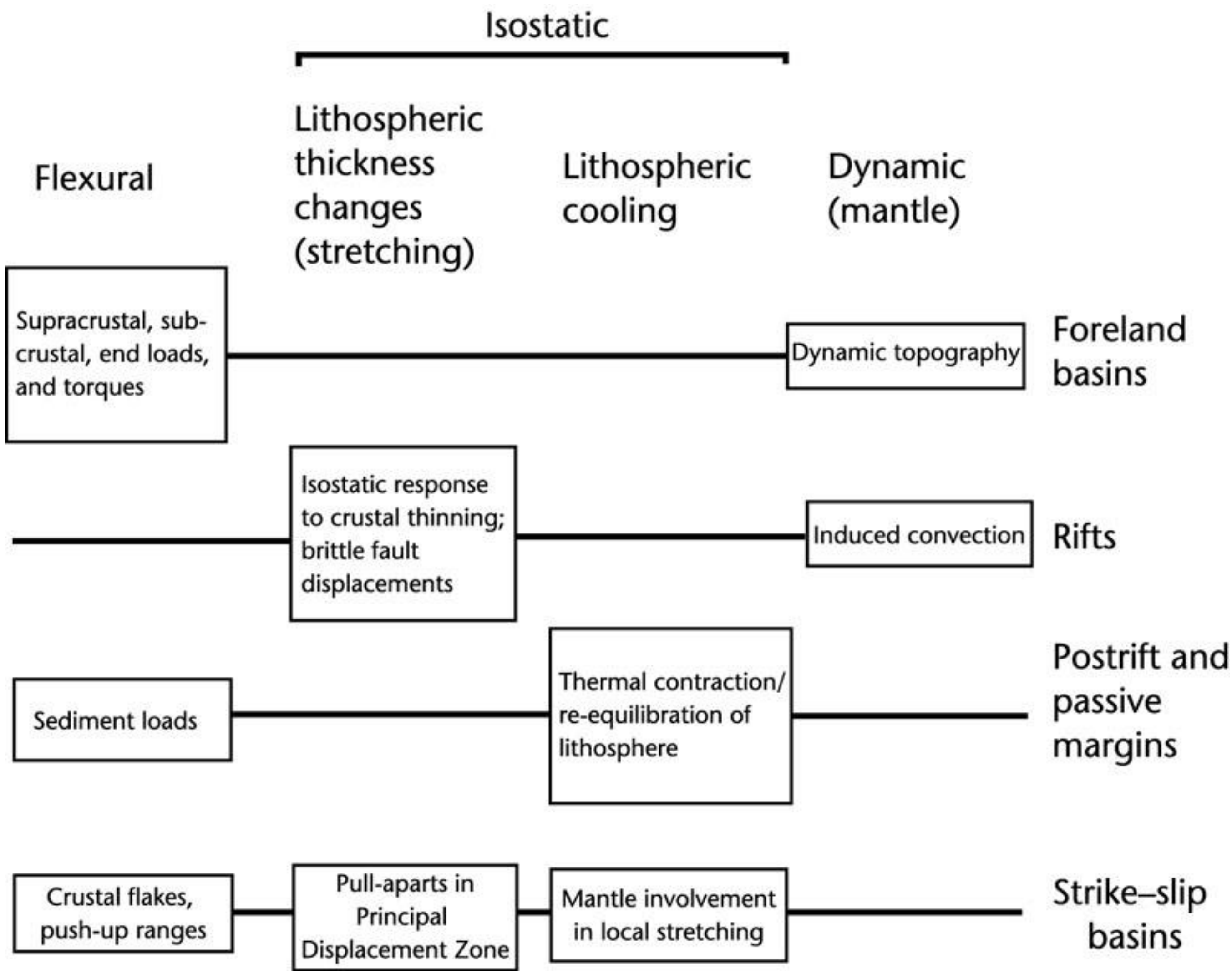
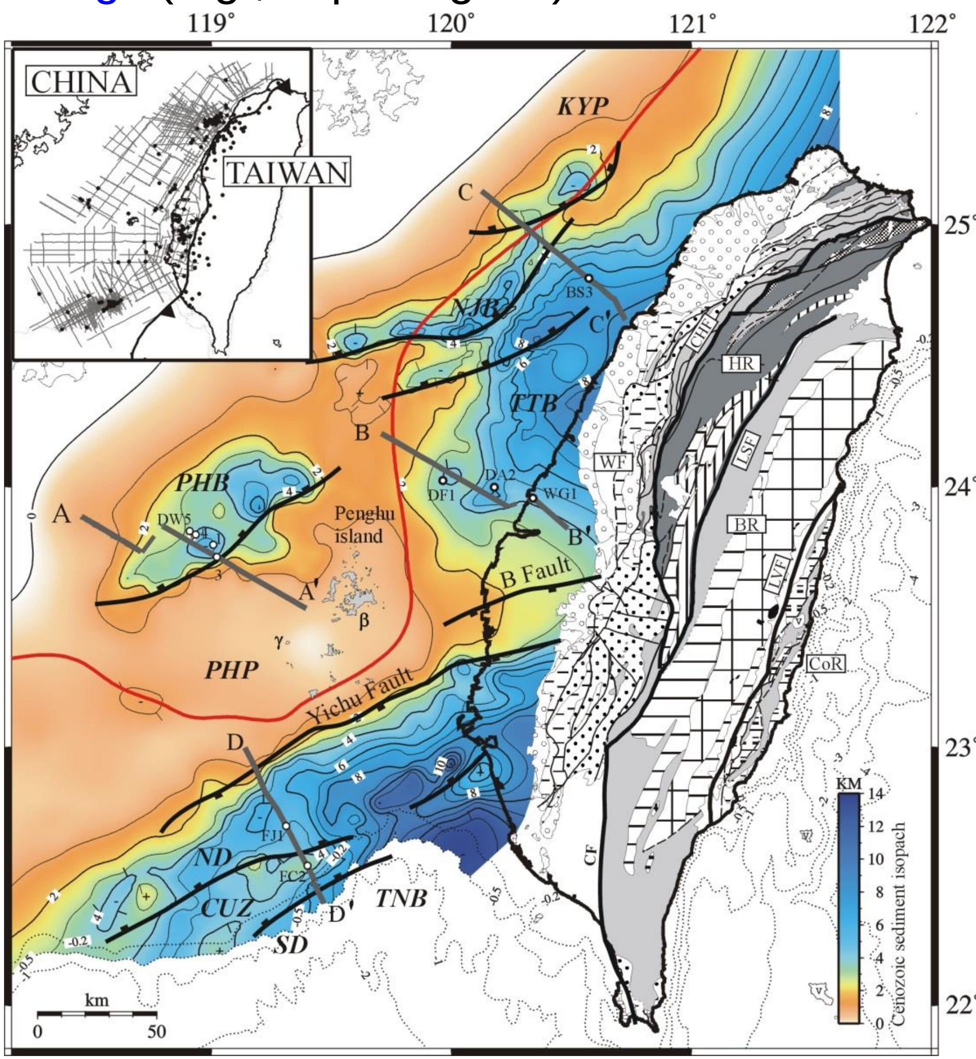


Fig. 1.11 Fundamental mechanisms of basin formation: flexural, isostatic, and dynamic. The importance of these mechanisms in foreland, rift, postrift and passive margin, and strike-slip basins is indicated by the size of the boxes.

Basin classification:
Divergent settings (e.g., continental rift basins)
Intraplate settings (e.g., rifted/passive continental margins)
Convergent settings (e.g., foreland basins, forearc basins)
Transform settings (e.g., transtensional basins)
Hybrid settings (e.g., impactogens)

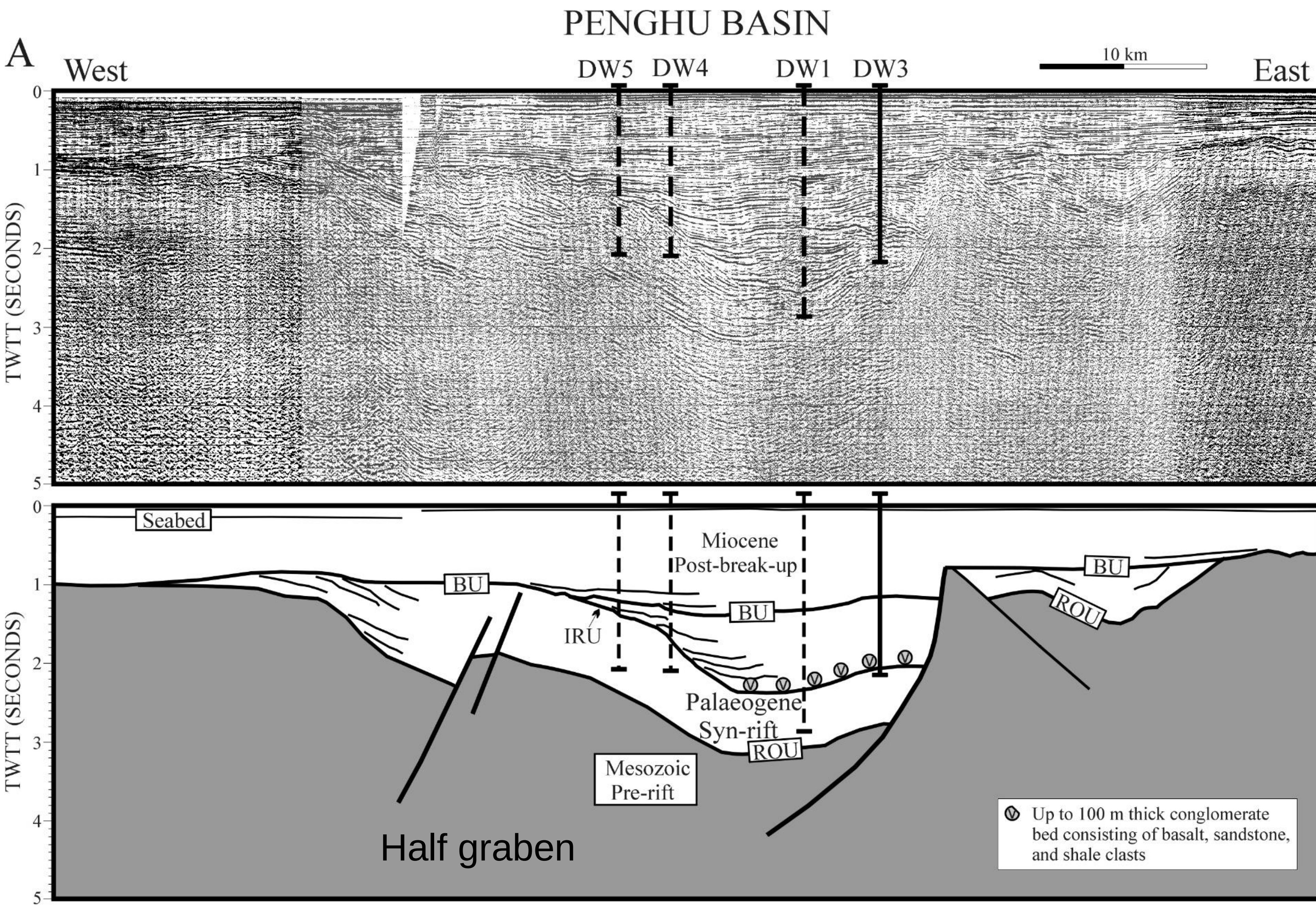


A basin should be classified according to its tectonic setting **at the time of deposition** of a given stratigraphic interval; thus for a given area, its "basin" type may change through geologic time.

Using the Taiwan Strait as an example, It was characterised by "intra-arc basins" during the Mesozoic, "continental rift basins" during the late Palaeocene to mid-Oligocene, "passive continental margin" during the mid-Oligocene to late Miocene; and "peripheral foreland basin" during the latest Miocene to the present day.

Lin et al. (2003)

In the Taiwan Strait, a terrestrial rift-valley phase developed during the Palaeogene.



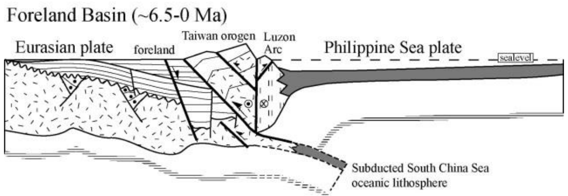
Lin et al. (2003)

After BU (breakup unconformity) rifting (faulting) stopped and seafloor spreading begins

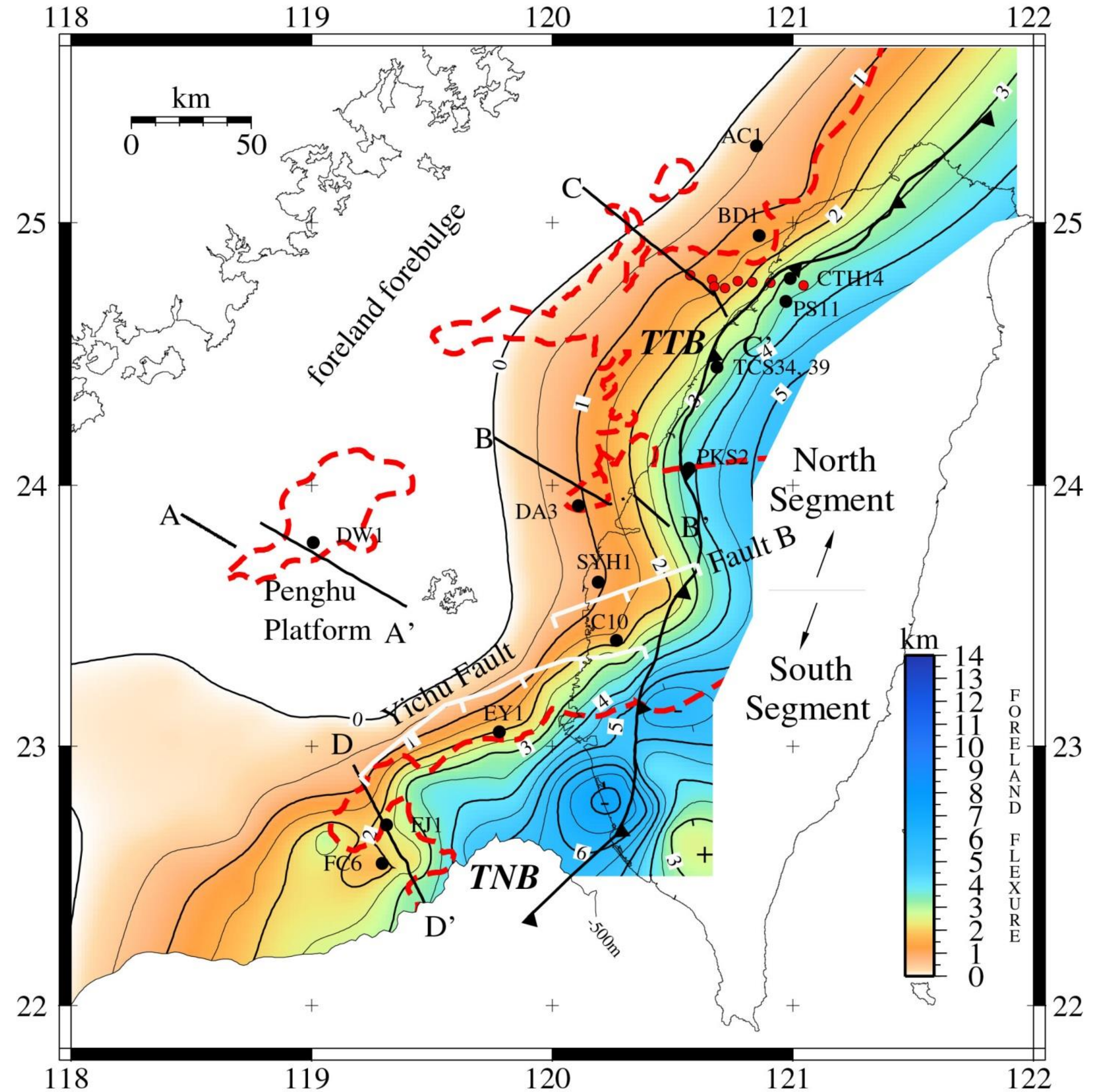
Taiwan foreland basin

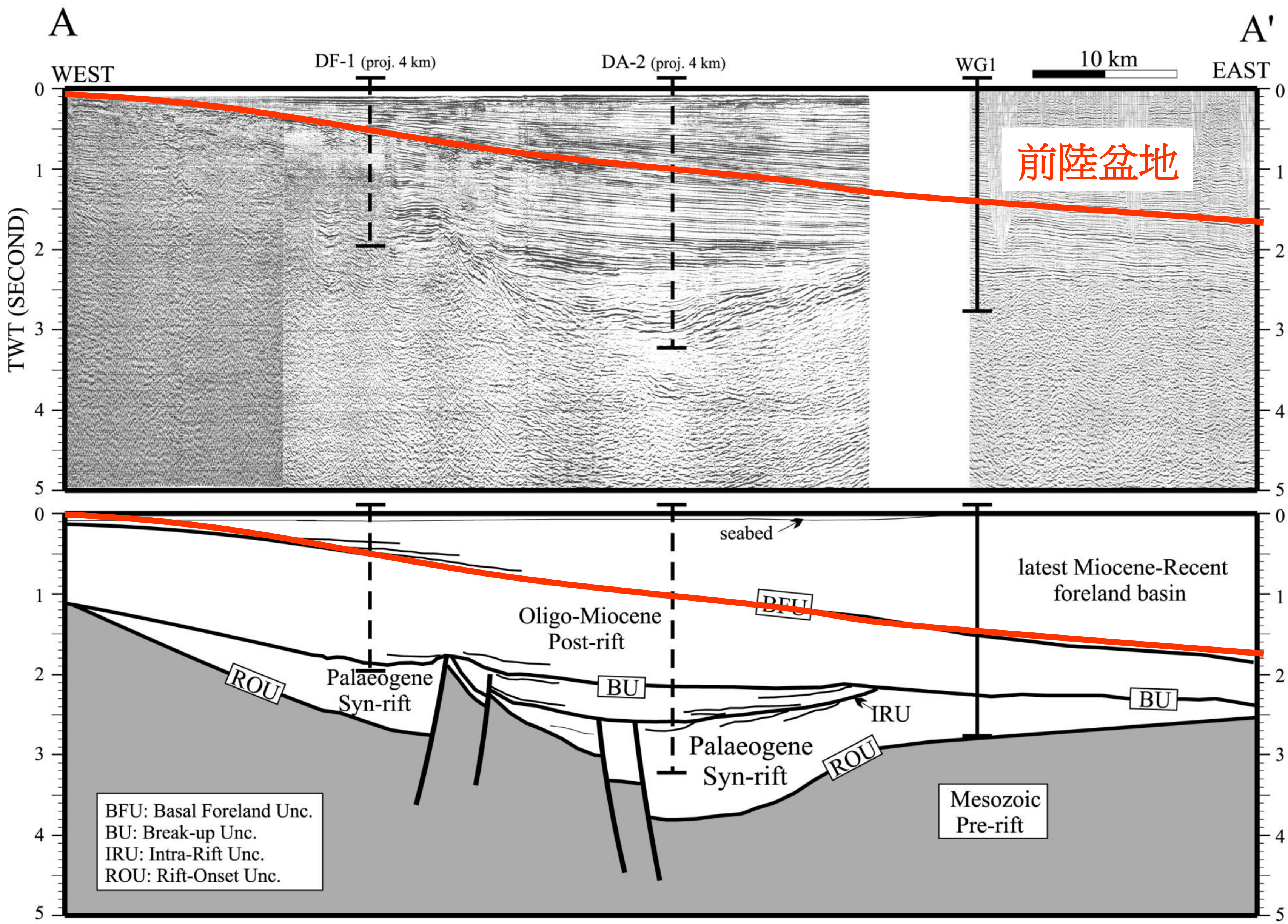
Depth map of the Taiwan foreland basin

Contour interval 0.5 km



Lin & Watts (2002)





Lin & Watts (2002)

Basin Analysis Practical 1

Basin classification (past and present), using the Taiwan region as an example

(due on October 13, 2021)

A basin should be classified according to its tectonic setting at the time of deposition of a given stratigraphic interval; thus, a basin may change its tectonic setting rapidly and often. Taiwan is located at plate boundaries which we are all familiar with. Many past and present basin types exist(ed) in this region, ranging from divergent to convergent settings. Using the figures provided and published geological/geophysical information, do the following,

1. On figure 1, mark the names of major morphotectonic features around Taiwan.
2. Figures 2~4 are three cross sections (AA', BB', and CC' shown in figure 1) drawn across and perpendicular to the plate boundaries around Taiwan. Also shown are the topography along these profiles. On these three sections:
    a. Construct the basin and crustal structures down to a depth of 60 km.
    b. Name the past and present basin types (e.g. rift basin, forearc basin etc.) seen in the sections that you have constructed.
3. Give a brief account (no more than 2 pages) on the basin/tectonic evolution along these three profiles. List the references that you have consulted.

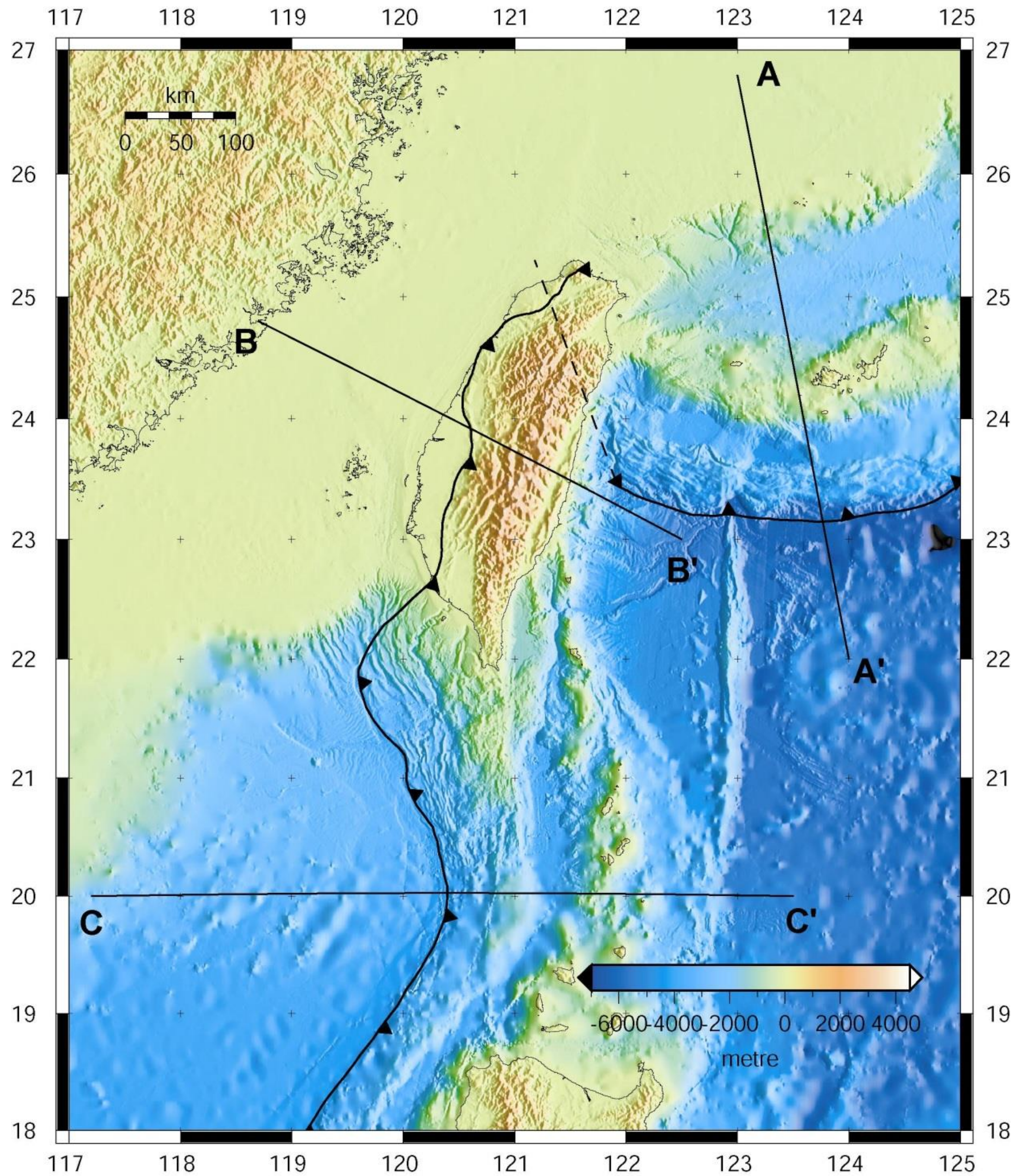


Figure 1: Topography/bathymetry in the Taiwan region and the locations for AA', BB' and CC' profiles shown in figures 2 to 4 respectively.

Figure 2: AA' section

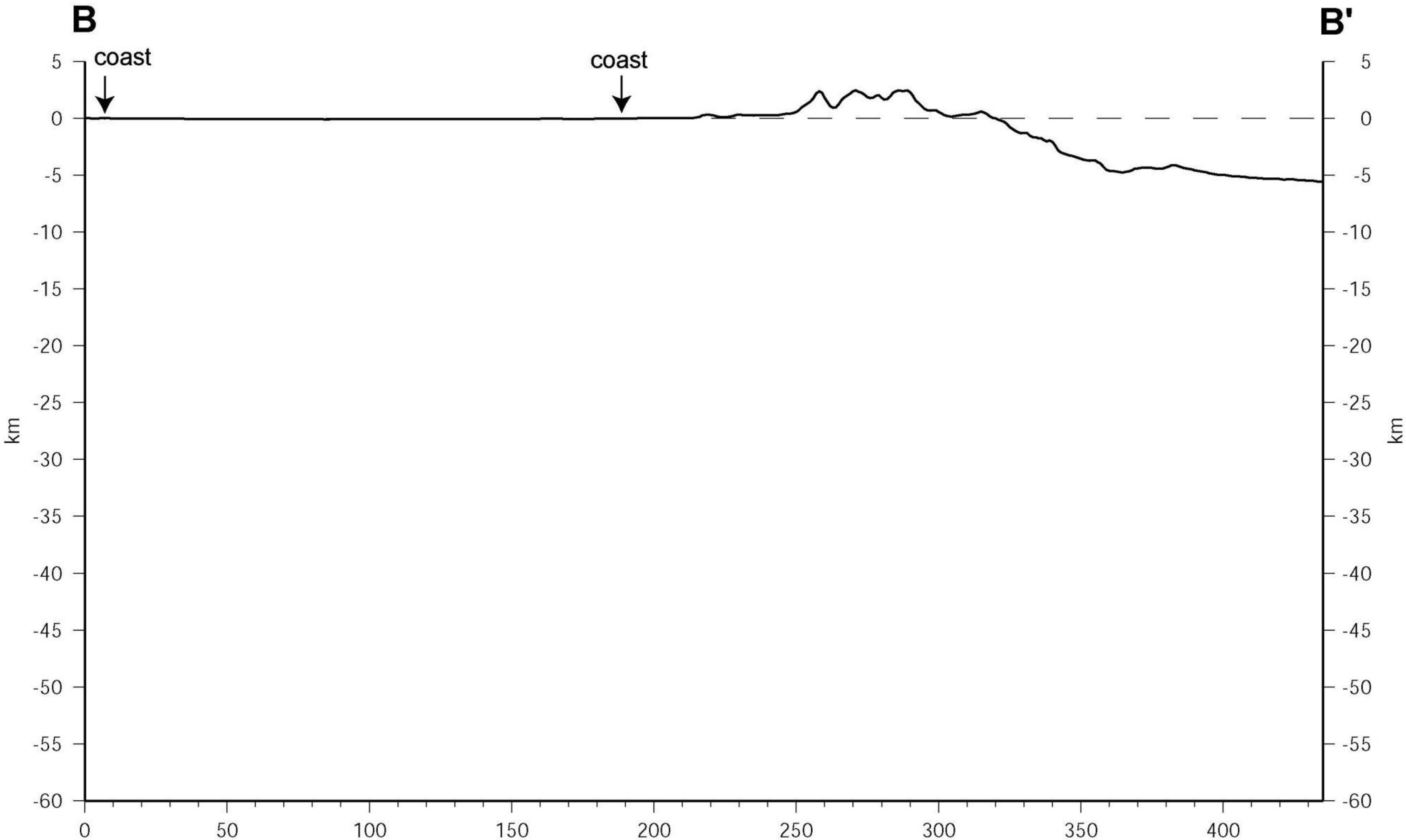


Figure 3: BB' section

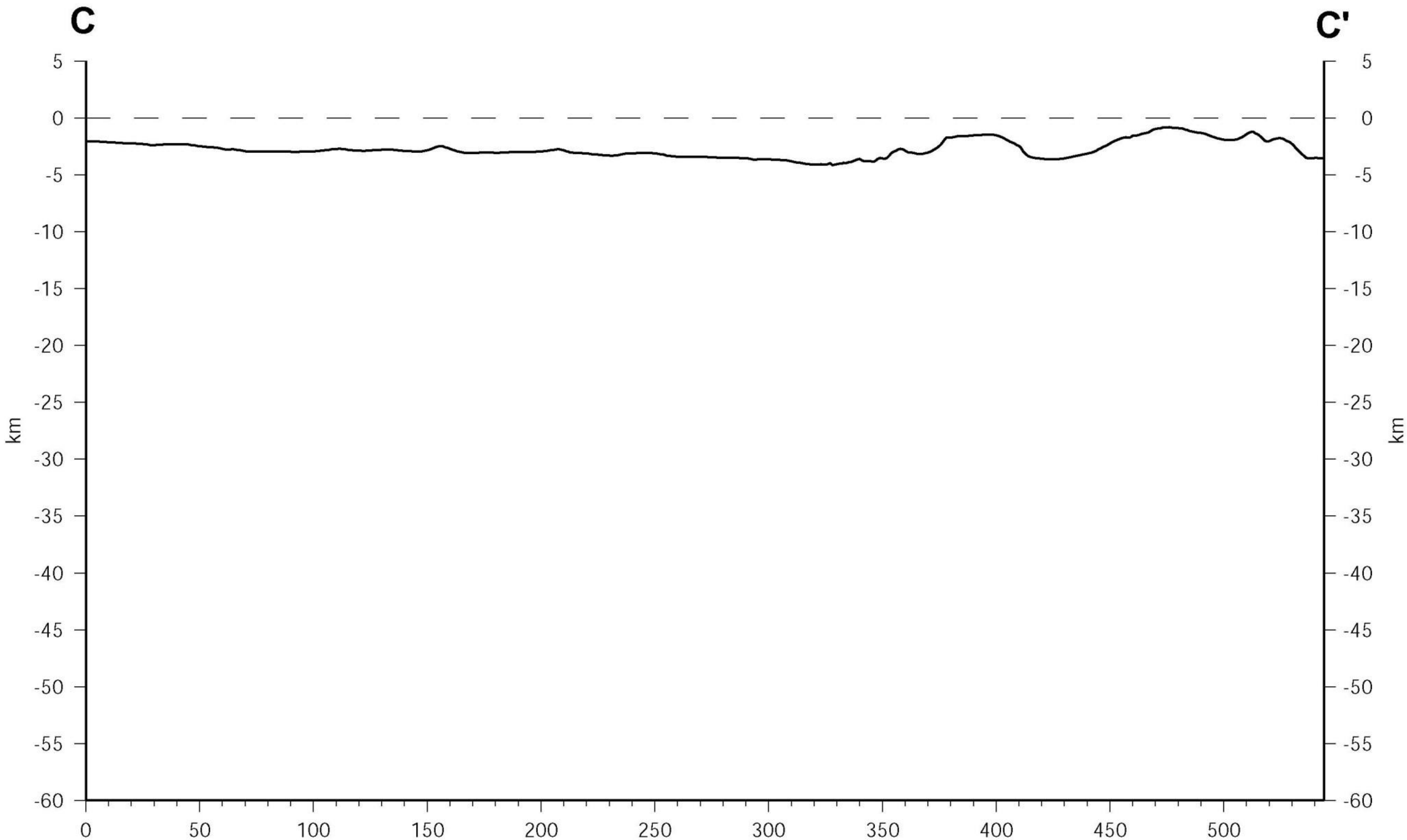


Figure 4: CC' section