# Pánevní analýza

# Literatura

- Philip A. Allen, John R. Allen (2013): Basin Analysis: Principles and Application to Petroleum Play Assessment, 642 p., 3rd Edition., Wiley-Blackwell

- Miall A. (1999) Principles of Sedimentary Basin Analysis. 616 p., Springer; 3rd, edition

- Busby CJ., Ingersoll, RV: Tectonics of Sedimentary Basins (1995)

- Burbank, DW, Anderson, RS (2011) Tectonic Geomorphology, 472 p., Wiley Blackwell,

# Definice

Sedimentary basin analysis is a geologic method by which the **history of a sedimentary basin** is revealed, by **analyzing the sediment fill itself**.

Aspects of the sediment, namely its **composition, primary structures, and internal architecture**, can be **synthesized** into a history of the basin fill. Such a synthesis can reveal how the basin formed, how the sediment fill was transported or precipitated, and reveal sources of the sediment fill. From such syntheses models can be developed to explain **broad basin formation mechanisms**. Examples of such basinal environments include **backarc, forearc, passive margin, epicontinental, and extensional basins.**

Sedimentary basin analysis is largely conducted by two types of geologists who have slightly different goals and approaches. The **petroleum geologist**, whose the ultimate goal is to determine the possible presence and extent of hydrocarbons and hydrocarbon-bearing rocks in a basin, and the **academic geologist**, who may be concerned with any or all facets of a basin's evolution. Petroleum industry basin analysis is often conducted on subterranean basins through the use of reflection seismology and data from well logging. Academic geologists study subterranean basins as well as those basins which have been exhumed and dissected by subsequent tectonic events. Thus academics sometimes use petroleum industry techniques, but in many cases they are able to study rocks at the surface. Techniques used to study surficial sedimentary rocks include: measuring stratigraphic sections, identifying sedimentary depositional environments and constructing a geologic map.

An important tool in sedimentary basin analysis is sequence stratigraphy, in which various sedimentary sequences are related to pervasive changes in sea level and sediment supply

# Sedimentační pánve

**Sedimentační pánve**

**definice**:

- oblasti, ve kterých se může akumulovat sediment a být zachován po delší geologické časové období

**tvar**: kruhový, podlouhlý, lineární, nepravidelný,
nemusí se jednat o **topografické deprese** (aluviální vějíře)
**pánve**: aktivní, neaktivní, deformované

**tři základní typy pánví**

- **pre-depoziční pánve (posttektonické)**
  morfologická deprese, později vyplněná posttektonickými sedimenty
- **syndepoziční pánve (syntektonické)**
  akumulace sedimentu je řízena syndepoziční tektonikou (subsidence), morfologie je řízena balancí mezi poklesem a výplní, pokles > výplň = vznik morfologické deprese
- **postdepoziční pánve (pretektonické)**
  akumulace sedimentu předchází tektonickou aktivitu, která vytvoří pánevní strukturu, vztahy mezi výplní, transportem a mocnostmi sedimentu nejsou řízeny morfologií

# PLÁN PŘEDNÁŠKY

- Sedimentační pánve, definice, morfologie
- Tektonická klasifikace sedimentačních pánví
- Eroze a erozní historie
- Subsidence a subsidenční historie pánví
- Sedimentační prostředí, architektura výplně pánví, řídící faktory výplně pánví
- Termální vývoj pánví
- Ekonomické aplikace: ropa a zemní plyn:
- Případové studie

# Morfologie pánve

- řízena vzájemným působením tektonické subsidence a přísunu sedimentu
- **Další faktory**
  - **depoziční prostředí**
  - **erozní báze**
  - **výplň pánve**

# Subsidence vs. přísun sedimentu

stanovení **rychlostí denudace** ve zdrojové oblasti sedimentu

- <u>uzavřené pánve</u> (jezero Chad)
- <u>polouzavřené pánve</u> (Černé moře)

metodika: **výpočet objemů sedimentu** přinášeného řekami do pánve (mechanická složka a chemická složka)

- výpočet **rychlostí sedimentace** : plocha pánve, plocha zdrojové oblasti, spolehlivý časový model

**Černé moře**,

- hlavní říční systémy, přínosu sedimentu: <u>50 mm/ka</u>
- průměrná rychlost sedimentace po kompakci 300 mm/ka
- plocha drenážního území je zhruba 4,4 krát větší než plocha depozičního území, odtud rychlost denudace = 300 / 4,4, což je cca <u>70 mm /ka – dobře odpovídá rychlosti přínosu sedimentu</u>

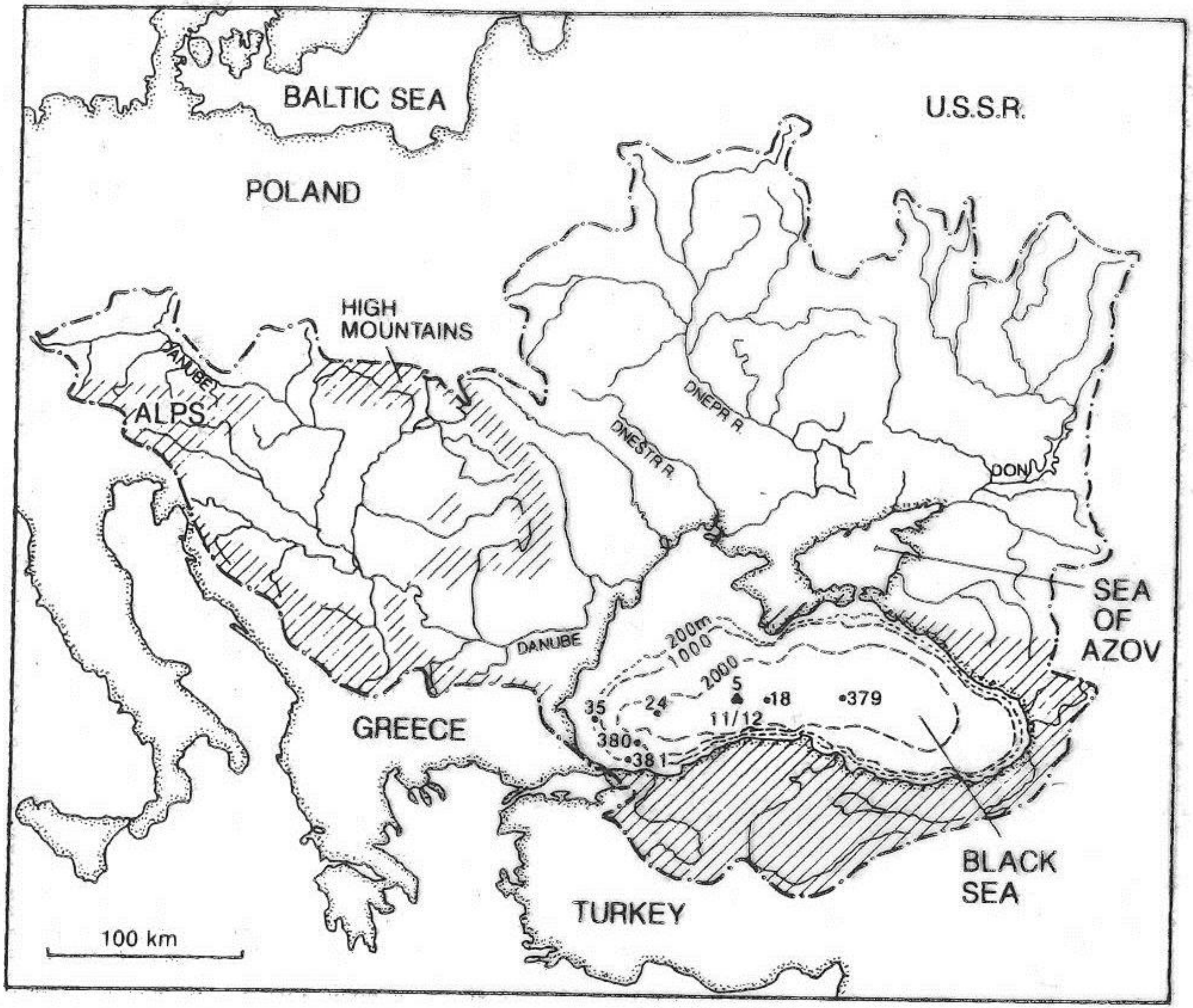


**Fig. 9.13.** Drainage area of the Black Sea and location of sediment cores and DSDP drilling sites (379 to 381) in the deep basin. (After Degens et al. 1978)

Různé rychlosti sedimentace podle sedimentačních prostředí

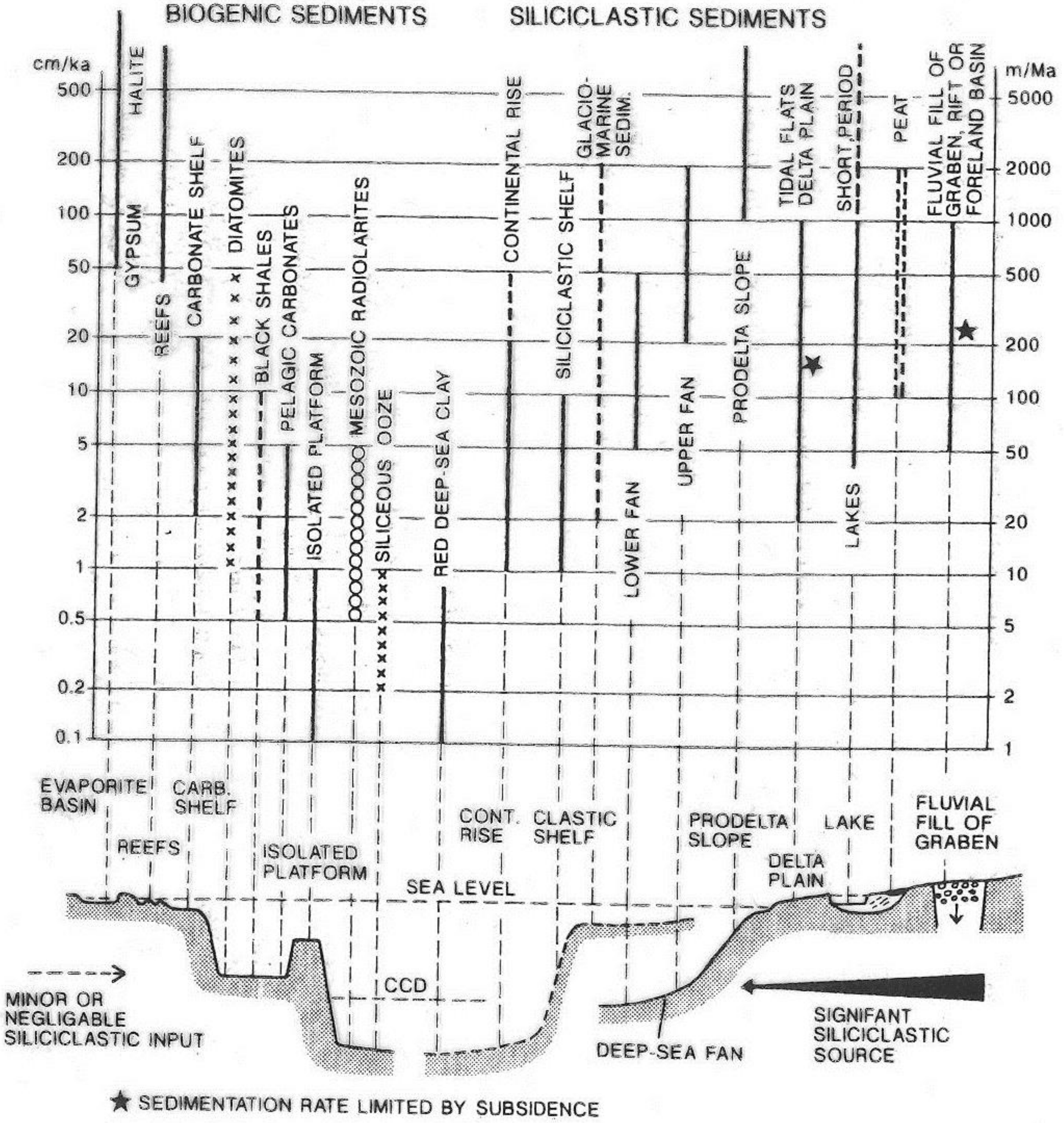


**Fig. 10.3.** Overview of sedimentation rates in various depositional environments which are either dominated by allochthonous, siliciclastic sediments, or autochthonous, biogenic materials. (Data from many sources, including Seibold and Berger 1982; Scholle et al. 1983; Nelsen and Stanley 1984; Stow et al. 1985; Jenkyns 1986; Lützner 1989)

# Tektonická klasifikace sedimentačních pánví

Sedimentace a denudace jsou zpravidla řízeny tektonickými procesy, proto - klasifikace sedimentačních pánví na základě globálních a regionálních tektonických procesů v rámci deskové tektoniky

- Roli hraje řada dalších faktorů: morfologie v okolí pánve, typy hornin, klima, tektonická aktivita ve zdrojové oblasti, atd.

# Tektonická klasifikace pánví

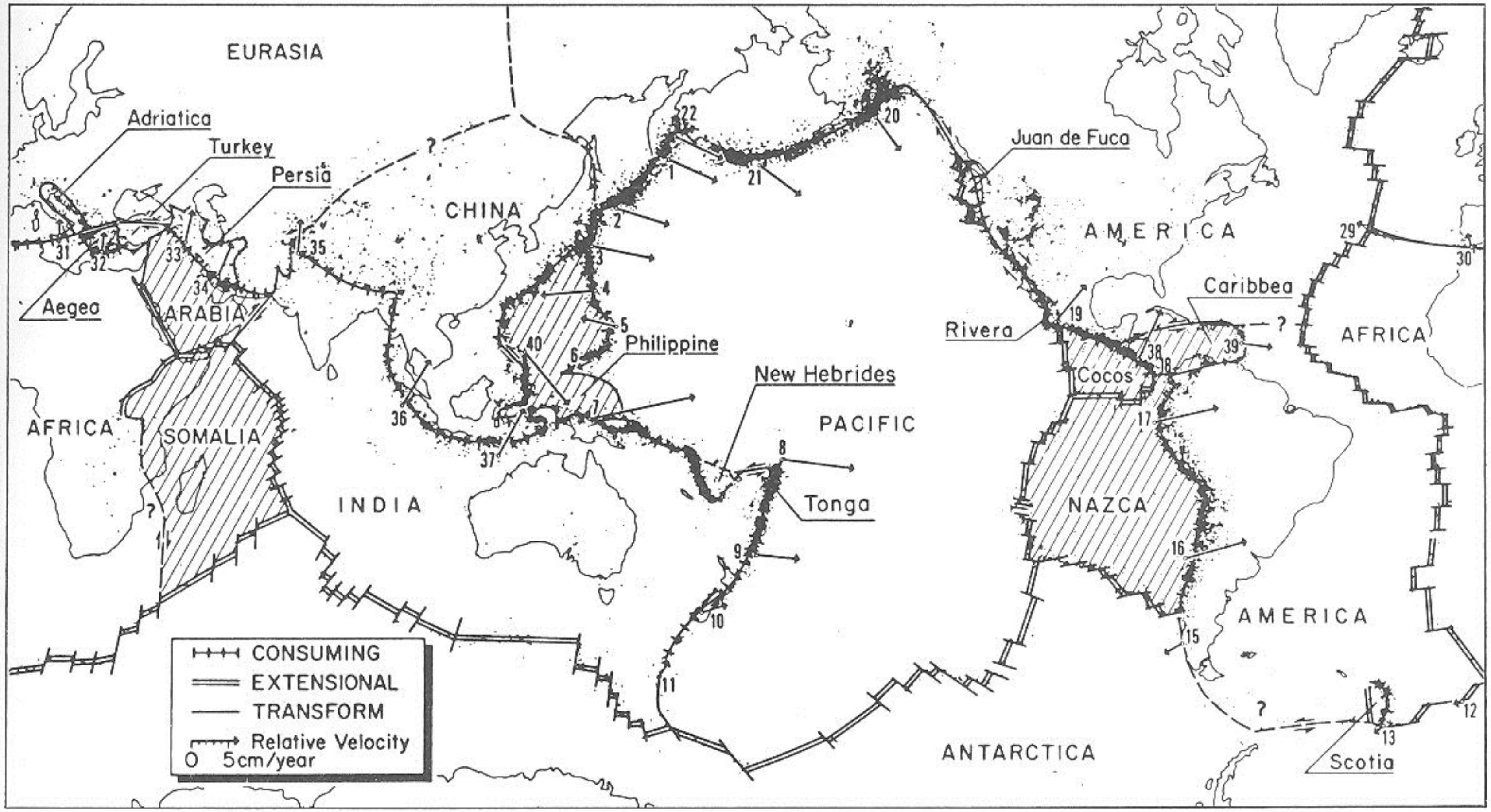


**Fig. 1.6.** Present distribution of lithospheric plates on the surface of the Earth showing the three main types of plate boundary (from Le Pichon *et al.* 1973).

Současná distribuce litosférických desek na povrchu Země s vyznačením tří hlavních typů deskových rozhraní

# Pánve na divergentních rozhraních

- kontinentální riftová údolí - ohraničená hlubokými zlomy
  - asymetrická (grabeny)
  - symetrická (half-grabeny)

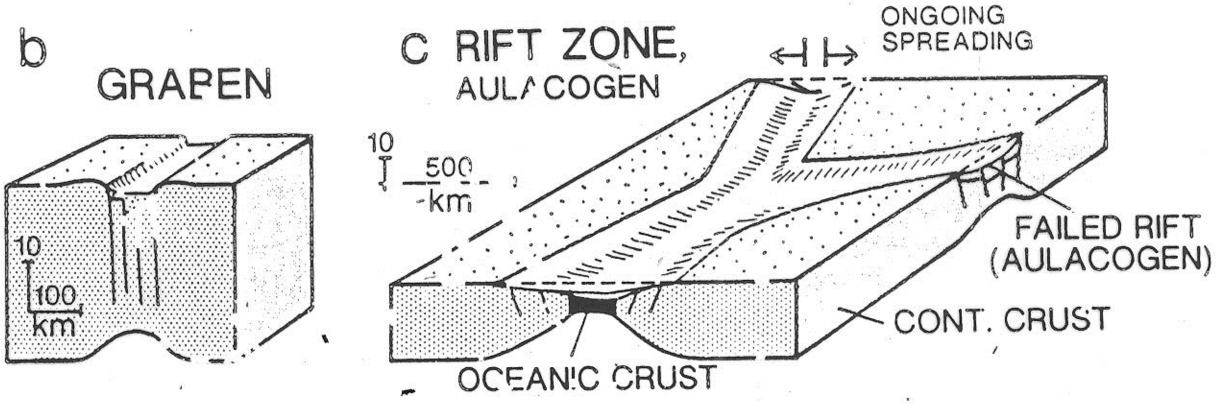
  velmi rychlá subsidence, velká mocnost sedimentární výplně (v km)

  Příklady: rift Rio Grande, východoafrický rift

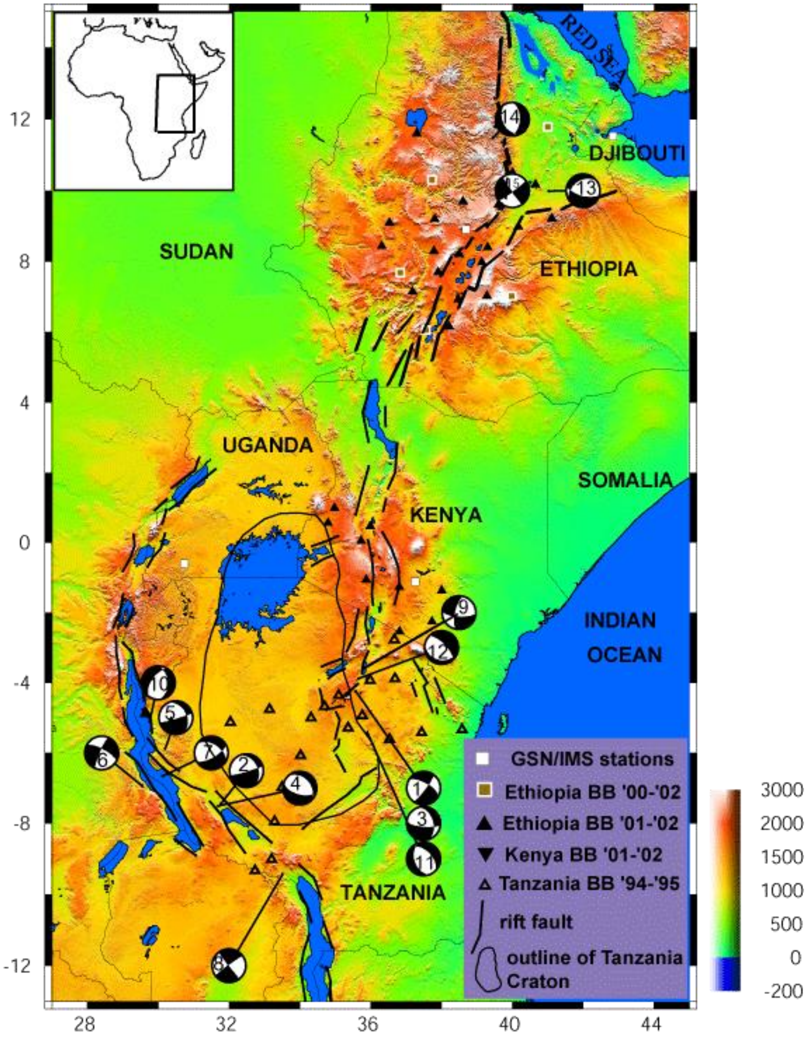
- protooceánská riftová údolí - počáteční oceánské pánve založené na oceánské kůře, ohraničené mladými kontinentálními okraji,

  rychlá subsidence, velká mocnost sedimentární výplně (km)

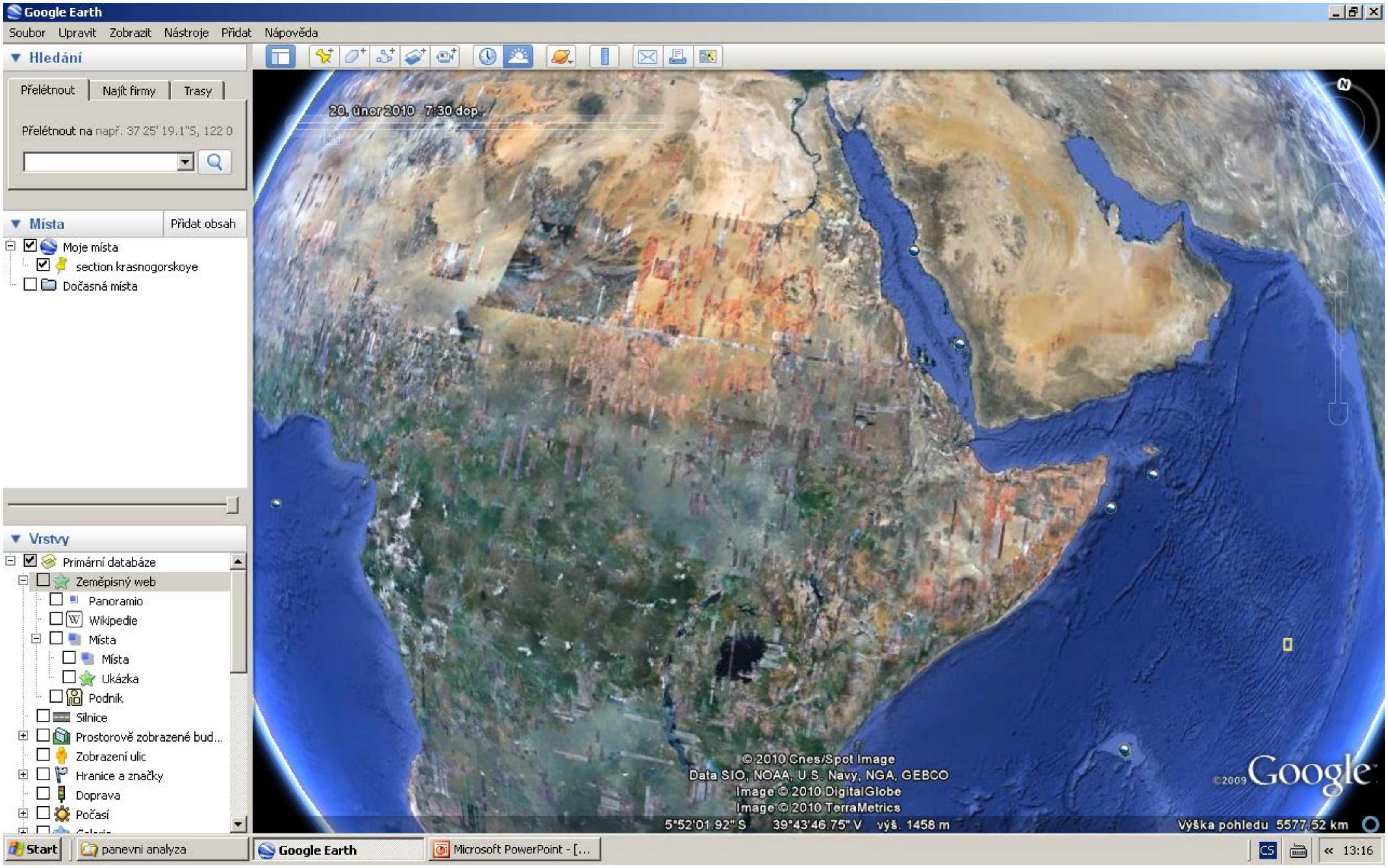
  Příklady: Rudé moře, jura východního Grónska



# East Africa Rift



# Triple junction, East Africa



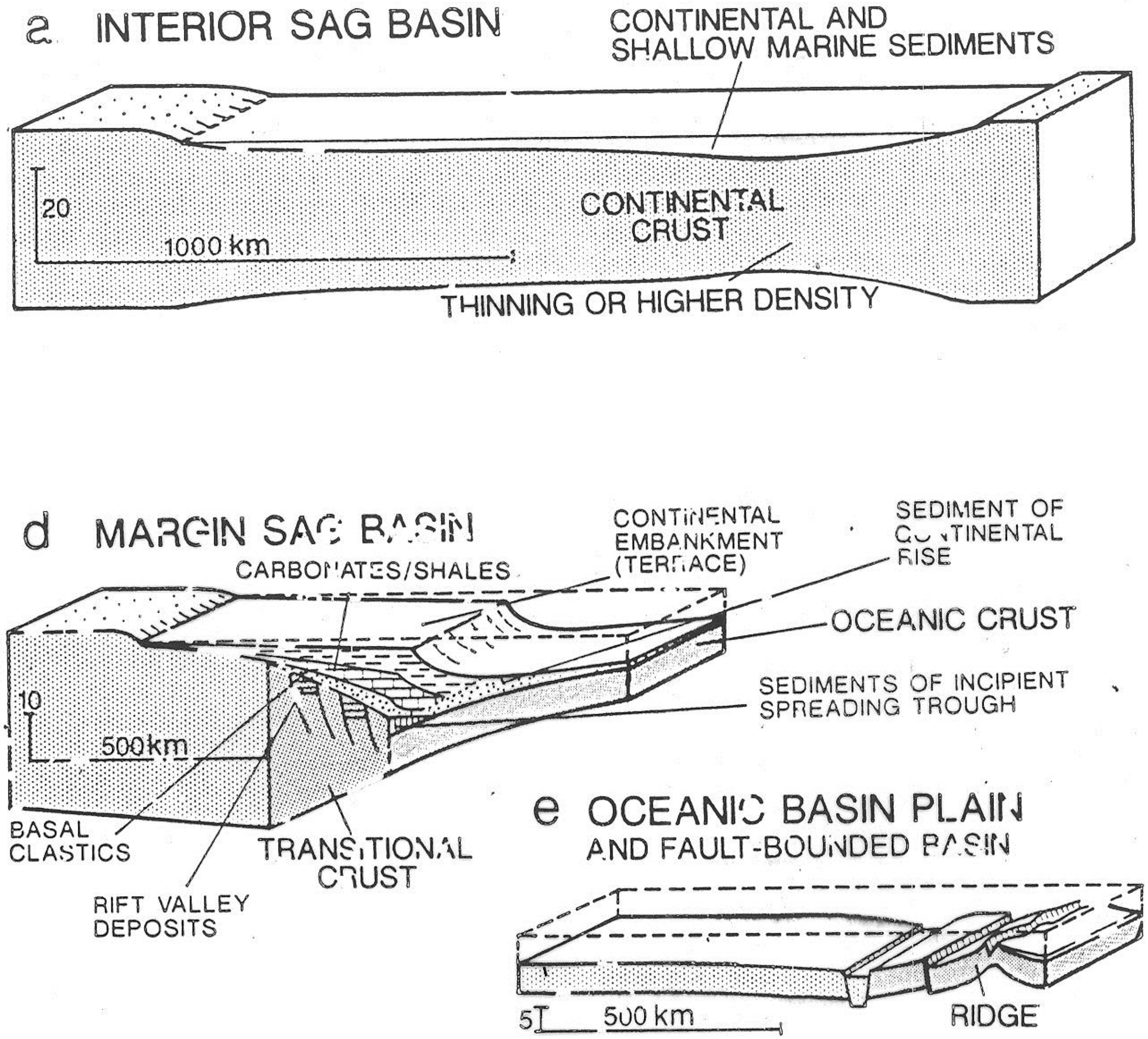
# Pánve ve vnitrodeskovém prostředí

**kontinentální terasy (pasivní zralé riftové kontinentální okraje na rozhraní kontinent - oceán,**

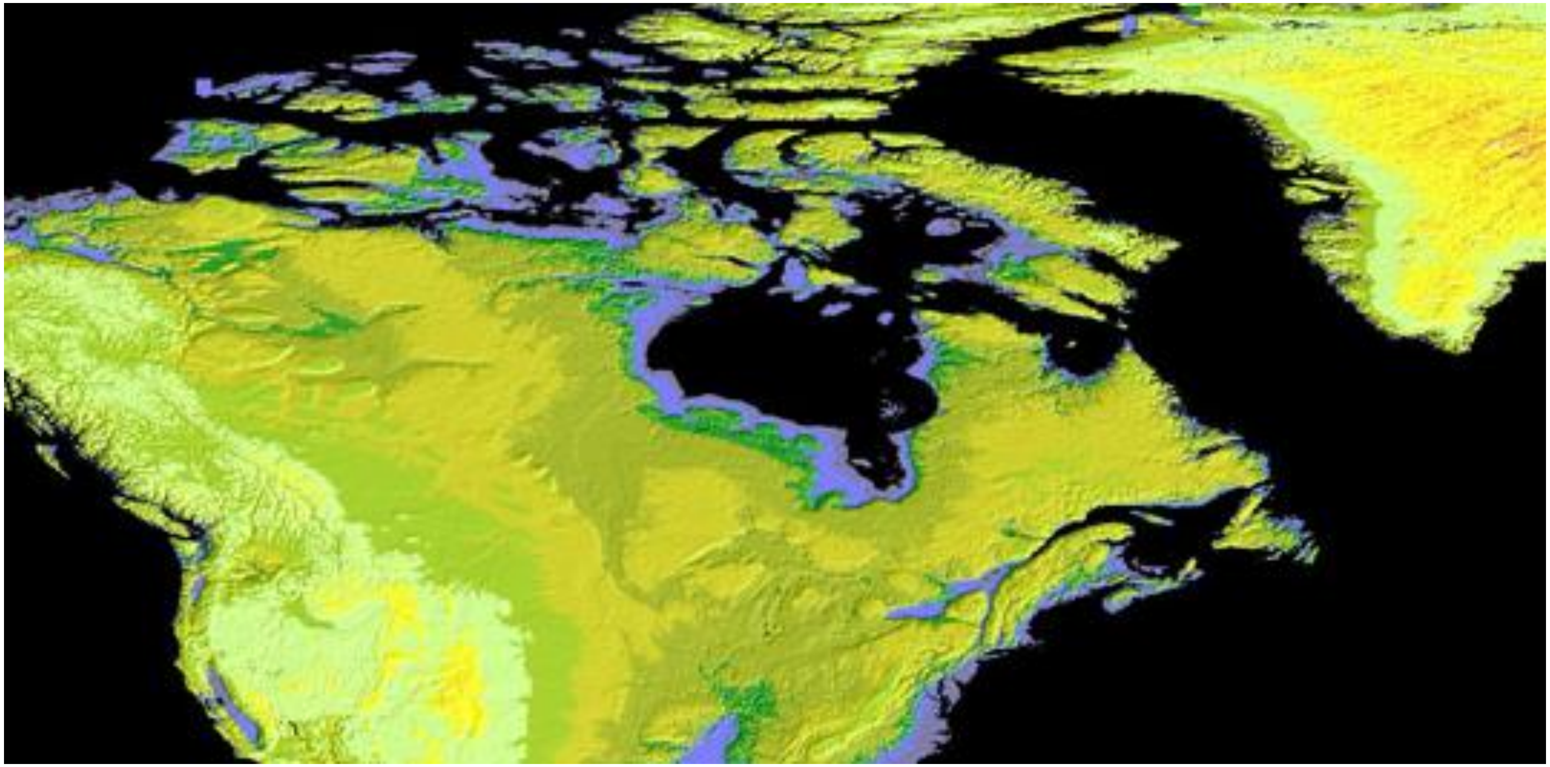
- **kontinentální okraje (Passive continental margin)** - maximum akumulace na kontinentální kůře, lineární prizmata sedimentu, která se ztenčují směrem k centru spreadingu,
  - rychlá subsidence, rychlost subsidence většinou v průběhu času klesá, velká mocnost sedimentární výplně
  - Příklady: atlantický okraj Sev. Ameriky, Jižní Ameriky, Afriky, austroalpinská zóna Východních Alp

- **kontinentální platformy (Interior sag basin)** - pánve založené na kontinentální kůře, stabilní kratony pokryté tenkou vrstvou sedimentu, někdy s centrálním mrtvým riftem, ohraničeným zlomy,
  - pomalá subsidence,
  - Příklady: Hudsonův záliv, spodní paleozoikum Sev. Ameriky (oblast Velkých jezer)

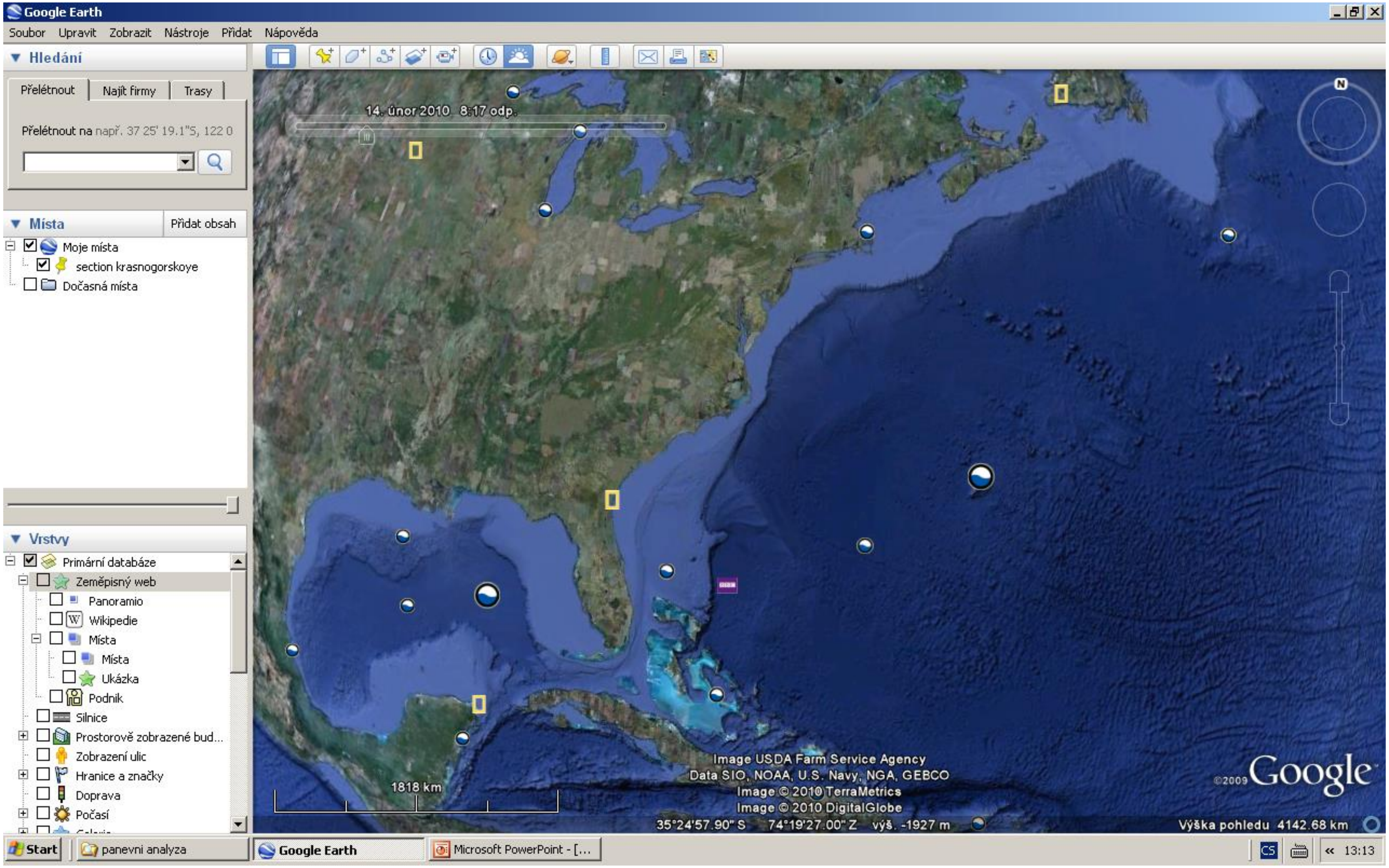
- **aktivní intraoceánské pánve (Oceanic basin plain)** - pánve založené na oceánské kůře, které nesouvisí s tektonickým vývojem oblouk-příkopových systémů, akumulace sedimentů na úpatí aseismických hřbetů, podmořských hor
  - pomalá subsidence, místy značná mocnost sedimentů (hlubokomořské vějíře)
  - Příklady: Tichý oceán, Mexický záliv, různé ofiolitové systémy


a INTERIOR SAG BASIN
CONTINENTAL AND SHALLOW MARINE SEDIMENTS
20
1000 km
CONTINENTAL CRUST
THINNING OR HIGHER DENSITY
d MARGIN SAG BASIN
CARBONATES/SHALES
CONTINENTAL EMBANKMENT (TERRACE)
SEDIMENT OF CONTINENTAL RISE
OCEANIC CRUST
SEDIMENTS OF INCIPIENT SPREADING TROUGH
10
500 km
BASAL CLASTICS
RIFT VALLEY DEPOSITS
TRANSITIONAL CRUST
e OCEANIC BASIN PLAIN AND FAULT-BOUNDED BASIN
5
500 km
RIDGE

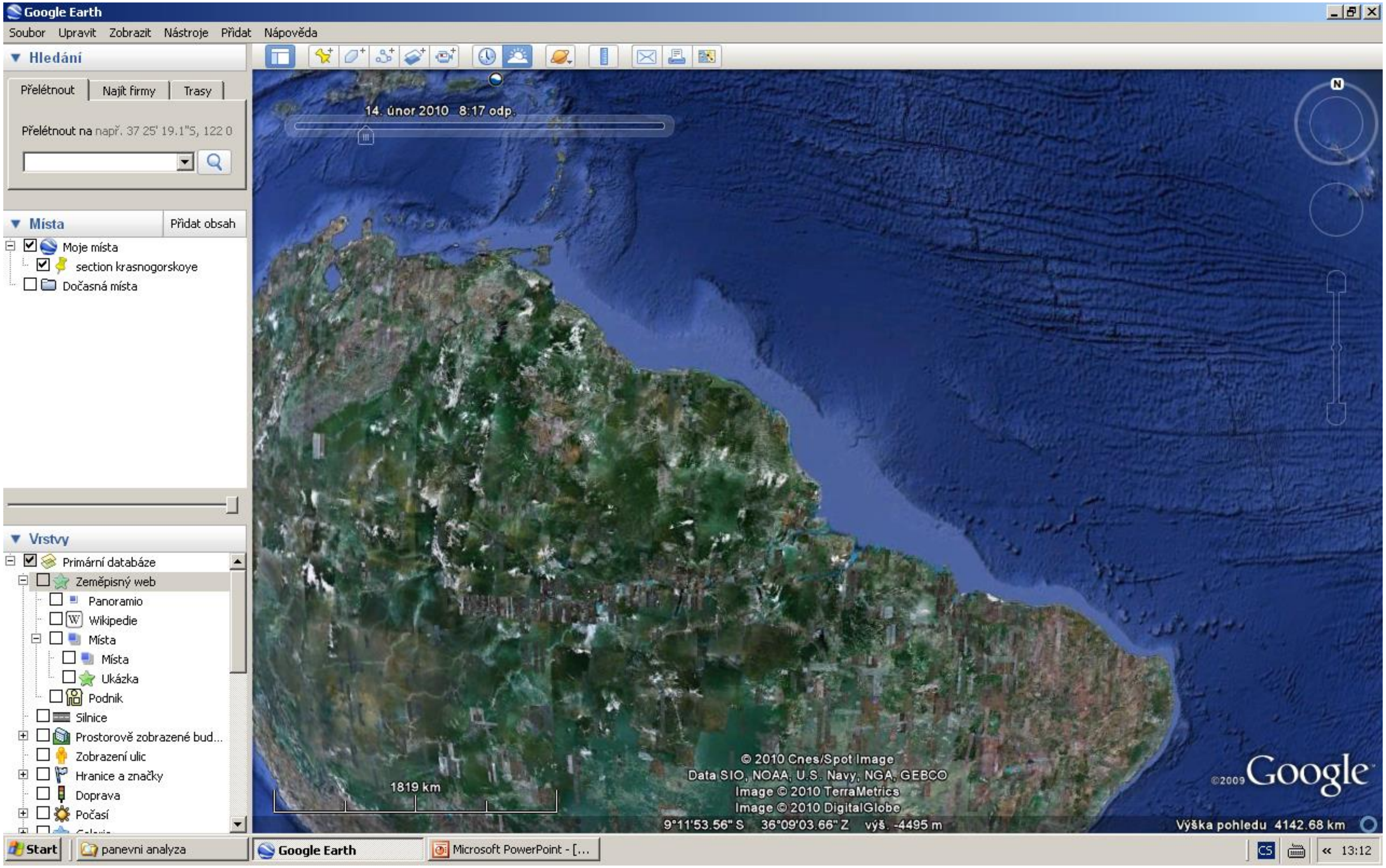
# Hudson Bay



# North Atlantic passive margin



# Amazon Fan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9°11'53.56" S 36°09'03.66" Z výš. -4495 m
©2009 Google
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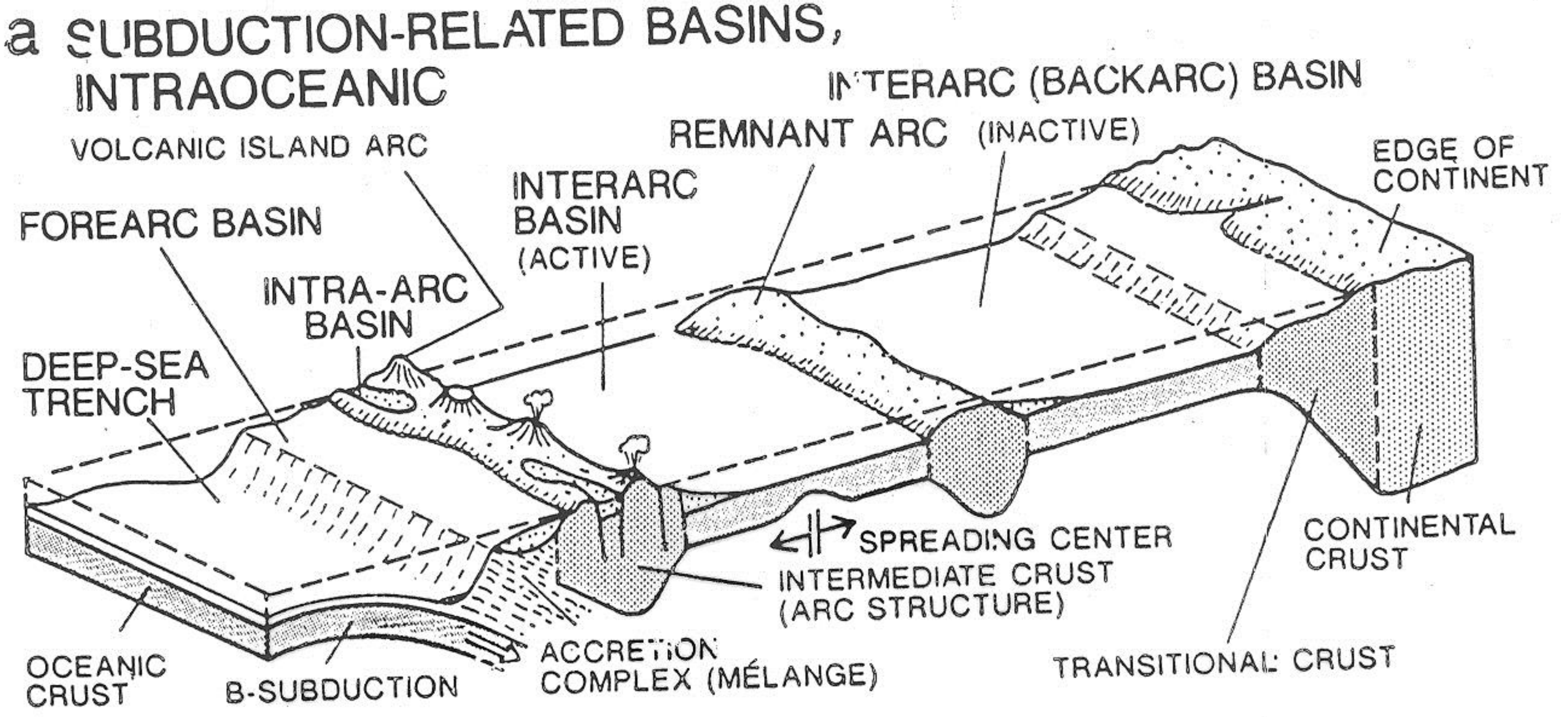
# Pánve na konvergentním deskovém rozhraní

- **Hlubokomořské příkopy (Trench)**, pánve na svazích trenčů - hluboké příkopy generované subdukcí oceánské kůry
  - pomalá nebo nulová subsidence, mocnost sedimentu kolísá podle přísunu sedimentu, malá až velká
  - Příklady: chilský trench, Torlesský terán, Nový Zéland, křída

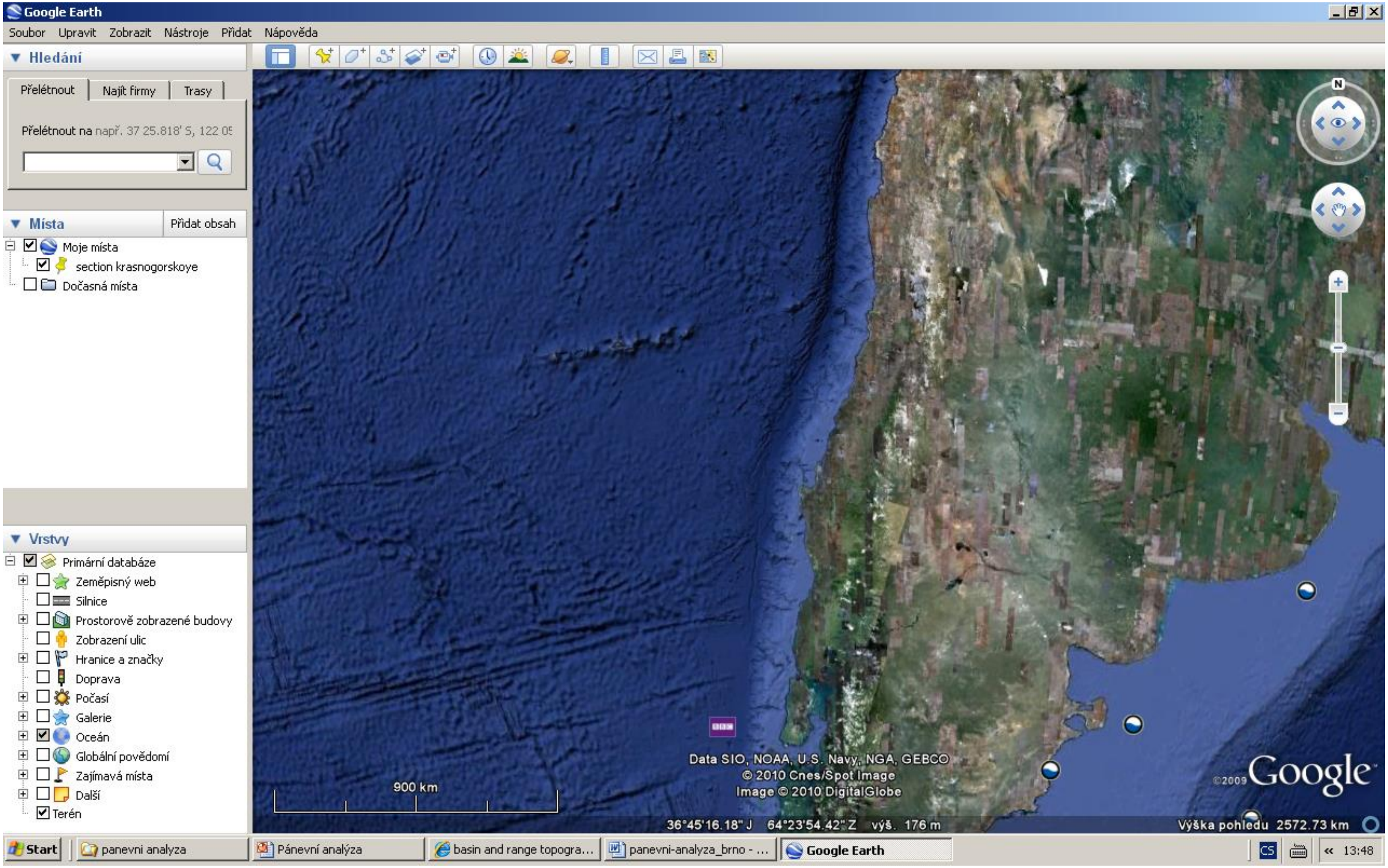
- **Předobloukové pánve (Forearc basin)** - pánve v prostoru mezi hranou svahu trenče a magmatickým obloukem
  - podloží tvořené přechodnou nebo oceánskou kůrou
  - subsidence pomalá až rychlá,
  - Příklady: Sumatra

- **Vnitroobloukové pánve (Intraarc basin)** - pánve uvnitř magmatických oblouků nebo mezi dvěma magmatickými oblouky
  - podloží tvořené přechodnou nebo kontinentální kůrou
  - subsidence středně rychlá
  - Příklad: Lago di Nicaragua,

- **Zaobloukové pánve (Backarc basin)** - pánve generované riftingem a spreadingem v týlu magmatických oblouků, vývoj podobný riftu a pasivnímu okraji
  - rychlá subsidence
  - Příklady: Japonské moře, Okinawa trough


a SUBDUCTION-RELATED BASINS, INTRAOCEANIC
INTERARC (BACKARC) BASIN
REMNANT ARC
(INACTIVE)
VOLCANIC ISLAND ARC
INTERARC BASIN (ACTIVE)
EDGE OF CONTINENT
FOREARC BASIN
INTRA-ARC BASIN
DEEP-SEA TRENCH
SPREADING CENTER
INTERMEDIATE CRUST (ARC STRUCTURE)
CONTINENTAL CRUST
OCEANIC CRUST
B-SUBDUCTION
ACCRETION COMPLEX (MÉLANGE)
TRANSITIONAL CRUST

# Chile trench



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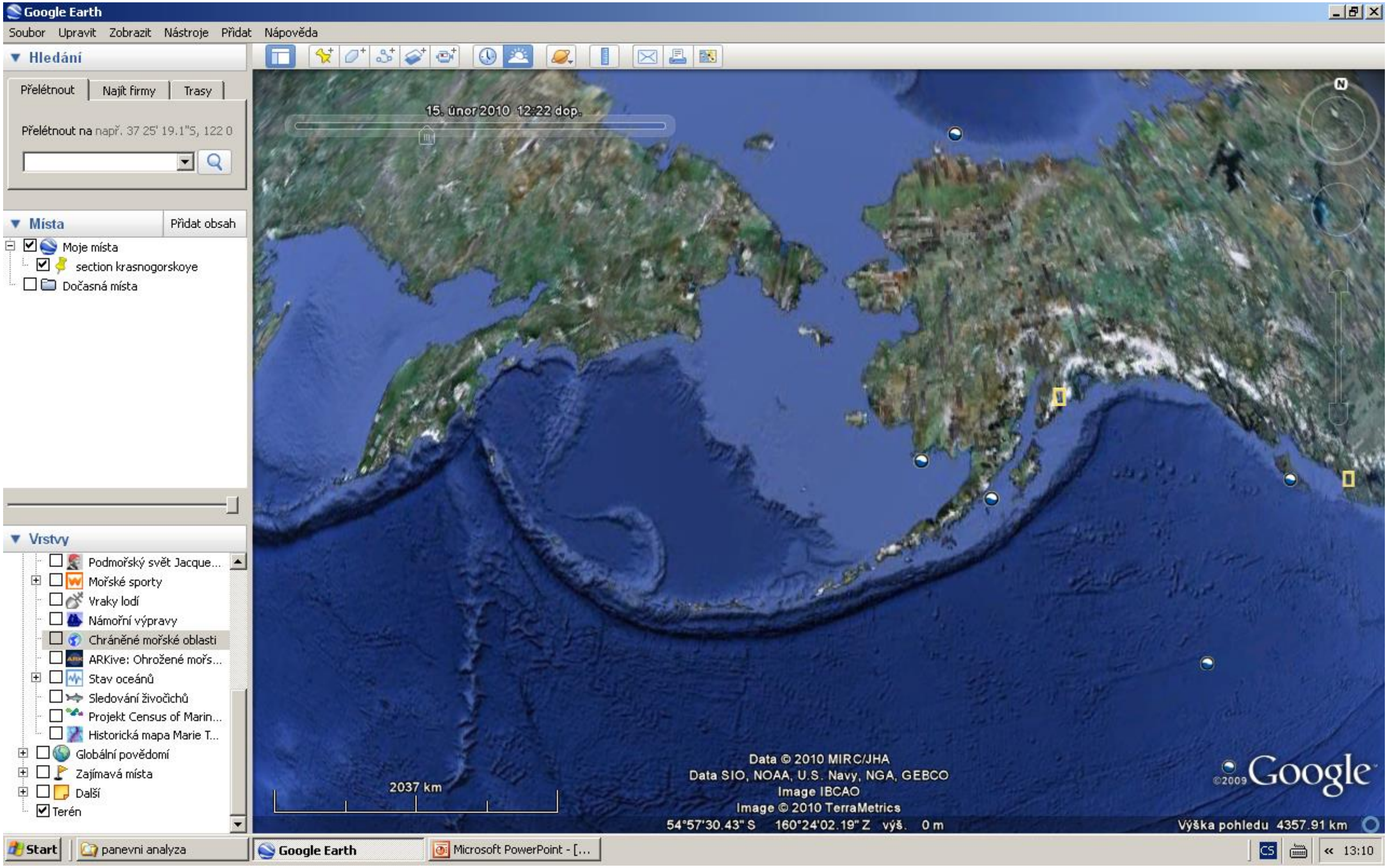
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☑ section krasnogorskoye
☐ Dočasná místa
▼ Vrstvy
☐ Podmořský svět Jacque...
☐ Mořské sporty
☐ Vraky lodí
☐ Námořní výpravy
☐ Chráněné mořské oblasti
☐ ARKive: Ohrožené mořs...
☐ Stav oceánů
☐ Sledování živočichů
☐ Projekt Census of Marin...
☐ Historická mapa Marie T...
☐ Globální povědomí
☐ Zajímavá místa
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Výška pohledu 4357.91 km
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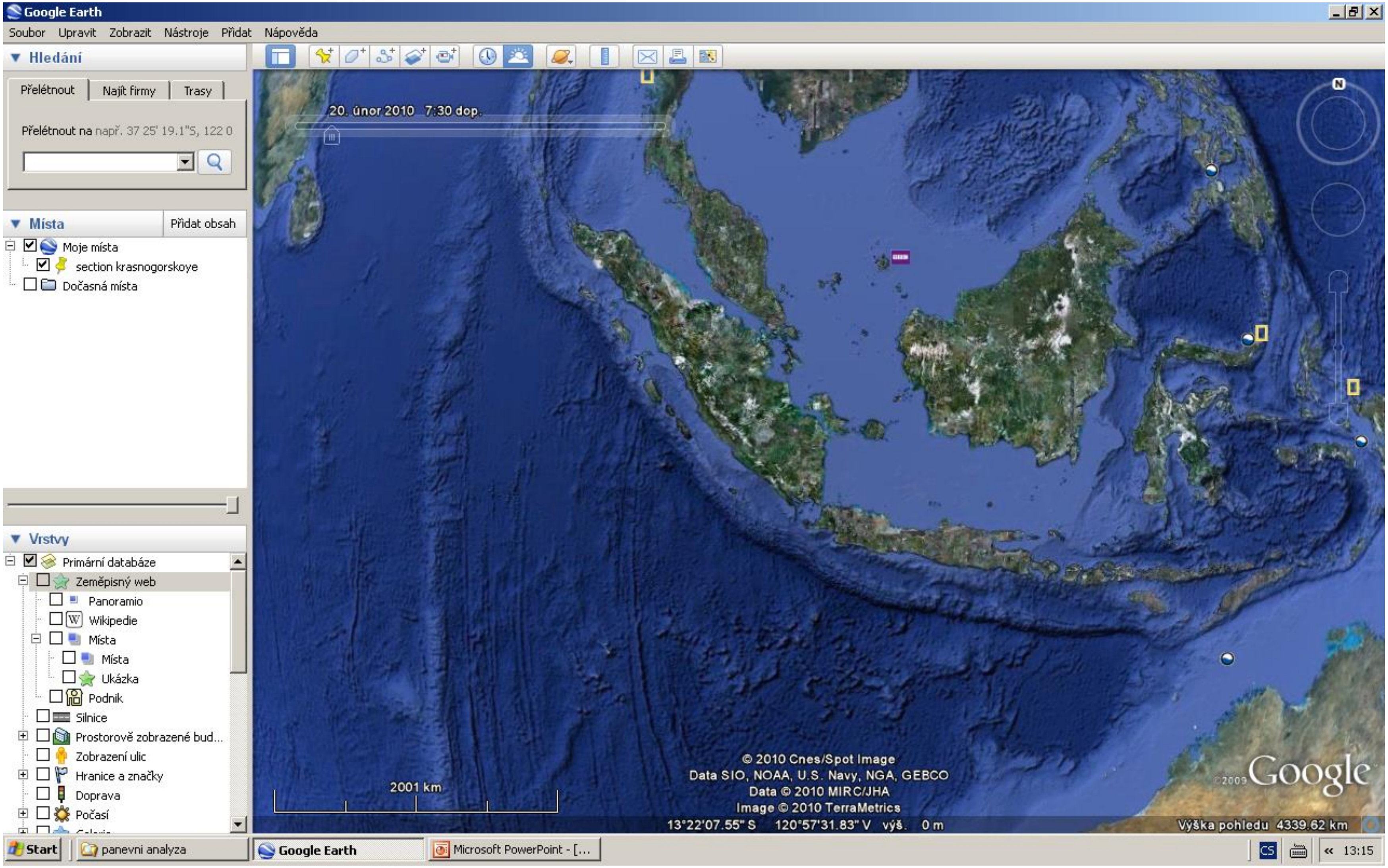
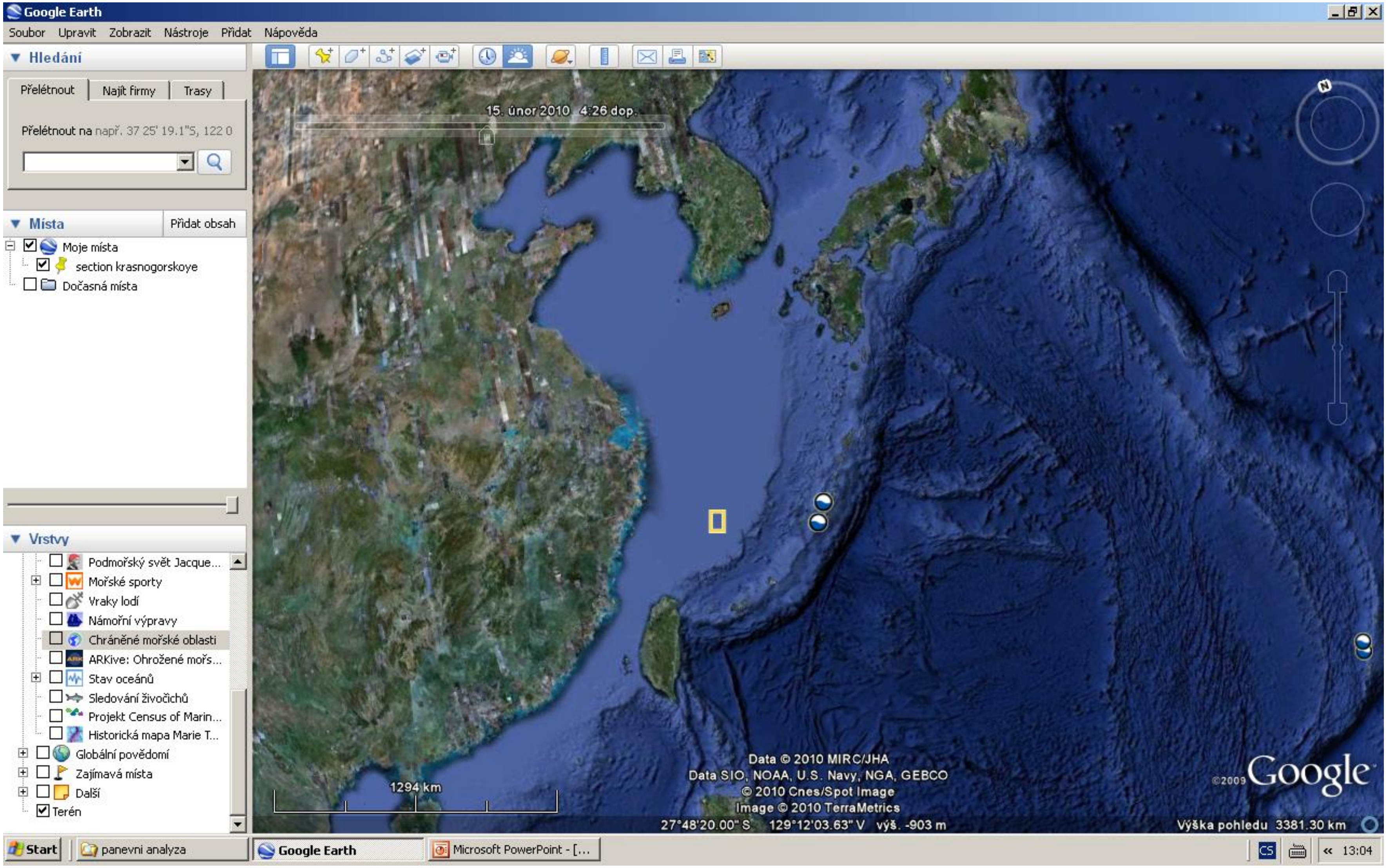
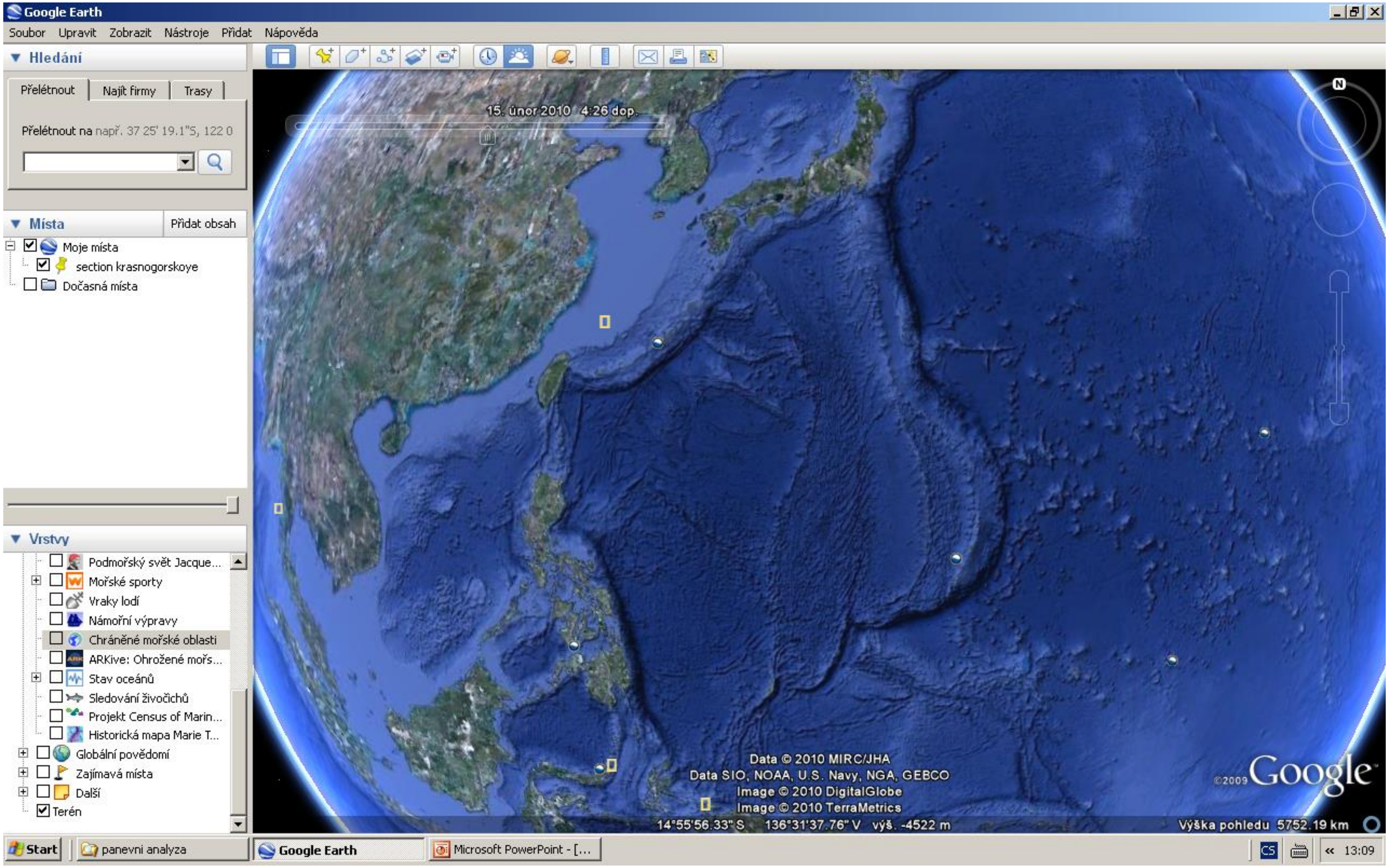
# Forearc basins, Java



# Okinawa trough



# Remnant arcs



# Pánve na konvergentním rozhraní 2

- **zbytkové pánve (remnant basin)** - pánve generované na zanikající oceánské kůře mezi dvěma konvergujícími kontinenty
  - subsidence pomalá, mocnosti sedimentu velké
  - Příklady: Bengálský záliv, karbon, pohoří Quachita, Sev. Amerika

- **týlové předpolní pánve (retroarc foreland basin)** - pánve vznikající v týlu magmatického oblouku na kontinentální kůře
  - pomalá až rychlá subsidence, střední až velké mocnosti sedimentu
  - Příklady: křídové pánve amerického středozápadu, kontinentální podhůří And

- **periferní předpolní pánve (peripheral foreland basin)** - pánve vznikající na kontinentální kůře v depresi před nasouvanou zónou příkrovů
  - subsidence pomalá až rychlá, střední až velké mocnosti sedimentu
  - Příklady: Timor, Perský záliv, molasové pánve v předpolí Alp a Karpat
  - nesené pánve „piggyback“ - pánve generované na podkladu sunoucích se příkrovů, subsidence středně rychlá až rychlá, mocnosti sedimentu střední až velké (neogén Apenniny, Vídeňská pánev)

- **intramontánní pánve (intramontane basin)** - pánve vznikající v důsledku postorogenní divergence mezi dvěma příkrovovými zónami
  - založené na kontinentální nebo přechodné kůře
  - Příklad: panonská pánev

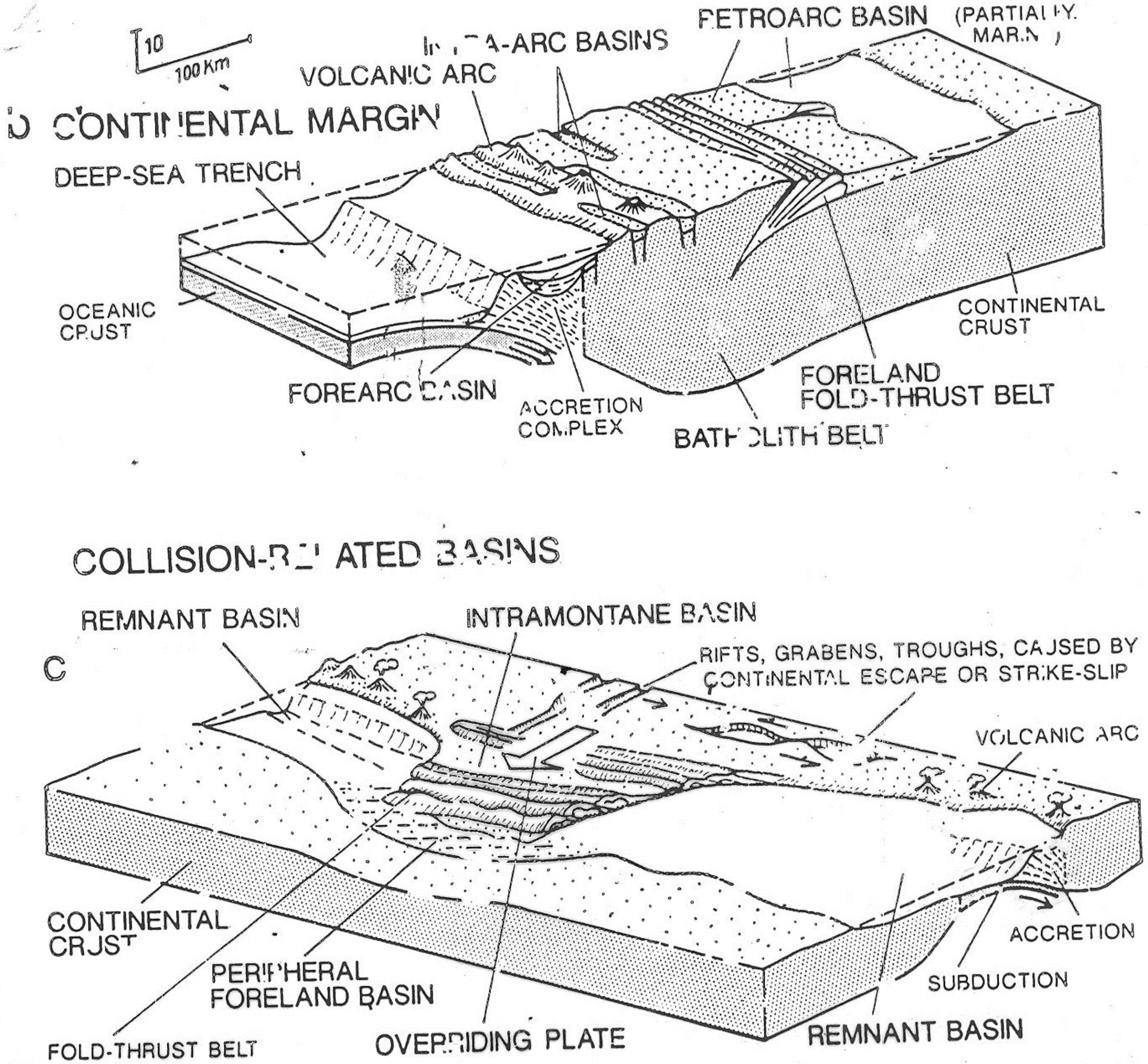
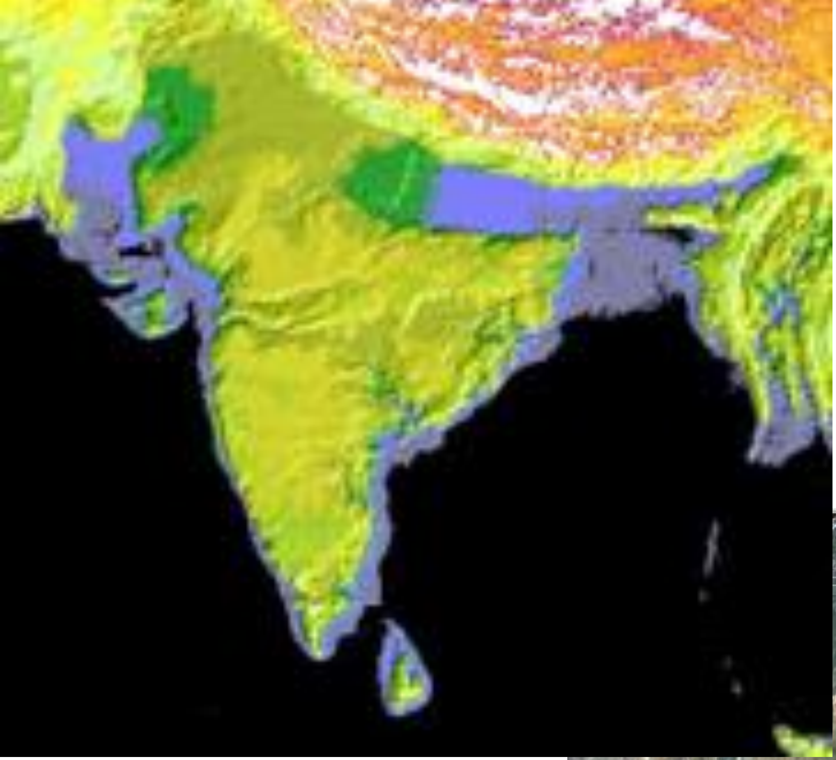
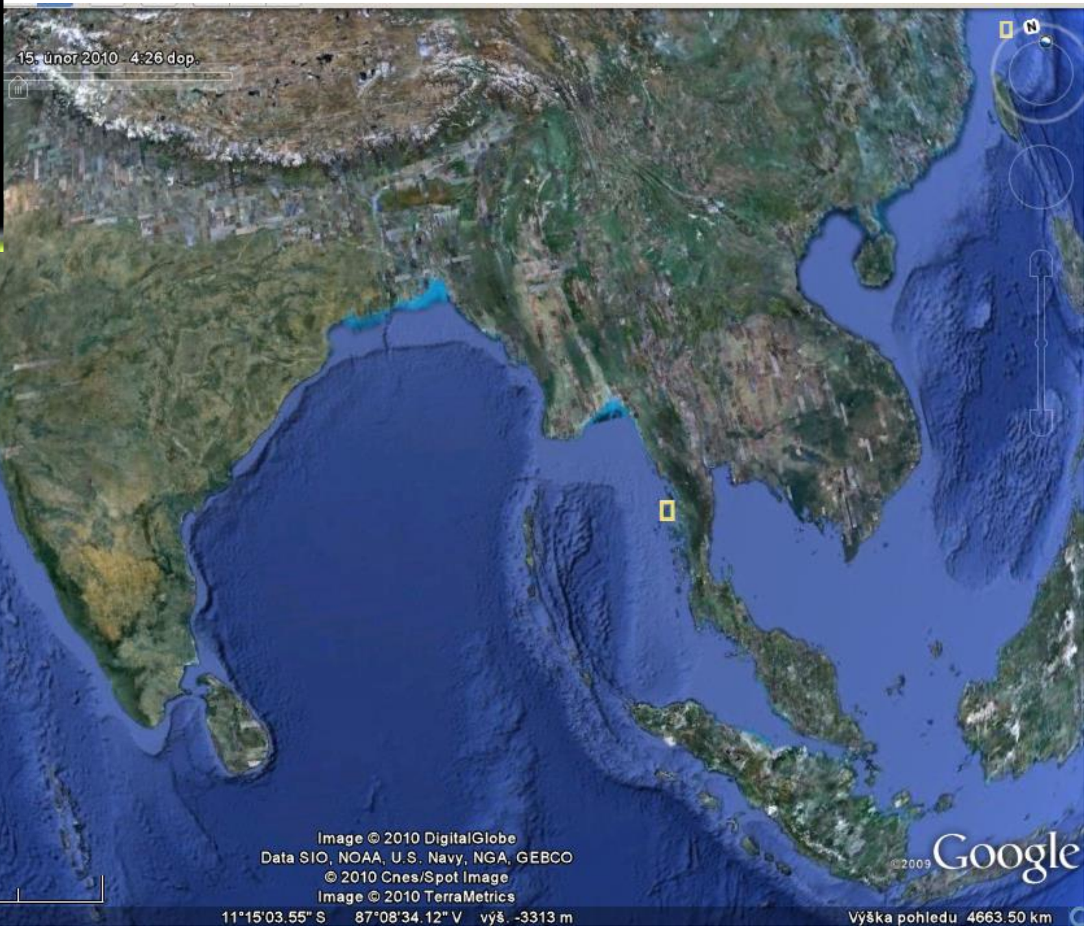


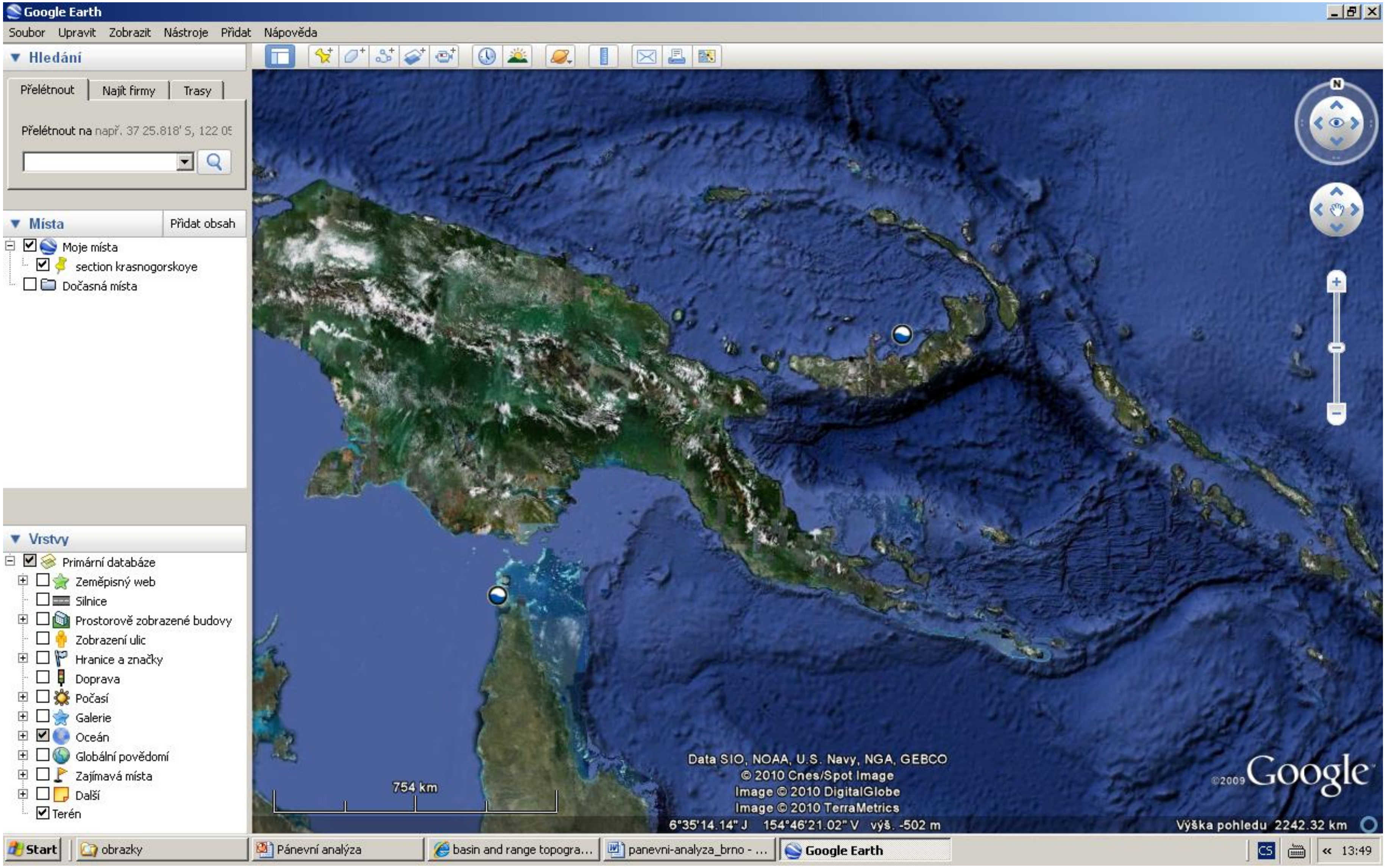
**Fig. 1.2a-c.** Tectonic basin classification (Fig. 1.1 continued). Subduction and collision-related basins (remnant basin). See text for explanation

# Bengálský záliv

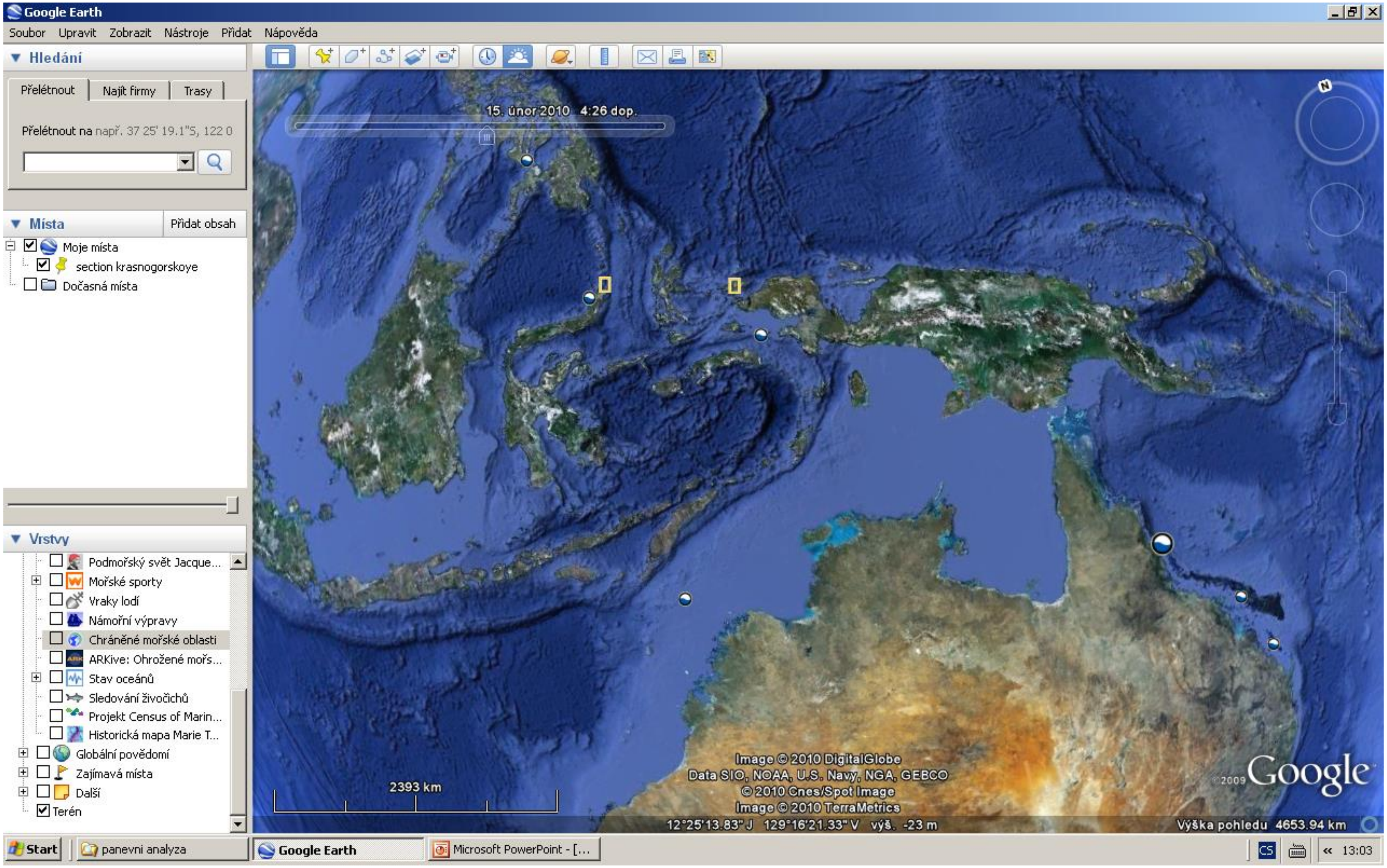




# Papua New Guinea remnant basin



# Timor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Chráněné mořské oblasti
ARKive: Ohrožené mořs...
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Sledování živočichů
Projekt Census of Marin...
Historická mapa Marie T...
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Image © 2010 DigitalGlobe
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2010 Cnes/Spot Image
Image © 2010 TerraMetrics
12°25'13.83" J 129°16'21.33" V výš. -23 m
Výška pohledu 4653.94 km
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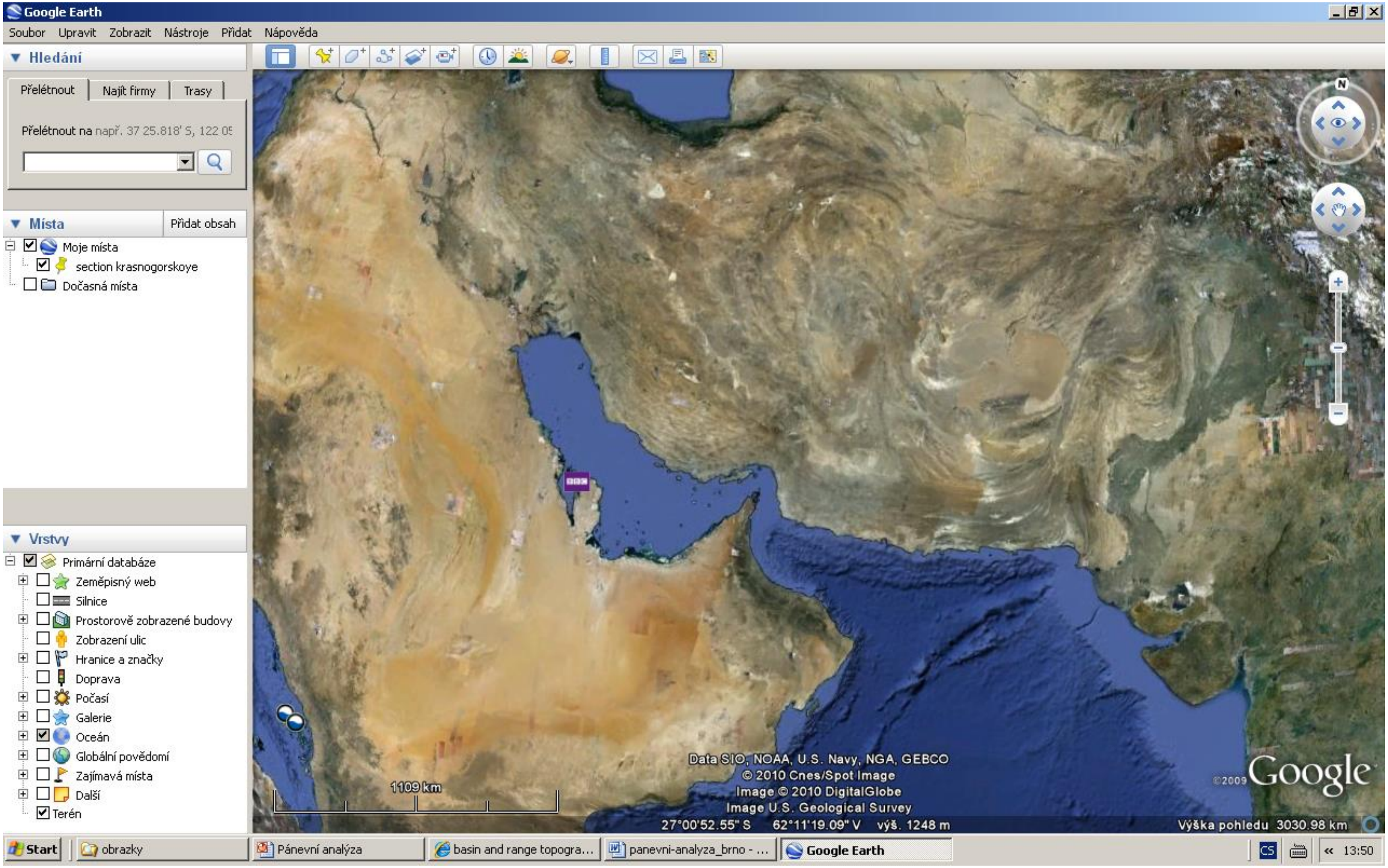
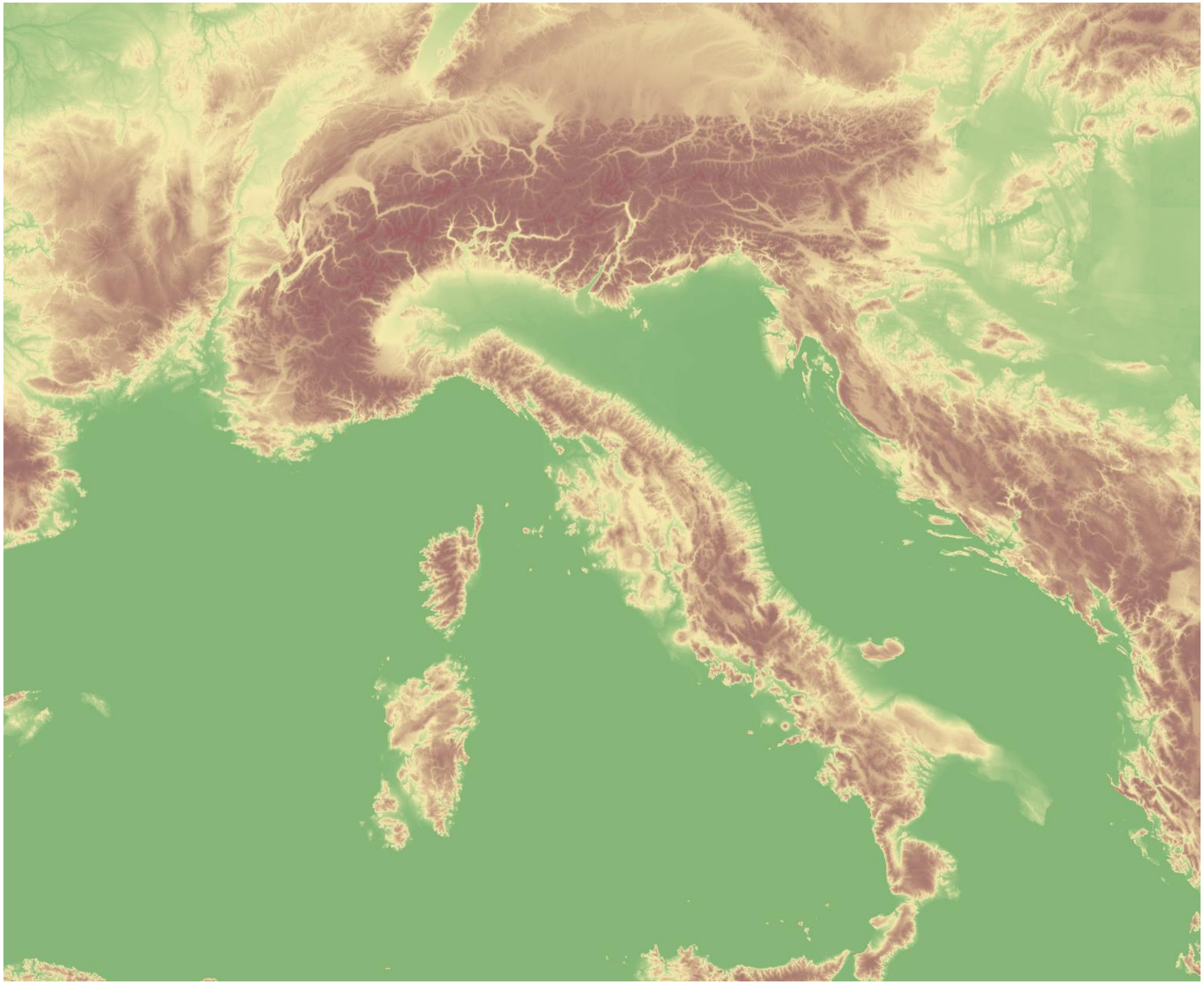
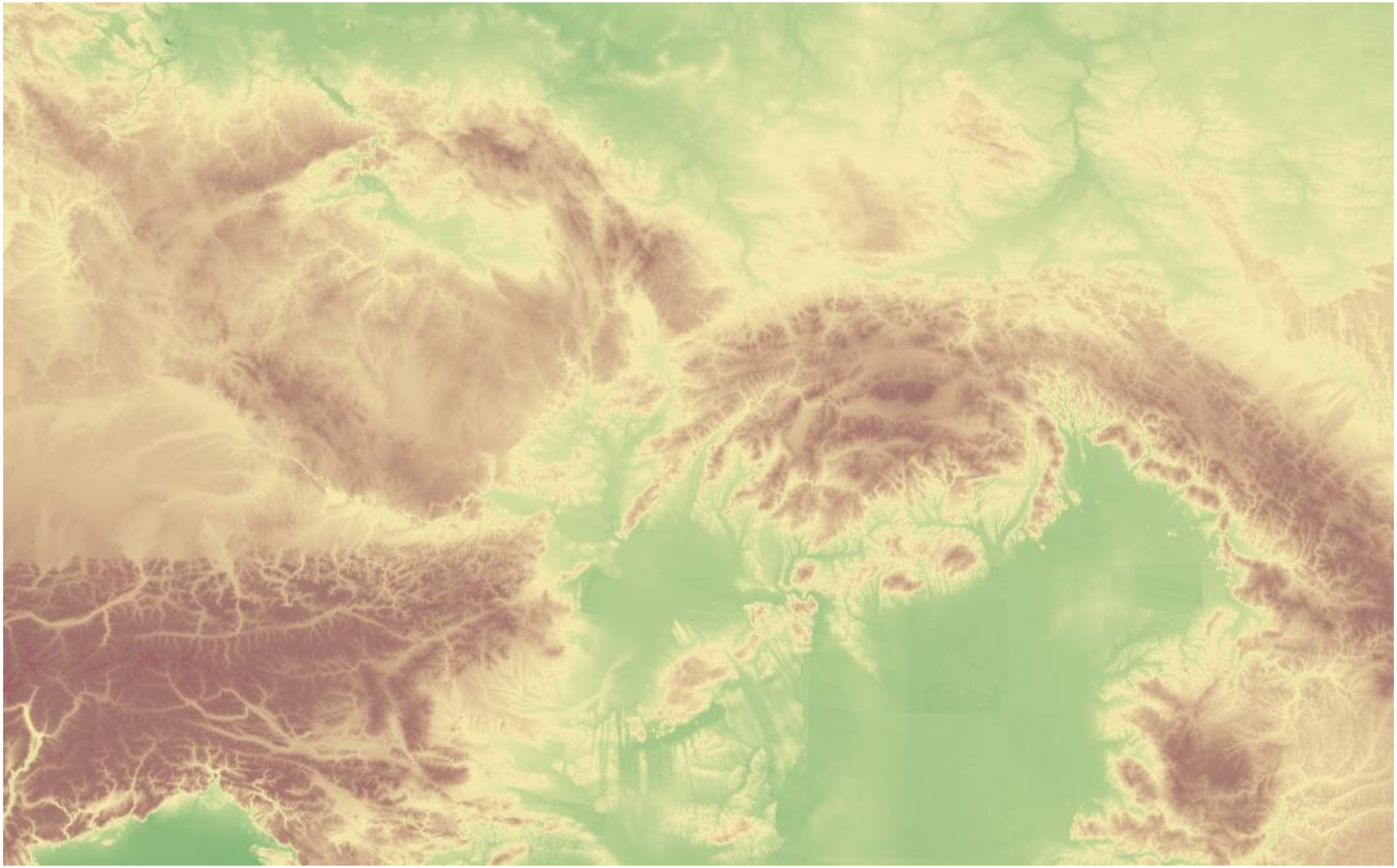
# Persian Gulf peripheral foreland basin



# North Adriatic foreland



# Vienna Basin



# Pánve na transformním rozhraní

- transtenzní pánve - extenzní pánve vznikající na horizontálních posunech, založené na kontinenální kůře
  - mohou vést ke generaci nové oceánské kůry
  - velmi vysoká rychlost subsidence
  - Příklad: záliv sv. Vavřince, karbon

- transpresní pánve - kompresní pánve vznikající na horizontálních posunech
  - Příklad: pánev Santa Barbara, Kalifornie, recent

- transrotační pánve - pánve generované rotací krustálních bloků podél jejich vertikálních os uvnitř zón horizontálního posunu
  - Příklad: Los Angeleská pánev, miocén

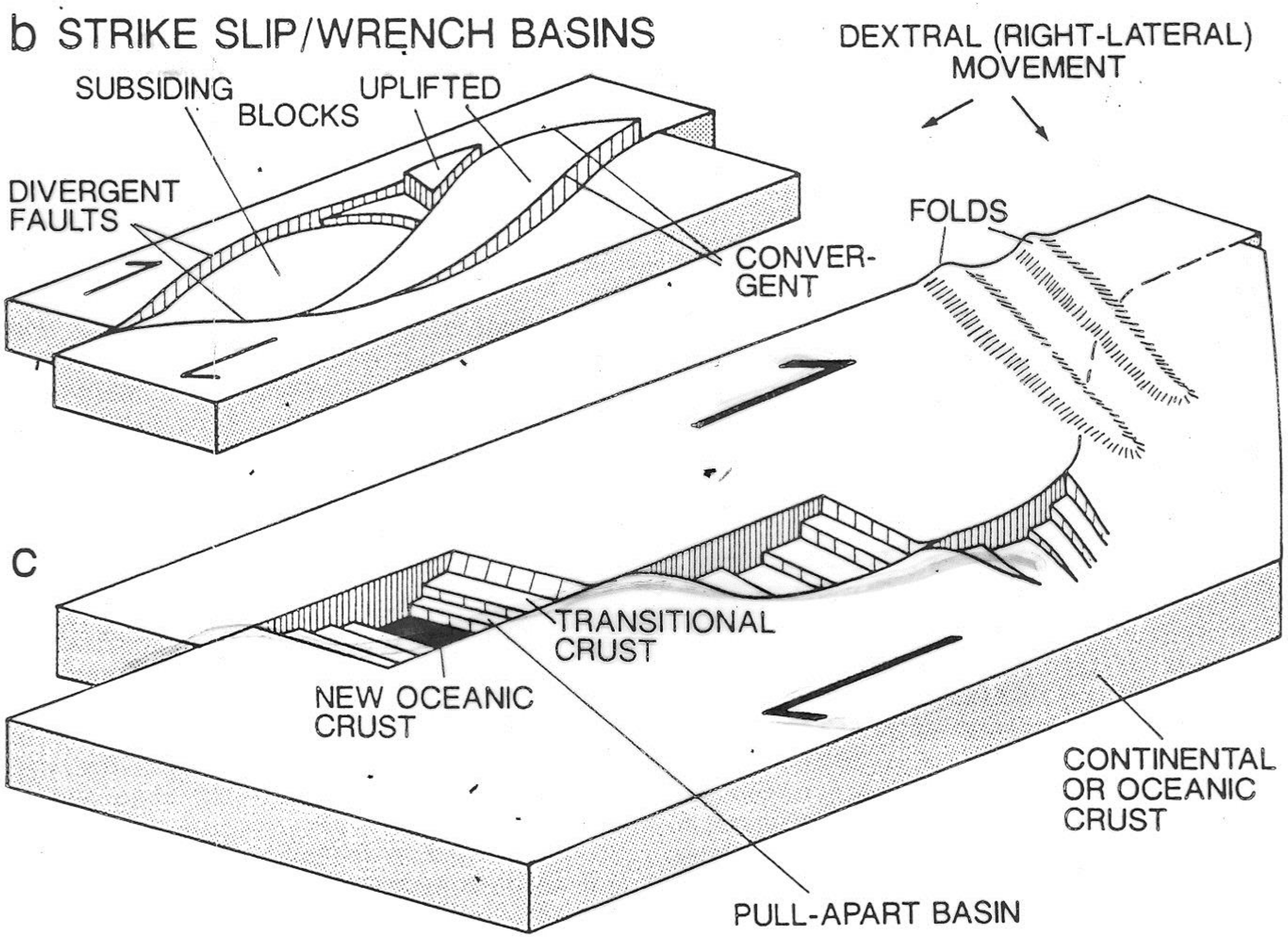
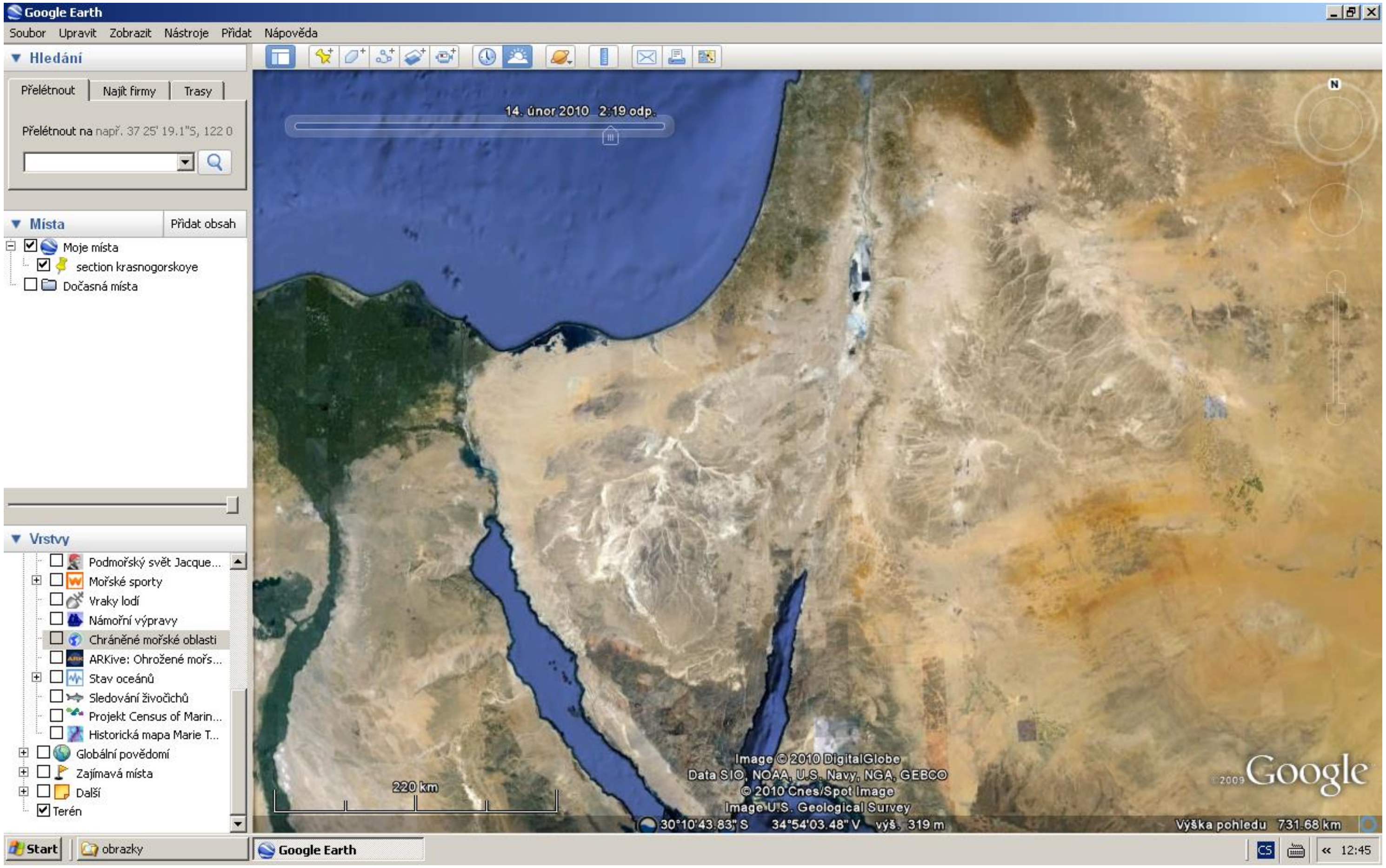


**Fig. 1.3a-c.** Tectonic basin classification (Fig. 1.2 continued). Collision-related basins and strike-slip/wrench basins. See text for explanation

# Dead sea


Google Earth
Soubor
Upravit
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Přidat
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▼ Hledání
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Přidat obsah
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☑ section krasnogorskoye
☐ Dočasná místa
▼ Vrstvy
☐ Podmořský svět Jacque...
☐ Mořské sporty
☐ Vraky lodí
☐ Námořní výpravy
☐ Chráněné mořské oblasti
☐ ARKive: Ohrožené mořs...
☐ Stav oceánů
☐ Sledování živočichů
☐ Projekt Census of Marin...
☐ Historická mapa Marie T...
☐ Globální povědomí
☐ Zajímavá místa
☐ Další
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Image © 2010 DigitalGlobe
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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Image U.S. Geological Survey
30°10'43.83" S 34°54'03.48" V výš. 319 m
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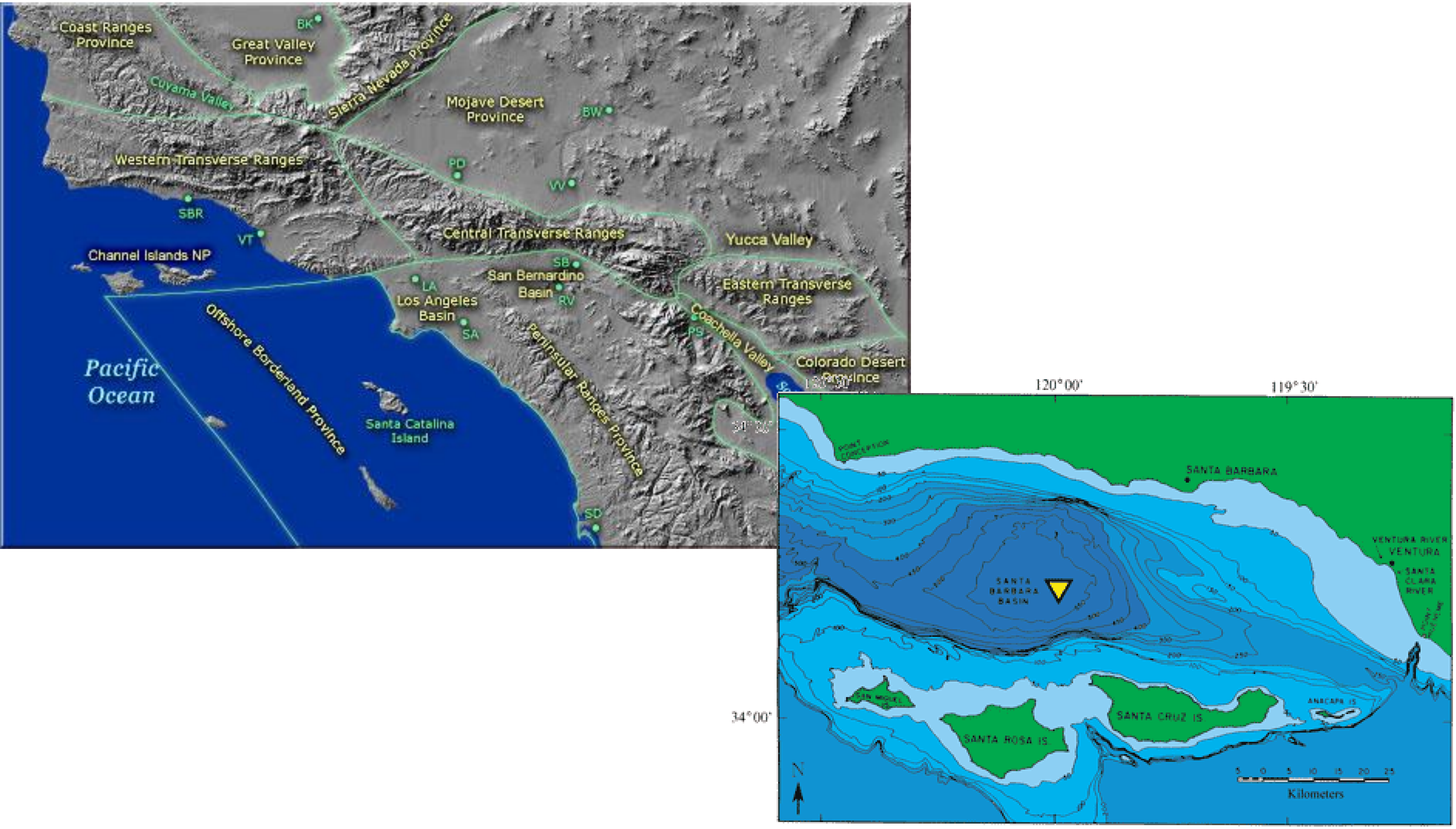
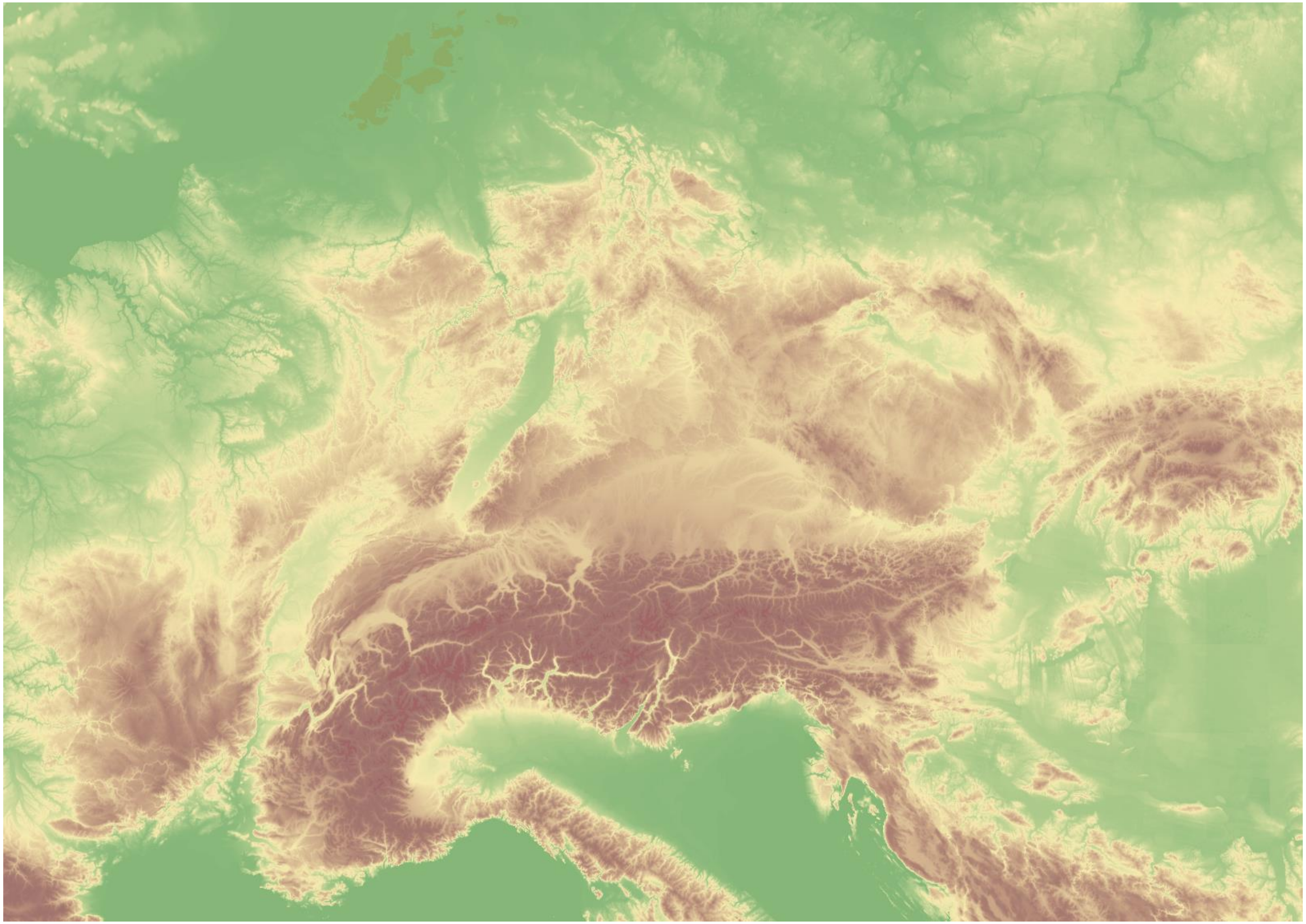
# Los Angeles and Santa Barbara Basins



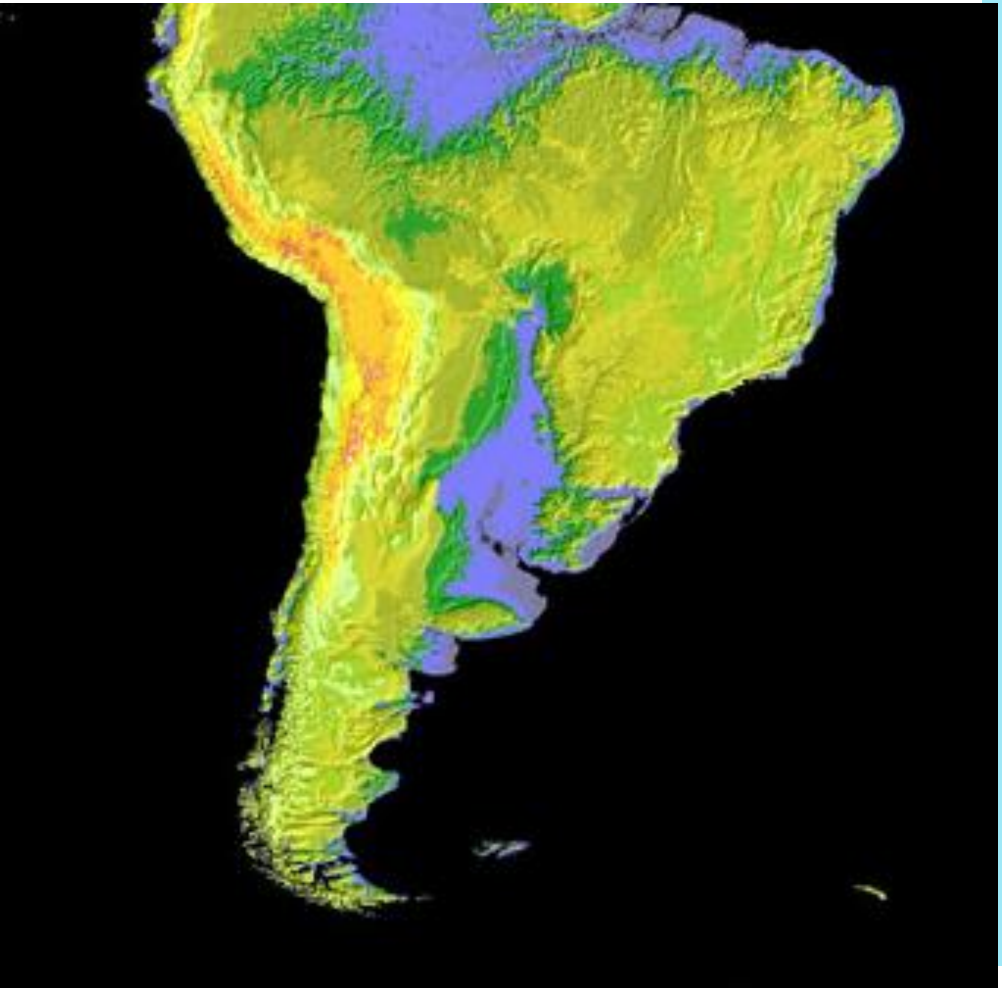
# Pánve v hybridním tektonickém prostředí

- mrtvé rifty, aulakogény - ukončení riftingu před zahájením spreadingu, mrtvé rameno trojného bodu
- impaktogény
  - Příklad: údolí Amazonky, Parana, jezero Bajkal, Rýnský prolom

# Rhine graben



# South America, Parana Basin



# SUBSIDENCE
# A
# SUBSIDENČNÍ HISTORIE PÁNVE

# Rozhraní ve vrstevnaté stavbě Země

- Hlavní kompoziční rozhraní: kůra-plášť (MOHO)
- Hlavní reologické rozhraní: litosféra-astenosféra
- Litosféra: rigidní deska

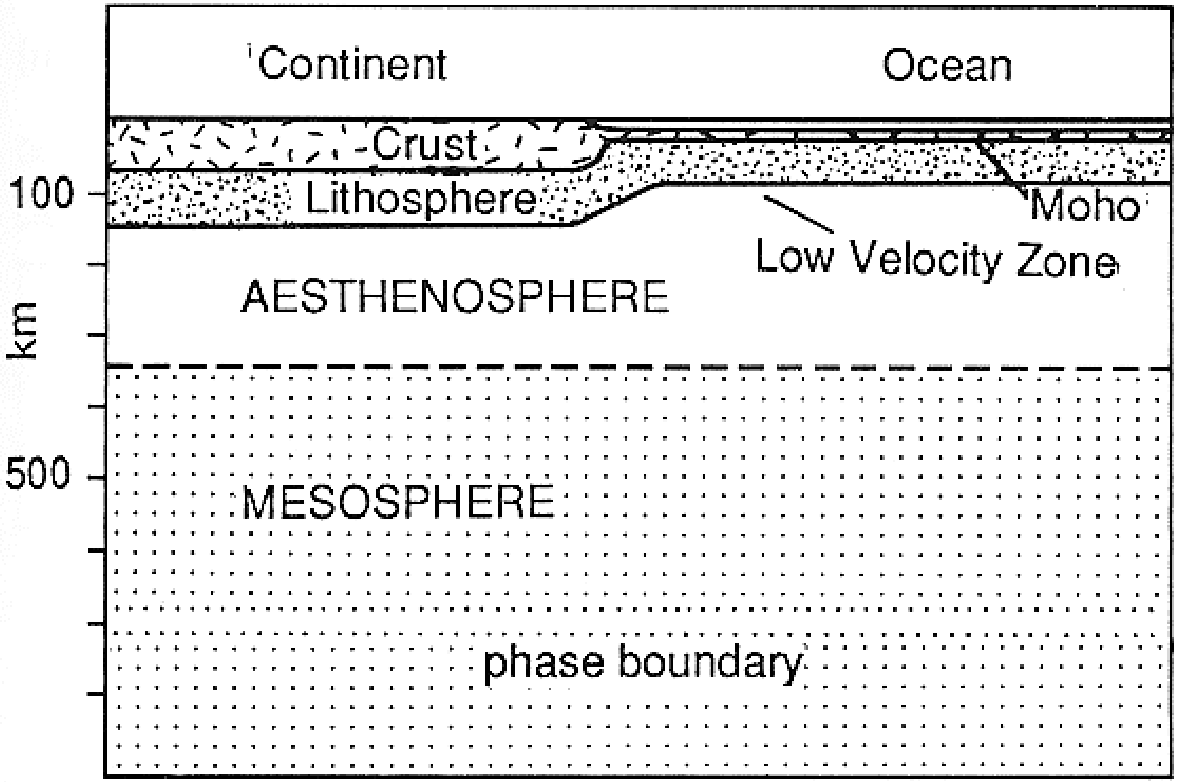


**Fig. 1.1.** The main compositional and rheological boundaries of the Earth. The most important compositional boundary is between the crust and the mantle, although there are certainly strong compositional variations within the continental crust. The base of the crust is marked by the Moho. The main rheological boundary is between the lithosphere and the aesthenosphere. The lithosphere is rigid enough to act as a coherent plate.

# Mocnosti kůry

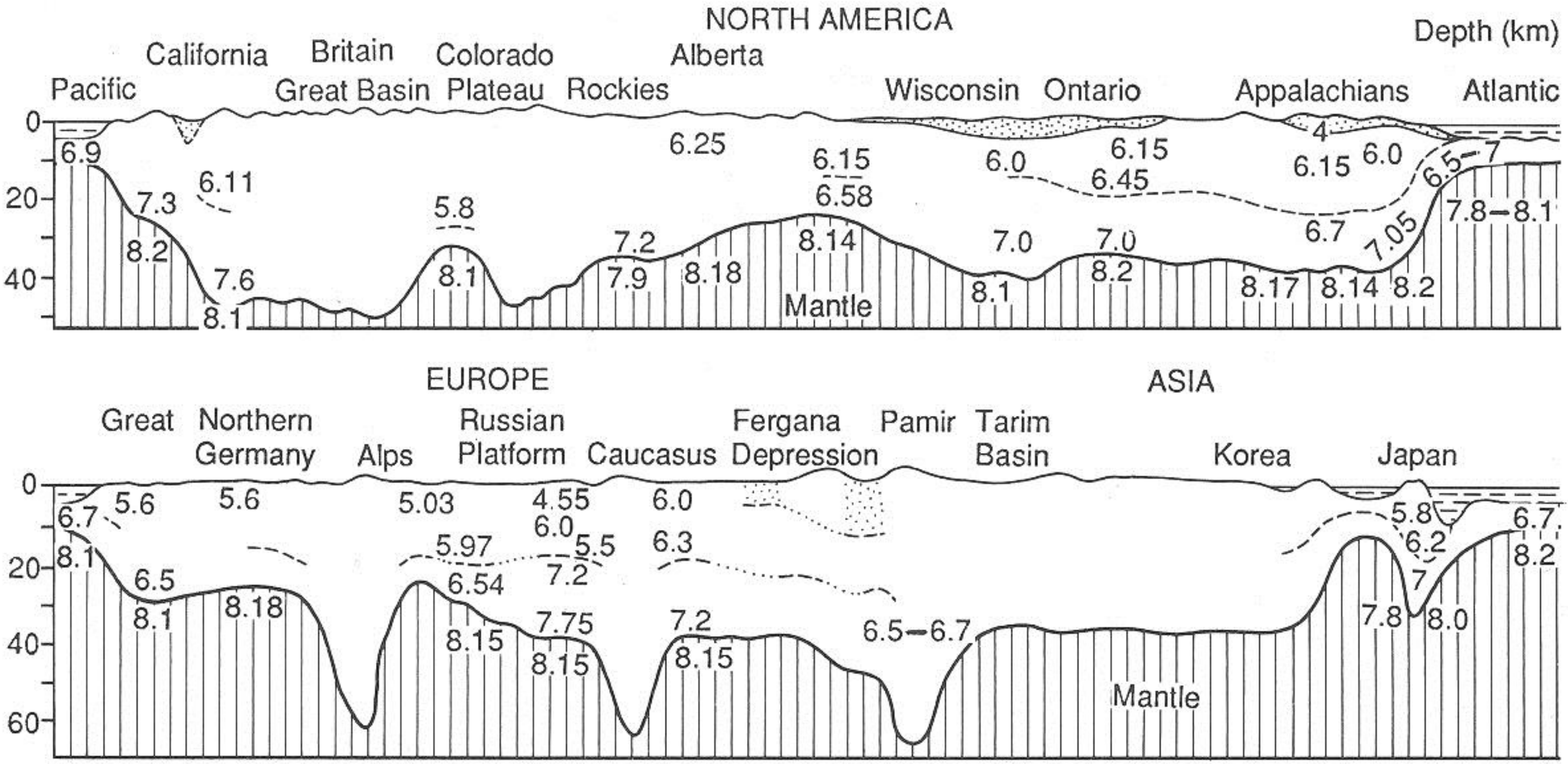


**Fig. 1.3.** Variations in crustal thickness across two continents (a) North America, (b) Eurasia, based on P wave velocities (after Holmes 1965). Mountains have well-developed crustal roots, as under the Alps, Caucasus and Pamir Range in the Eurasian section.

**Variabilní mocnost kůry (hloubka MOHO) napříč (a) Severní Amerikou a (b) Eurasií; (rychlosti šíření P vln): Hory (Alpy, Kavkaz, Pamír, atd.) mají dobře vyvinuté „kořeny“**

# Tavení pláště: báze litosféry

Změna teploty s hloubkou (geoterma) a teplota tavení solidu pro plášťový materiál.

Tam, kde se křivka solidu ($T_m$) a geoterma dotknou, nastává možnost parciálního tavení pláště – kanál nízkých seismických rychlostí pláště

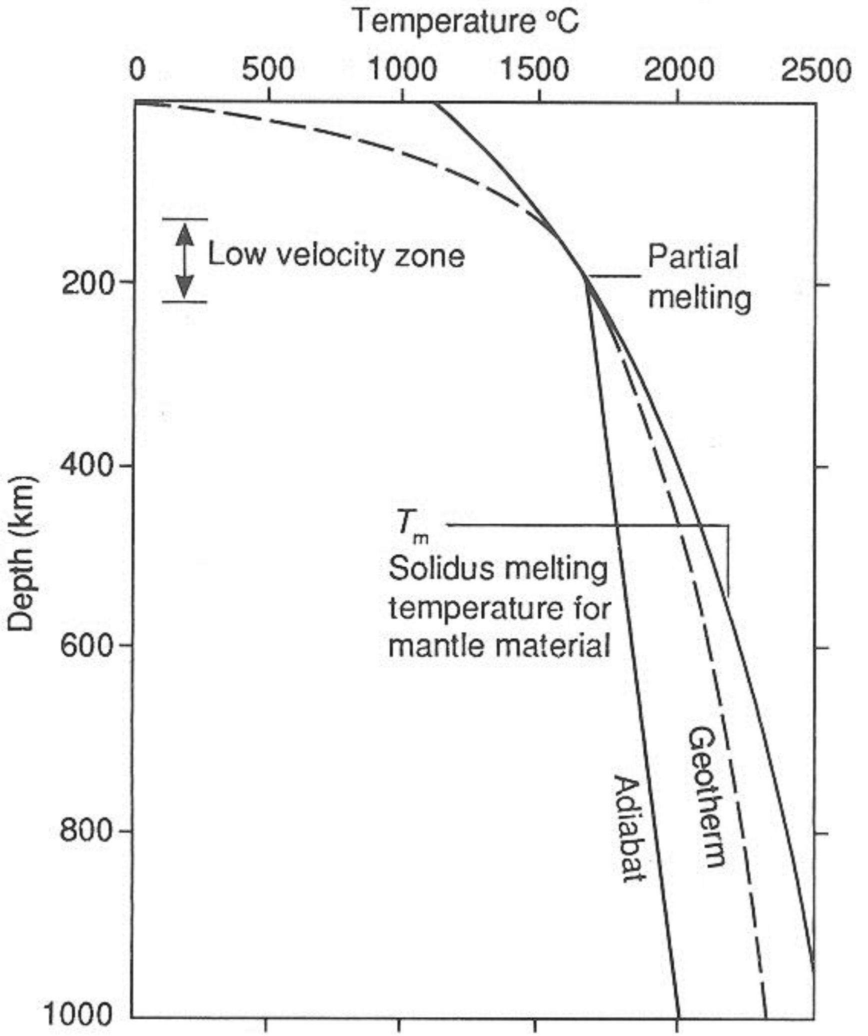


**Fig. 1.5.** Variation of temperature with depth, or geotherm, and the solidus melting temperature for mantle material. Where the solidus curve ($T_m$) and the geotherm become tangential, partial melting in the mantle is likely to take place, resulting in a zone of low seismic wave velocities (low velocity zone).

# Gravitační režim litosféry, izostáze

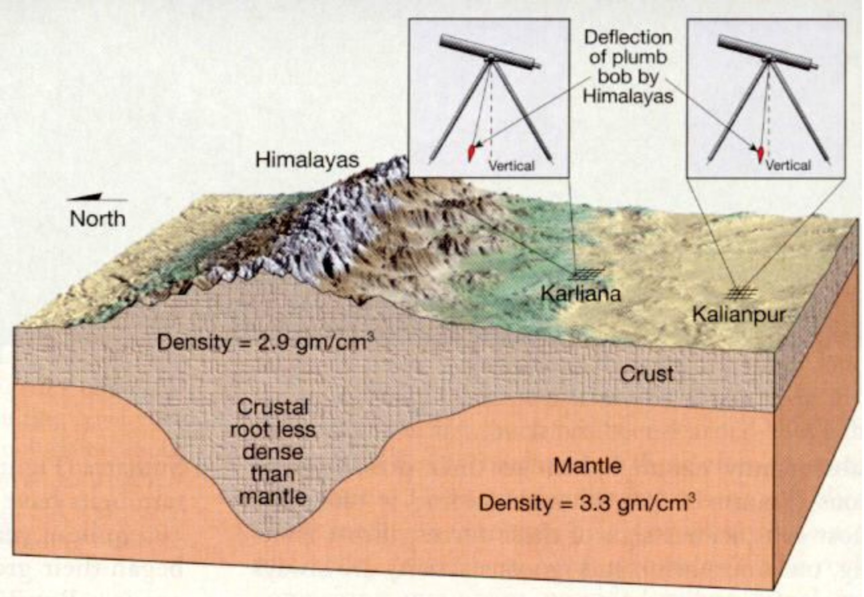
- **Geodetická měření v 19. stol.** – výchylka olovnice od vertikály menší než naznačoval výpočet

**Vysvětlení** – Airyho model izostatického vyrovnání

**sir George Biddel Airy (1801 – 1892)**

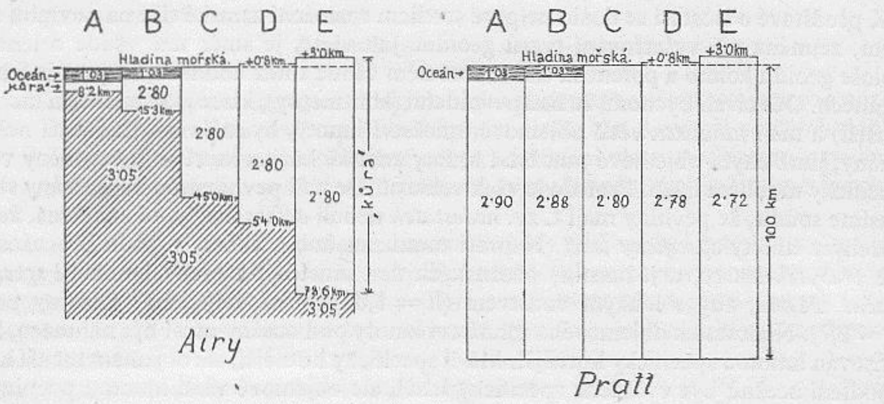
hustotní a reologický kontrast mezi litosférou a astenosférou

model pevných bloků lehké látky plovoucí na hladině těžší kapaliny



◆ **Figure 20.A** During the first survey of India, an error in measurement occurred because the plumb bob on an instrument was deflected by the massive Himalayas. Later work by George Airy predicted that the mountains have roots of light crustal rocks. Airy's model explained why the plumb bob was deflected much less than expected.

# Prattův a Airyho model izostáze

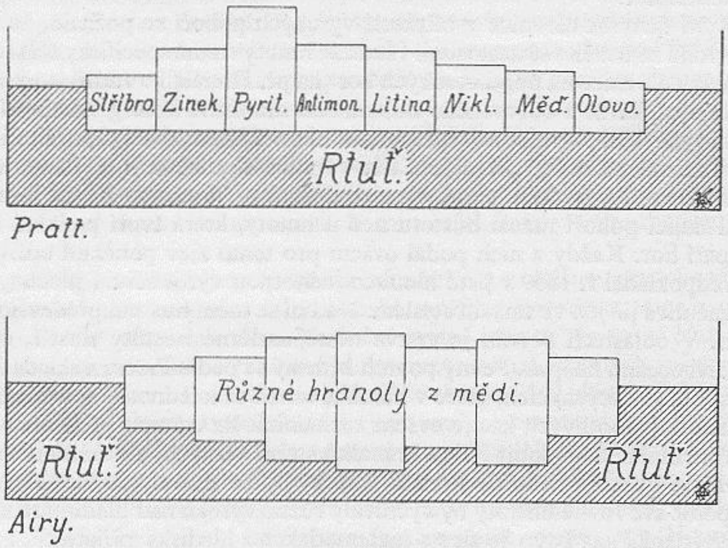


Obr. 3. *Schematické znázornění isostatického vyrovnání sektorů A až E podle Prattova a Airyho výkladu isostase.* (Podle R. A. DALYHO.)

**Pratt**

Litosféra pod horami má menší hustotu než pod nížinami

NE !



Obr. 4. *Experiment znázorňující různost v pojetí Prattově a Airyho při výkladu isostase.* (Podle W. BOWIEHO.)

**Airy**

Litosféra pod horami sahá hlouběji než pod nížinami (hory mají „kořeny“)

ANO !

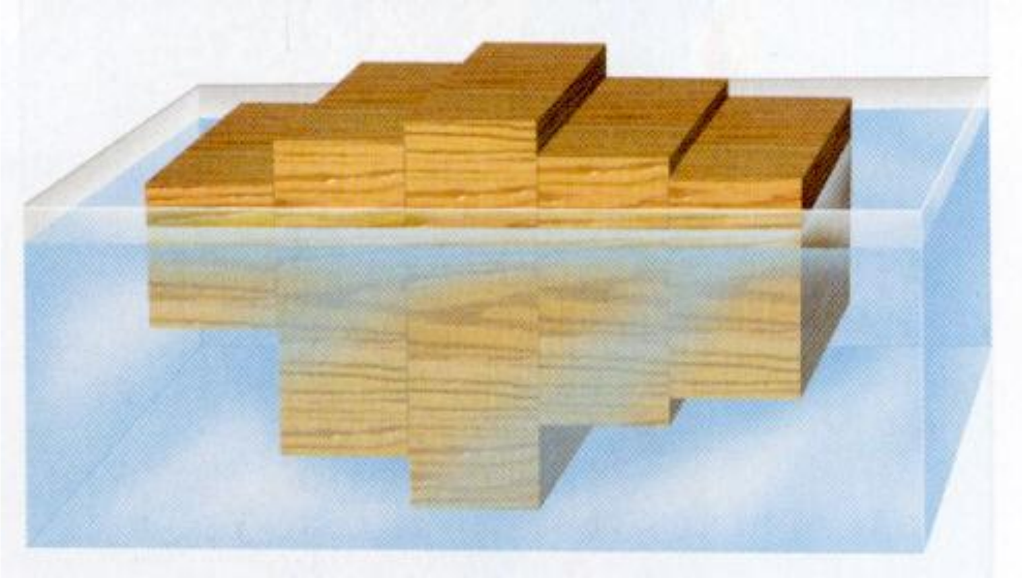
# Gravitační režim litosféry, izostáze

- **Litosféra:** rigidní (pevná látka), nižší hustota
- **Astenosféra**: plastická (kapalina), vyšší hustota

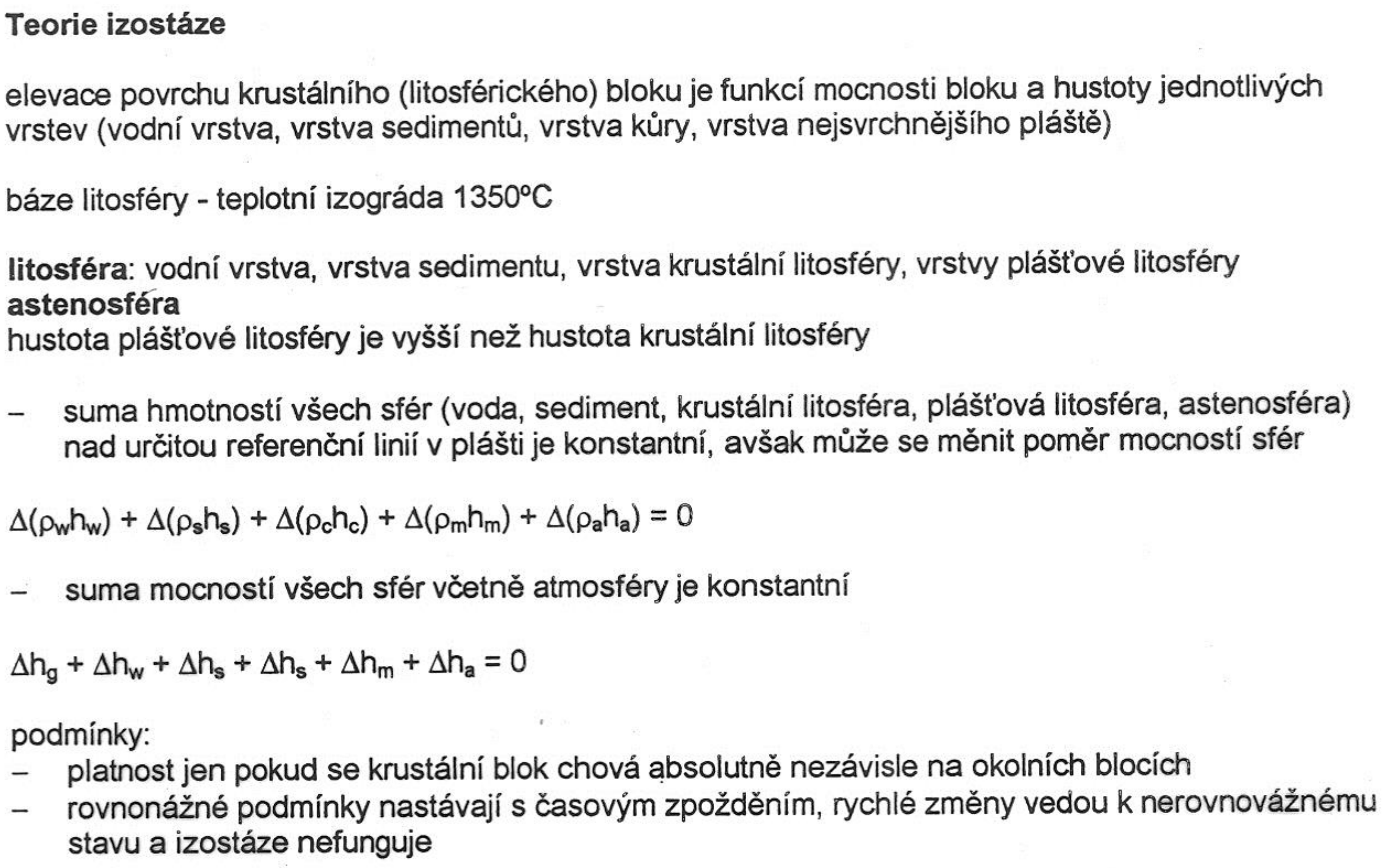
- Poměr ponořené a vynořené části bloku, referenční úroveň (hladina moře) je závislý na souhrnné hustotě bloku a u bloků se stejnou hustotou musí být zachován

- Hory mají „kořeny“

- Princip archimédova zákona



# Izostatické vyrovnání



**Teorie izostáze**

elevace povrchu krustálního (litosférického) bloku je funkcí mocnosti bloku a hustoty jednotlivých vrstev (vodní vrstva, vrstva sedimentů, vrstva kůry, vrstva nejsvrchnějšího pláště)

báze litosféry - teplotní izográda 1350°C

**litosféra**: vodní vrstva, vrstva sedimentu, vrstva krustální litosféry, vrstvy plášťové litosféry
**astenosféra**
hustota plášťové litosféry je vyšší než hustota krustální litosféry

- suma hmotností všech sfér (voda, sediment, krustální litosféra, plášťová litosféra, astenosféra) nad určitou referenční linií v plášti je konstantní, avšak může se měnit poměr mocností sfér

$$\Delta(\rho_w h_w) + \Delta(\rho_s h_s) + \Delta(\rho_c h_c) + \Delta(\rho_m h_m) + \Delta(\rho_a h_a) = 0$$

- suma mocností všech sfér včetně atmosféry je konstantní

$$\Delta h_g + \Delta h_w + \Delta h_s + \Delta h_s + \Delta h_m + \Delta h_a = 0$$

podmínky:
- platnost jen pokud se krustální blok chová absolutně nezávisle na okolních blocích
- rovnonážné podmínky nastávají s časovým zpožděním, rychlé změny vedou k nerovnovážnému stavu a izostáze nefunguje

# Izostatické vyrovnání

**Princip izostáze na příkladu dvou krustálních bloků (a: náhorní plošina, b: kontinentální šelf) složených z vrstev o různé mocnosti a hustotě na povrchu s konstatním tlakem**

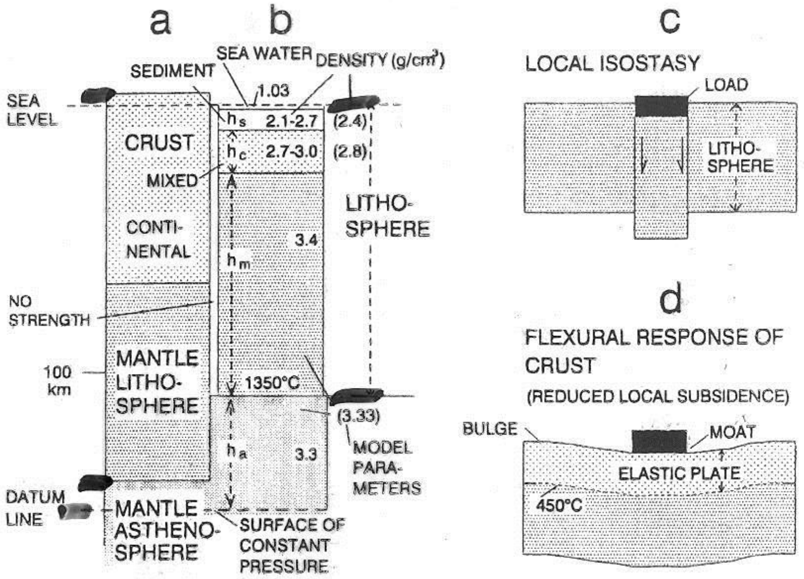


Fig. 8.1a-d. Principle of isostasy demonstrated by two crustal columns (a high plateau; b continental shelf) consisting of layers of different thickness and density on top of a surface of constant pressure. Values in *parenthesis* are used in the models (see text). c Local isostatic response of lithosphere to additional load. d Reduced but more widely extended subsidence due to flexural response of rigid crust

**Model extenzní riftové pánve**

**a) Před riftingem**

**b) Iniciální subsidence vyvolaná izostatickým vyrovnánm na konaci riftové extenze, zvýšení geotermického gradientu**

**c) Termální subsidence vyvolaná pomalu chládnoucí litosférou, geotermický gradient se snižuje přibližně na do původní hodnotu**

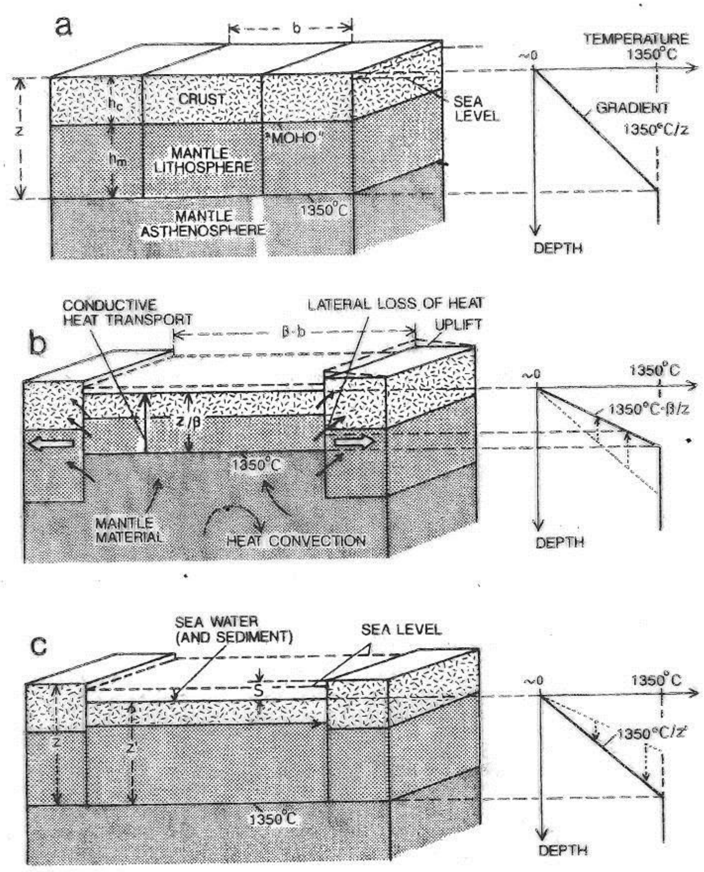
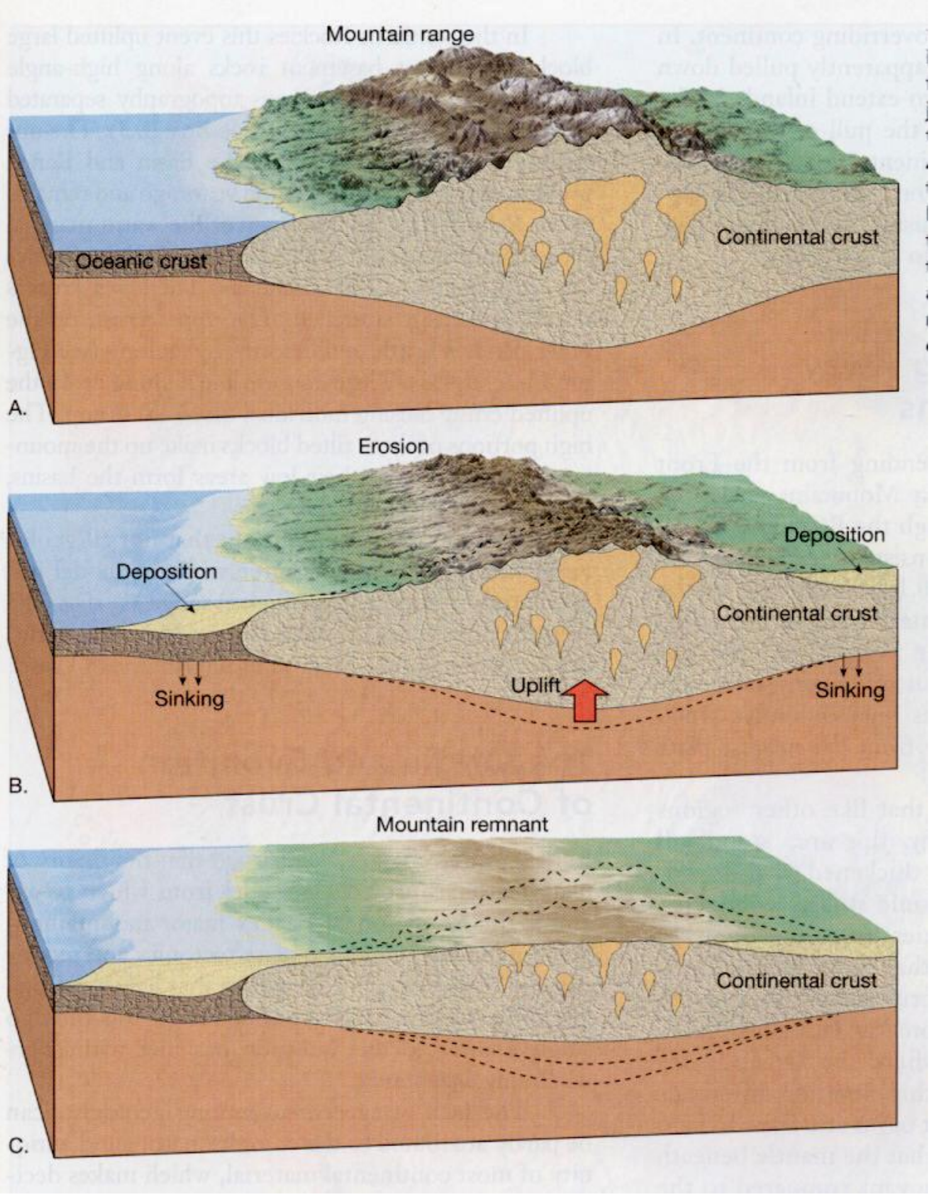


Fig. 8.2a-c. Finite-length extensional rift basin model. a Prior to rifting. b Initial subsidence due to isostatic adjustment at the end of short rifting event, buildup of high geothermal gradient. c Thermal subsidence due to slowly cooling lithosphere, geothermal gradient approximately reduced to original state. See text for explanation. (After McKenzie 1978)

# Gravitační režim litosféry, izostatické vyrovnání

- **Izostatické vyrovnání** následuje po:
  - **změně hustoty litosféry**
    **+: intruze „těžkých“ (mafických) hornin**
    **- : chládnutí litosféry**
    **- : intruze lehkých (granitoidních) magmat**
    **- : prohřátí litosféry, apod.**
  - **změně mocnosti litosféry**
    **+: přesunutí litosféry (kolize)**
    **- : eroze**

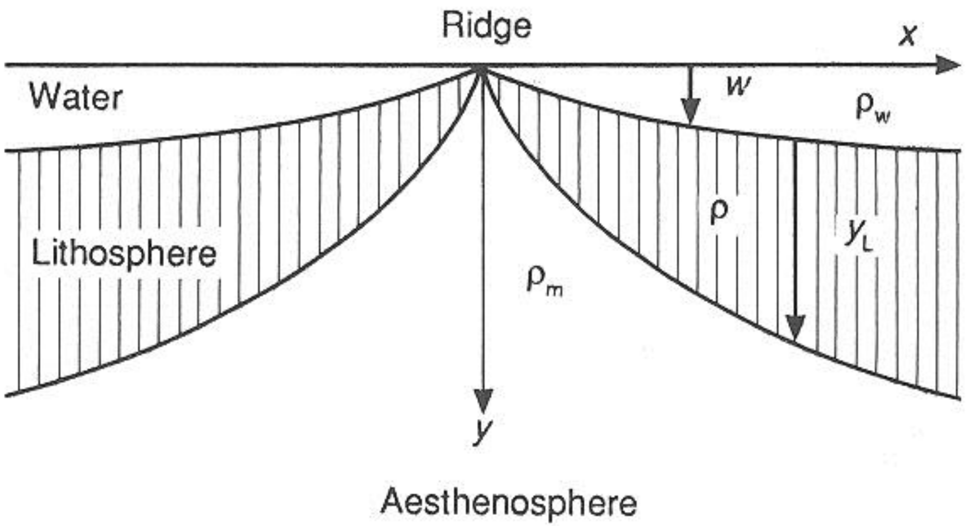


Princip izostáze vyžaduje prohlubování oceánského dna v čase, které kompenzuje tepelné smršťování oceánské litosféry

w: hloubka vody pod vrcholem hřbetu

$y_L$: mocnost oceánské litosféry

$\rho_m$, $\rho_w$, $\rho$: hustoty pláště, vody a litosféry



At any point, mass per unit area = $\int_o^{y_L} \rho dy + w\rho_w$
At ridge crest, mass per unit area at depth
$(w + y_L) = \rho_m(w + y_L)$
For equilibrium, $w(\rho_w - \rho_m) + \int_o^{y_L}(\rho - \rho_m)dy = 0$

**Fig. 2.21.** The principle of isostasy requires the ocean to deepen with age to offset the effects of thermal contraction of the ocean lithosphere. The water depth below the level of the ridge crest is *w*, the thickness of the oceanic lithosphere is $y_L$ and $\rho_m$, $\rho_w$ and $\rho$ are the mantle, water and lithospheric densities respectively.

Hloubka oceánského dna pod vrcholem středooceánského hřbetu jako funkce stáří oceánské kůry

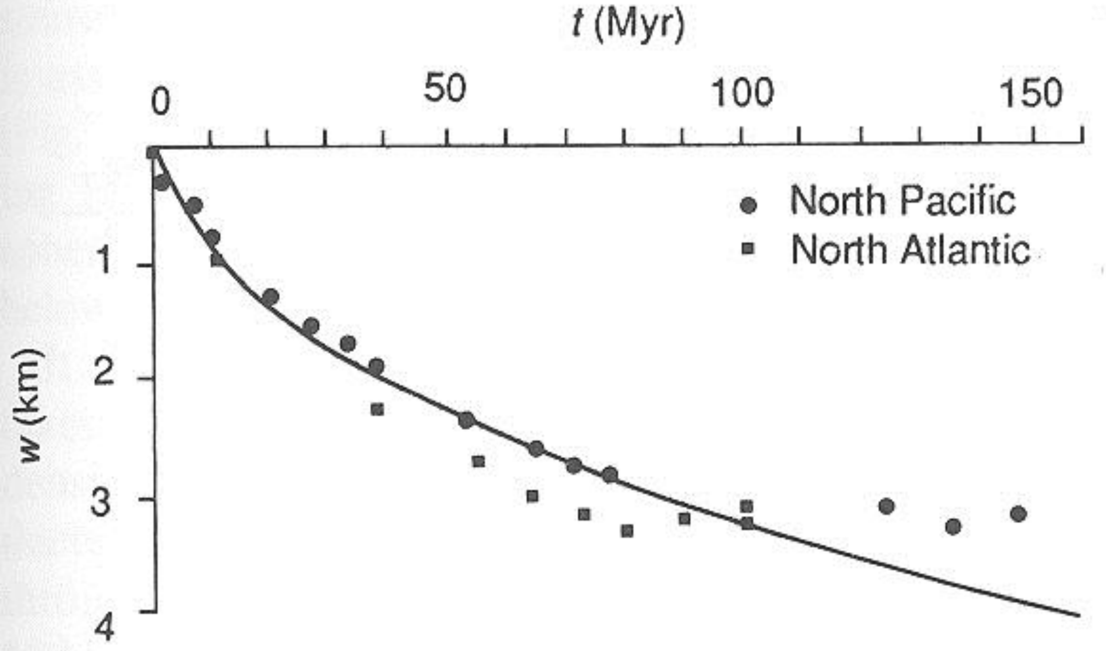


**Fig. 2.22.** Depth of the ocean floor below the level of the ridge crest as a function of age of the sea floor (after Parsons and Sclater 1977). The solid line shows the theoretical result for an instantaneous cooling model. It is in close agreement with observations from the North Pacific and North Atlantic.

Srovnání tepelného toku oceánské kůry (průměr a směrodatná odchylka)

a předpokládané hodnoty vypočtené z modelu okamžitého chládnutí

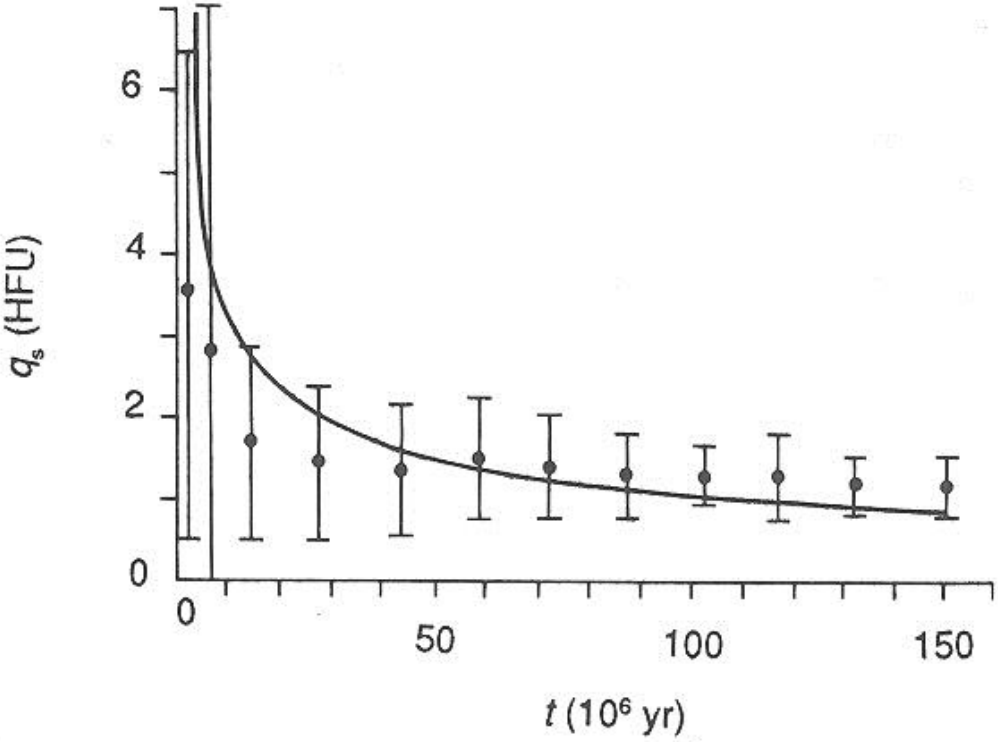


**Fig. 2.20.** Comparison of measured ocean floor heat flows (mean and standard deviation) and those predicted using the instantaneous cooling model, as a function of age. Data are from Sclater, Jaupart and Galson (1980).

Vypočtené izotermy oceánské litosféry s okamžitým chládnutím

Hodnoty izoterm jsou T – Ts °K

Tečky jsou odhady mocností ocánské litosféry v Pacifiku

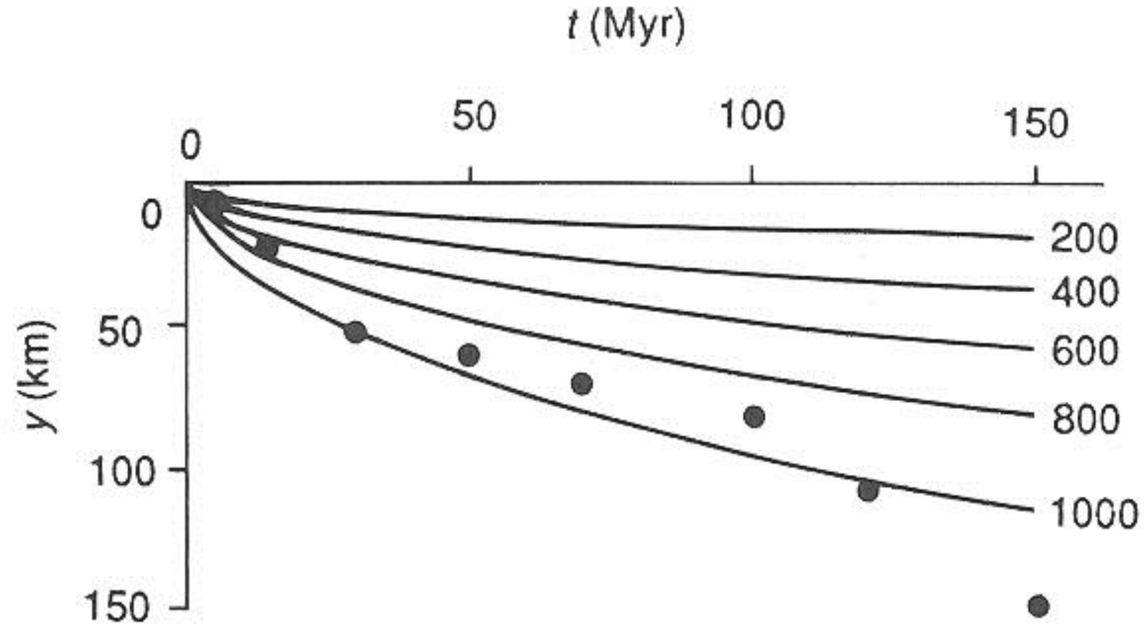
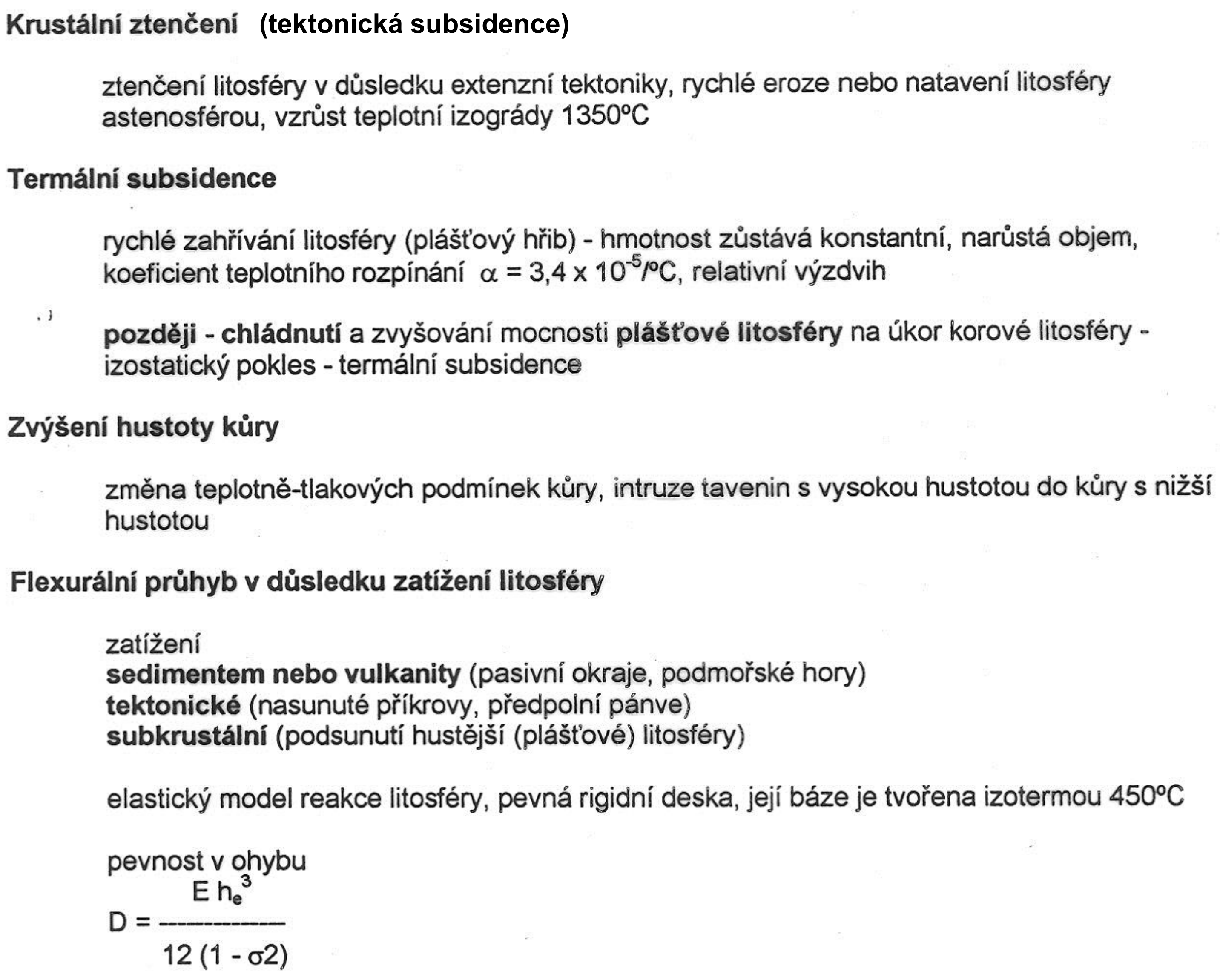


**Fig. 2.19.** Calculated isotherms for an oceanic lithosphere that is instantaneously cooled. The values of the isotherms are $T - T_s$ °K. The dots are estimated thicknesses of the oceanic lithosphere in the Pacific from Leeds, Knopoff and Kausel (1974).

# Mechanismy subsidence



**Krustální ztenčení** **(tektonická subsidence)**

ztenčení litosféry v důsledku extenzní tektoniky, rychlé eroze nebo natavení litosféry astenosférou, vzrůst teplotní izogrády 1350ºC

**Termální subsidence**

rychlé zahřívání litosféry (plášťový hřib) - hmotnost zůstává konstantní, narůstá objem, koeficient teplotního rozpínání $\alpha = 3{,}4 \times 10^{-5}/^{\circ}C$, relativní výzdvih

**později - chládnutí** a zvyšování mocnosti **plášťové litosféry** na úkor korové litosféry - izostatický pokles - termální subsidence

**Zvýšení hustoty kůry**

změna teplotně-tlakových podmínek kůry, intruze tavenin s vysokou hustotou do kůry s nižší hustotou

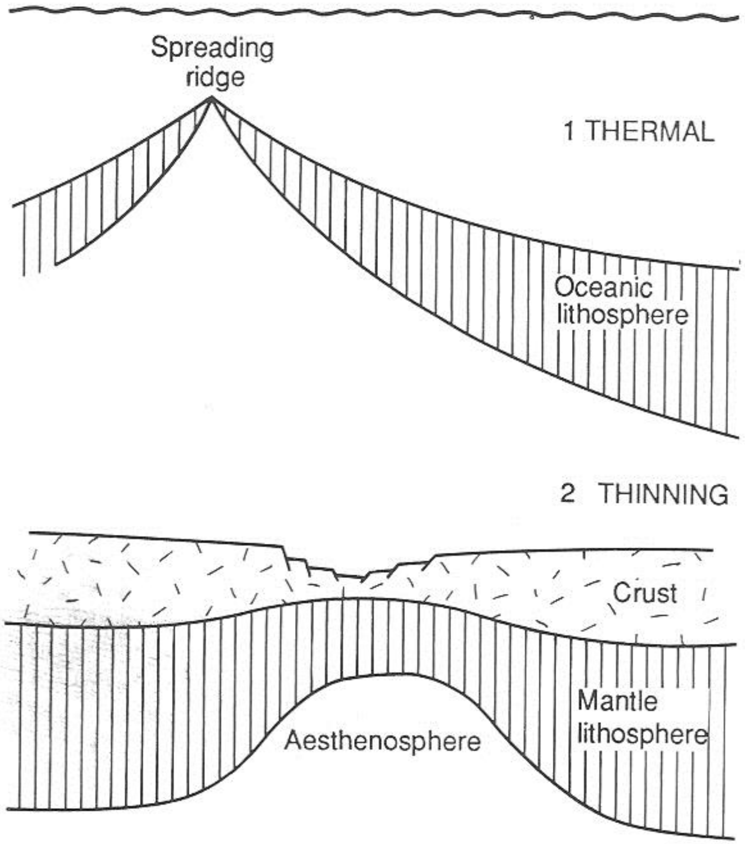
**Flexurální průhyb v důsledku zatížení litosféry**

zatížení
**sedimentem nebo vulkanity** (pasivní okraje, podmořské hory)
**tektonické** (nasunuté příkrovy, předpolní pánve)
**subkrustální** (podsunutí hustější (plášťové) litosféry)

elastický model reakce litosféry, pevná rigidní deska, její báze je tvořena izotermou 450ºC

pevnost v ohybu

$$D = \frac{E h_e^3}{12 (1 - \sigma 2)}$$



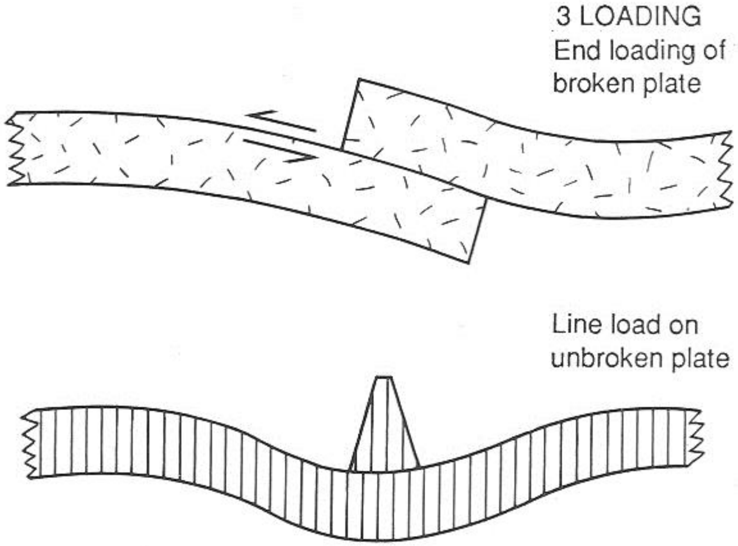
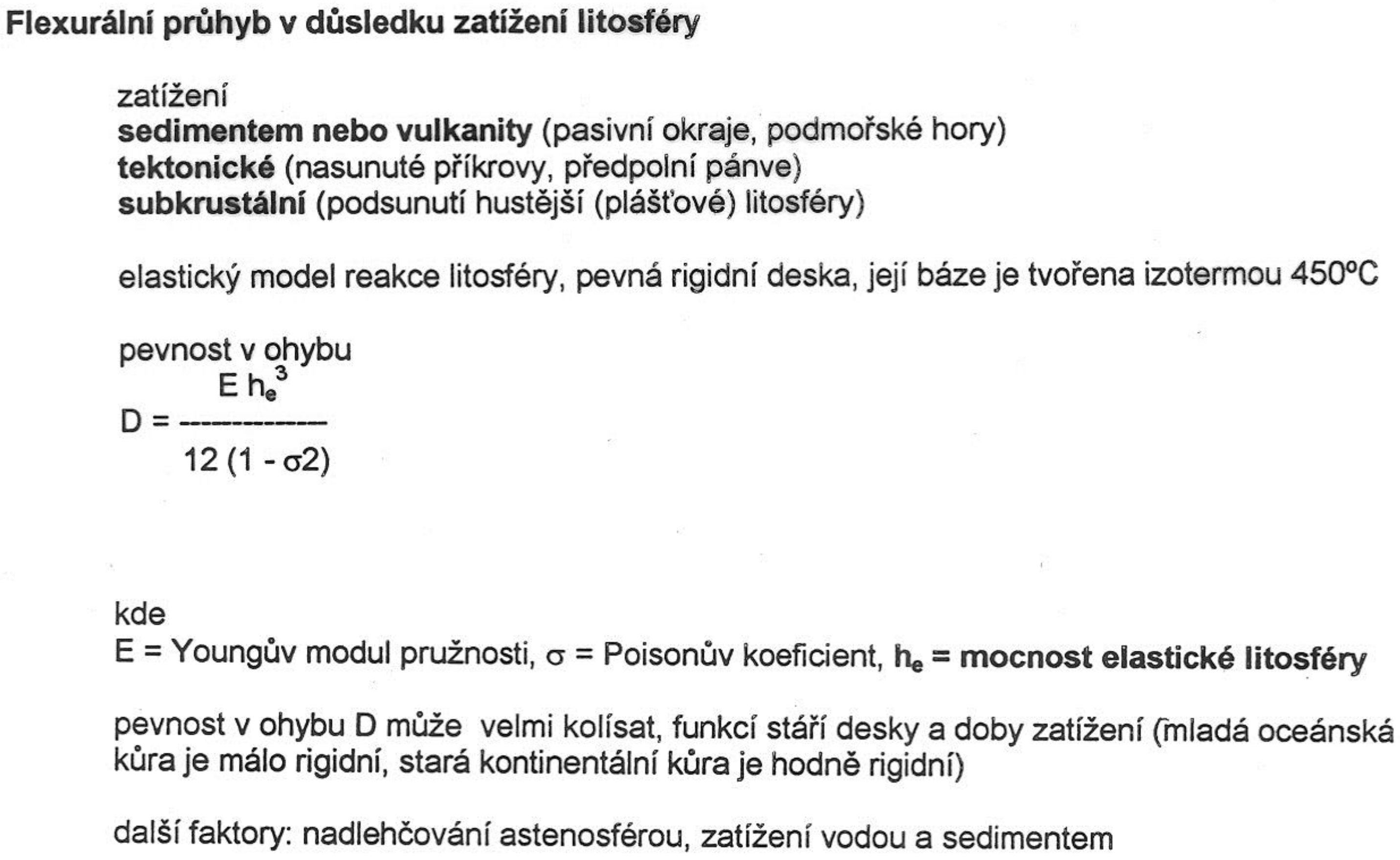


**Fig 1.12** The three basic mechanisms for basin subsidence.

Tři základní mechanismy subsidence pánví:

- Termální subsidence
- Krustální ztenčení
- Zatížení (flexurální subsidence)

# Mechanismy subsidence



**Flexurální průhyb v důsledku zatížení litosféry**

zatížení
**sedimentem nebo vulkanity** (pasivní okraje, podmořské hory)
**tektonické** (nasunuté příkrovy, předpolní pánve)
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elastický model reakce litosféry, pevná rigidní deska, její báze je tvořena izotermou 450ºC

pevnost v ohybu

$$D = \frac{E h_e^3}{12 (1 - \sigma 2)}$$

kde
E = Youngův modul pružnosti, σ = Poisonův koeficient, **$h_e$ = mocnost elastické litosféry**

pevnost v ohybu D může velmi kolísat, funkcí stáří desky a doby zatížení (mladá oceánská kůra je málo rigidní, stará kontinentální kůra je hodně rigidní)

další faktory: nadlehčování astenosférou, zatížení vodou a sedimentem

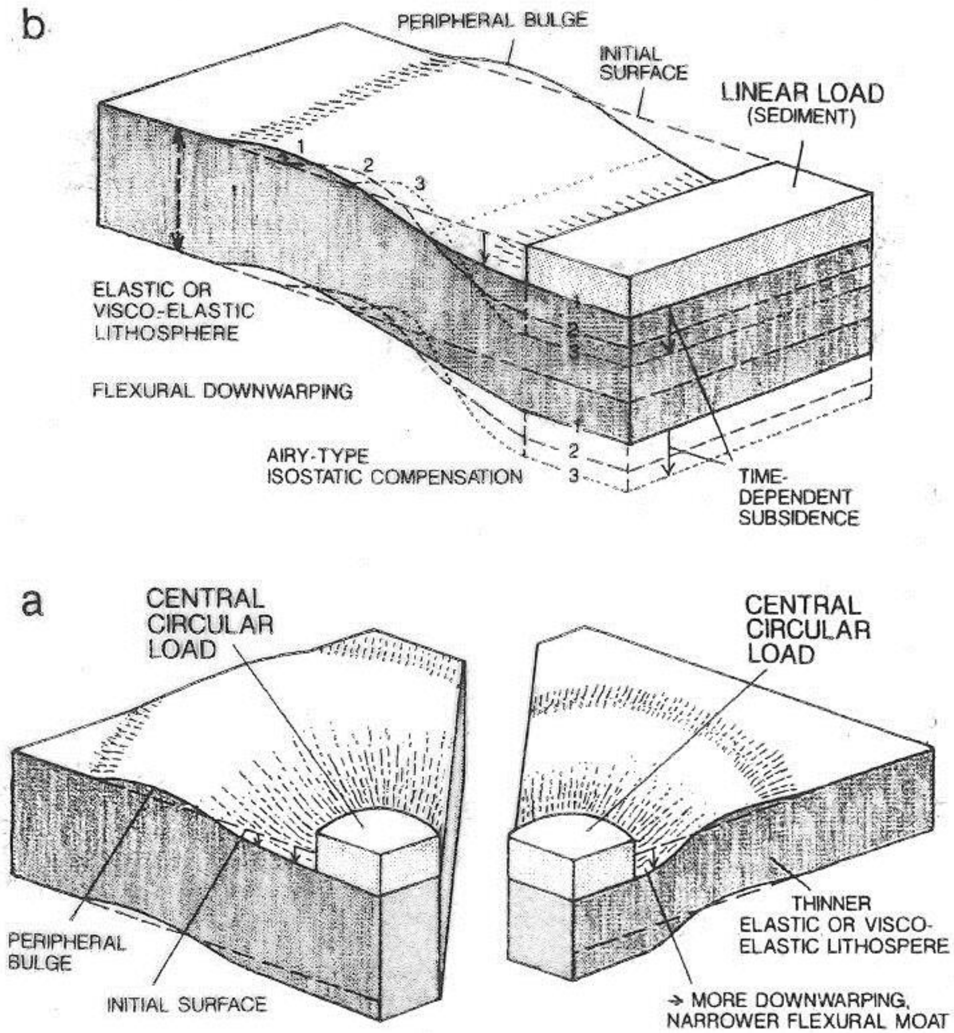
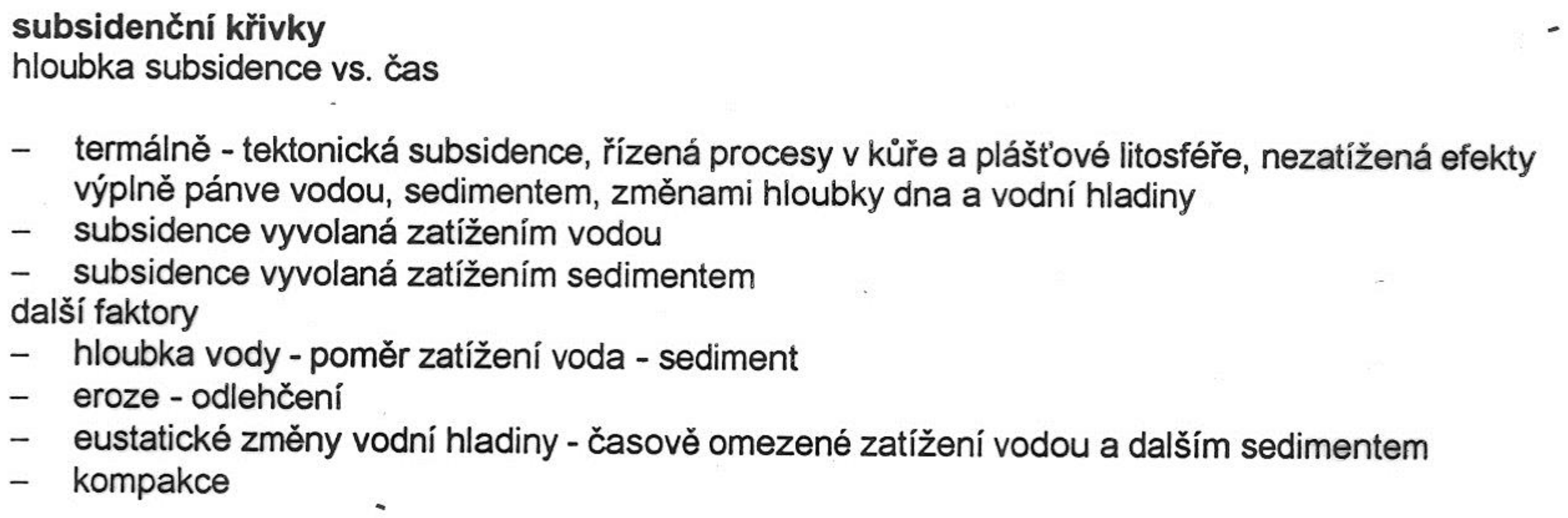


**Fig. 8.4a,b.** Flexural response of lithosphere adjacent to (a) local small or (b) large, wide linear load, not to scale. **a** A load on top of relatively young, thin lithosphere creates a deeper, narrower flexural moat than a load on thick, old lithosphere. **b** Under a long-persisting load, rapid initial subsidence *(1)* may be followed by further slow subsidence *(2)* until the load is ultimately compensated by local isostasy *(3)*. Simultaneously, the peripheral bulge migrates toward the load. (Partially based on Quinlan and Beaumont 1984).

**Flexurální průhyb litosféry v okolí (a) menší a lokální nebo (b) větší lineární zátěže. Zatížení relativně mladé a tenké litosféry vytváří hlubší a užší průhyb než zátež starší litosféry o vyšší mocnosti. Při déletrvající zátěži je rychlá iniciální subsidence (1) vystřídána delší a pomalejší subsidencí (2), dokud zátěž není kompletně kompenzována lokální izostází (3). Zároveň dochází k migraci periferní výdutě (bulge) směrem ke zdroji zátěže.**

# SUBSIDENČNÍ HISTORIE PÁNVE



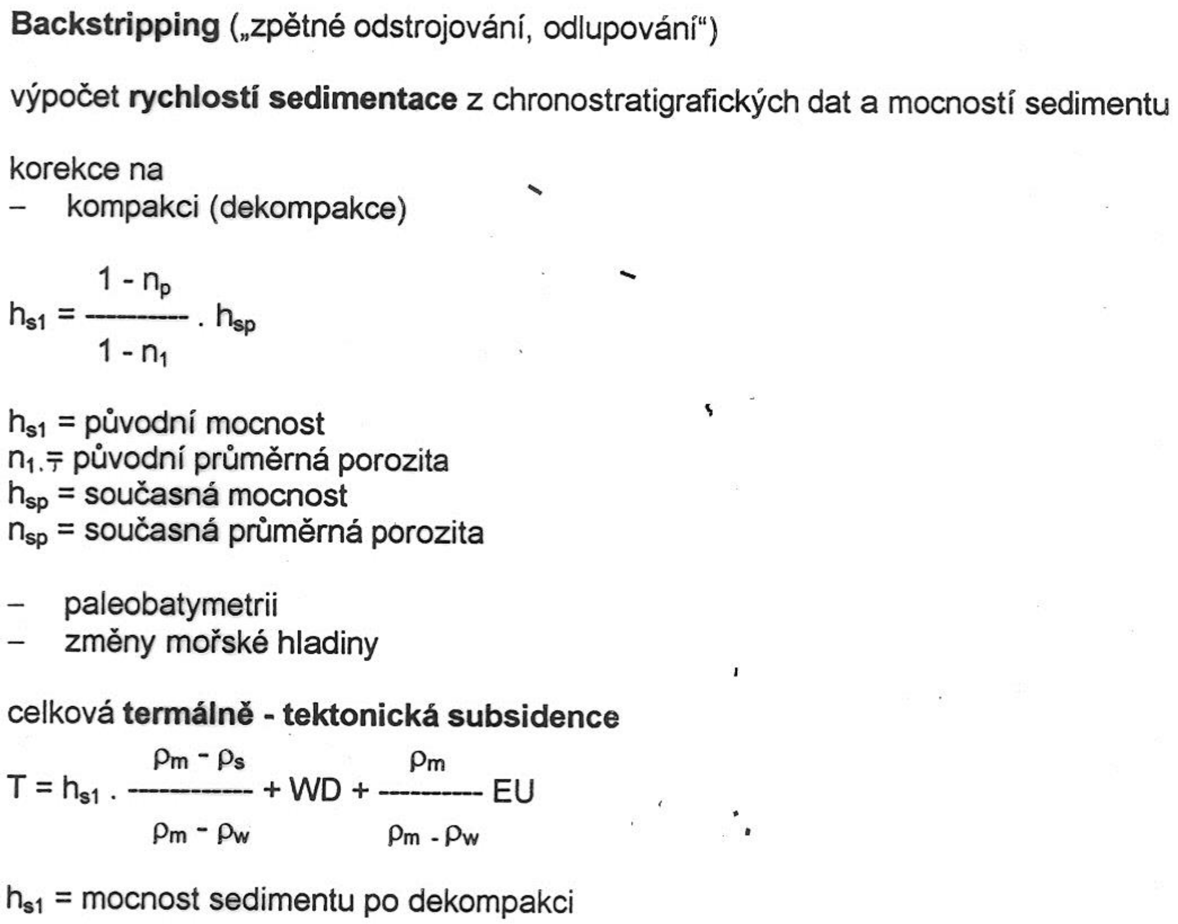
**subsidenční křivky**
hloubka subsidence vs. čas

- termálně - tektonická subsidence, řízená procesy v kůře a plášťové litosféře, nezatížená efekty výplně pánve vodou, sedimentem, změnami hloubky dna a vodní hladiny
- subsidence vyvolaná zatížením vodou
- subsidence vyvolaná zatížením sedimentem

další faktory

- hloubka vody - poměr zatížení voda - sediment
- eroze - odlehčení
- eustatické změny vodní hladiny - časově omezené zatížení vodou a dalším sedimentem
- kompakce

# Metody výpočtu subsidence



**Backstripping** („zpětné odstrojování, odlupování")

výpočet **rychlostí sedimentace** z chronostratigrafických dat a mocností sedimentu

korekce na
- kompakci (dekompakce)

$$h_{s1} = \frac{1 - n_p}{1 - n_1} . h_{sp}$$

$h_{s1}$ = původní mocnost
$n_1$ = původní průměrná porozita
$h_{sp}$ = současná mocnost
$n_{sp}$ = současná průměrná porozita

- paleobatymetrii
- změny mořské hladiny

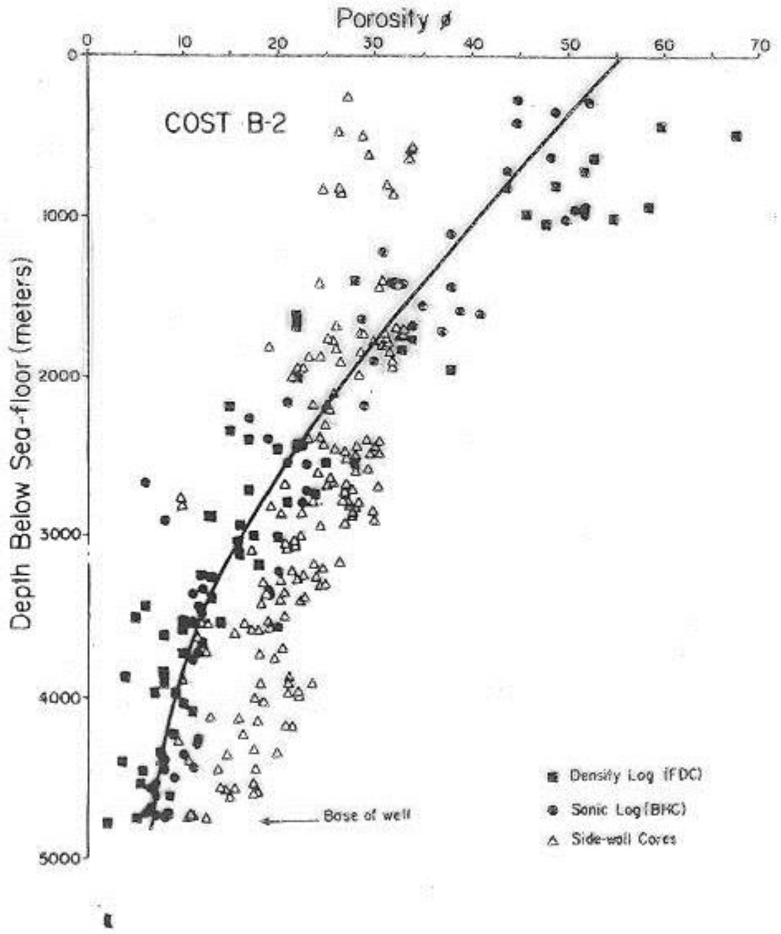
celková **termálně - tektonická subsidence**

$$T = h_{s1} . \frac{\rho_m - \rho_s}{\rho_m - \rho_w} + WD + \frac{\rho_m}{\rho_m - \rho_w} EU$$

$h_{s1}$ = mocnost sedimentu po dekompakci

# Porozita a dekompakce

Fig. 7.7. Porosity–depth data for the COST B-2 well. The smooth curve through the data is the curve used in the backstripping calculations (Watts, 1981. Reprinted by permission of the American Association of Petroleum Geologists).



**Závislost porozity na hloubce ve vrtu COST B-2. Křivka proložená daty (best fit) je použita jako funkce pro výpočty subsidenční křivky .**

Vliv přítomnosti duktilních horninových fragmentů na kompakci nezpevněných terciérních písků

Jižní Louisiana

Kompakce se projevuje jako pokles průměrné porozity s rostoucí hloubkou

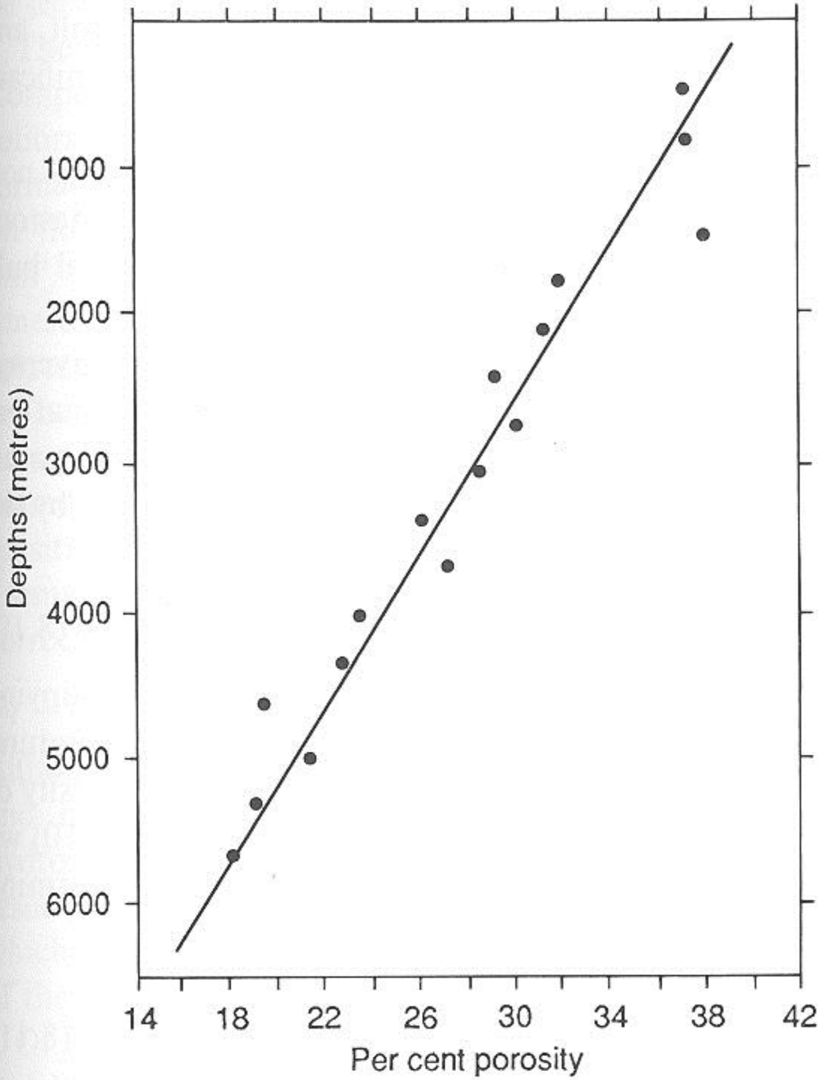


Fig. 8.1. The effect of the presence of ductile rock ragments on compaction of uncemented Tertiary sands n the subsurface of southern Louisiana (after Blatt in chluger 1979). Compaction is reflected in the decrease n average porosity with depth. Based on over 17 000 ores, averaged at every 1000 ft (*c.* 300 m).

# Porozita a dekompakce

**Grafické znázornění dekompakce mocnosti jednotek $A_4$, $B_3$, $C_2$ na jejich původní mocnosti ($A_1$, $B_1$, $C_1$)**

a) **Růst sedimentačního sloupce v čase, t, a postupná kompakce pohřbených jednotek.**

b) **Dva příklady hloubkové závislosti porozity u různých sedimentů a dekompakce jednotky A a B ($A_4$ na $A_1$ nebo $A_2$), $B_3$ na $B_1$)**

c) **Výsledná subsidenční křivka a její srovnání s křivkou bez dekompakce. Změny v paleobatymetrii nejsou zohledněny)**

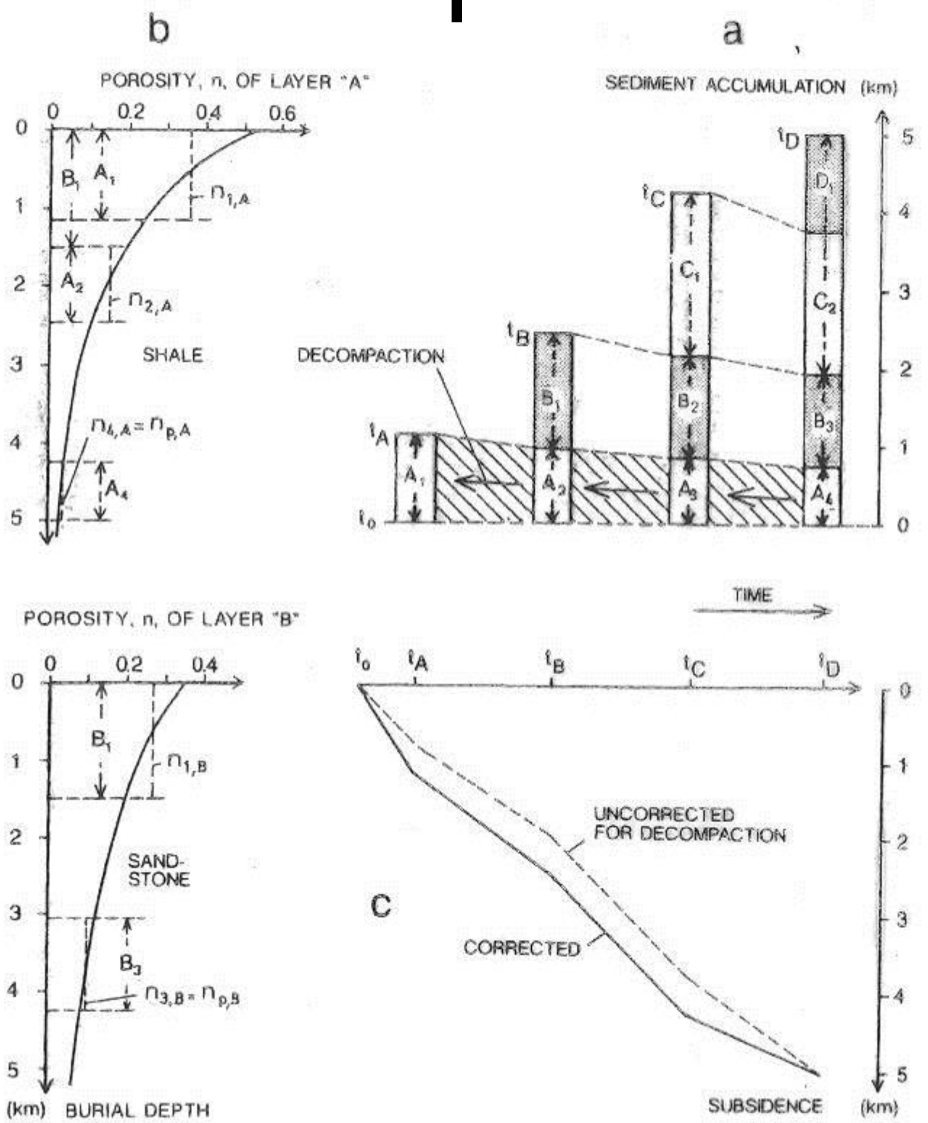


**Fig. 8.6a-c.** Graphical method for decompacting present sediment thicknesses of units $A_4$, $B_3$, $C_2$ to their original thicknesses ($A_1$, $B_1$, $C_1$). **a** Growth of sedimentary column with time, *t*, and progressive compaction of buried units. **b** Two examples of porosity-depth curves for different sediments demonstrating decompaction of units A and B ($A_4$ to $A_1$ or $A_2$, respectively, and $B_3$ to $B_1$) using Eq. (8.12) in text. **c** Resulting corrected subsidence curve in comparison to uncorrected curve; no changes in paleowater depth and eustatic sea level

# Backstripping

**Syntetický semikvantitativní příklad vertikálního sledu sedimentů a odvozená subsidenční křivka.**

**(A) Čistá termo-tektonická subsidence v pánvi vyplněné vzduchem (hypotetická)**

**(B) pánev zatížená vodou, korigováno na dnešní hladinu moře (hypotetická)**

**(C) Pánev permanentně zatížená sedimentem až po dnešní úroveň hladiny moře (hypotetická)**

**Křivka (C) je ovlivněna kompakcí sedimentu, paleobatymetrií a eustatickými změnami hladiny moře. Dalším vlivem může být eroze.**

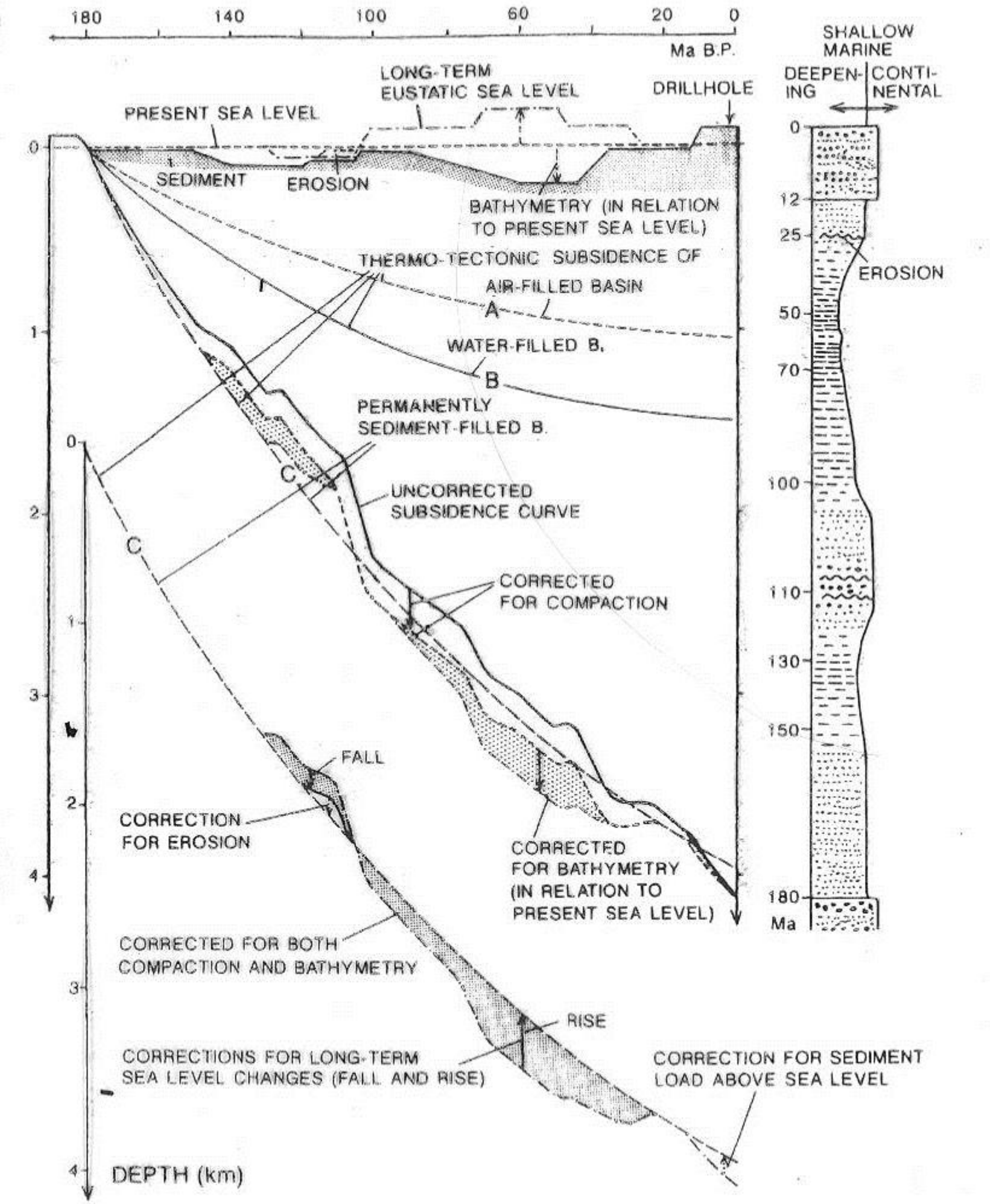


Fig. 8.5. Synthetic, semi-quantitative example showing drilled vertical sediment succession and derived, uncorrected subsidence curve at a given location within a basin. Purely thermo-tectonic subsidence in an air-filled basin (Curve *A*) is magnified by a water load (*B*, related to present sea level) and the load of a permanently sediment-filled basin *(C)* up to the present sea level. Curve *C* i modified by sediment compaction, a reduced sediment loa (increasing paleo-water depth or bathymetry), and eustati sea level changes. In addition, erosion can diminish sub sidence, or a sediment load above sea level can enhanc subsidence

# Stratigrafický profil vrtem Conoco 15/30-1, Central Graben, Severní moře

Vstupní parametry pro dekompakci

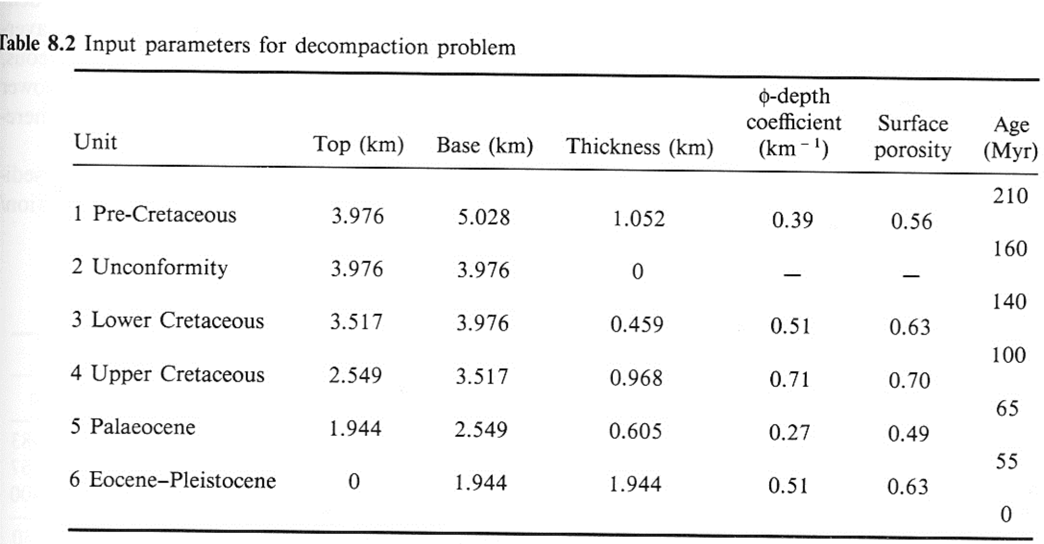
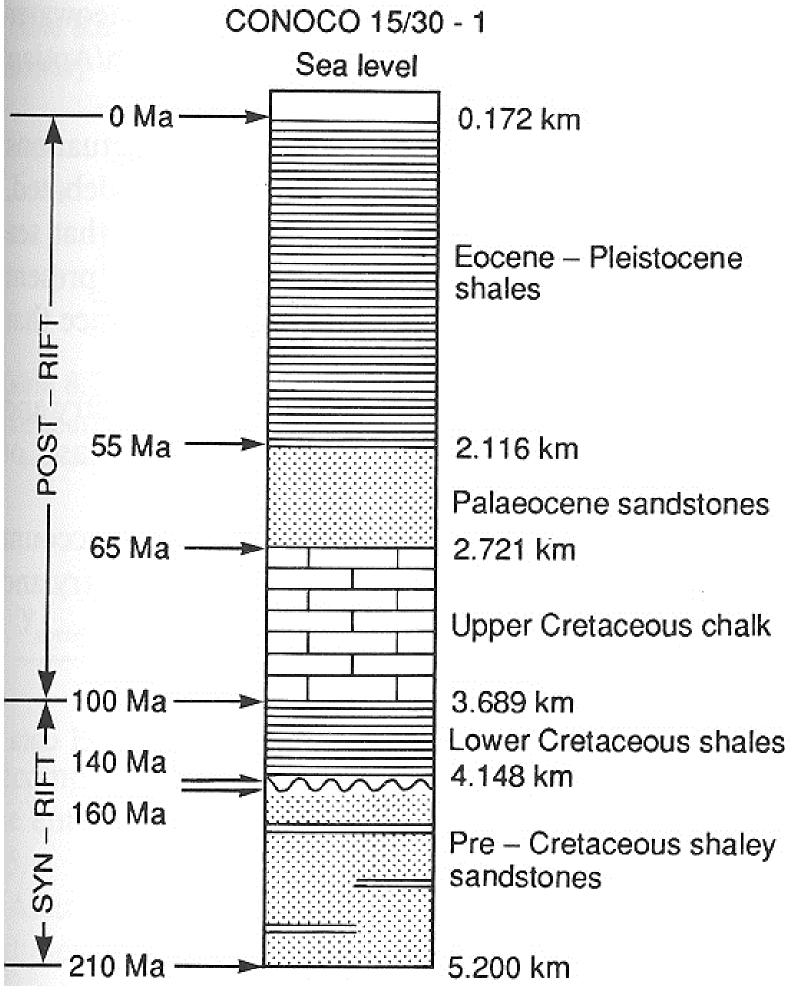


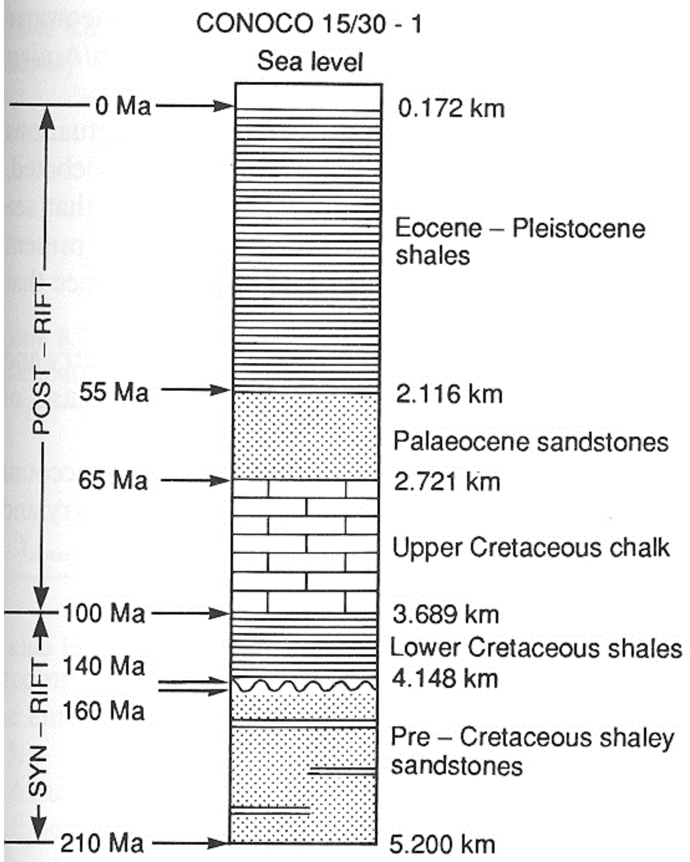
**Table 8.2** Input parameters for decompaction problem

| Unit | Top (km) | Base (km) | Thickness (km) | φ-depth coefficient ($km^{-1}$) | Surface porosity | Age (Myr) |
|---|---|---|---|---|---|---|
| | | | | | | 210 |
| 1 Pre-Cretaceous | 3.976 | 5.028 | 1.052 | 0.39 | 0.56 | |
| | | | | | | 160 |
| 2 Unconformity | 3.976 | 3.976 | 0 | – | – | |
| | | | | | | 140 |
| 3 Lower Cretaceous | 3.517 | 3.976 | 0.459 | 0.51 | 0.63 | |
| | | | | | | 100 |
| 4 Upper Cretaceous | 2.549 | 3.517 | 0.968 | 0.71 | 0.70 | |
| | | | | | | 65 |
| 5 Palaeocene | 1.944 | 2.549 | 0.605 | 0.27 | 0.49 | |
| | | | | | | 55 |
| 6 Eocene–Pleistocene | 0 | 1.944 | 1.944 | 0.51 | 0.63 | |
| | | | | | | 0 |



**ig. 8.10.** Summary stratigraphic column from Conoco 5/30–1 in the Central Graben of the North Sea.

# Graf hloubky po dekompakci vs. čas ve stratigrafickém profilu vrtu Conoco 15/30-1



ig. 8.10. Summary stratigraphic column from Conoco 5/30–1 in the Central Graben of the North Sea.

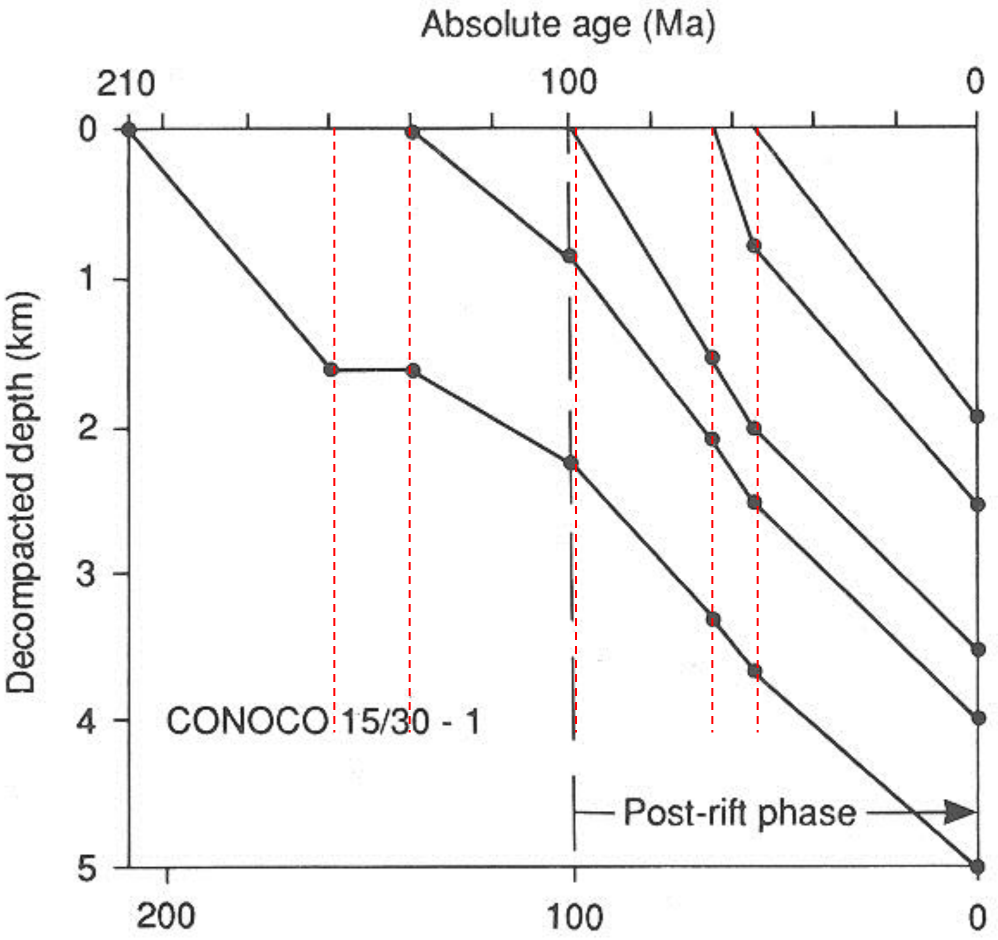


**Fig. 8.11.** Plot of decompacted depth versus time for the stratigraphy penetrated in Conoco 15/30-1.

Subsidenční křivka

Vrtu Conoco 15/30-1

po backstrippingu (Airyho izostatický model)

Postriftová fáze (posledních 100 Myr)

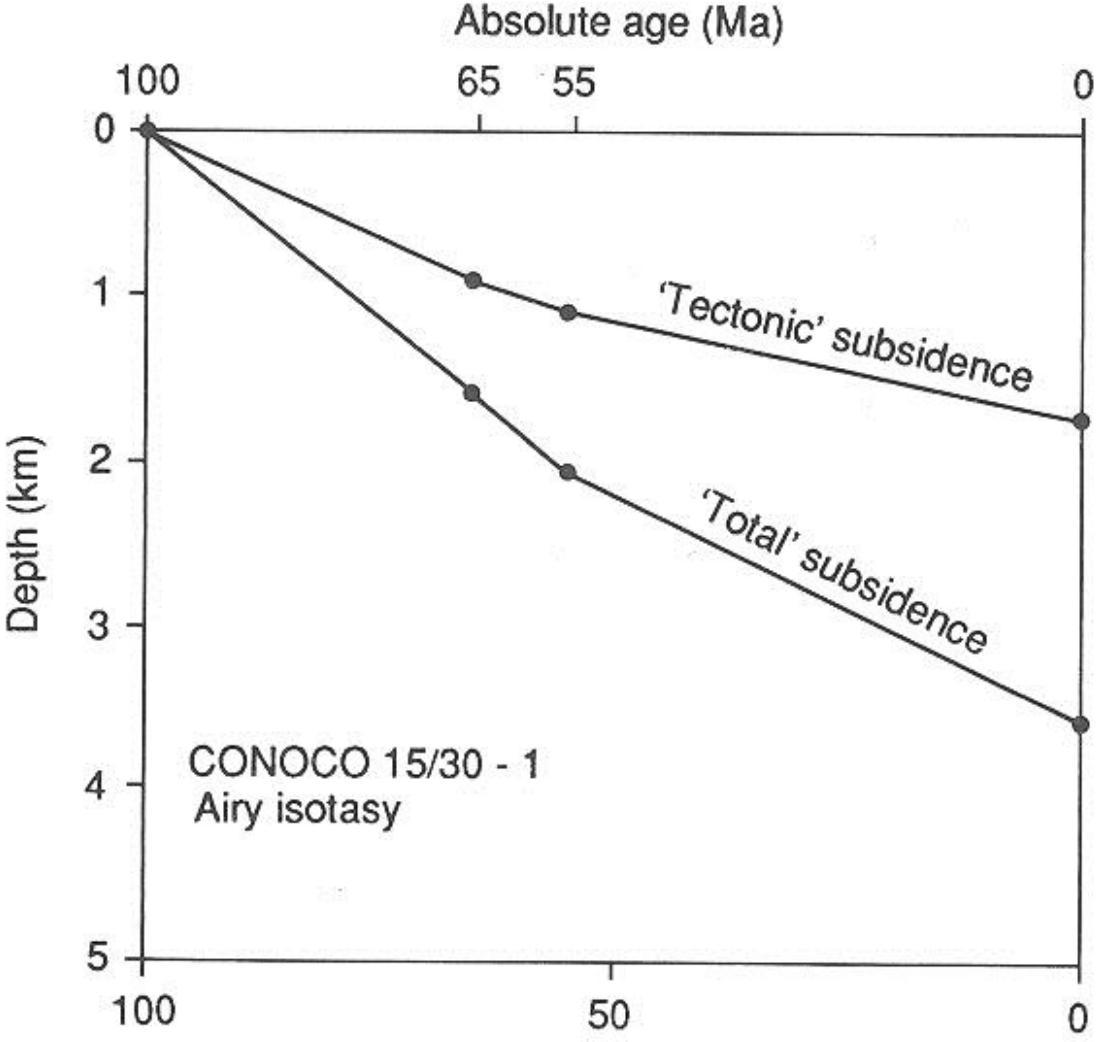


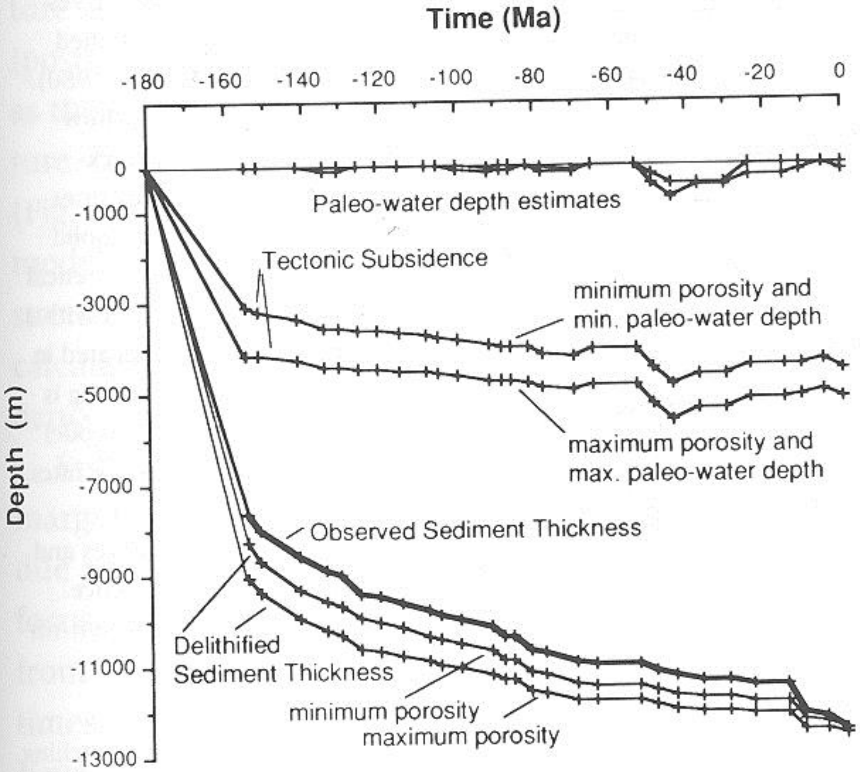
**Fig. 8.12.** Backstripped subsidence plot for 15/30-1 using an Airy isostatic model.

celková **termálně - tektonická subsidence**

$$T = h_{s1} \cdot \frac{\rho_m - \rho_s}{\rho_m - \rho_w} + WD + \frac{\rho_m}{\rho_m - \rho_w} EU$$

$h_{s1}$ = mocnost sedimentu po dekompakci

# Subsidenční křivka na pasivním okraji



The equation for obtaining tectonic subsidence from a sedimentary basin:

$$T.S. = S^*\left(\frac{\rho_a - \rho_{s*}}{\rho_a - \rho_w}\right) - \Delta SL\left(\frac{\rho_a}{\rho_a - \rho_w}\right) + WD$$

where:

$S^*$ = the decompacted sediment thickness
$\rho$ = density
a = asthenosphere
w = water
$\Delta SL$ = change in sea-level
WD = paleo-water depth of the sediments
T.S. = tectonic subsidence, or the subsidence of the basin floor beneath water, without any sediment load. No sea-level correction has been made.

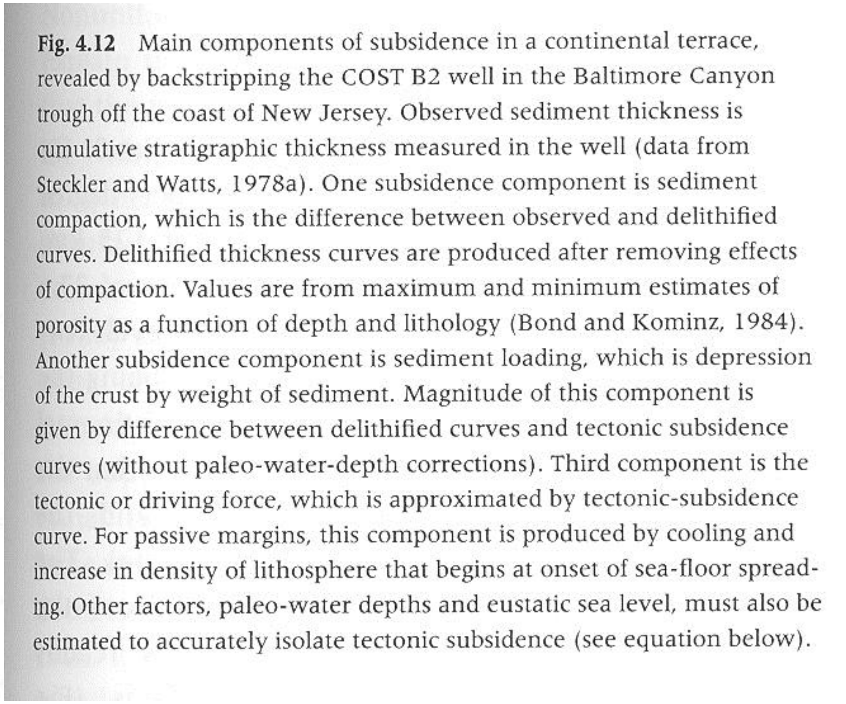


**Fig. 4.12** Main components of subsidence in a continental terrace, revealed by backstripping the COST B2 well in the Baltimore Canyon trough off the coast of New Jersey. Observed sediment thickness is cumulative stratigraphic thickness measured in the well (data from Steckler and Watts, 1978a). One subsidence component is sediment compaction, which is the difference between observed and delithified curves. Delithified thickness curves are produced after removing effects of compaction. Values are from maximum and minimum estimates of porosity as a function of depth and lithology (Bond and Kominz, 1984). Another subsidence component is sediment loading, which is depression of the crust by weight of sediment. Magnitude of this component is given by difference between delithified curves and tectonic subsidence curves (without paleo-water-depth corrections). Third component is the tectonic or driving force, which is approximated by tectonic-subsidence curve. For passive margins, this component is produced by cooling and increase in density of lithosphere that begins at onset of sea-floor spreading. Other factors, paleo-water depths and eustatic sea level, must also be estimated to accurately isolate tectonic subsidence (see equation below).

# Subsidenční křivky v periferní předpolní pánvi

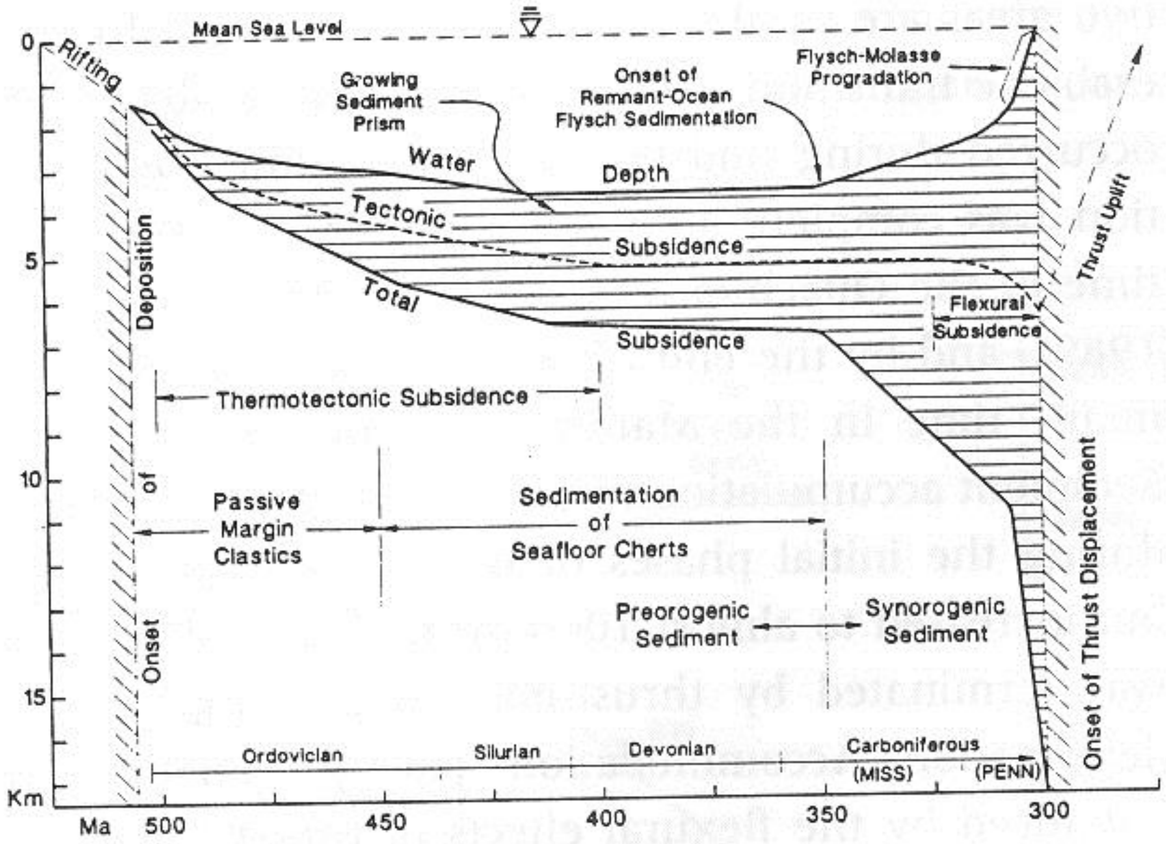


**Fig. 10.18** Hypothetical geohistory diagram for Ouachita succession of Ouachita Mountains (see Fig. 10.16). Thicknesses from Lowe (1989) and Morris (1989), and ages from Ethington et al. (1989) using DNAG time scale (Palmer, 1983). Thermotectonic subsidence constrained to rates established for cooling of oceanic lithosphere (350 m times square root of elapsed time in million years after rifting) for a period of 100 my after rifting, with no tectonic subsidence thereafter until onset of flexural subsidence under influence of structural loading by thrust sheets of Ouachita allochthon. Flexural subsidence constrained with flexural geometry inferred by Goebel (1991), assuming allochthon movement of 10 km/my (faster rate of 100 km/my would confine flexural subsidence to last 2.5 my of depositional history, and would smooth elbow of water-depth curve at transition from aggradational to progradational phases of flysch sedimentation, but would also sharpen corresponding elbow in curve for total subsidence of substratum). Backstripping constrained by net sediment densities inferred from equations for depth-porosity relations given by Dickinson et al. (1987).

# Odhad vývoje hladiny světového oceánu za posledních 160 Myr

- Data ze subsidenční historie na pasivním kontinentálním okraji Severní Ameriky
- Data odvozená z pobřežního onlapu na seismických profilech
- data odvozená z plochy záplavy severoamerického kontinentu

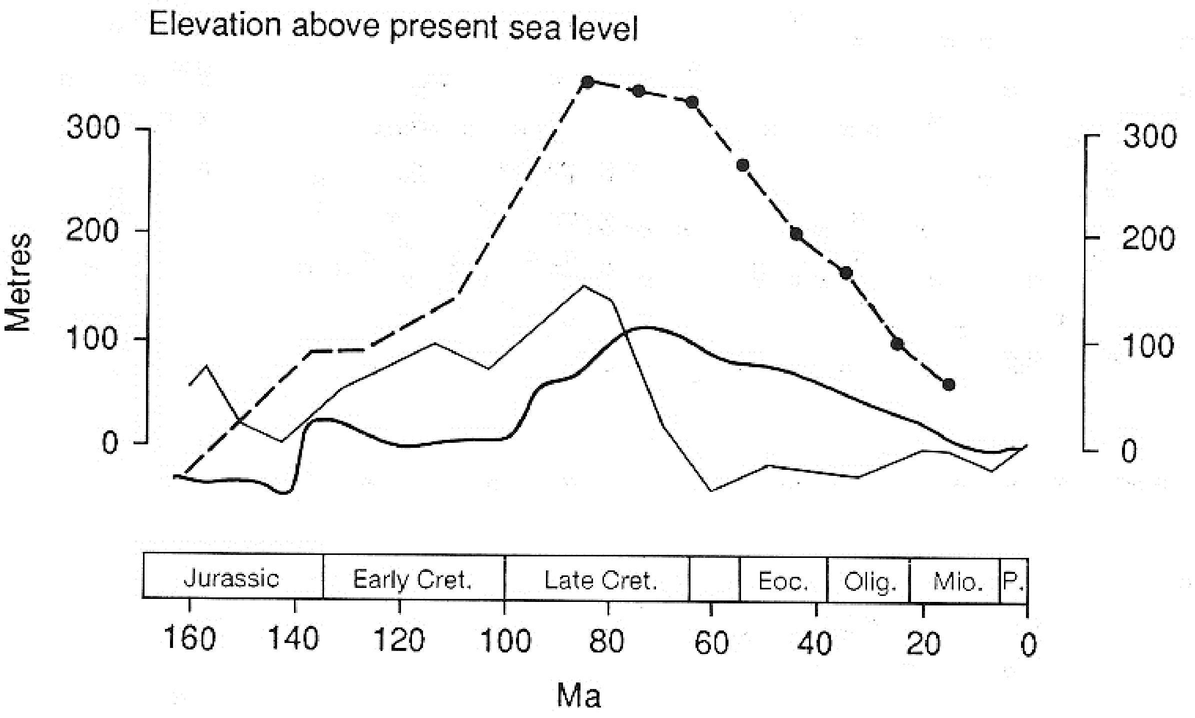


**Fig. 6.22.** A comparison of estimates of sea level changes in the last 160 Myr after Watts and Steckler (1979). The heavy solid line is based on the subsidence history of boreholes from the continental margin of eastern North America (Watts and Steckler 1979). The dashed line is the estimate of Vail *et al.* (1977) based on patterns of coastal onlap recognized on seismic reflection lines, calibrated by the data of Pitman (1978) (circles) based on changes in the rates of spreading of mid-ocean ridges. The fine solid line is from estimates of the amount of flooding of the continental area of North America (Wise 1974; see also Fig. 6.17).

# Objemové změny středooceánských hřbetů v závislosti na rychlosti rozpínání

(A) – rychlost rozpínání 20 mm/rok se v čase 0 mění na 60 mm/rok
(B) – rychlost rozpínání 60 mm/rok se v čase 0 mění na 20 mm/rok

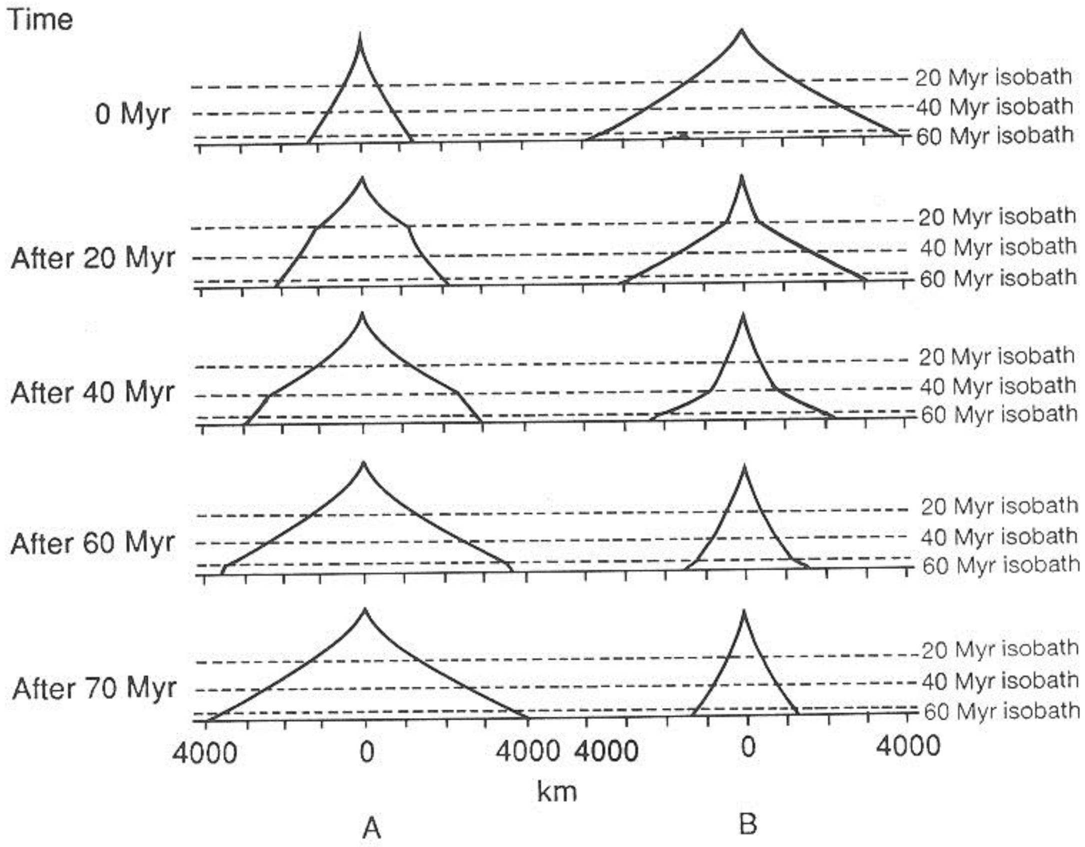
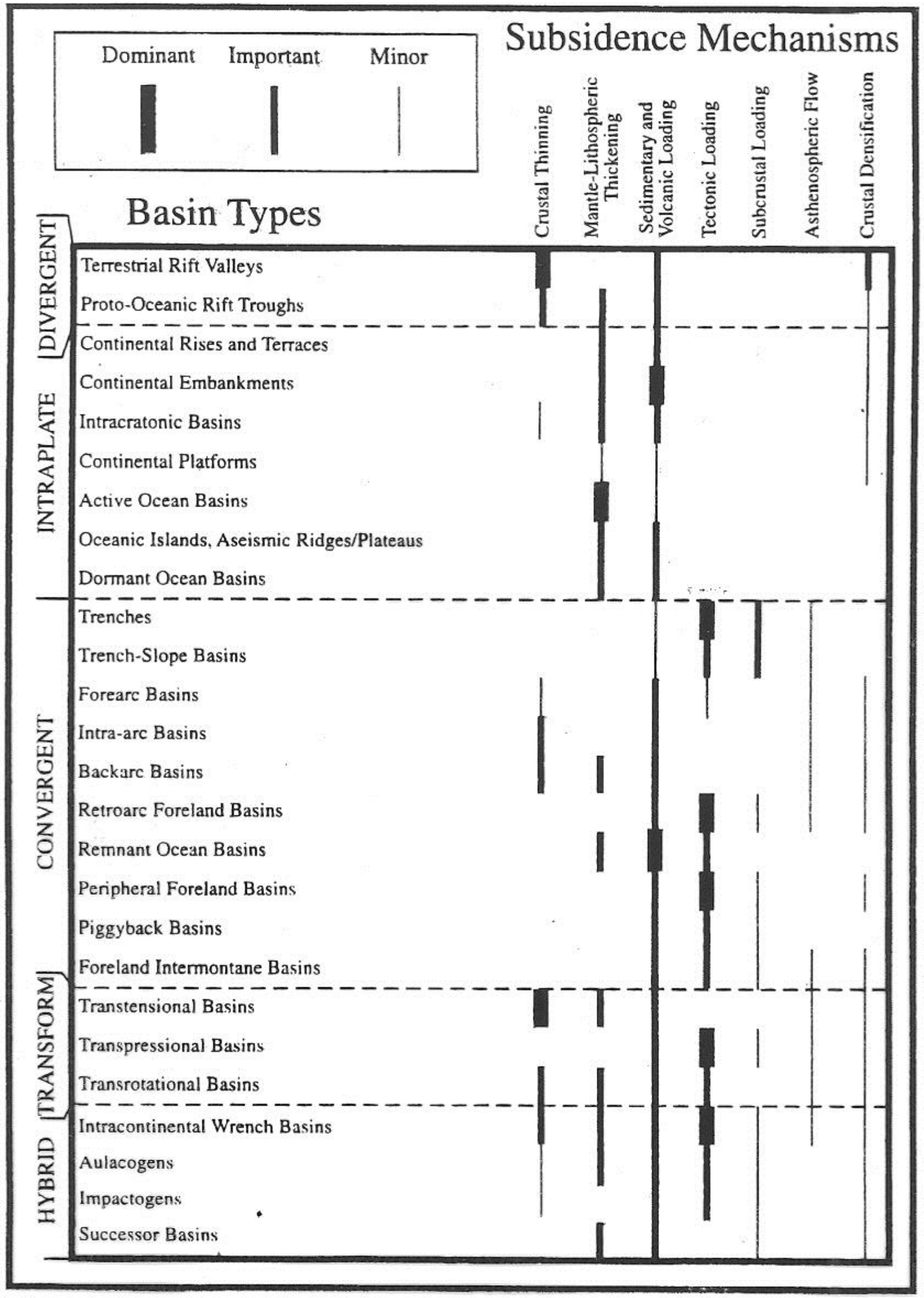


**Fig. 6.20.** Volume changes of spreading ridges as a function of spreading rate (after Pitman 1979). Sequence A shows a ridge that has been spreading at 20 mm yr$^{-1}$ for 70 Myr. At 0 Myr the spreading rate changes to 60 mm yr$^{-1}$. Subsequent diagrams show the sequential changes in the ridge cross-section. Sequence B shows the reverse evolution; a ridge that has been spreading at 60 mm yr$^{-1}$ for 70 Myr slows at 0 Myr to 20 mm yr$^{-1}$. The cross-sectional areas of equilibrium ridge profiles (after 70 Myr of spreading at the new rate) change by a factor of three in both cases.

# Mechanismy subsidence v různých typech pánví



# VÝZDVIH (UPLIFT) EROZE A EROZNÍ HISTORIE

**Eroze horských údolí**

**Model plovoucího ledu**

**- zvýšení reliéfu**

- Výzdvih vrcholků hor
- Snižování průměrné nadmořské výšky

# Izostatický výzdvih

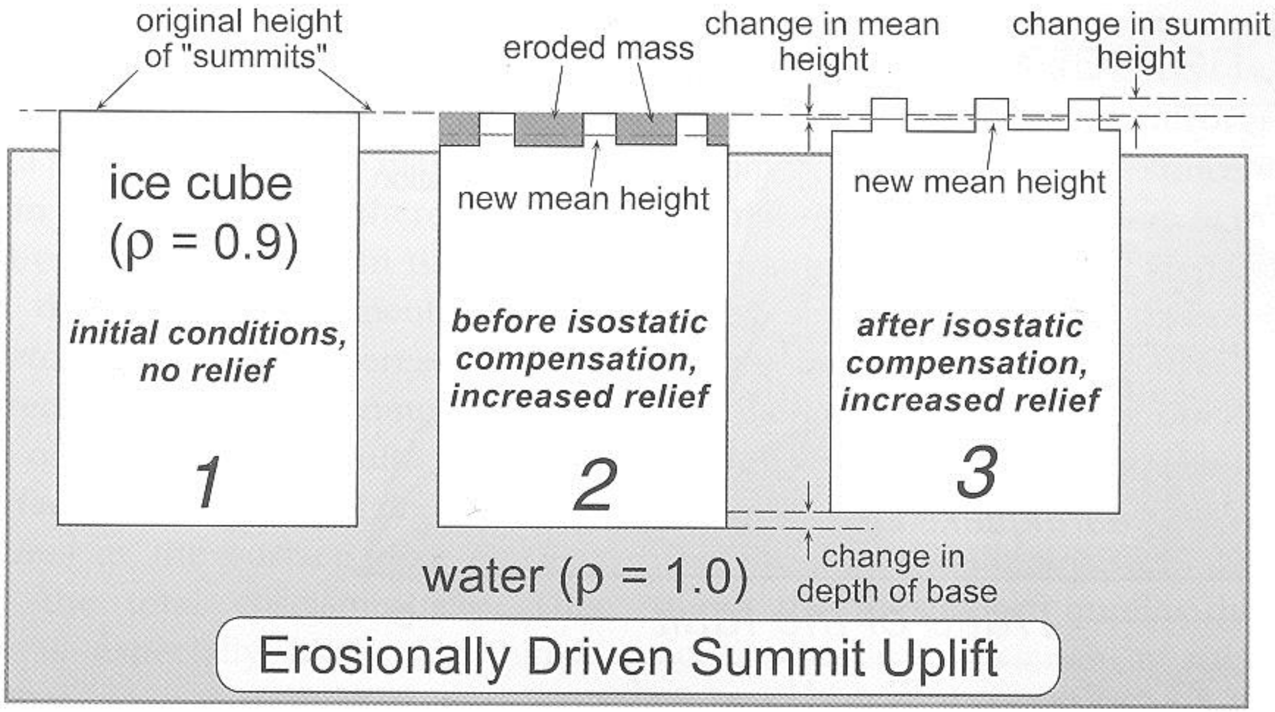


**Fig. 1.6 Isostatic uplift of mountain summits due to enhanced erosion.**
The density contrasts of ice and water are analogous to crust and mantle contrasts, respectively. Erosion of the top of the ice cube decreases its mass and its mean height. More rapid erosion of valley bottoms than of summits leads to increased relief and uplift of summits, at the same time that the mean elevation decreases. Note that stage 2 will never occur unless some force restrains the ice cube from rebounding due to melting at the surface.

# Rychlosti výzdvihu

## COOLING AGES-

### Rychlost výzdvihu z rychlostí chládnutí minerálů (thermochronology)

Výzdvih podloží je funkcí pohybu vzhůru podél geotermického gradientu

Historie chládnutí z termometrů: průchod přes izotermy

Hlavní termometry

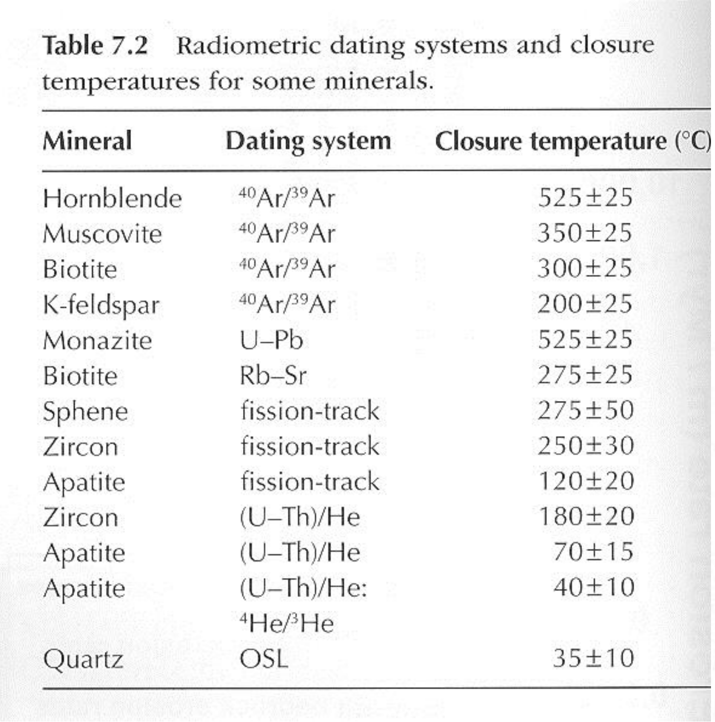
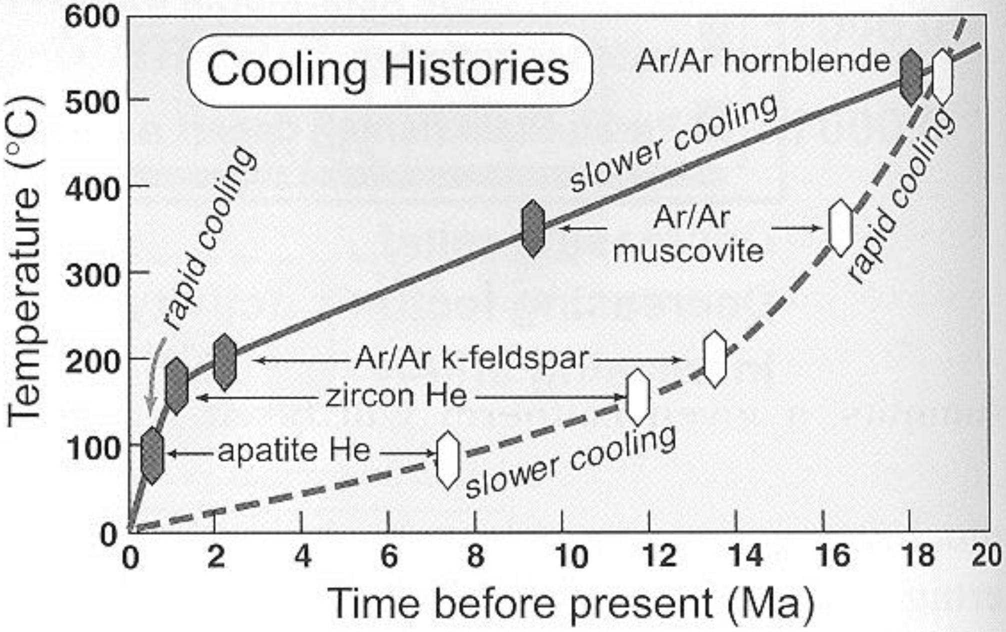


**Table 7.2** Radiometric dating systems and closure temperatures for some minerals.

| Mineral | Dating system | Closure temperature (°C) |
|---|---|---|
| Hornblende | $^{40}Ar/^{39}Ar$ | 525±25 |
| Muscovite | $^{40}Ar/^{39}Ar$ | 350±25 |
| Biotite | $^{40}Ar/^{39}Ar$ | 300±25 |
| K-feldspar | $^{40}Ar/^{39}Ar$ | 200±25 |
| Monazite | U–Pb | 525±25 |
| Biotite | Rb–Sr | 275±25 |
| Sphene | fission-track | 275±50 |
| Zircon | fission-track | 250±30 |
| Apatite | fission-track | 120±20 |
| Zircon | (U–Th)/He | 180±20 |
| Apatite | (U–Th)/He | 70±15 |
| Apatite | (U–Th)/He: $^4He/^3He$ | 40±10 |
| Quartz | OSL | 35±10 |



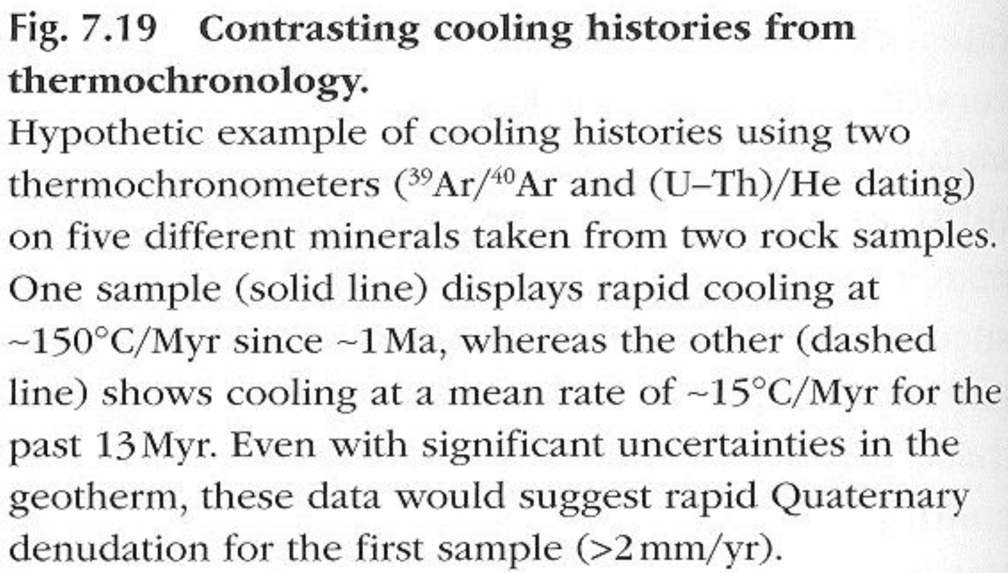


**Fig. 7.19 Contrasting cooling histories from thermochronology.**
Hypothetic example of cooling histories using two thermochronometers ($^{39}Ar/^{40}Ar$ and (U–Th)/He dating) on five different minerals taken from two rock samples. One sample (solid line) displays rapid cooling at ~150°C/Myr since ~1 Ma, whereas the other (dashed line) shows cooling at a mean rate of ~15°C/Myr for the past 13 Myr. Even with significant uncertainties in the geotherm, these data would suggest rapid Quaternary denudation for the first sample (>2 mm/yr).

# Rychlost výzdvihu

## Stratigrafie korálových útesů

**změna geometrie karbonátových těles v reakci na relativní vzestup / pokles hladiny moře (relativní pokles / výzdvih podloží)**

B) Stoupající hladina moře (pokles podloží)

C) Klesající hladina moře (výzdvih podloží)

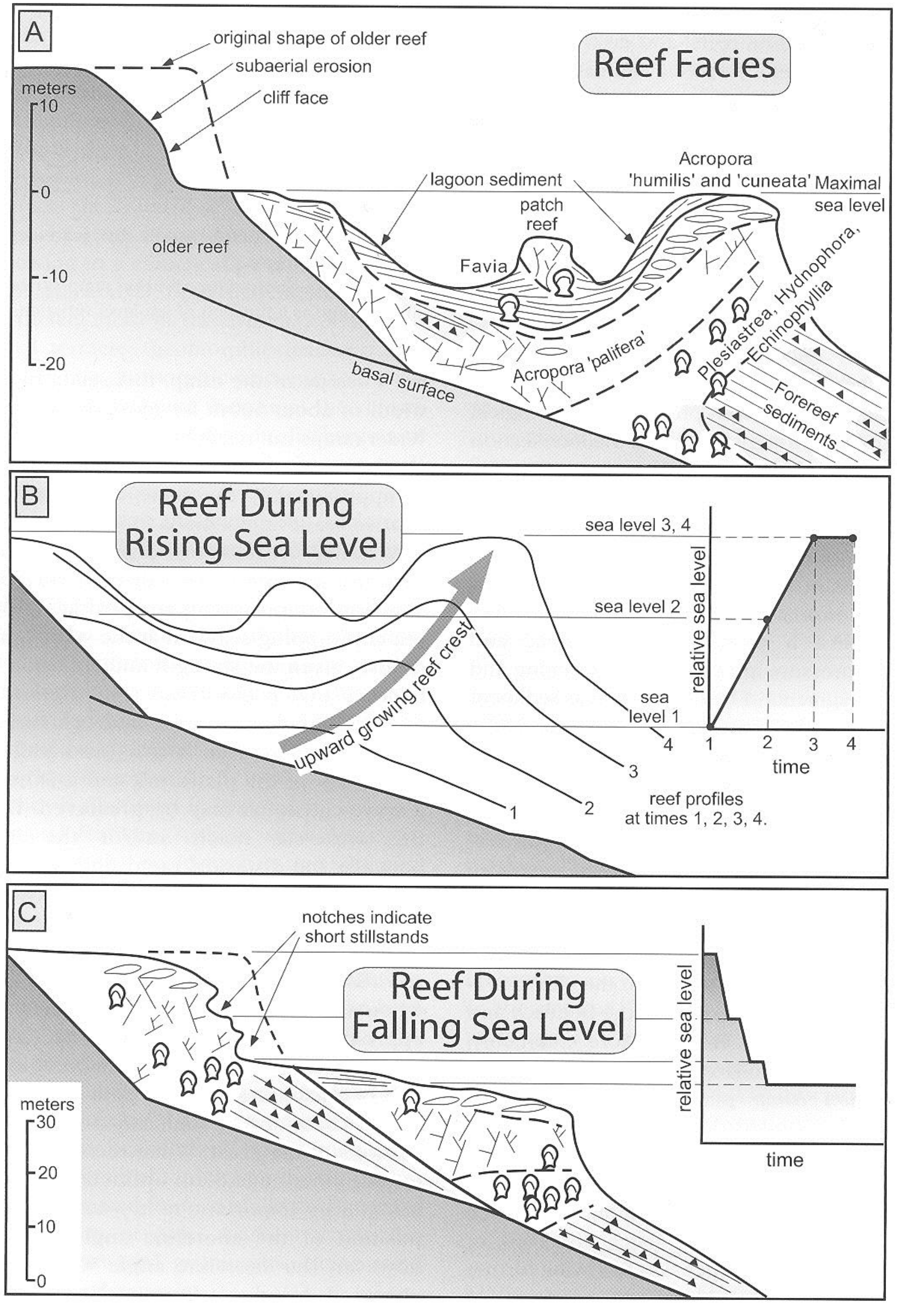


**Fig. 2.2 Coral reef stratigraphy and sea-level change.**
A. Idealized model of facies zonation and geometry of a coral reef that grew in response to rising sea level. Note that the coral species *Acropora humilis* and *A. cuneata* occupy the reef crest and most closely approximate sea level.

# Tektonický výzdvih a reakce reliéfu

**Délka trvání tektonického výzdvihu a reakce reliéfu (rozdíl mezi nejvyššími vrcholky a nadm. výškou hlavních říčních údolí)**

**Modelové situace**

- **Krátkodobý výzdvih, konstantní rychlost, klesající reliéf**

- **Zrychlující a zpomalující výzdvih, rostoucí a klesající reliéf**

- **Dlouhodobý výzdvih, konstantní rychlost, dynamická rovnováha topografie**

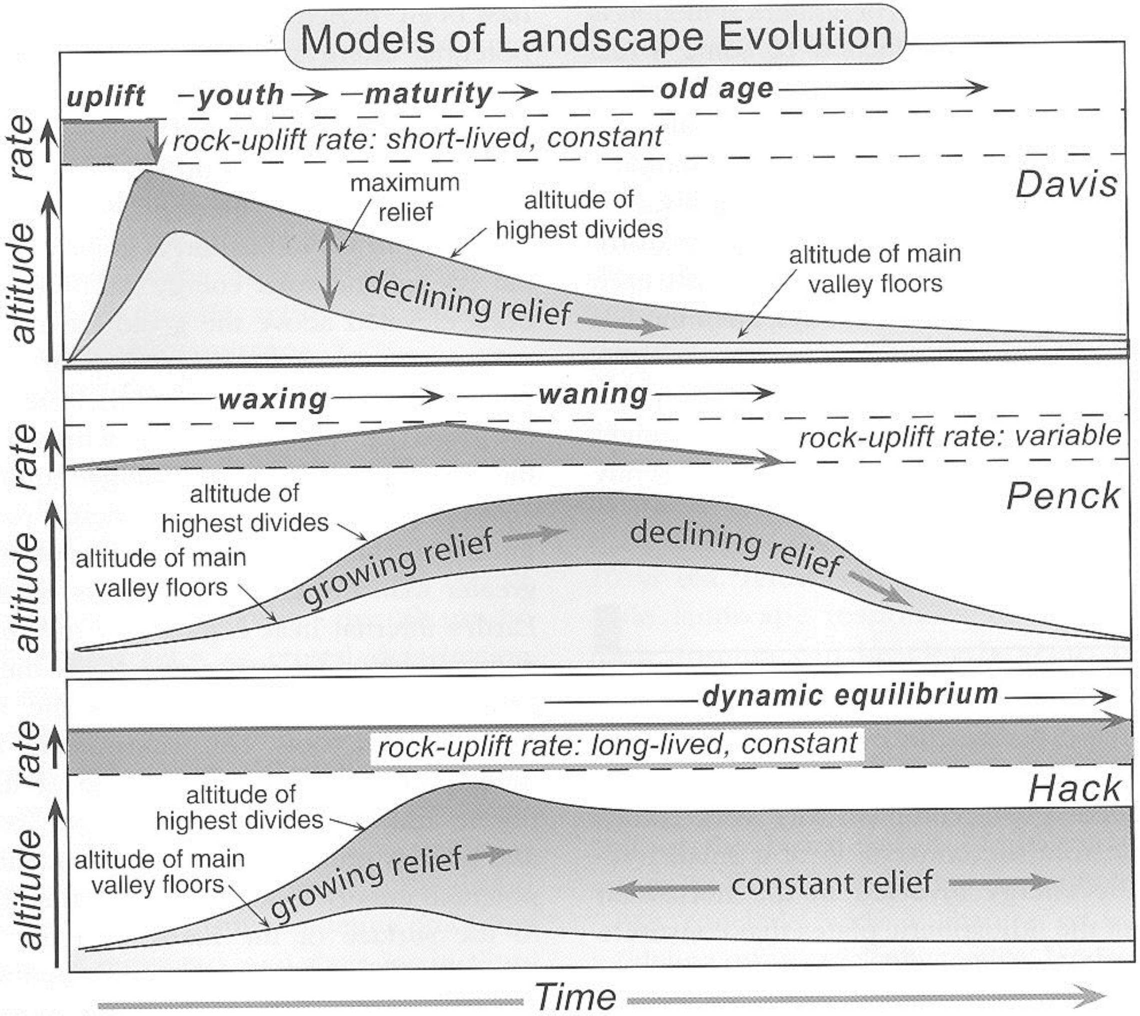


**Fig. 1.2 Classical models of tectonic forcing and landscape responses.** Based on the landscape response theories of (top) Davis (1899), (middle) Penck (1953), and (bottom) Hack (1975), each panel is characterized by differences in the duration and rate of tectonic forcing (rock uplift) and by the topographic response engendered by these different styles of rock uplift. Modified after Summerfield (1991).

# Výzdvih a eroze

## Faktory ovlivňující výzdvih (uplift)

výzdvih povrchu = výzdvih basementu + depozice – eroze (denudace) – kompakce

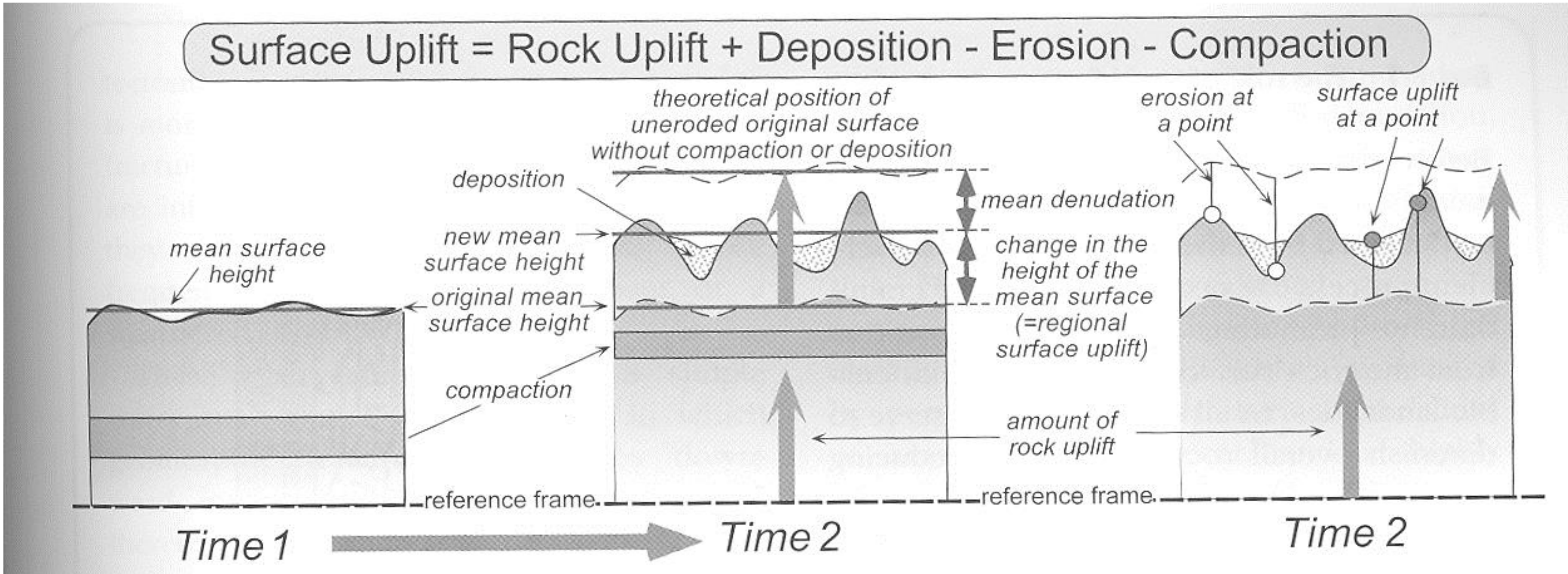
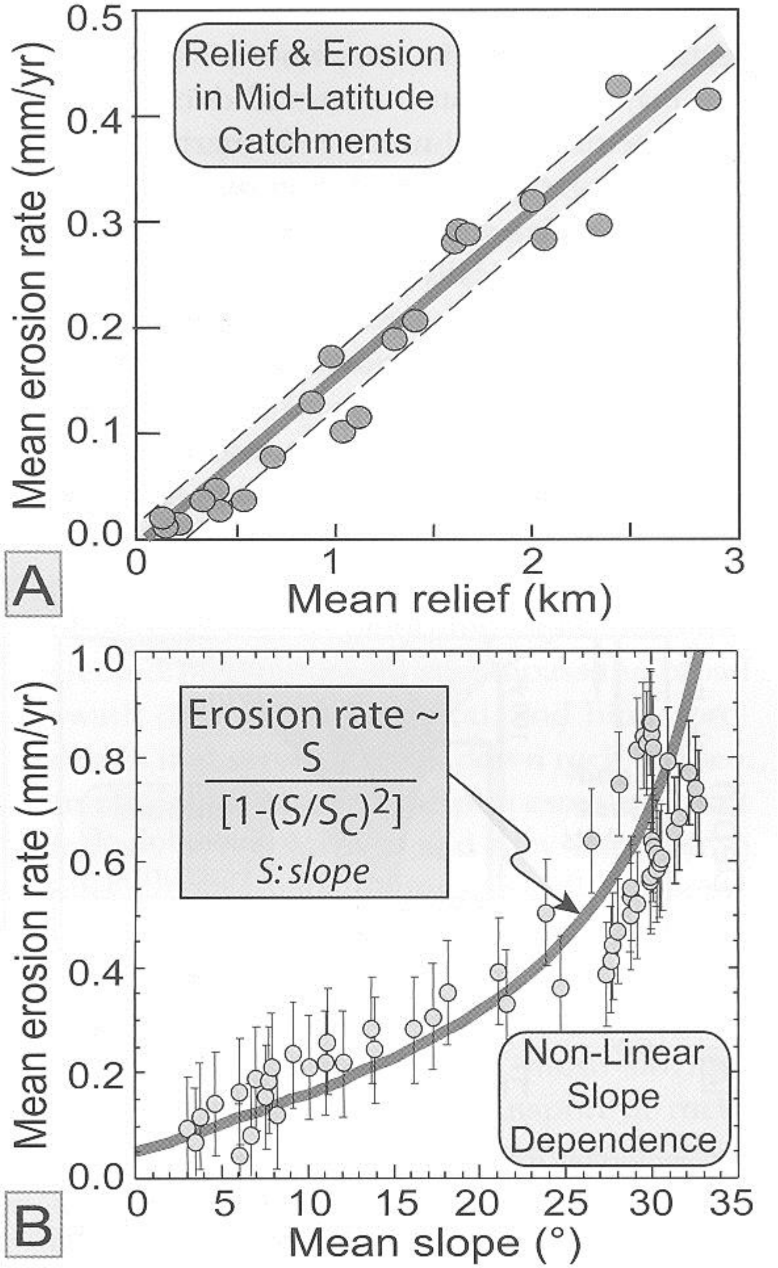


Fig. 7.2 **Factors controlling surface uplift.**
Between times 1 and 2, a specified amount of rock uplift occurs (vertical arrow). Center panel emphasizes changes in the means of quantities of interest: denudation, surface height, and changes in surface height. Right panel emphasizes changes at a point in the landscape: surface uplift or erosion. Note that erosion is measured *downward* from theoretical position of the uplifted original surface in the absence of erosion, whereas surface uplift is measured *upward* from the original surface at time 1.

# Reliéf a rychlost eroze

**Rychlost eroze v závislosti na reliéfu a sklonu svahů**



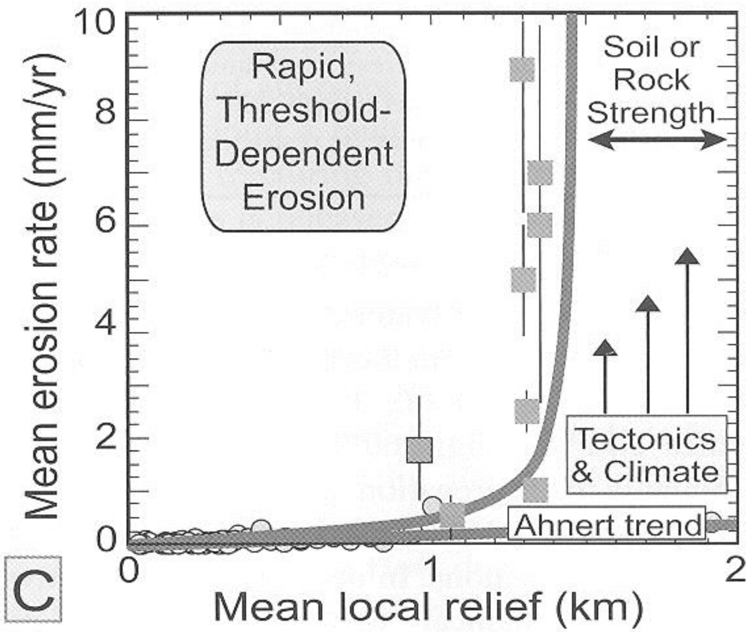


**Fig. 7.3 Erosion rates as a function of relief and hillslope angles.**
A. Topographic relief versus erosion rate, showing a linear correlation for mid-latitude, temperate catchments with rates <0.5 mm/yr. B. Erosion rate as a function of hillslope

# Globální rozsah rychlostí eroze

**Data:**

**koncentrace kosmogenních radionuklidů v klastických sedimentech nebo v podloží**

**(logaritmická škála!)**

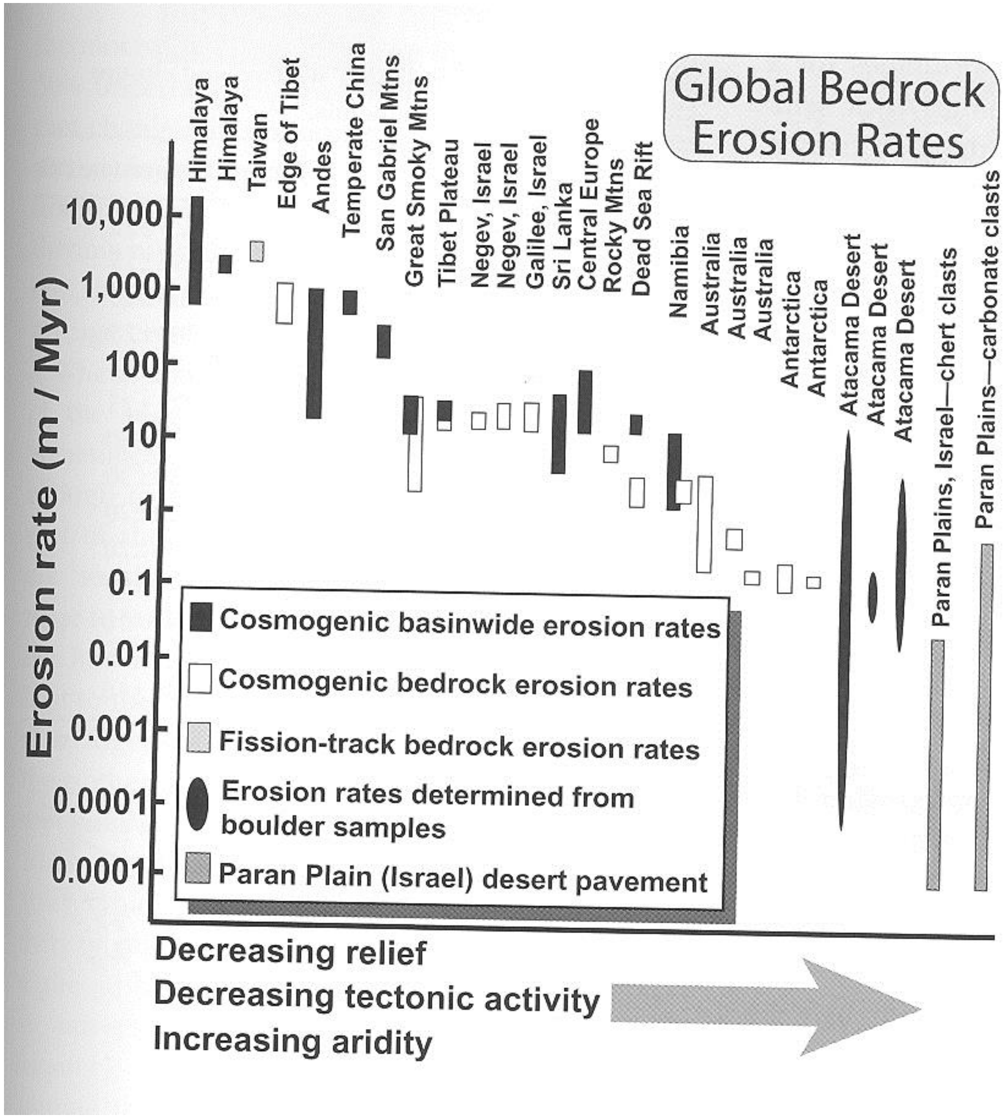


**Fig. 7.18 Global span of erosion rates.** Most rates are derived from cosmogenic nuclide concentrations in either detrital sediments or in bedrock. Rates range from 10 km/Myr in very active orogenic belts to as low as 1 mm/Myr – over seven orders of magnitude. Modified after Matmon *et al.* (2009).

# Rychlost eroze

## Odhady rychlostí eroze

Rekonstrukce původní topografie → objem „chybějícího“ materiálu = přederozní topografie – dnešní topografie

Odhad rychlosti eroze → objem a časový rozsah sedimentu v pánvi a plocha zdrojové oblasti

Průměrná rychlost eroze = rychlost sedimentace x plocha zdrojové oblasti

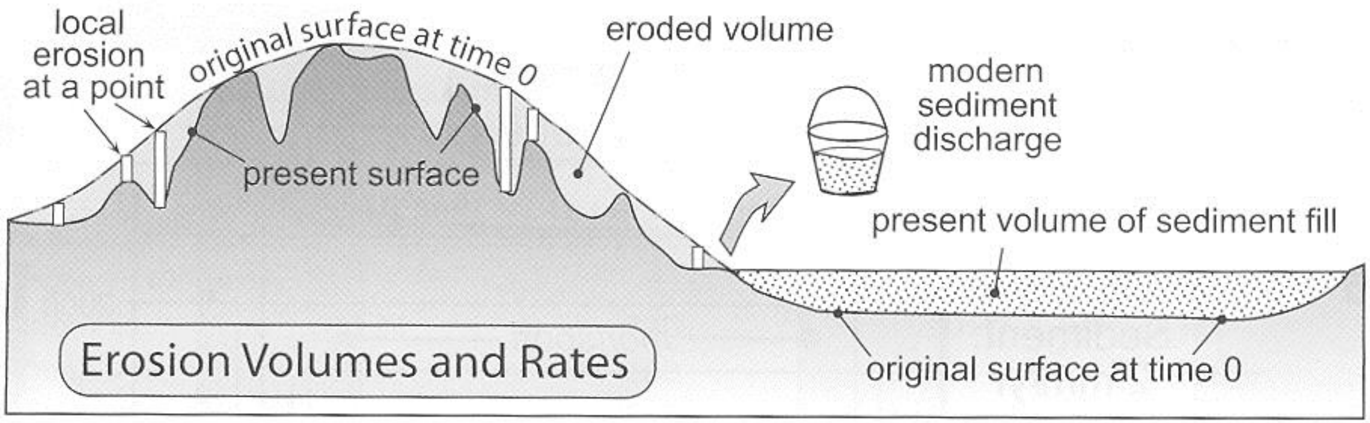


Fig. 7.4 **Approaches to estimating erosion rates.** If the original surface topography can be reconstructed, then the missing volume of material can be determined by subtracting the present-day topography from the pre-erosion topography. If the age of that initial surface is known, then a mean erosion rate can be calculated. Similarly, if the volume of sediment in a basin and the age span of its filling are known, and if the size of the area contributing sediment to the basin can be estimated, a mean erosion rate can be approximated. Alternatively, the modern rate of sediment discharge and the contributing area can be used to compute a mean erosion rate.

# Rychlost eroze

**Použití stopování ke stanovení relativní a absolutní rychlosti eroze**

A. Podíl stopy z povodí je závislý na litologické variabilitě, rychlosti denudace a velikosti povodí.

B. Dekonvoluce signálu ze zdrojových oblastí s diskrétními izotopickými záznamy může odhalit relativní rychlosti eroze. Pokud je pro kteroukoliv zdrojovou oblast známa aktuální rychlost eroze, pak lze rychlost všech zdrojových oblastí odhadnout z jejich izotopického podílu

C. Modely mísení populací stáří detritu ze dvou povodí. Pravděpodobnostní distribuce stáří detritu (vpravo) je možno rozšifrovat a stanovit tak relativní podíl z povodí obou přítoků, pokud je známa distribuce stáří detritu z těchto povodí. Záznamy povodí dosahují 40% a 60% jejich stáří z přítoků A a B.

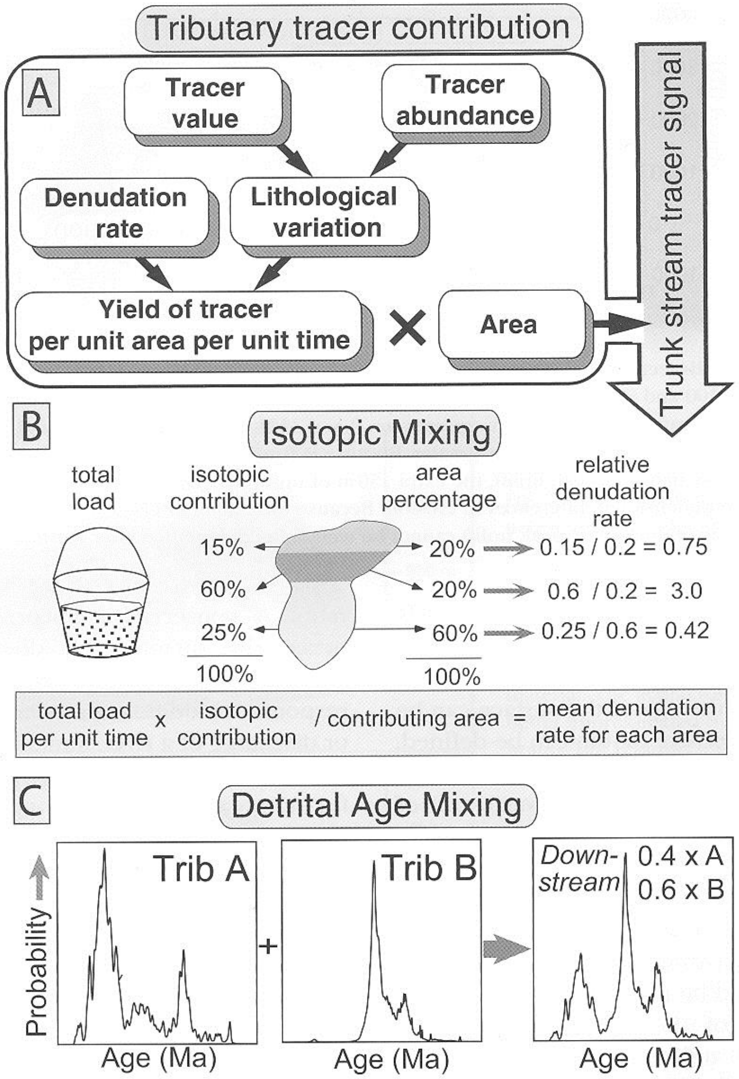


**Fig. 7.11 Use of tracers to determine relative and absolute erosion rates.**
A. The contribution of a tracer from a tributary catchment depends on lithologic variability, denudation rates, and catchment size. B. Unmixing of the downstream signal derived from source areas with discrete isotopic signatures can reveal relative erosion rates. If the actual erosion rate is known for any of the source areas, then a rate for each source area can be estimated from the isotopic contribution. C. Mixing models for populations of detrital ages from two catchments. The downstream probability distribution of detrital ages (right) can be deconvolved to determine the relative contribution from two tributary catchments, if the detrital age distribution from each catchment is known. Here, the downstream catchment records 40% and 60% of its ages from tributaries A and B, respectively. Modified after Brewer *et al.* (2005) and Amidon *et al.* (2005).

# Říční eroze

**Model vzniku říčních teras:**

**Model současné hloubkové + boční eroze**

**Model agradace sedimentu (boční erozi předchází hloubková eroze a výplň sedimentem)**

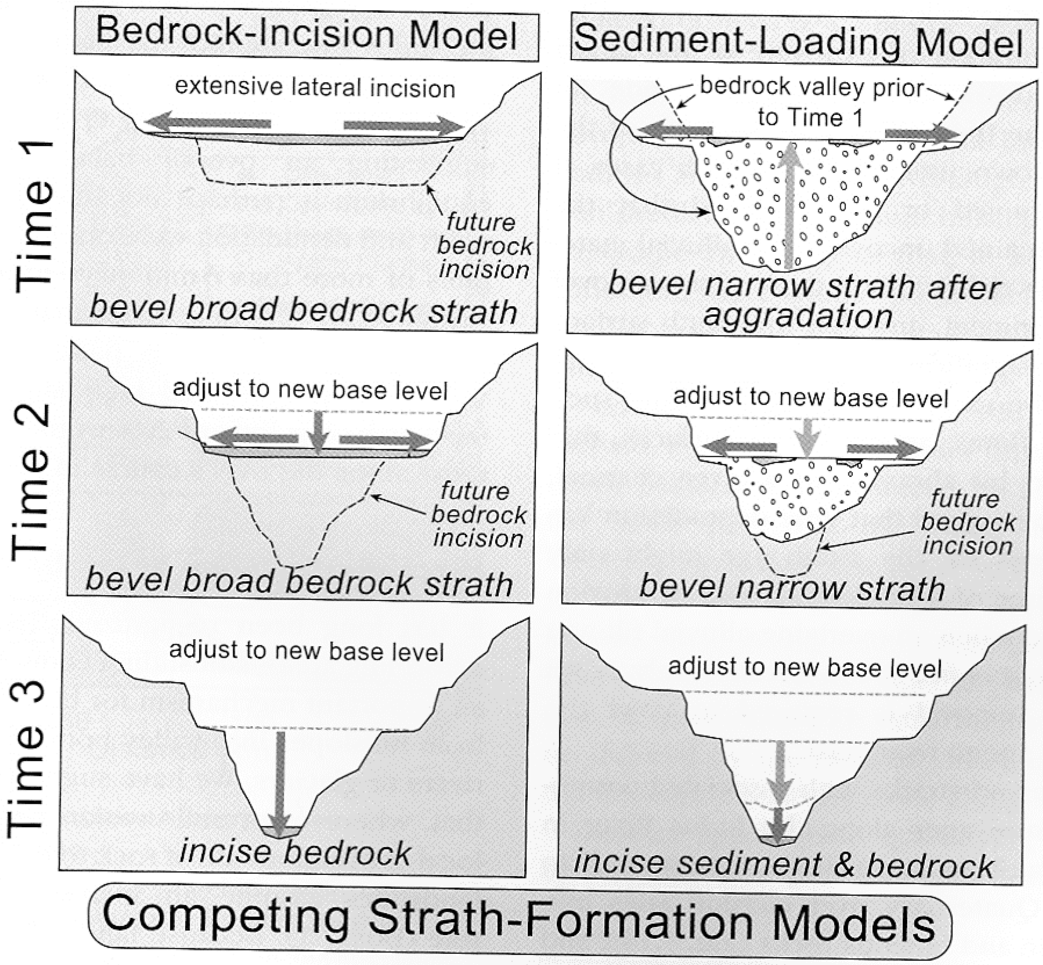


Fig. 7.13 **Competing models for the formation of bedrock straths by river incision.** The "bedrock incision model" (left side) is the traditional model in which straths are formed at or near the base of the bedrock channel. When combined with the age of the strath, the amount of subsequent channel incision serves to define the rate of bedrock incision. The "sediment loading model" (right side) predicts that strath formation occurs after aggradation has covered a bedrock channel that was incised previously. The magnitude and timing of bedrock incision is difficult to deduce in this model.

# Říční eroze

**Model vzniku říčních teras:**

**-hloubková + boční eroze**

**-Hloubková eroze, agradace, boční eroze**

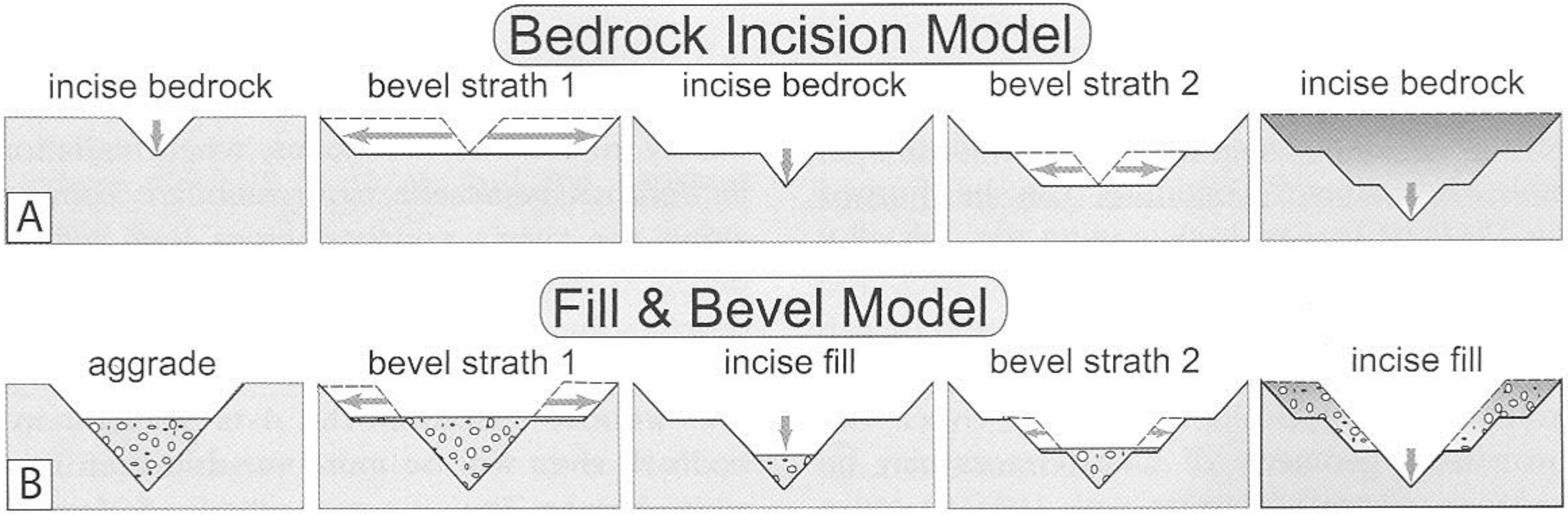


**Fig. 2.12 Models for formation of strath terraces.**
A. Traditional bedrock incision model for strath terrace formation results from extensive lateral beveling by a river, causing a broadening of the valley floor and retreat of the valley walls. Intervals of strath cutting are separated by intervals of river downcutting through the bedrock. Height of a strath above the bedrock valley floor indicates how much bedrock incision has occurred since strath formation. B. Fill-and-bevel model (e.g., Hancock and Anderson, 2002) occurs within a valley already incised into the bedrock. Aggradation within the valley protects the bedrock valley floor from erosion, but enables the river to attack the valley walls above the bedrock floor, where new straths are then cut. If the river subsequently incises partway through its fill, new straths at a lower level can be cut. Note that the height of the strath above the bedrock valley floor is unrelated to the amount of bedrock incision since the strath formed. Although the geometry of the straths for the two models is identical, strong contrasts exist in the volume of bedrock that must be removed during strath formation and in the strath's relationship to the history of bedrock incision.

# Říční eroze

**Konfigurace říčních teras:**

**A) Agradační a degradační terasy**

**B) Párové a nepárové terasy**

**C) Sekvence agradačních a degradačních povrchů, časová série střídání eroze a výplně**

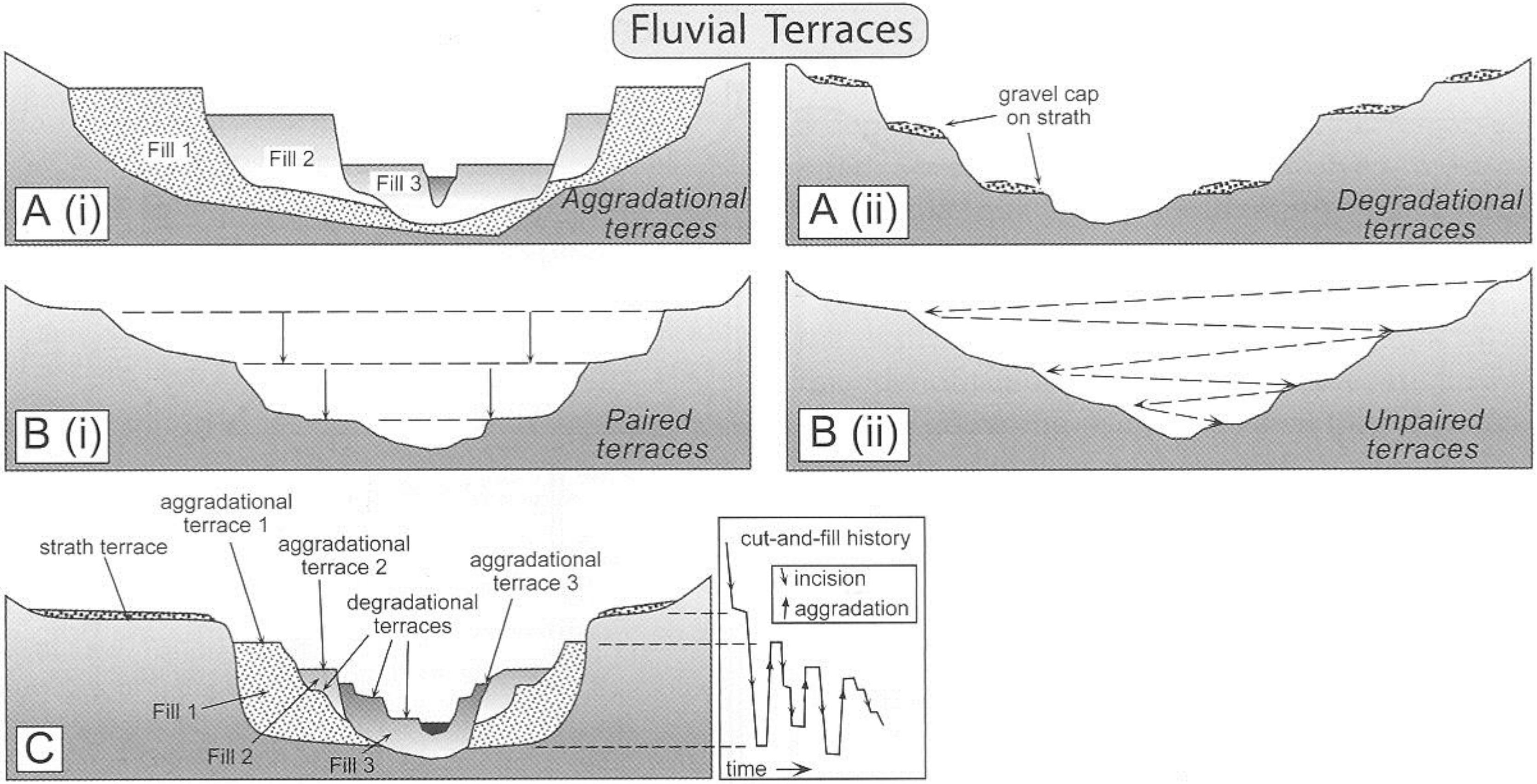


**Fig. 2.11 Schematic configurations of river terraces.**
A. Cross-sectional sketches of (i) aggradational and (ii) degradational fluvial terraces. B. (i) Paired and (ii) unpaired river terraces. C. Cross-section showing complex sequence of aggradational and degradational surfaces. Multiple cut-and-fill events are outlined in the right-hand box.

# Říční eroze

**Bilance energie toku (agradační vs. erozní tendence toku)**

**Zrnitost sedimentu + naložení sedimentem vs. průtok + sklon svahu**

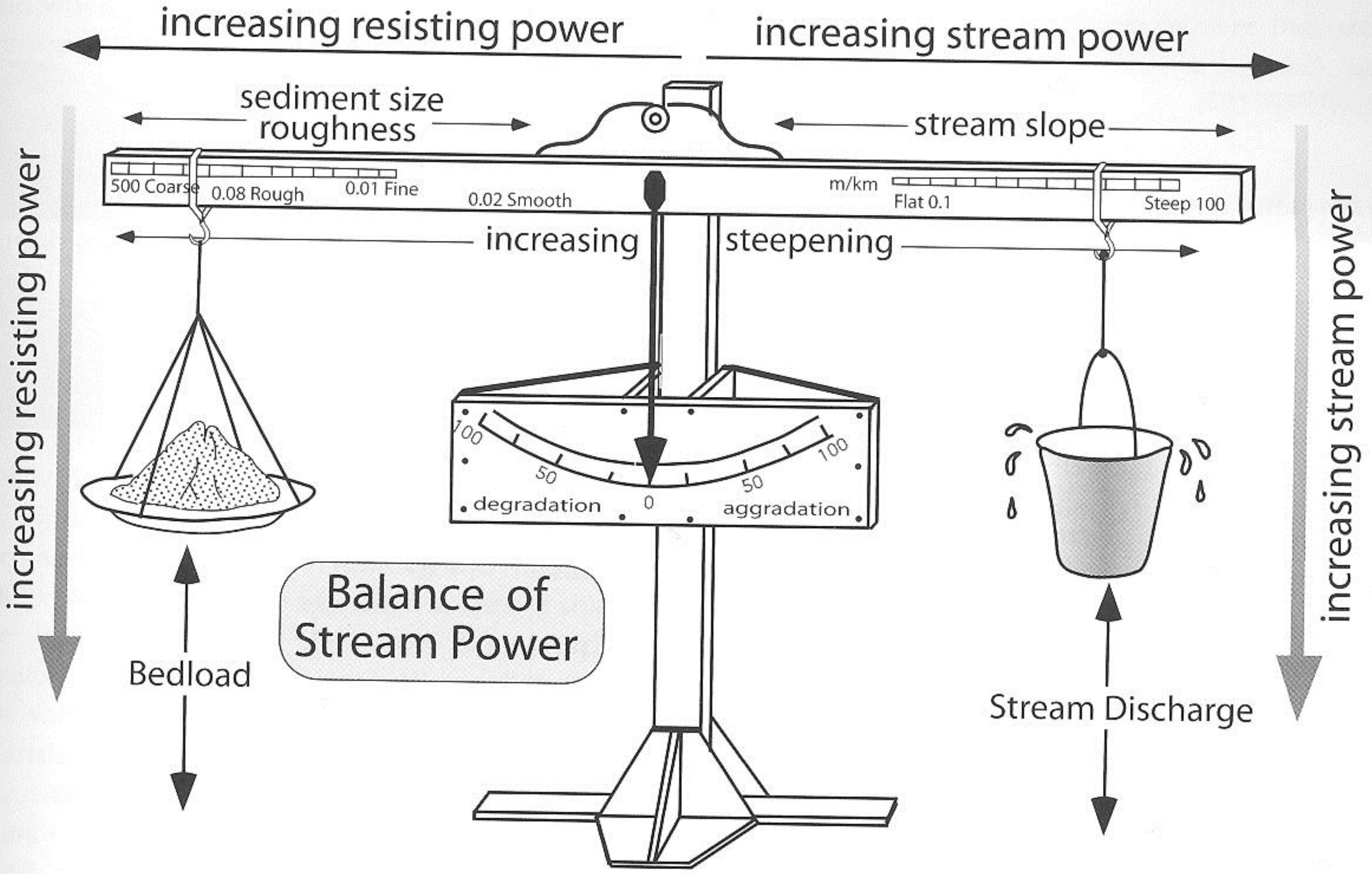


Fig. 2.10 **Schematic representation of the threshold of critical power as a balance between eroding and resisting forces.**

An increase in stream slope or discharge, or a decrease in sediment load, sediment caliber, or bed roughness, will move the system toward erosion of its bed. Modified after Bull (1991).

# Říční eroze

**Sedimentární transport a eroze u hlavních řek světa**

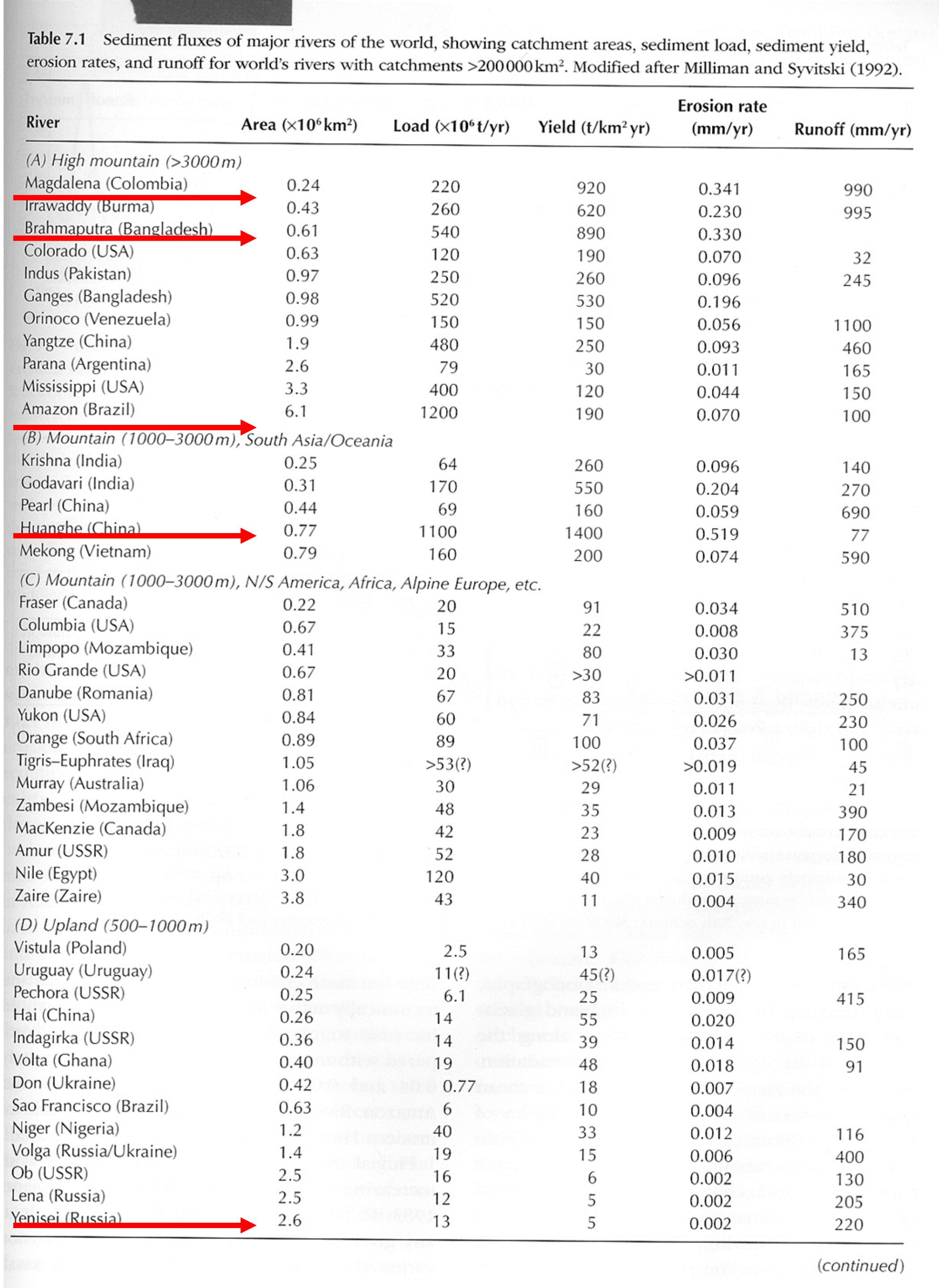


Table 7.1 Sediment fluxes of major rivers of the world, showing catchment areas, sediment load, sediment yield, erosion rates, and runoff for world's rivers with catchments >200 000 km². Modified after Milliman and Syvitski (1992).

| River | Area (×10⁶ km²) | Load (×10⁶ t/yr) | Yield (t/km² yr) | Erosion rate (mm/yr) | Runoff (mm/yr) |
|---|---|---|---|---|---|
| *(A) High mountain (>3000 m)* | | | | | |
| Magdalena (Colombia) | 0.24 | 220 | 920 | 0.341 | 990 |
| Irrawaddy (Burma) | 0.43 | 260 | 620 | 0.230 | 995 |
| Brahmaputra (Bangladesh) | 0.61 | 540 | 890 | 0.330 | |
| Colorado (USA) | 0.63 | 120 | 190 | 0.070 | 32 |
| Indus (Pakistan) | 0.97 | 250 | 260 | 0.096 | 245 |
| Ganges (Bangladesh) | 0.98 | 520 | 530 | 0.196 | |
| Orinoco (Venezuela) | 0.99 | 150 | 150 | 0.056 | 1100 |
| Yangtze (China) | 1.9 | 480 | 250 | 0.093 | 460 |
| Parana (Argentina) | 2.6 | 79 | 30 | 0.011 | 165 |
| Mississippi (USA) | 3.3 | 400 | 120 | 0.044 | 150 |
| Amazon (Brazil) | 6.1 | 1200 | 190 | 0.070 | 100 |
| *(B) Mountain (1000–3000 m), South Asia/Oceania* | | | | | |
| Krishna (India) | 0.25 | 64 | 260 | 0.096 | 140 |
| Godavari (India) | 0.31 | 170 | 550 | 0.204 | 270 |
| Pearl (China) | 0.44 | 69 | 160 | 0.059 | 690 |
| Huanghe (China) | 0.77 | 1100 | 1400 | 0.519 | 77 |
| Mekong (Vietnam) | 0.79 | 160 | 200 | 0.074 | 590 |
| *(C) Mountain (1000–3000 m), N/S America, Africa, Alpine Europe, etc.* | | | | | |
| Fraser (Canada) | 0.22 | 20 | 91 | 0.034 | 510 |
| Columbia (USA) | 0.67 | 15 | 22 | 0.008 | 375 |
| Limpopo (Mozambique) | 0.41 | 33 | 80 | 0.030 | 13 |
| Rio Grande (USA) | 0.67 | 20 | >30 | >0.011 | |
| Danube (Romania) | 0.81 | 67 | 83 | 0.031 | 250 |
| Yukon (USA) | 0.84 | 60 | 71 | 0.026 | 230 |
| Orange (South Africa) | 0.89 | 89 | 100 | 0.037 | 100 |
| Tigris–Euphrates (Iraq) | 1.05 | >53(?) | >52(?) | >0.019 | 45 |
| Murray (Australia) | 1.06 | 30 | 29 | 0.011 | 21 |
| Zambesi (Mozambique) | 1.4 | 48 | 35 | 0.013 | 390 |
| MacKenzie (Canada) | 1.8 | 42 | 23 | 0.009 | 170 |
| Amur (USSR) | 1.8 | 52 | 28 | 0.010 | 180 |
| Nile (Egypt) | 3.0 | 120 | 40 | 0.015 | 30 |
| Zaire (Zaire) | 3.8 | 43 | 11 | 0.004 | 340 |
| *(D) Upland (500–1000 m)* | | | | | |
| Vistula (Poland) | 0.20 | 2.5 | 13 | 0.005 | 165 |
| Uruguay (Uruguay) | 0.24 | 11(?) | 45(?) | 0.017(?) | |
| Pechora (USSR) | 0.25 | 6.1 | 25 | 0.009 | 415 |
| Hai (China) | 0.26 | 14 | 55 | 0.020 | |
| Indagirka (USSR) | 0.36 | 14 | 39 | 0.014 | 150 |
| Volta (Ghana) | 0.40 | 19 | 48 | 0.018 | 91 |
| Don (Ukraine) | 0.42 | 0.77 | 18 | 0.007 | |
| Sao Francisco (Brazil) | 0.63 | 6 | 10 | 0.004 | |
| Niger (Nigeria) | 1.2 | 40 | 33 | 0.012 | 116 |
| Volga (Russia/Ukraine) | 1.4 | 19 | 15 | 0.006 | 400 |
| Ob (USSR) | 2.5 | 16 | 6 | 0.002 | 130 |
| Lena (Russia) | 2.5 | 12 | 5 | 0.002 | 205 |
| Yenisei (Russia) | 2.6 | 13 | 5 | 0.002 | 220 |

*(continued)*

# Říční eroze

## Časové řady průtoku v režimu monzunových srážek

Korelace průtoku (discharge) a zatížení sedimentem (sediment flux) u letních monzunů v Indii

**Sesuvy** přispívají k celkové zátěži sedimentem (suspended sediment) >95%. Minimální rychlost eroze dosahuje cca 2 mm/rok pro celé povodí

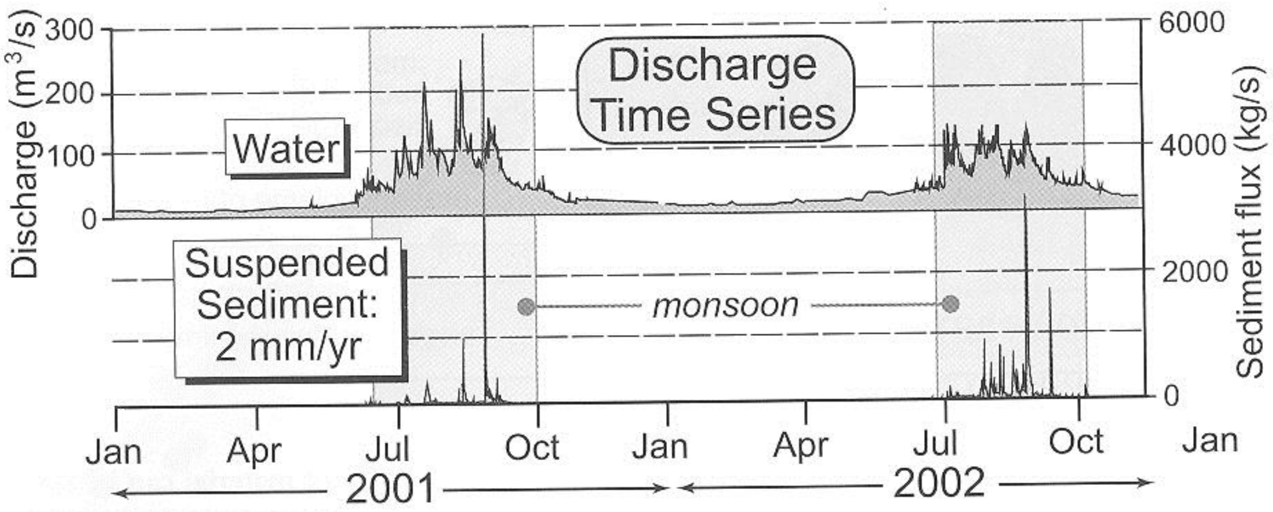


**Fig. 7.5 Discharge time series under a monsoonal rainfall regime.**
Water discharge during the summer Indian monsoon dominates the annual flow in the Nepalese Himalaya. Storms a few days in length create peaks in the monsoonal discharge. High suspended sediment discharge is typically related to landsliding events that create very peaked sediment fluxes and account for >95% of the total sediment discharge. Integration of the suspended sediment load defines a minimum erosion rate of ~2 mm/yr across the catchment. Modified after Gabet *et al.* (2008).

# Říční eroze

**Stáří (SED data, kosmogenní nuklidy) teras řeky Indus (Pákistán) a jejich výška nad dnešní hladinou řeky**

**C) Rychlost bazální eroze (incision) vs. vzdálenost podél toku**

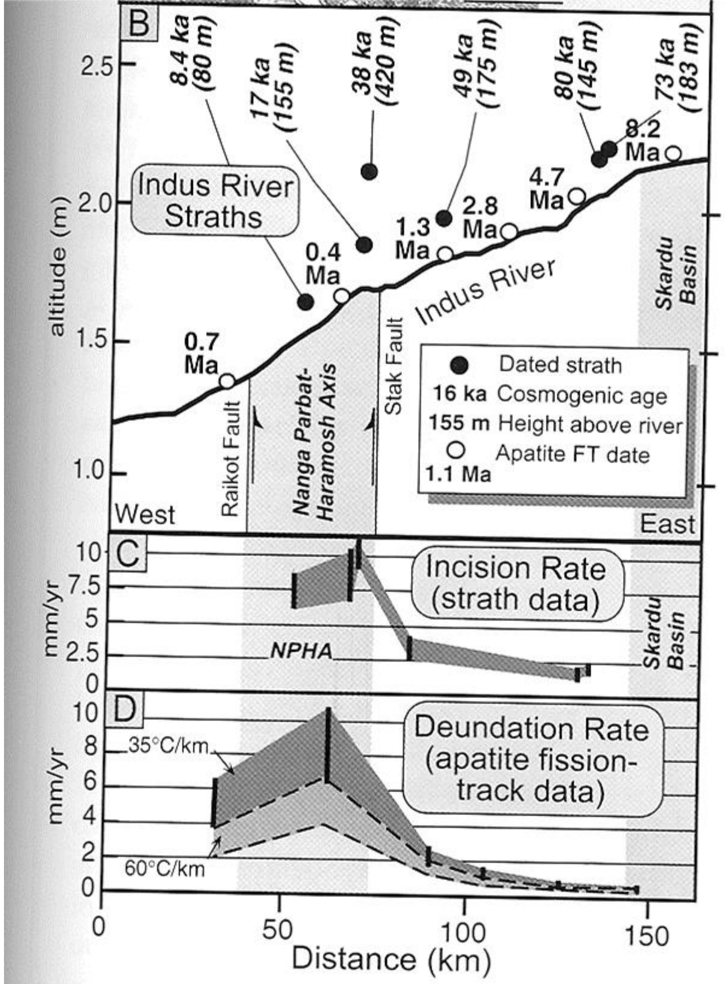


Fig. 7.14 **Bedrock incision along the Indus River, Pakistan.**
A. Annotated photograph of 80-m-high strath above the Indus River near Haramosh, northern Pakistan.
B. Strath terraces with their cosmogenic nuclide exposure ages and their heights above the modern river. At river level, apatite fission-track ages are shown. Note that the fission-track ages get progressively older toward the Skardu Basin in the east. C. Incision rates (based on strath ages) versus distance along the Indus. Note that the highest rates are associated with the steepest

# Říční eroze: klimatické faktory

**Lokální vs. globální faktory ovlivňující říční erozi**

**Pozdně pleistocenní stáří teras v Ťan Šanu**

**$^{14}$C data**

**Histogramy distribuce $^{14}$C dat**

**Soulad stáří indikuje, že vznik teras byl kontrolován klimaticky**

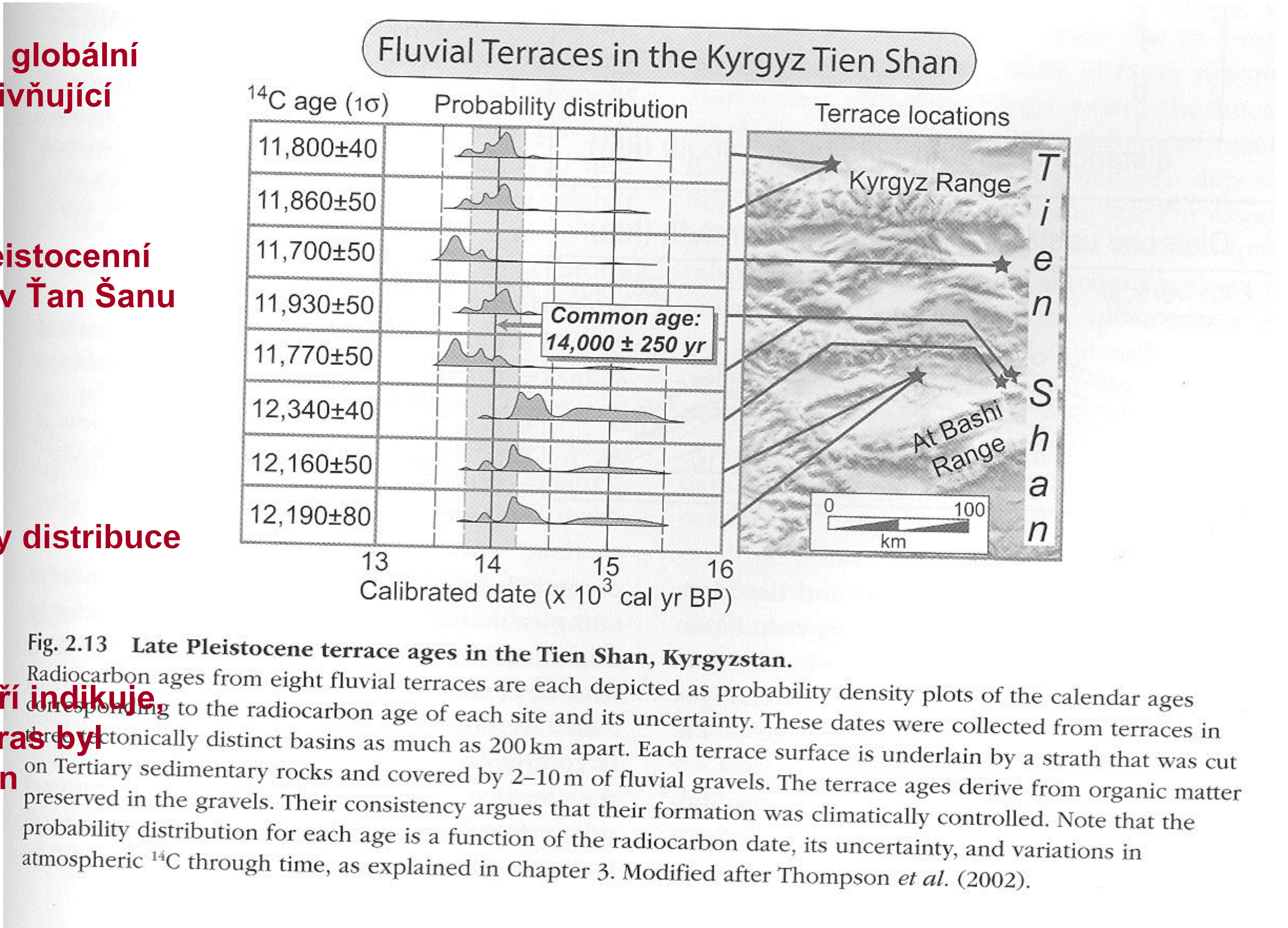


Fig. 2.13 **Late Pleistocene terrace ages in the Tien Shan, Kyrgyzstan.** Radiocarbon ages from eight fluvial terraces are each depicted as probability density plots of the calendar ages corresponding to the radiocarbon age of each site and its uncertainty. These dates were collected from terraces in three tectonically distinct basins as much as 200 km apart. Each terrace surface is underlain by a strath that was cut on Tertiary sedimentary rocks and covered by 2–10 m of fluvial gravels. The terrace ages derive from organic matter preserved in the gravels. Their consistency argues that their formation was climatically controlled. Note that the probability distribution for each age is a function of the radiocarbon date, its uncertainty, and variations in atmospheric $^{14}$C through time, as explained in Chapter 3. Modified after Thompson *et al.* (2002).

# Říční eroze: eustatické faktory

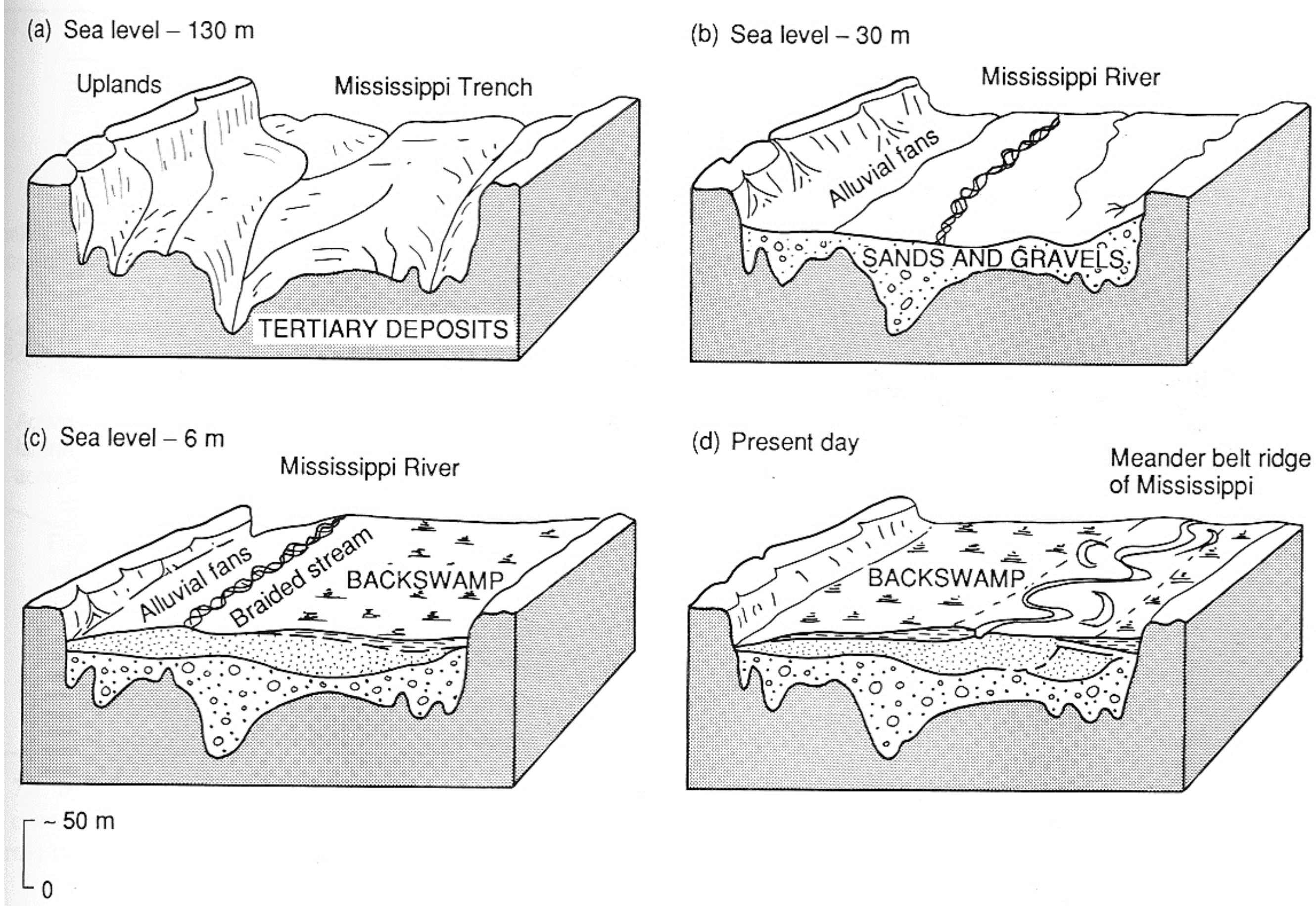
**Pleistocenní – recentní historie údolí Mississippi v reakci na eustatické změny**

(a) Erozní fáze, pozdní pleistocén, pokles hladiny moře 130 m pod dnešní úroveň

(b) agradace, vzestup hladiny moře na 30 m pod dnešní úroveň

(c) Agradace, vznik jemnozrnných povodňových plošin, vzestup hladiny moře na -6 m

(d) Moderní meandrující řeka, high sinuosity, maximum boční eroze, minimum hloubkové eroze



ig. 7.6. Schematic illustration of the late Pleistocene to Recent history of the Mississippi River Valley (after Fisk 944). (a) Late Pleistocene entrenchment during a sea level fall/lowstand at 130 m below present sea level. A low nuosity river system carried gravel to the Gulf of Mexico. (b) Aggradation of gravels and sands during the sea vel rise to 30 m below present. (c) Development of fine-grained floodplains (backswamps) adjacent to a braided luvial ridge, at 6 m below present sea level. (d) The modern high-sinuosity Mississippi River meanders in a ell-developed alluvial ridge with flanking extensive floodplains. Modified from Leeder (1982).

# Glaciální eroze

## Rychlosti glaciální eroze a ústupu ledovců

- Ústup ledovců a glaciální eroze (odvozené z objemu sedimentů) spolu dobře korelují (Tyndallův ledovec, od r. 1960)
- Během ústupu je spádová křivka ledovce nevyrovnaná (ledovec má obecně vyšší spád než řeka)

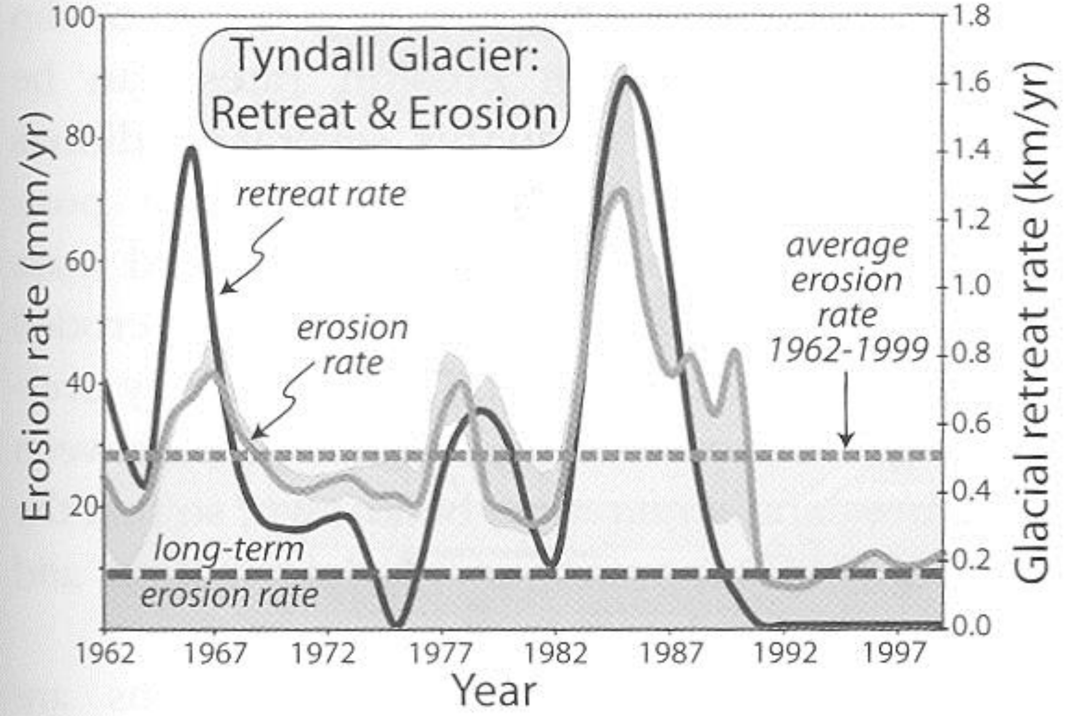


Fig. 7.7 **Comparisons of late 20th-century glacial erosion rates and glacier retreat rates.** Rates of ice-margin retreat and glacial erosion (as inferred from sediment volumes) are strongly correlated for the Tyndall tide-water glacier since 1960. Because the glacier is out of equilibrium (the glacier is steeper and ice-flow rates are faster during retreat), the well-constrained erosion rate (~28 mm/yr) is more than three times greater than the estimated long-term equilibrium rate (~9 mm/yr), which is deduced to be equal to the erosion rate during stillstands (1992–99). Modified after Koppes and Hallet (2006).

# Glaciální vs. říční eroze

**Srovnání rychlostí říční a ledovcové eroze**

U říční eroze rychlost eroze klesá s velikostí pánve

ledovce erodují obecně menší území a korelace eroze vs. území je pozitivní

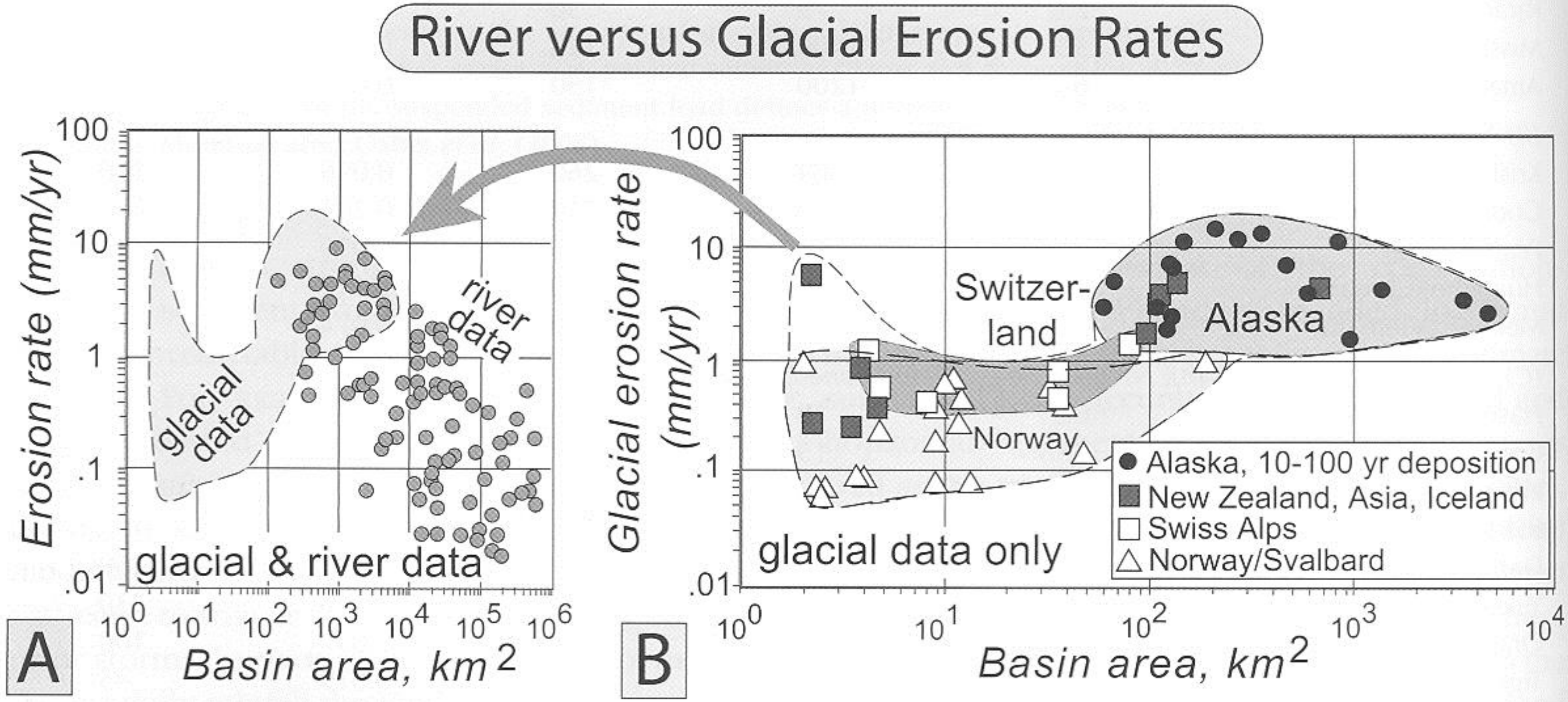


**Fig. 7.6 Comparisons of glacial and fluvial erosion rates for basins of different sizes.** A. Fluvial erosion rates (gray dots) from catchments spanning four orders of magnitude in area. Note that rates generally decrease with larger basin size, but show 10- to 100-fold variation for any given basin size. These rates are approximately equivalent to the glacial erosion rates (enclosed dashed field). B. Glacial erosion rates. Alaskan tide-water glacier rates are reduced about three-fold to account for the apparently exceptional rates during rapid glacial recession in the 20th century. Modified after Hallet *et al.* (1996) and Koppes and Hallet (2006).

# Jezerní / mořská abraze

**Lakustrinní terasy (jezero Bonneville)**

Abrazní terasy (eroze vlivem vlnění) v pohledu z perspektivy a v mapě

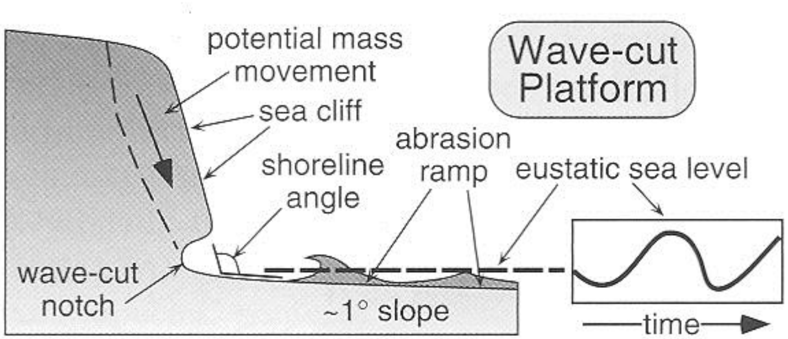


Fig. 2.1 **Abrasion platform, sea cliff, wave-cut notch, and shoreline angle.**
The vertical position of the abrasion ramp varies through time as a function of sea-level variations.

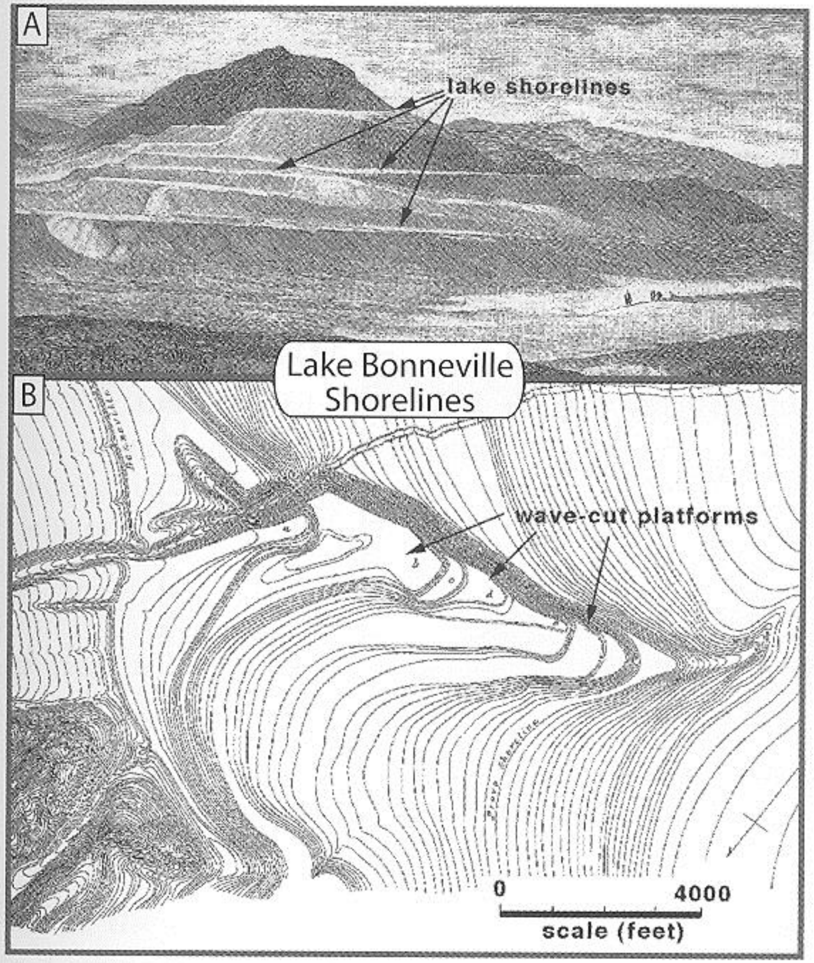


Fig. 2.7 **Lacustrine shorelines formed by Pleistocene Lake Bonneville.**
Wave-cut platforms are incised into headlands, the flanks of islands, and across spits. A. Perspective view of shorelines. B. Topographic map of wave-cut platforms incised into an elongate spit.
Modified after Gilbert (1890).

# Tektonická eroze

## Rychlosti eroze z vyzdvihovaného příkrovu

Výpočet rychlostí eroze ze strukturních a stratigrafických dat. Vstupní data: mocnost a tvar vyzdvihované nadložní desky; datování počátku pohybu na zlomu; datování stáří prvních permských klastů z podloží. Eroze kompenzuje výzdvih – za předpokladu, že špatně litifikované horniny jsou vyzdviženy nad erozní bázi

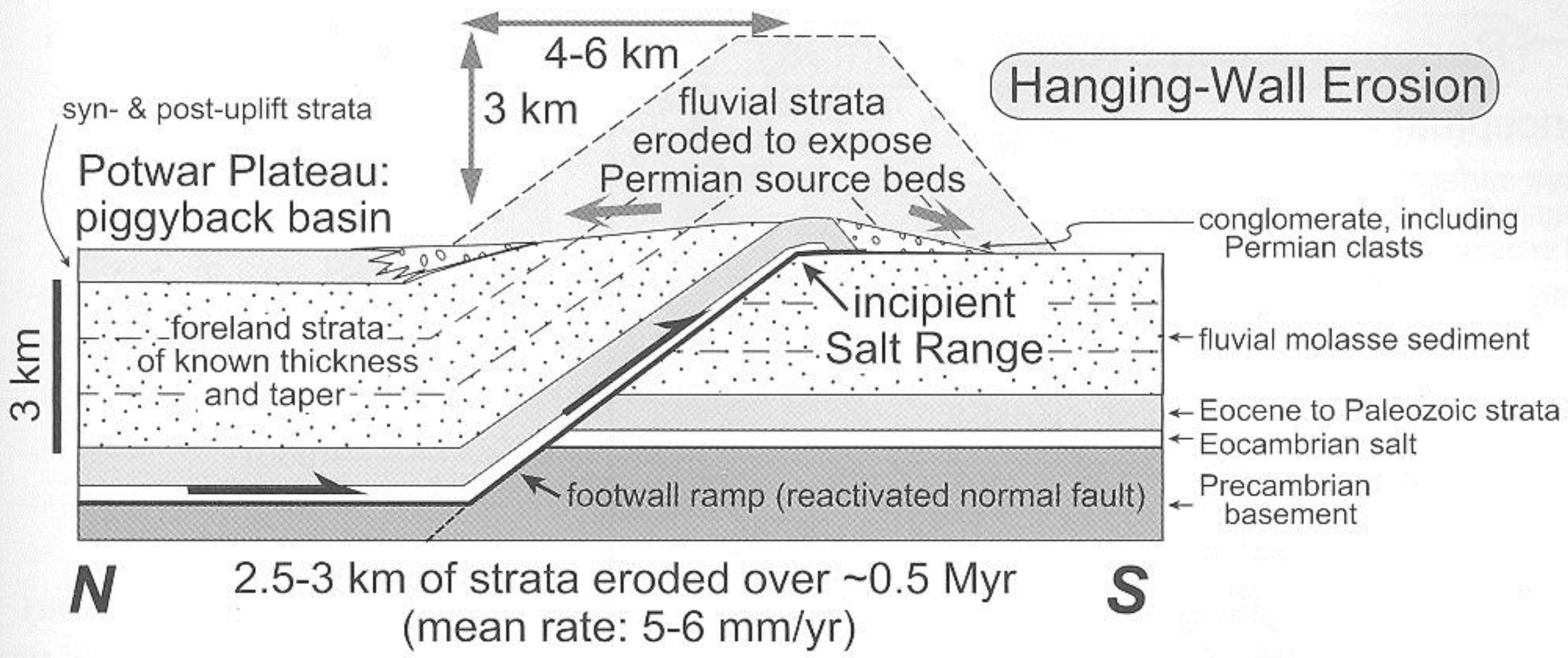


Fig. 7.8 **Erosion rates from uplifted hanging-wall strata.** Calculations of erosion rates based on combined structural and stratigraphic data in the Salt Range, northern Pakistan. Three ingredients to calculate rates are available here: thickness and shape of the uplifted hanging wall; timing of initiation of fault slip; and timing of the first appearance of clasts eroded from the Permian rocks beneath the foreland strata. These data define erosion rates that essentially balance rock uplift rates, a common occurrence when poorly lithified rocks are raised above base level. Modified after Burbank and Beck (1991).

# Tektonická eroze

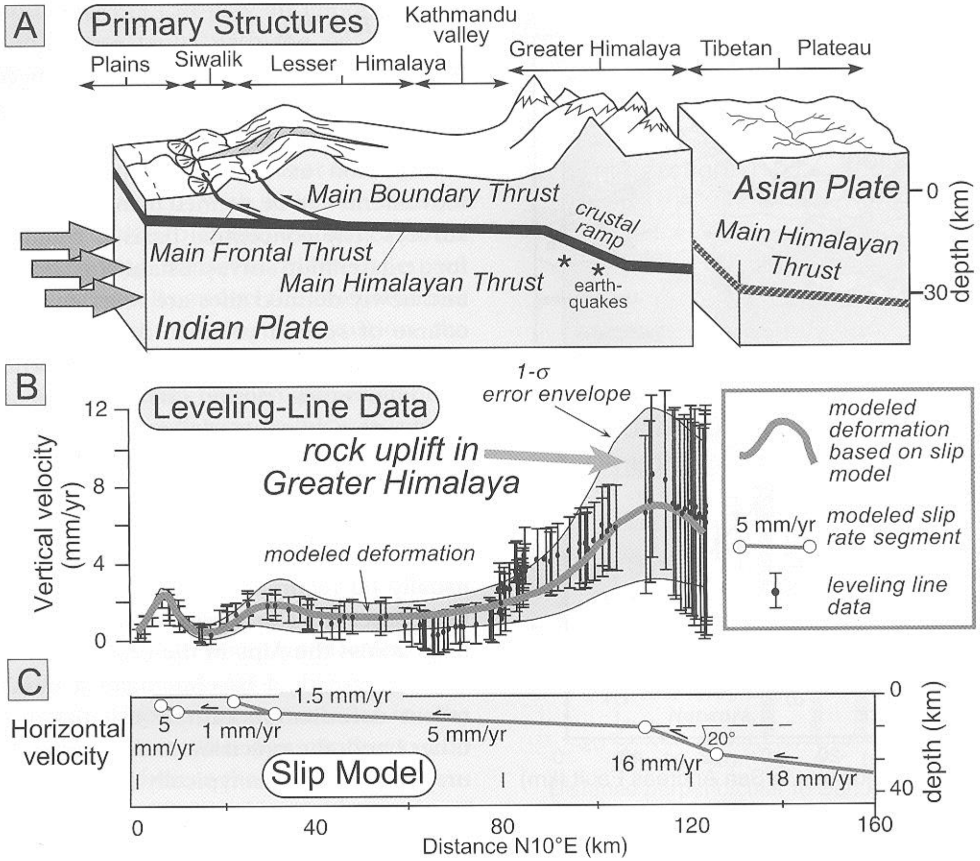


**Fig. 5.7 Leveling-line data in an active orogen.**
Comparison of (A) large-scale structure and topography with (B) observed and (C) modeled rock uplift rates. Relative rock uplift rates are calculated along a 250-km-long spirit-leveling line (B) oriented approximately perpendicular to the Himalayan Range in central Nepal. From the profile's origin at its southern end, errors become cumulatively larger to the north. The southernmost peak of uplift (~2 mm/yr) is interpreted as a response to a growing anticline above the Main Frontal Thrust in the foreland. No distinct topographic signature is associated with this deformation, probably due to ready erosion of the uplifting, but weak strata. Slow rock uplift occurs above the Main Boundary Thrust, whereas relative subsidence prevails in the intermontane Kathmandu region of the Lesser Himalaya. Relative uplift within the Greater Himalaya occurs at the highest rates (~6 mm/yr) and is associated with high topography, suggesting some permanent strain. C. Finite-element modeling of deformation of an elastic crust assigns variable slip to different fault segments. Note the striking rate change from 18 mm/yr in the north to 5 mm/yr to the south of the steeper crustal ramp lying beneath the Greater Himalaya (Bilham *et al.*, 1997). This abrupt gradient suggests that strain above and south of the crustal ramp could generate the observed pattern of uplift. In particular, the strong southward-sloping gradient in uplift within the Lesser Himalaya is consistent with a large component of elastic interseismic strain that should be released in future large earthquakes. Modified after Jackson and Bilham (1994a).

# Svahová eroze

## Říční eroze vs. snižování sklonu okolních svahů

Rychlost říční hloubkové eroze (incision) definuje erozní bázi (okolních svahů. Rozdíly v incizi a snižování okolních svahů:

A) Stabilní topografie, vyrovnaná incize a snižování svahů

B) Pokud snížení sklonu svahů převyšuje incizi, reliéf se snižuje

C) Pokud je incize rychlejší než snižování svahů, reliéf se zvyšuje a svahy se více uklání

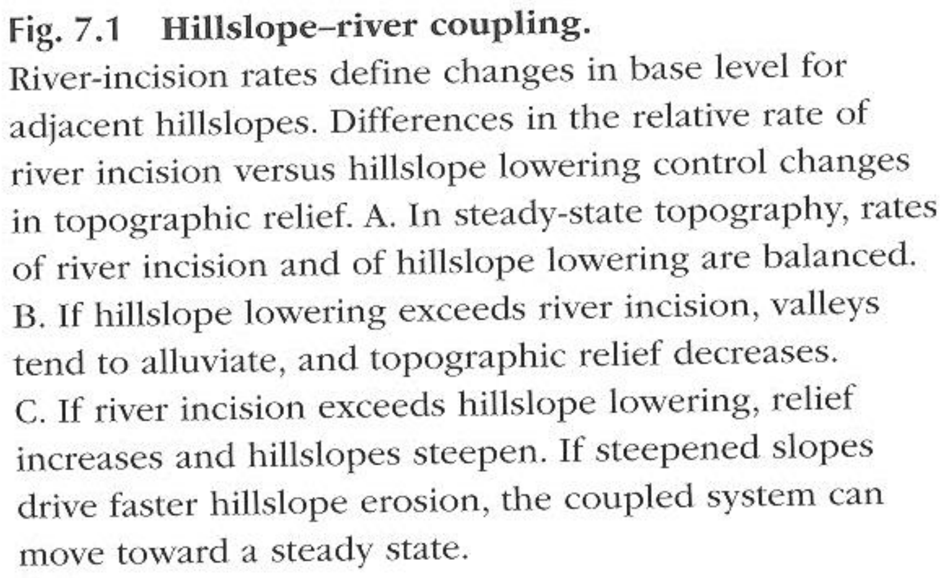
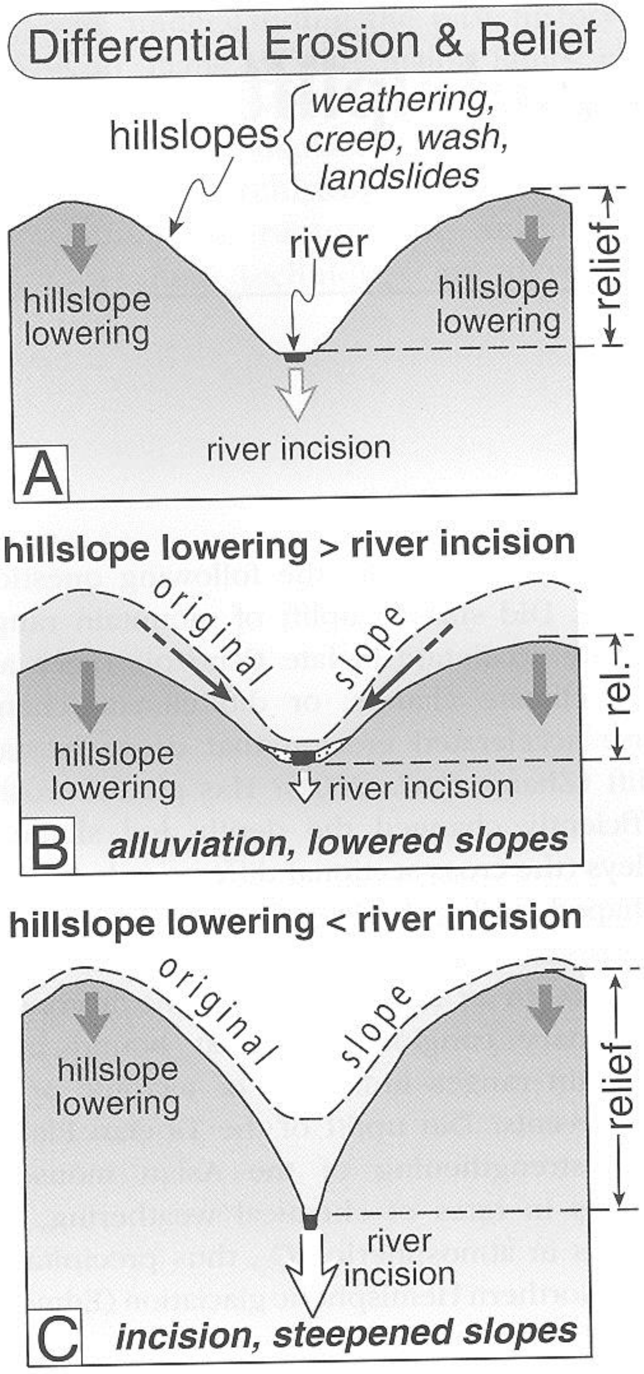


**Fig. 7.1 Hillslope–river coupling.** River-incision rates define changes in base level for adjacent hillslopes. Differences in the relative rate of river incision versus hillslope lowering control changes in topographic relief. A. In steady-state topography, rates of river incision and of hillslope lowering are balanced. B. If hillslope lowering exceeds river incision, valleys tend to alluviate, and topographic relief decreases. C. If river incision exceeds hillslope lowering, relief increases and hillslopes steepen. If steepened slopes drive faster hillslope erosion, the coupled system can move toward a steady state.



# Metody číselného datování v geomorfologii

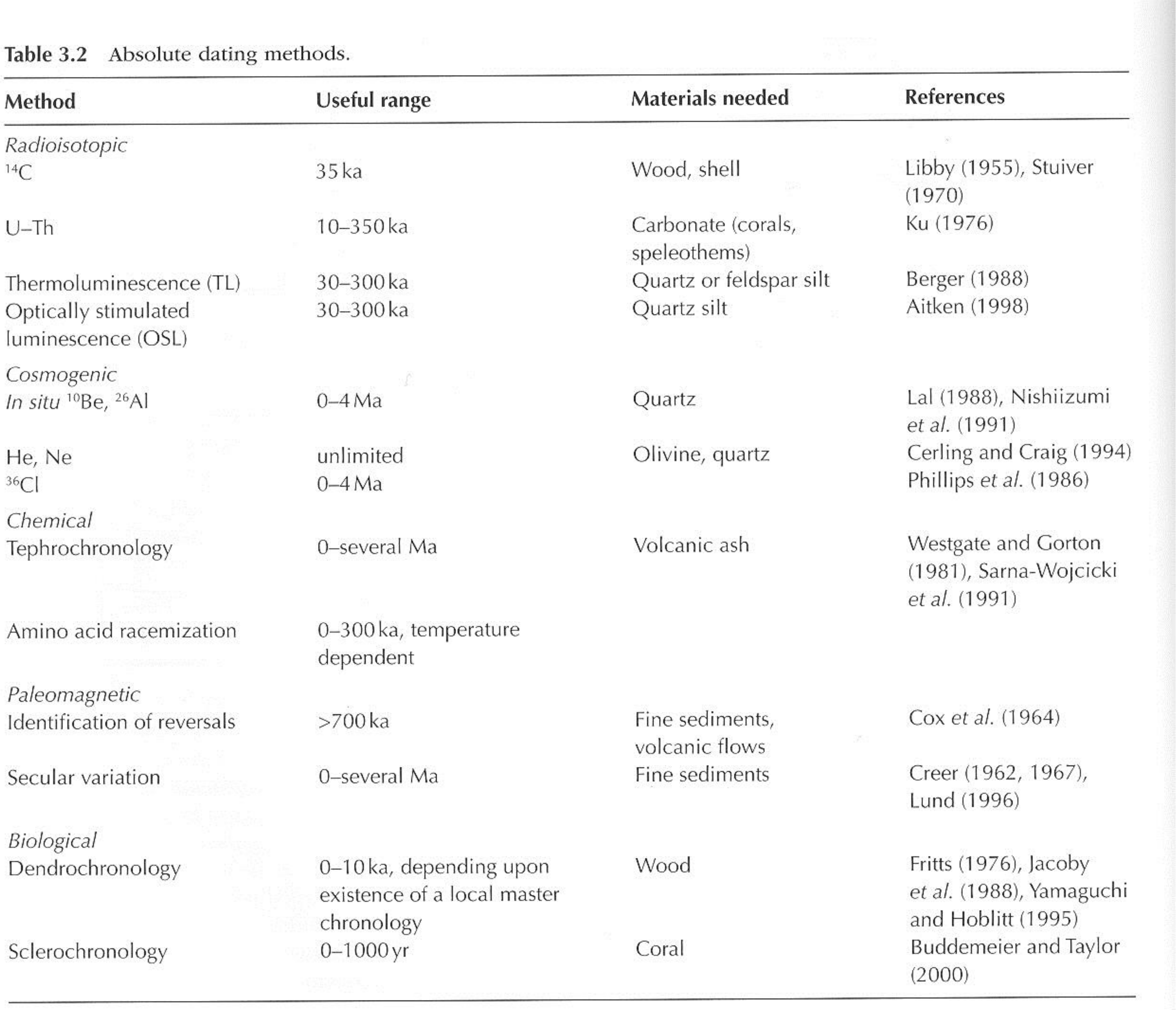


**Table 3.2** Absolute dating methods.

| Method | Useful range | Materials needed | References |
|---|---|---|---|
| *Radioisotopic* | | | |
| $^{14}C$ | 35 ka | Wood, shell | Libby (1955), Stuiver (1970) |
| U–Th | 10–350 ka | Carbonate (corals, speleothems) | Ku (1976) |
| Thermoluminescence (TL) | 30–300 ka | Quartz or feldspar silt | Berger (1988) |
| Optically stimulated luminescence (OSL) | 30–300 ka | Quartz silt | Aitken (1998) |
| *Cosmogenic* | | | |
| *In situ* $^{10}Be$, $^{26}Al$ | 0–4 Ma | Quartz | Lal (1988), Nishiizumi *et al.* (1991) |
| He, Ne | unlimited | Olivine, quartz | Cerling and Craig (1994) |
| $^{36}Cl$ | 0–4 Ma | | Phillips *et al.* (1986) |
| *Chemical* | | | |
| Tephrochronology | 0–several Ma | Volcanic ash | Westgate and Gorton (1981), Sarna-Wojcicki *et al.* (1991) |
| Amino acid racemization | 0–300 ka, temperature dependent | | |
| *Paleomagnetic* | | | |
| Identification of reversals | >700 ka | Fine sediments, volcanic flows | Cox *et al.* (1964) |
| Secular variation | 0–several Ma | Fine sediments | Creer (1962, 1967), Lund (1996) |
| *Biological* | | | |
| Dendrochronology | 0–10 ka, depending upon existence of a local master chronology | Wood | Fritts (1976), Jacoby *et al.* (1988), Yamaguchi and Hoblitt (1995) |
| Sclerochronology | 0–1000 yr | Coral | Buddemeier and Taylor (2000) |

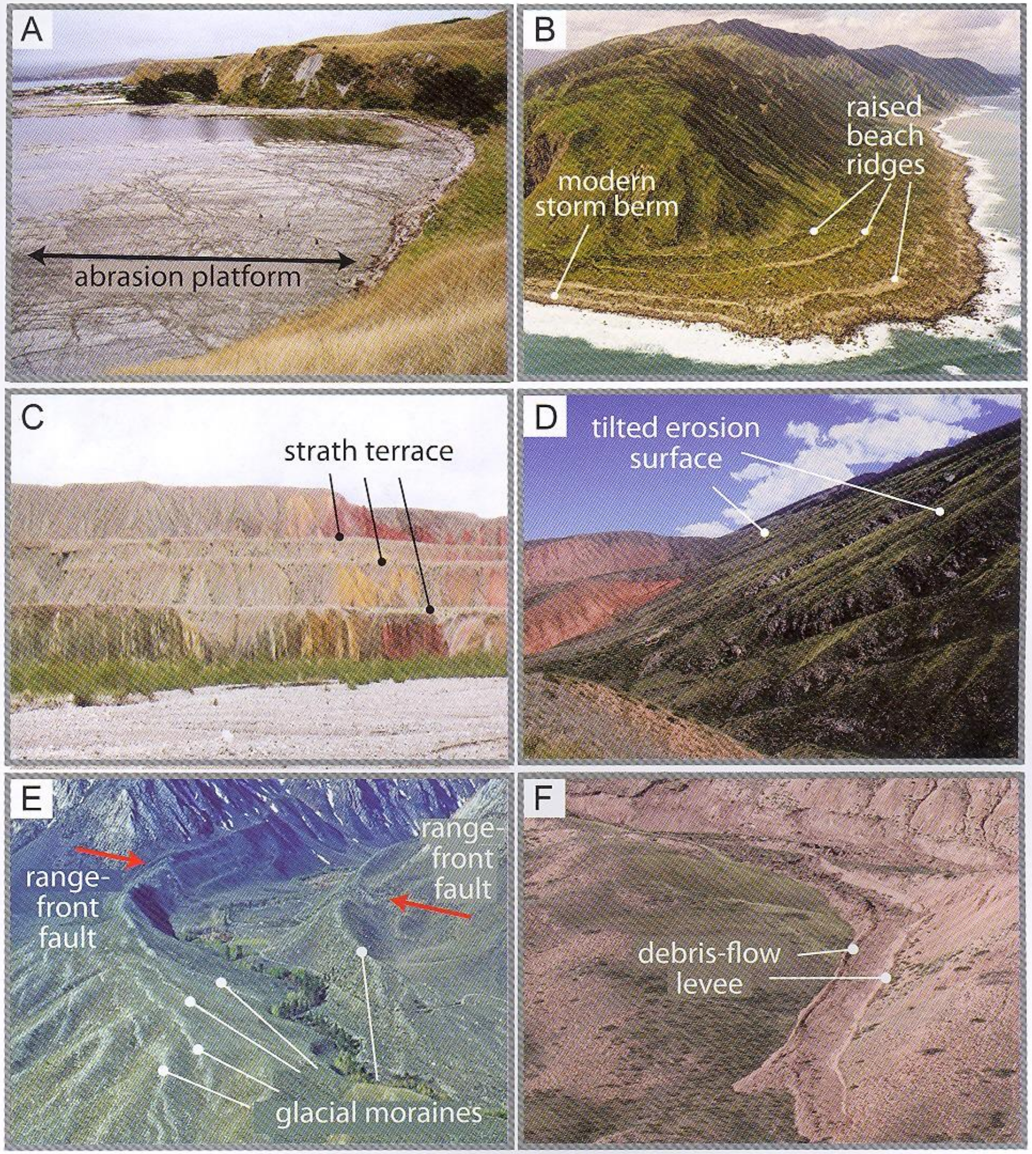


**Plate 1** A. Abrasion platform exposed during low tide at Kaikoura, New Zealand. B. Beach ridges uplifted by earthquakes at Turakirae Head, Wairarapa, New Zealand. Note that the lowest ridge of sand is the modern storm berm. Image modified from Lloyd Homer, GNS Science. C. Strath terraces in the southern Tien Shan, western China. D. Regional unconformity surface that is beveled across Paleozoic strata and exposed following tilting and subsequent stripping of weakly cemented Cenozoic strata at Gory Baybeiche, Tien Shan, Kyrgystan. E. Glacial moraines cut by range-front normal fault at McGee Creek, Sierra Nevada, California. F. Debris-flow levees in the Tien Shan, Kyrgyzstan.

# Potenciál pro zachování sedimentačních pánví

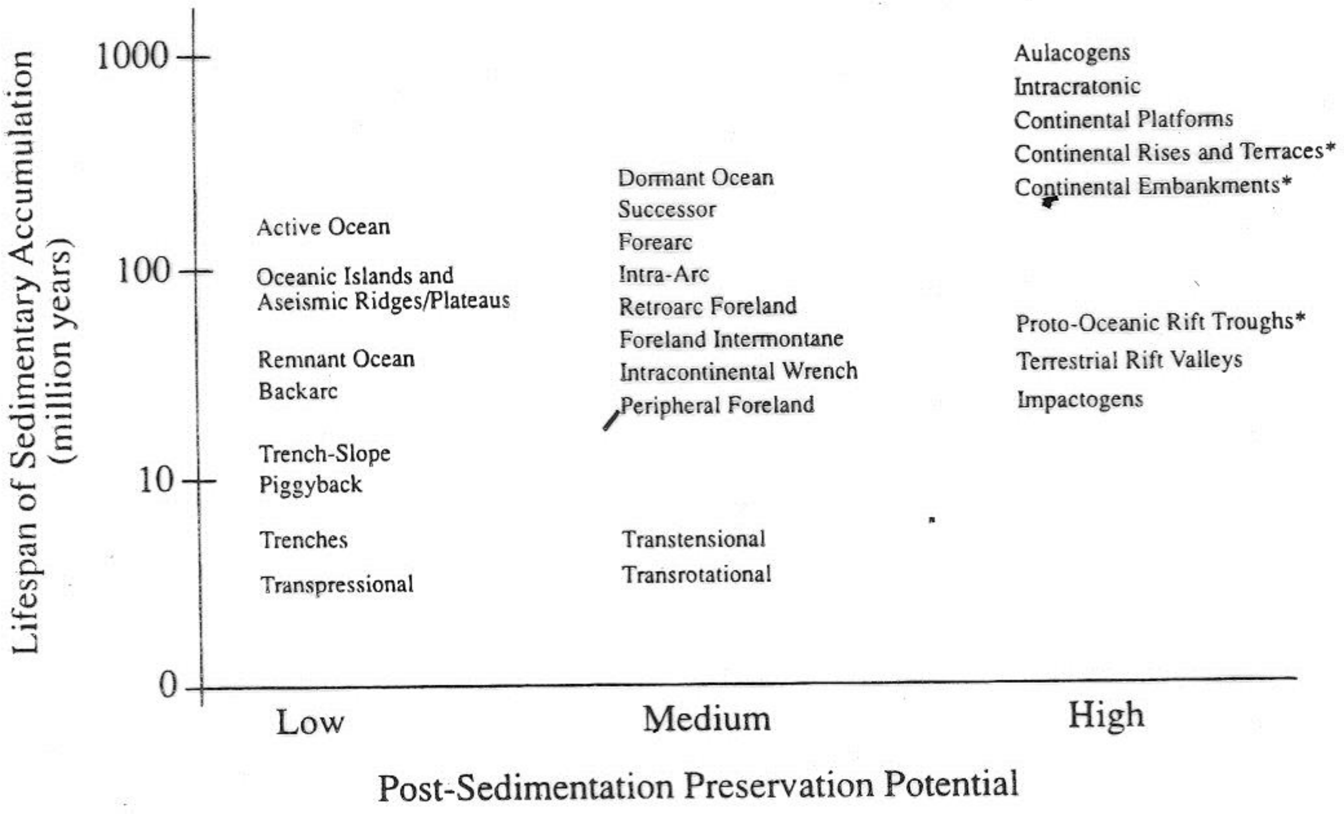


**Figure 1.2** Typical life spans for sedimentary basins versus their post-sedimentation preservation potential. "Preservation potential" refers to average amount of time during which basins will not be uplifted and eroded, or be tectonically destroyed during and following sedimentation. Sedimentary or volcanic fill may be preserved as accretionary complexes during and after basin destruction (true of all strata deposited on oceanic crust). Basins with asterisks (intraplate continental margins) are "preserved" in the sense of retaining their basement, but they are likely to be subcreted beneath or within suture belts, and are difficult to recognize in the ancient record in such settings.

# Riftové pánve

**Geometrická klasifikace riftů**

- **solitérní** rifty
- riftové **hvězdy** (trojné body)
- riftové **řetězce**
- **shluky** riftů

**Kinematická klasifikace riftů**

- **vnitrodeskové rifty** (vzácné, solitérní)
- **rifty na divergentním rozhraní** (hojné, mohou nebo nemusí být předcházeny fází vyklenutí - aktivní vs. pasivní), východoafrický rift
- **rifty na konzervativním rozhraní** (transtezní pánve, pull-apart pánve), např. suezský záliv
- **rifty na konvergentním rozhraní** (impaktogény - rýnský prolom), v důsledku extenzních sil vyvolaných kolizí
- **rifty na trojných bodech** (rifty vznikající v důsledku rozkladu napětí na trojných bodech spojených se subdukcí

**Dynamická klasifikace riftů (**podle sil, které vyvolávají rifting)

- **aktivní rifting** - vzestup plášťové hmoty (horké skvrny v plášti), následná extenze je vyvolána termálním vyklenutím a ztenčením litosféry

  **problém**: bez následné extenze není aktivní rifting schopen déletrvající činnosti

  extenze může být vyvolána: střižným napětím v plášťovém chocholu nebo okolními geometrickými podmínkami, nejčastěji série aktivních riftů v linii a vhodná deskově-tektonická konfigurace v okolí - východoafrický rift - separace kontinentů
- **pasivní rifting** - plášť v podloží riftu hraje pasivní roli, rifting je vyvolán dvourozměrným pohybem litosféry, bez termálního vyklenutí

# Riftové pánve

**Modely subsidence**

- krátká fáze horizontálního natahování – extenze, tektonická subsidence + izostatické vyrovnání
- prohřátí + laterální výměna tepla - uplift na rameni riftu
- termální subsidence centra riftu - zvýšení mocnosti plášťové litosféry
- flexurální průhyb v důsledku zatížení sedimentem

**Model sedimentární výplně**

- **pure shear** - lokalizace spreadingového centra leží v místě dřívějšího riftingu (rýnský prolom), graben
- **simple shear** (atlantický typ) - klouzání po intrakrustální zóně odlepení (detachment), half graben
- vulkanická činnost - závislá na termálních podmínkách astenosféry

**Sedimentace na half grabenu**

- klastická sedimentace, fault-bounded, asymetrické výplně, aluviální kužely, fluviální systémy, fan delty, marinní systémy - turbidity, podmořské vějíře
- hanging wall - mírný sklon svahu,

# Riftové pánve (Rift basins)

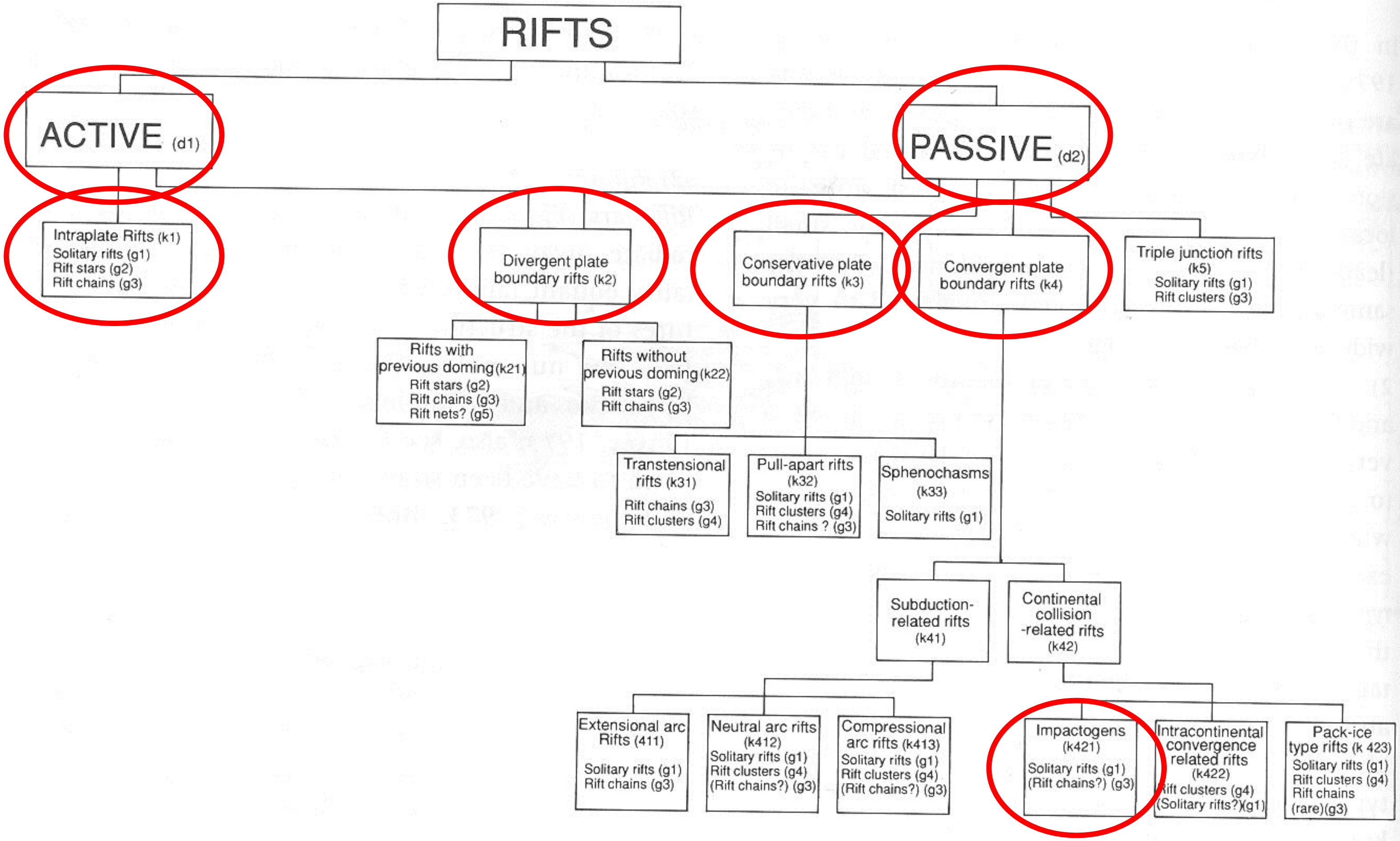


**Figure 2.5** Classification of rifts

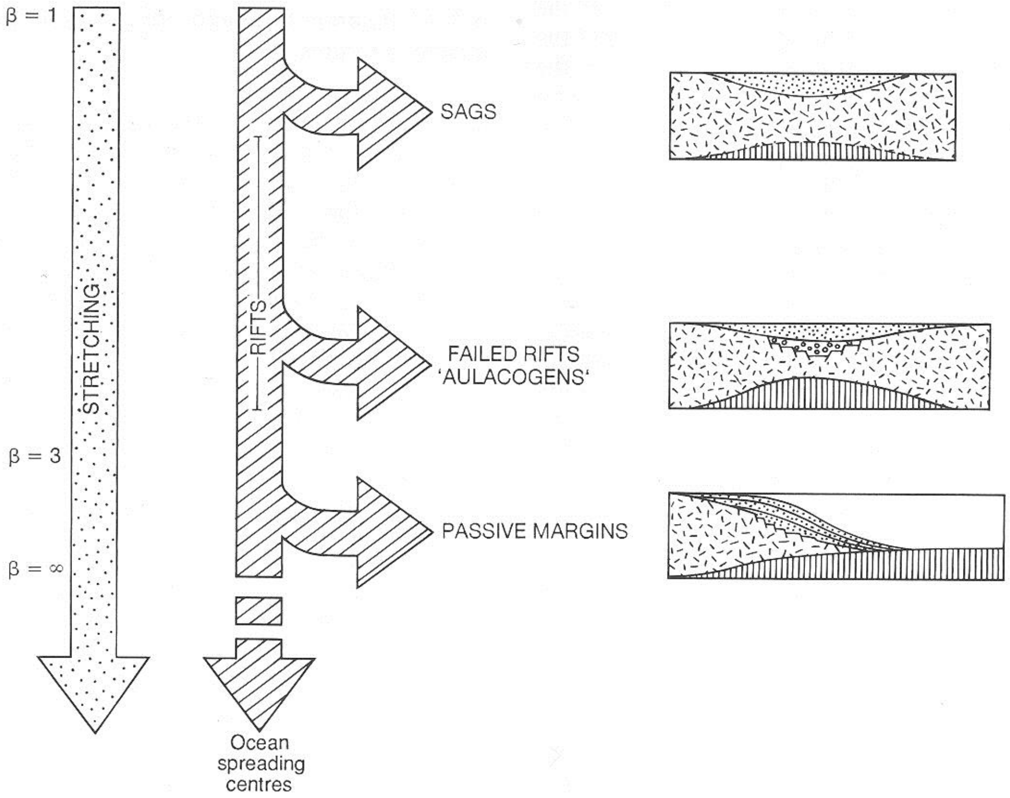


**Fig. 3.31.** Relation between sags, rifts, aulacogens and passive margins.

# Aktivní kontinentální extenze

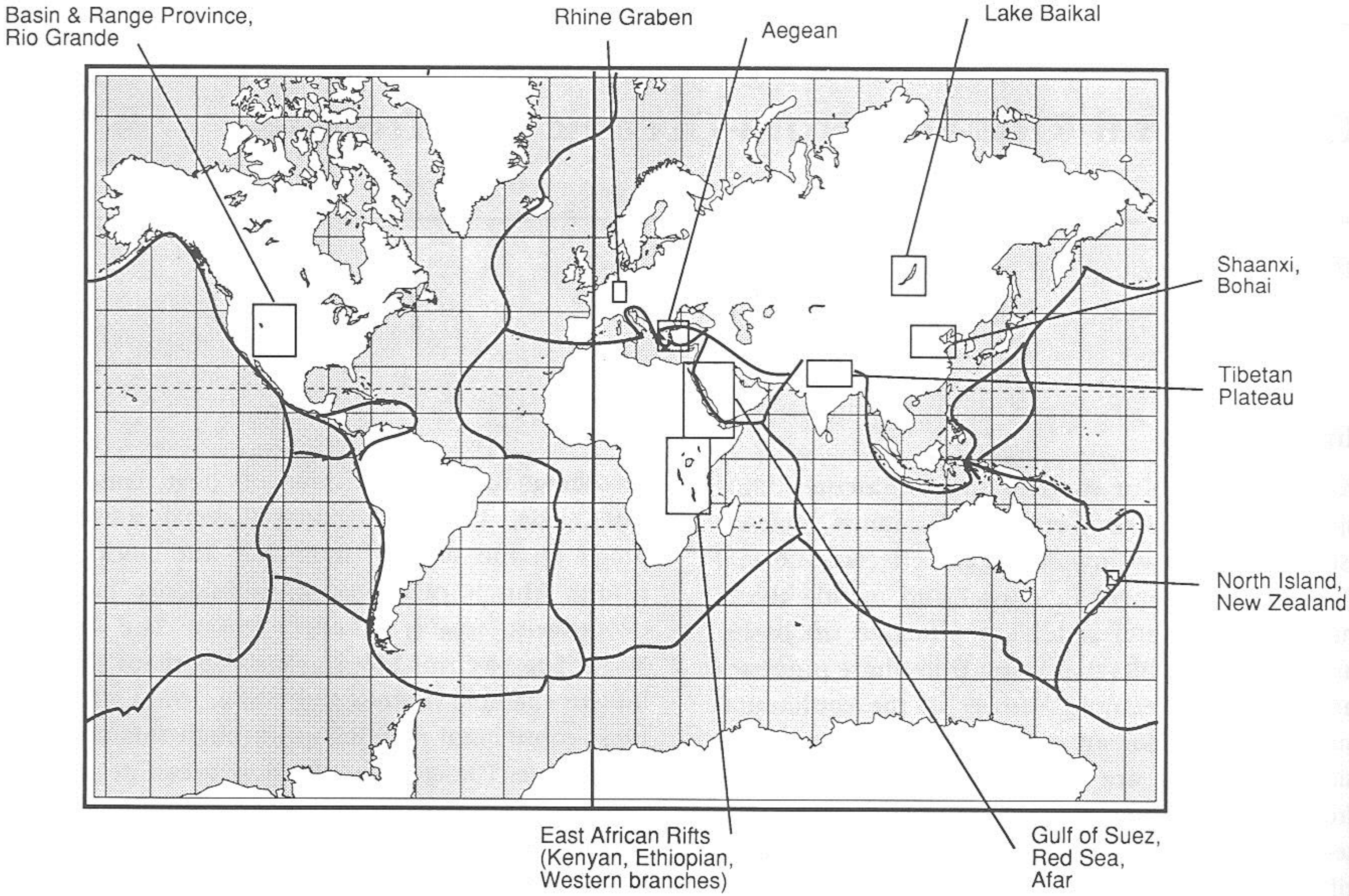


**Figure. 3.1** World map (Mercator projection) with plate boundaries (solid lines), to show main areas of active continental extension. (Also see Fig. 2.2.)

# PROSTÝ (SIMPLE) A ČISTÝ (PURE) STŘIH

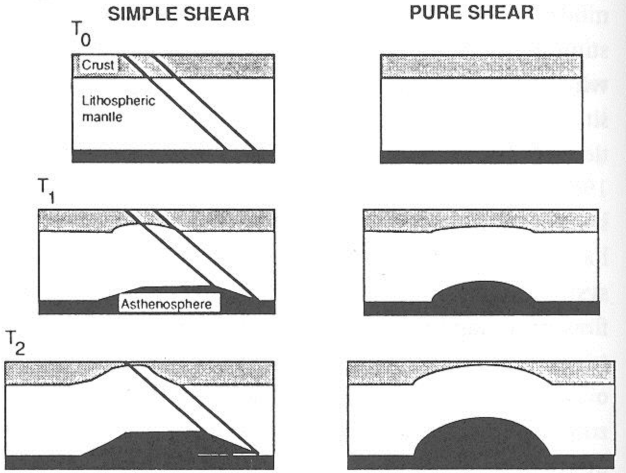


**Figure 3.16** Sketches to illustrate extension of layered lithosphere by simple shear and pure shear (after Buck et al., 1988). The inclined lines in the simple-shear case represent a shear zone. Note the obvious asymmetry in the simple shear case and the symmetry in the pure-shear case.

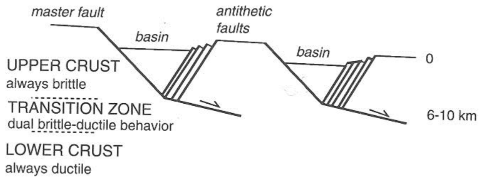


**Figure 3.12** Sketches to illustrate change from steeply dipping faults in the brittle upper crust into shallow-dipping faults in the ductile lower crust and the generation of steep antithetic faults that progressively nucleate at the discordance (after Eyidogan and Jackson, 1985). The antithetic faults are large in the seismic sense that they generate big earthquakes, but do not appreciably affect the regional tilt of the basement and the synrift sediments. The resultant symmetrical form of the basin and horst blocks is seen in several examples in both the Aegean and the Basin and Range (see Leeder and Jackson, 1993).

*1*

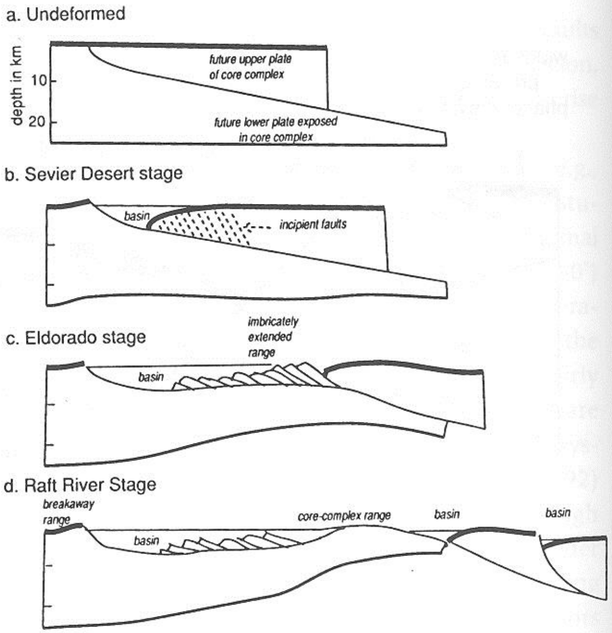


**Figure 3.15** Evolution of a crustal section being extended under a regime of simple shear, according to the model of Wernicke (1985). Note that in the footwall of the sinuous low-angle normal fault, lower-crustal rocks are eventually exposed, forming core complexes now widely recognized in the western United States and elsewhere. For an alternative model of simple-shear deformation, see Gans et al., (1985).

# Simple / pure shear
# tavení astenosféry

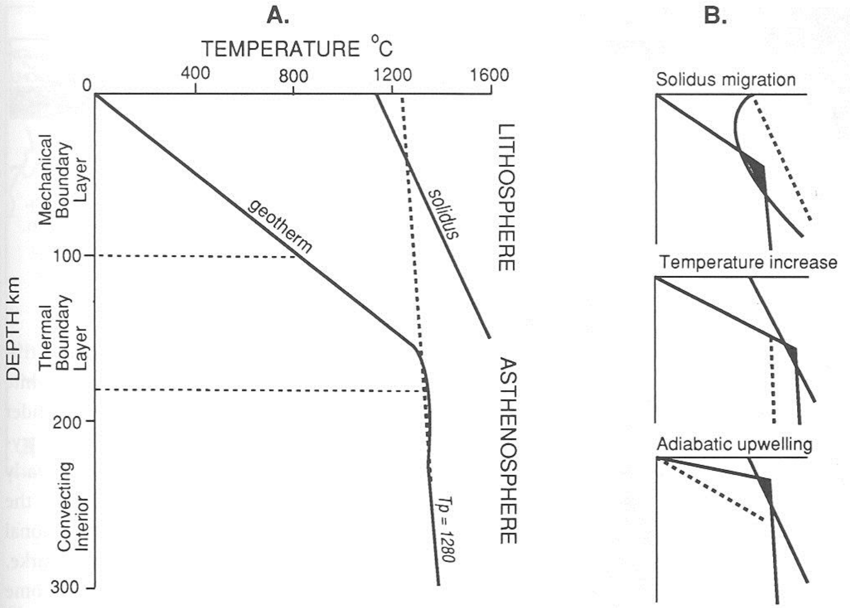


**Figure 3.4** Rifting and melting. A. Horizontally averaged thermal structure of lithosphere for potential temperature (Tp: the temperature on adiabatic gradient projected to surface pressure) of 1280°C, mechanical-boundary-layer (lithosphere) thickness of 100 km, and interior viscosity of $2.10^{17}$ $m^2$ $s^{-1}$ (after McKenzie and Bickle, 1988). B. Sketch graphs (after Latin et al., 1990) to summarize three possible mechanisms for producing melts during rifting from results of Fig. 3.4A. In B1, solidus migrates to left because volatiles like water are added to the system, as in island-arc environments. In B2, potential temperature is raised, causing geotherm to migrate to right, due to rising hot spot or plume (open-system melting). In B3, the lithosphere is thinned mechanically by closed-system stretching, with asthenosphere rising to be partially melted due to adiabatic decompression.

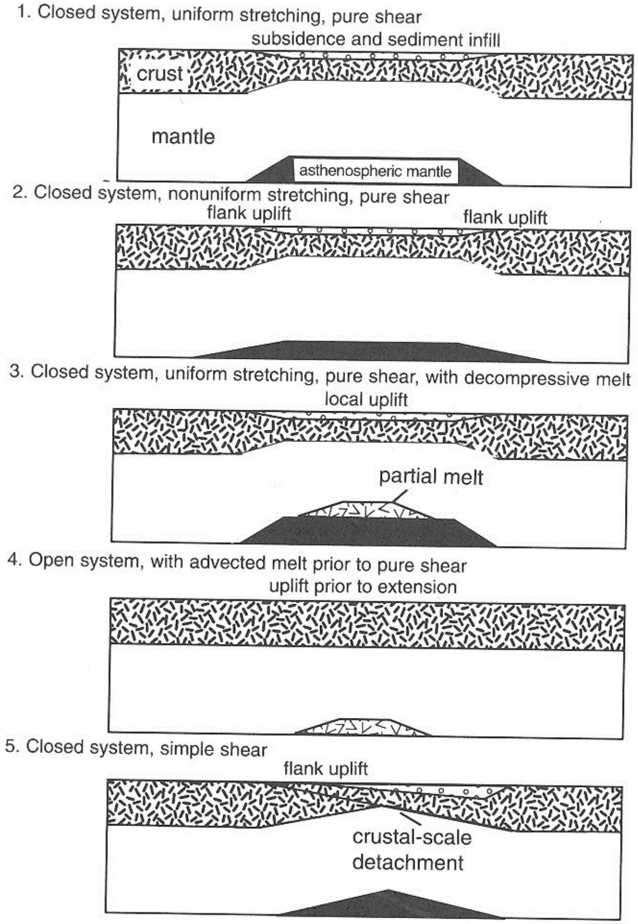
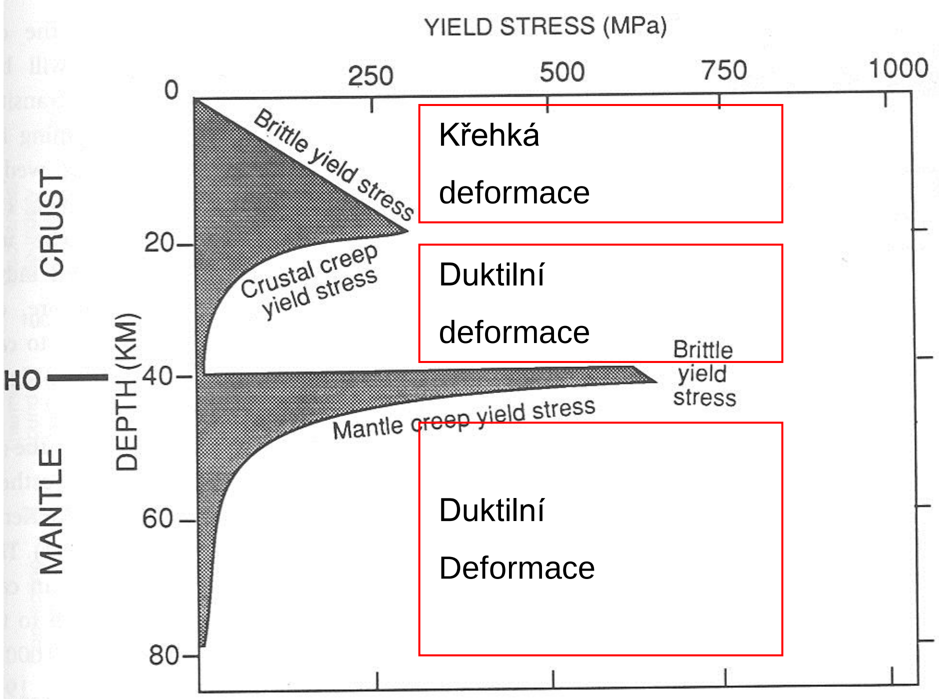

1. Closed system, uniform stretching, pure shear
2. Closed system, nonuniform stretching, pure shear
3. Closed system, uniform stretching, pure shear, with decompressive melt
4. Open system, with advected melt prior to pure shear
5. Closed system, simple shear

**Figure. 3.3** Schematic diagrams to illustrate possible combinations of pure and simple shear, uniform or nonuniform stretching and magma production. Local (Airy) isostatic compensation assumed throughout (i.e., lithosphere has small elastic thickness). Surface and upper-crustal deformation by faulting not shown.

# Mez deformace litosféry



Křehká

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**Figure. 3.2** Variation of strength (yield stress: heavy curve) with depth for lithosphere extending at $10^{-14}$ $sec^{-1}$ with heat flow of 42 mW $m^{-2}$ (after Lynch and Morgan, 1987). The integral of this profile over the full depth of the lithosphere is the total yield stress of the lithosphere. Creep rheologies are for 40 km-thick mafic-dominated crust and ultramafic mantle. Note two brittle-ductile transition zones, with brittle deformation at 0–19 and 40–42 km. Remaining areas flow by ductile-dislocation (power-law) creep. The lower crust in an extending regime behaves in ductile fashion and is assumed to be in a near-constant state of steady plane strain due to dislocation creep. Strain energy stored by brittle upper crust is then periodically released by fracture (causing stress drop) during earthquakes. Increase in the strain rate by a factor of 10 depresses creep curves and brittle-ductile transitions by about 4 km; vice versa for a decrease in strain rate. Brittle-ductile transition in the crust occurs at shallower depth for hotter lithosphere.

# Model prostého střihu na profilu litosférou

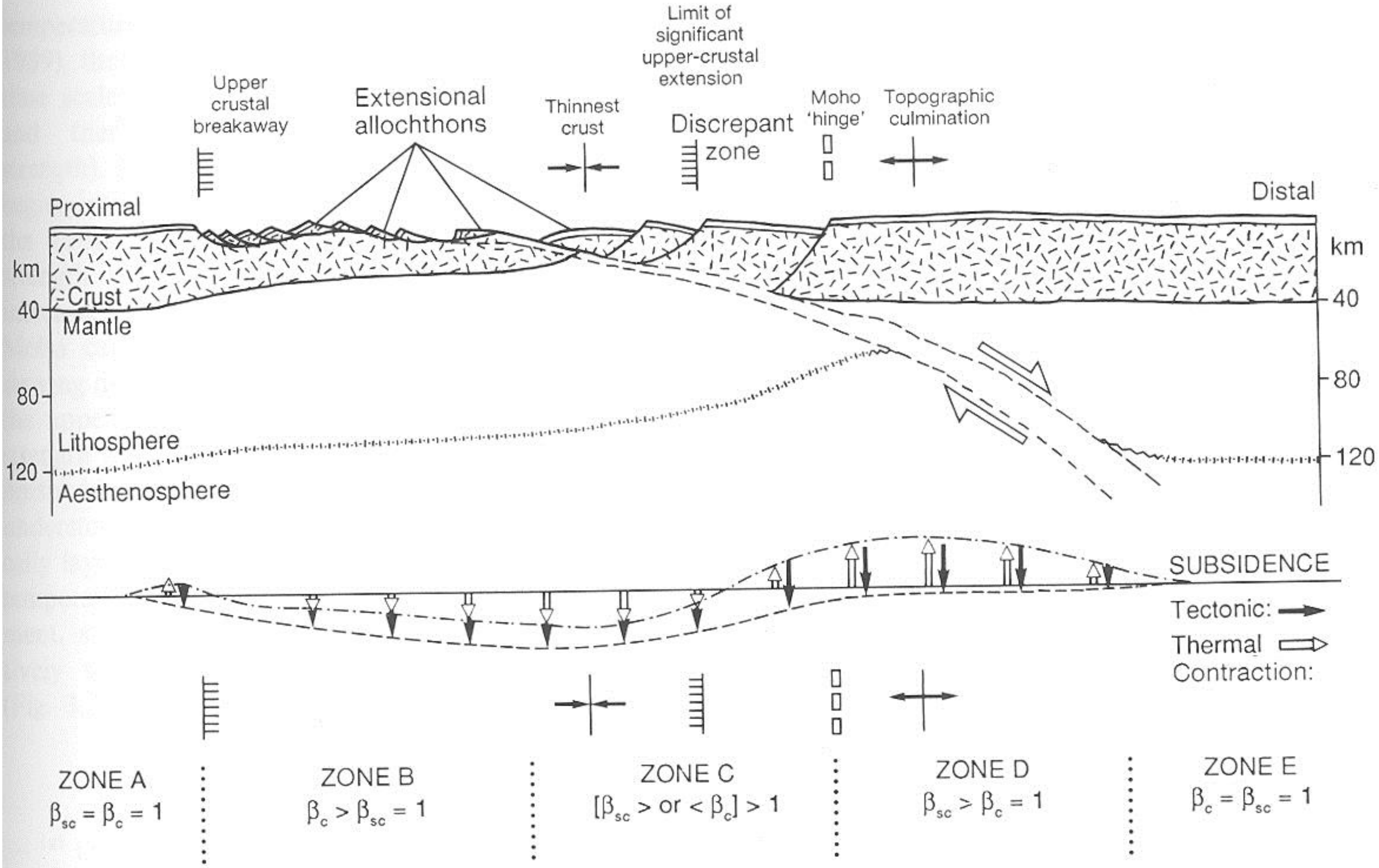


**Fig. 3.23.** The Wernicke model of normal simple shear of the entire lithosphere (after Wernicke 1985).

# Heterogenní ztenčení litosféry

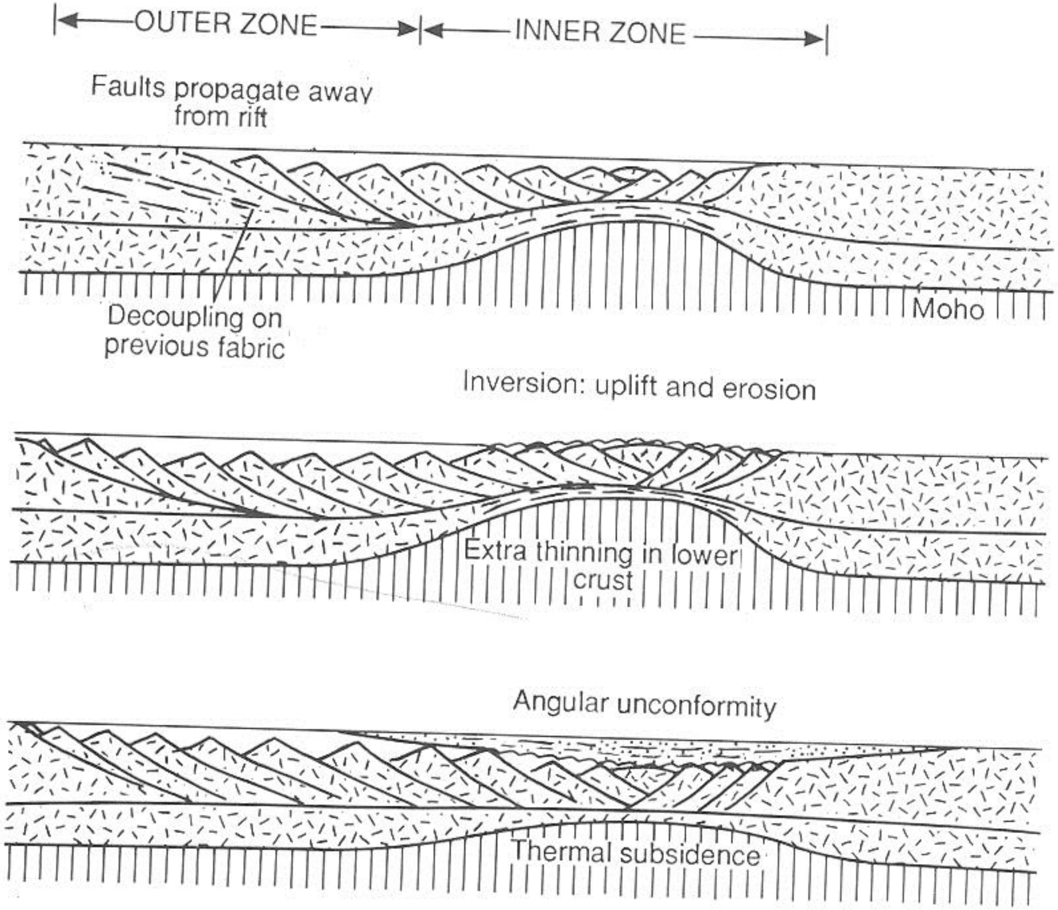


**Fig. 3.22.** Heterogeneous thinning of the lithosphere (after Coward 1986). The upper crustal extension spreads outwards asymmetrically over a wide region, possibly reactivating previous tectonic fabrics. The lower crust and subcrustal lithosphere, however, are shown extending over a much smaller region. This lower crustal/subcrustal thinning may produce thermal domes and erosional unconformities and older extensional faults may be inverted.

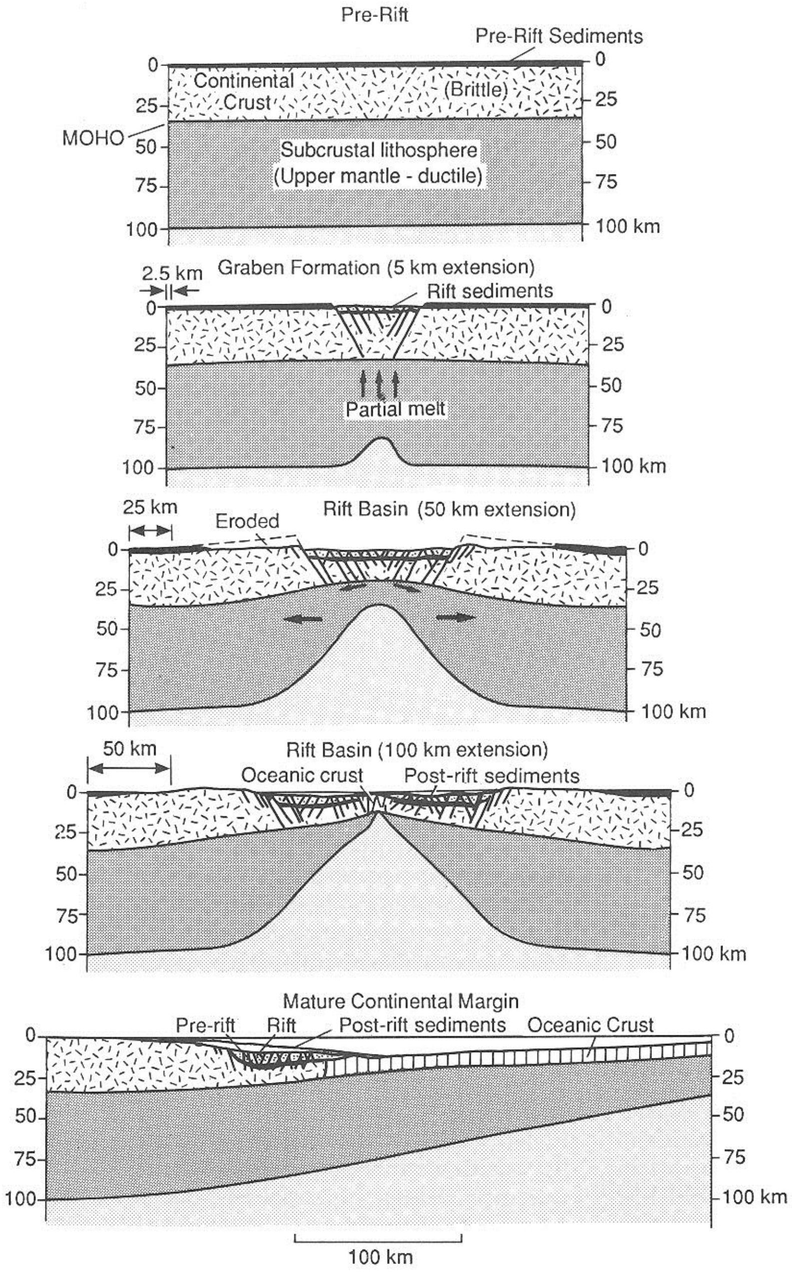
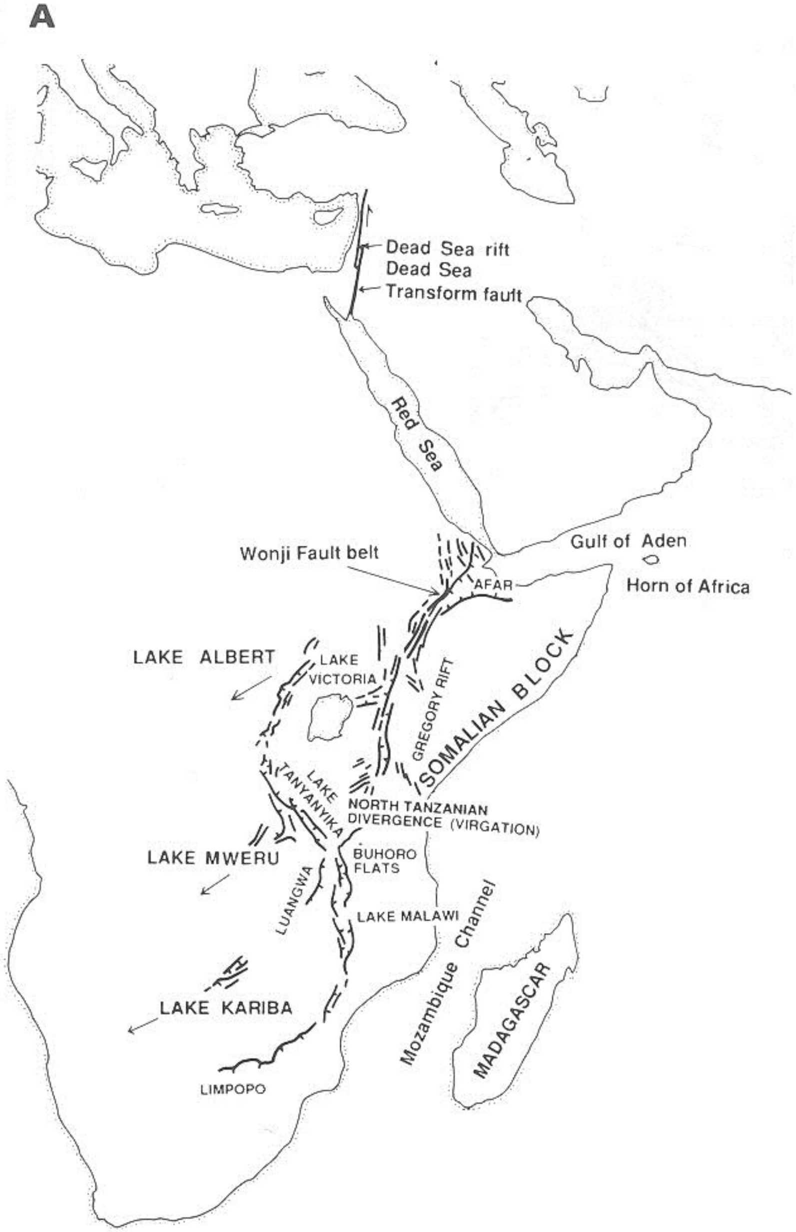


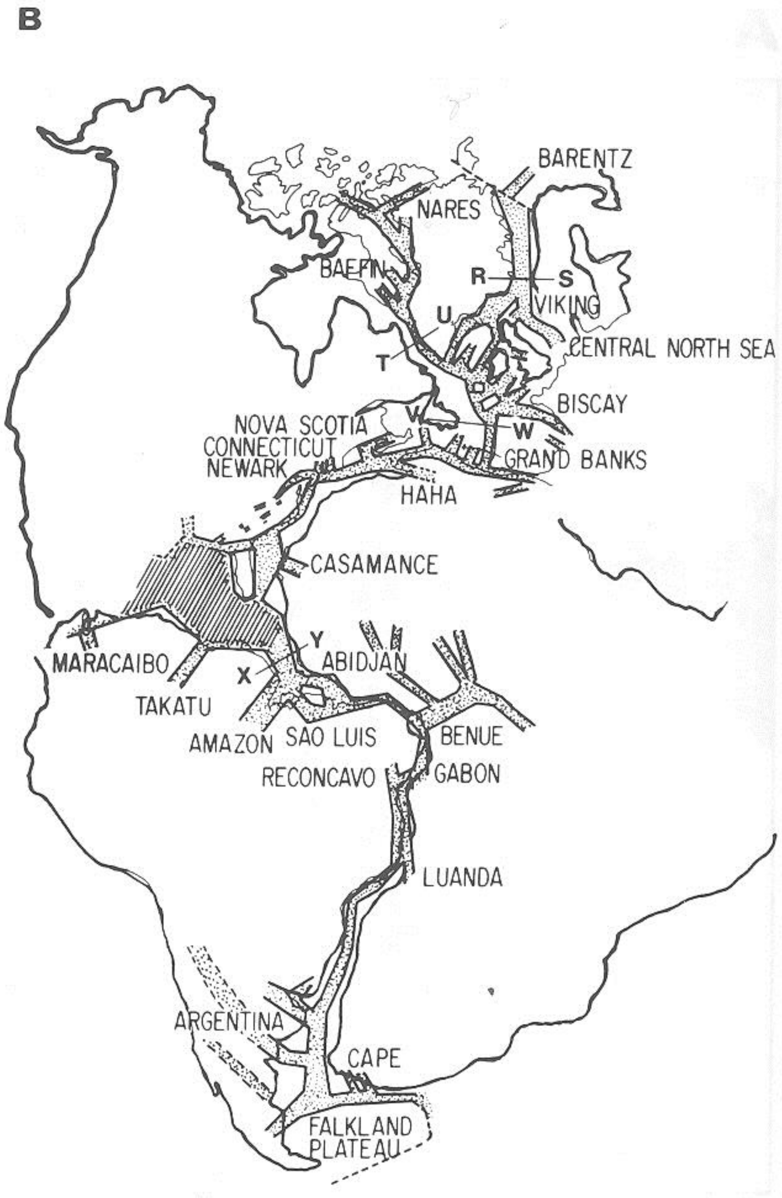
**Fig. 3.8.** Diagrammatic model of rift basin evolution following Salveson (1978). Tensional stresses causes the continental crust to fail by brittle fracture, whereas the mantle lithosphere fails by ductile necking. The formation of a sediment-filled graben causes isostatic disequilibrium and the compensating rise of the aesthenosphere; this leads to regional uplift. Partial melting of mantle promotes surface volcanism and an upward transfer of heat. The uplifted rift shoulders become eroded and the rift continues to fill with sediment. Eventually, as crustal extension continues, oceanic crust is created and the continent starts to cool as extension is transferred to the oceanic realm and a passive margin develops. Post-rift sediments drape the syn-rift fill and spread onto the newly created ocean floor.

**Fig. 3.1.** The volcanic provinces and sites of rifting in the African continent. The black areas represent regions with volcanic rocks with ages of less than 26 Ma. Large domal uplifts such as the Ethiopian and East African Swells are characterized by well-developed rifts. Smaller uplifts such as the Tibesti and Hoggar examples have volcanic activity but lack rifts.

# Východoafrický riftový systém



# Mrtvé rifty na okraji atlantického oceánu



# Trojné body a vznik aulakogénu (mrtvého riftu)

**Deskově-tektonické procesy vedoucí ke vzniku aulakogénů**

**A-C-D: riftové vyklenutí**

**B-C-D: tvorba aulakogénu pomocí „membránového“ stresu**

**E-F-G: opuštění riftu podél transformního zlomu**

**H-I: rifty vznikající v prostředí strike-slipu**

**J-K: rotace kontinentů**

**Trojný bod v nadloží plášťového chocholu a vznik aulakogénu:**

**Sekvence: vyklenutí-rift-drift**

**A: výzdvih, alkalické vulkanity**

**B: tři riftová údolí (rrr trojný bod)**

**C: dvě ramena se spojí do deskového rozhraní, třetí rameno zůstane inaktivní**

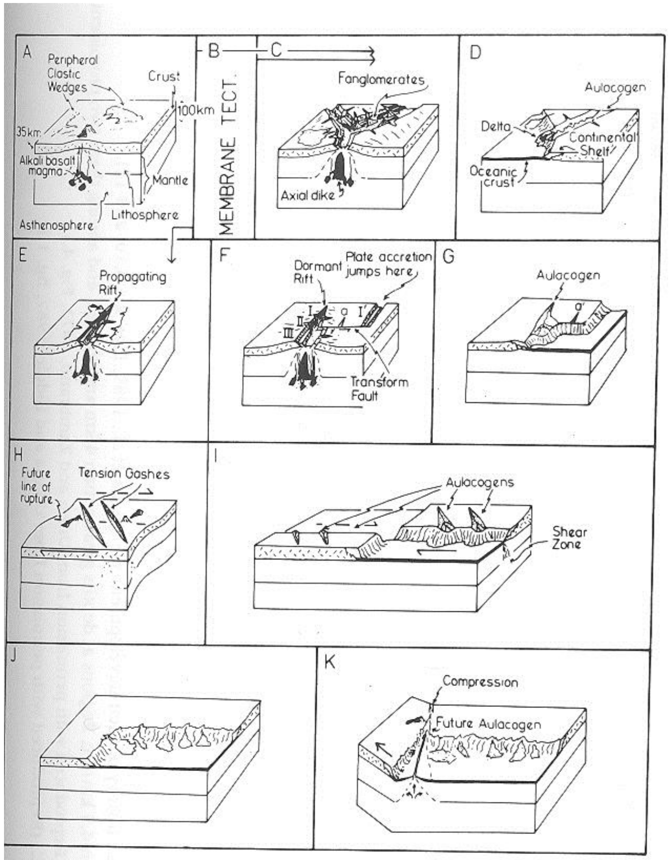


**Figure 2.11** Schematic block diagrams illustrating most significant and best documented plate-tectonic processes that lead to formation of aulacogens (reproduced with permission from Şengör, 1987a, fig. 1). **A-C-D**: Doming-rifting-drifting hypothesis (see also fig. 2.13); **B-C-D**: Hypothesis of aulacogen formation through "membrane stresses" (see also fig. 2.16); **E-F-G**: Rift-tip-abandonment hypothesis; **H-I**: Strike-slip-related secondary-extension hypothesis; **J-K**: Continental-rotation hypothesis. See text for discussion and other hypotheses.

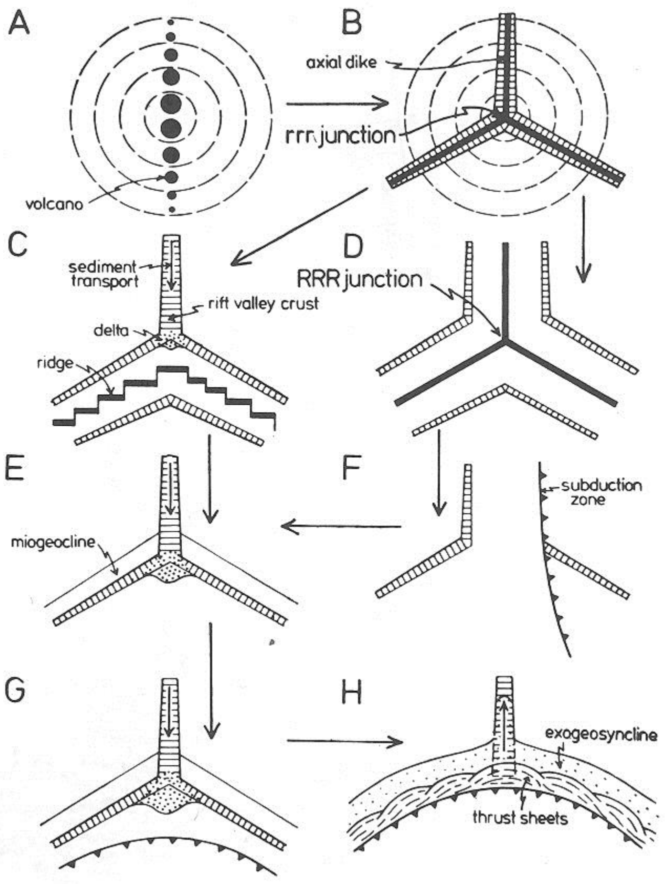


**Figure 2.12** Schematic origin and evolution of mantle-plume-generated triple junctions, leading to doming-rifting-drifting sequence creating oceans and aulacogens (from Burke and Dewey, 1973, Fig. 2, reproduced with permission). **A.** Uplift develops over plume with crestal alkalic volcanoes; **B.** Three rift valleys develop at an rrr (rift-rift-rift) junction (e.g., Nakuru: see Fig. 2.6A); **C.** Two rift arms develop into a single plate margin (ridge) and continental separation ensues, leaving third rift arm as an

# Aulakogén

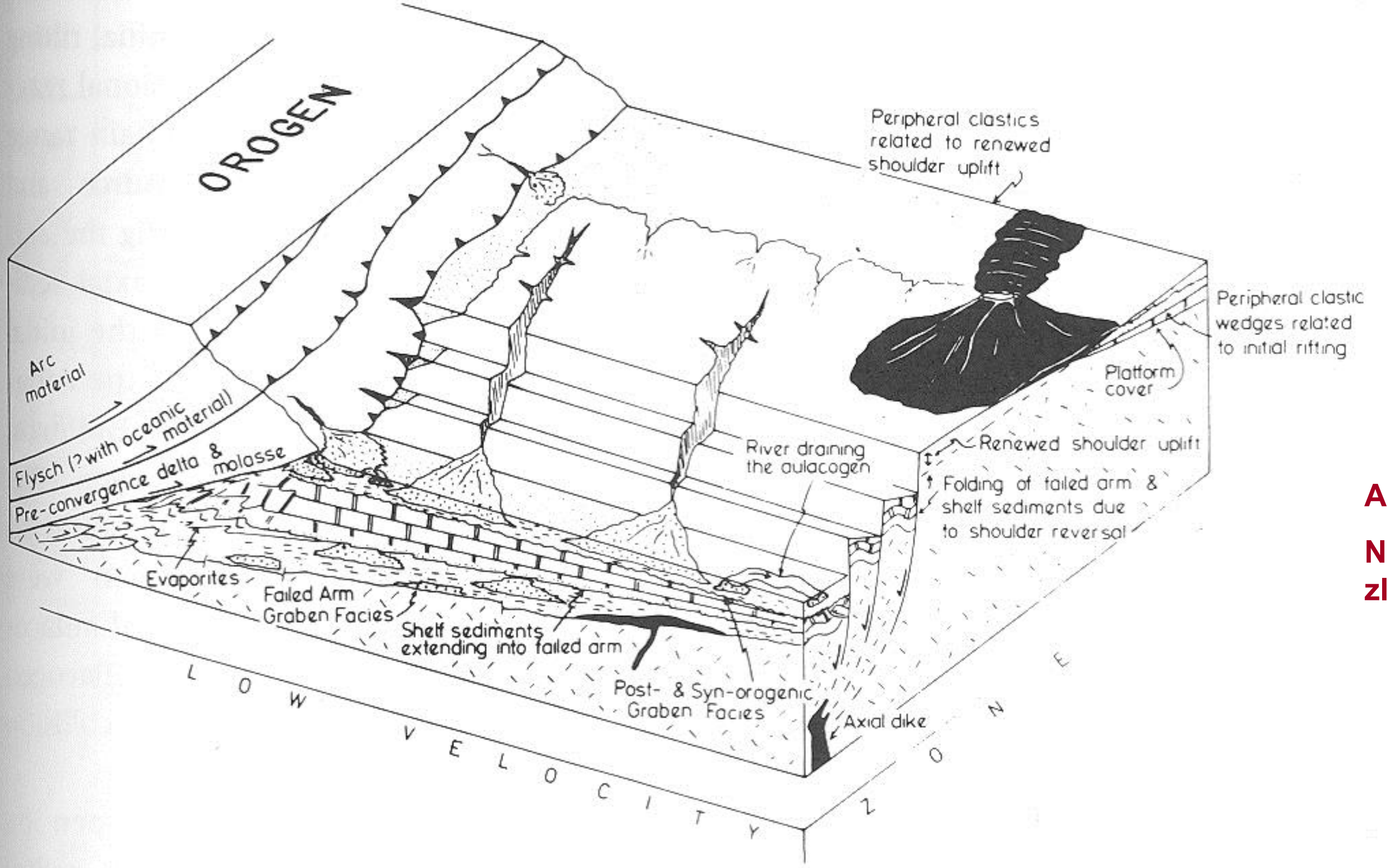


**Figure 2.19** Idealized schematic diagram illustrating anatomy of an aulacogen. Subaerial erosion is ignored to emphasize structure and reactivation is assumed to revitalize original faults to keep diagram simple. See text for discussion. (Reproduced with permission from Şengör, 1987a, Fig. 4.)

**Anatomie aulakogénu:**

**Násun orogénu reaktivuje zlomy mrtvého riftu**

# Aulakogény (mrtvé rifty) vs. impaktogóny (kolizní rifty)

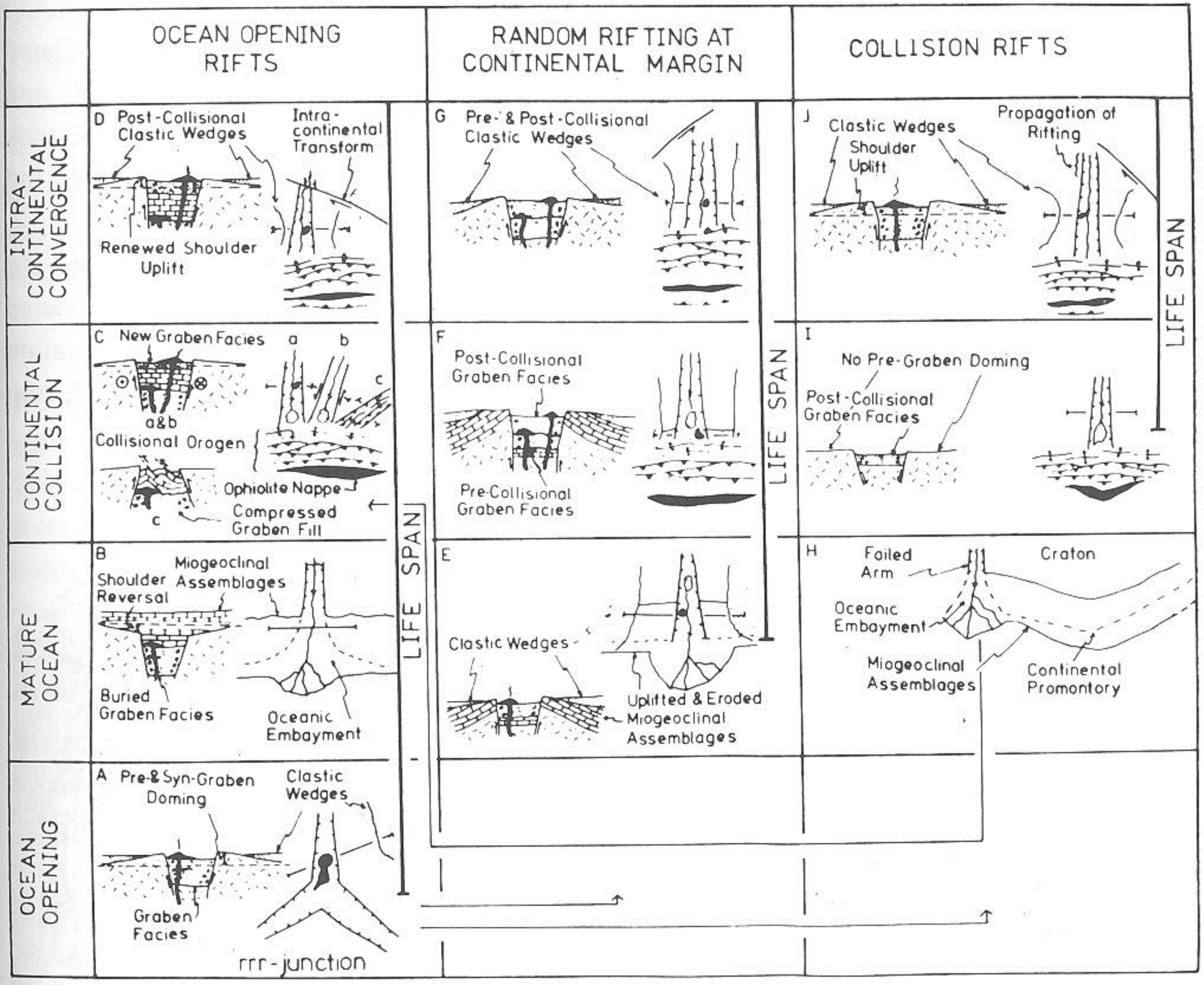


**Figure 2.21** A schematic illustration of events during origin and evolution of an aulacogen (**A-D**), a random rift at high angle to a continental margin (**E-G**), and an impactogen. Cross sections show expected differences in stratigraphic evolution of three kinds of "high angle" rifts. Note that in **C**, three differently trending aulacogens, with respect to their related continental margin, are illustrated to show varied response they display to collision (ranging from re-rifting at **Ca** to compression across axis at **Cc**; reproduced with permission from Şengör et al., 1978, Fig. 1).

**Vznik a vývoj aulakogénu (A-D), náhodného riftu pod vysokým úhlem vzhledem ke kontinentálnímu okraji (E-G) a impaktogénu (H-J)**

# kolizní rift

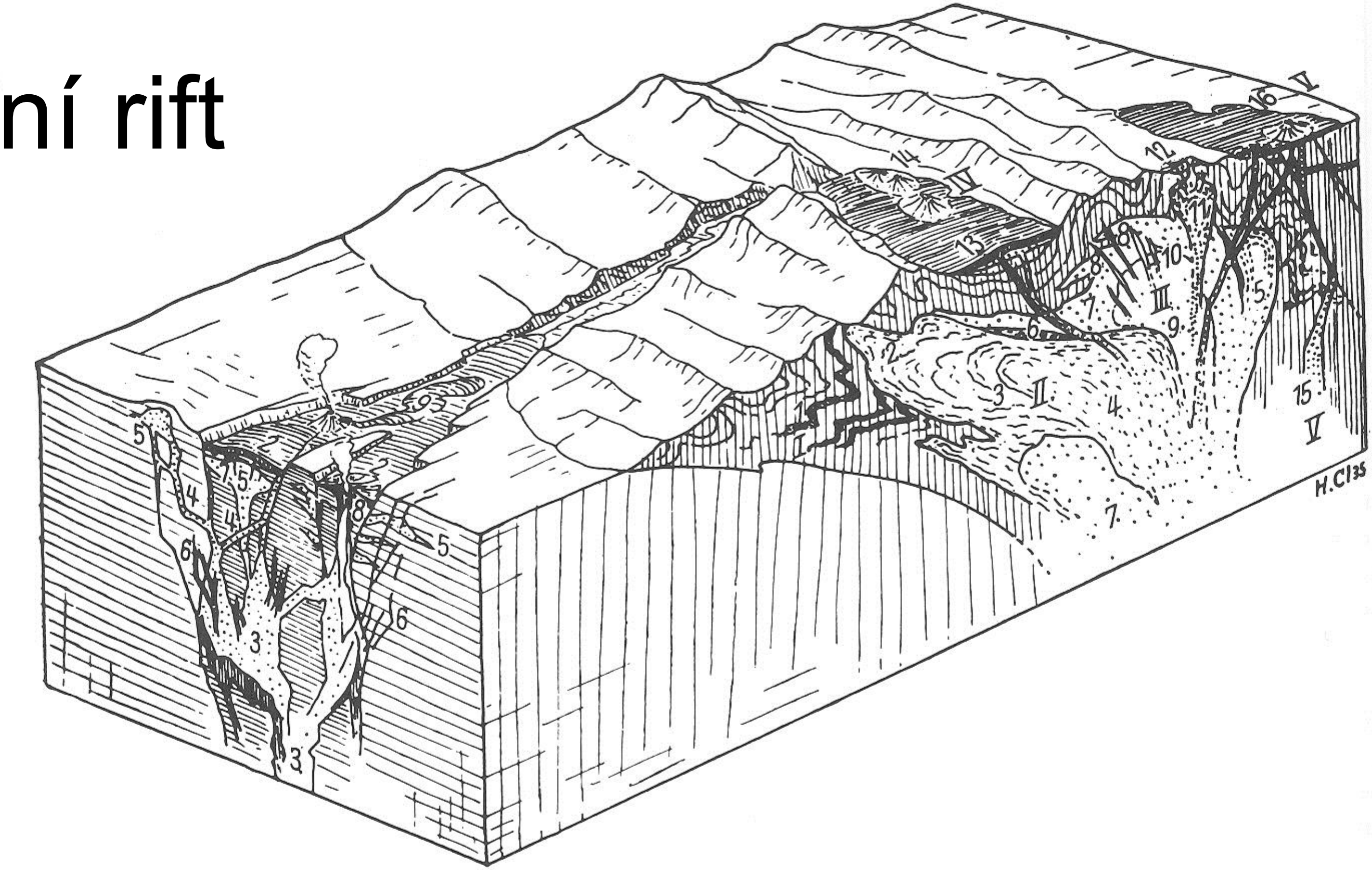


**Figure 2.22** A collision-related rift, as illustrated by Cloos (1936, Fig. 120, reproduced with permission) to illustrate related magmatism (Cloos' interpretation of the origin of the rift was different, as explained in text, but the way he drew the orogen and the rift speaks for itself!). Key to numbers (all italicized annotations are mine): Left: Alkalic rocks in regions of extension: 1. Mafic parent at depth; 2. Mafic parent at surface; 3. Intermediate and felsic melts in branched plutons; 4, 5. Intermediate and felsic melts in dikes and subvolcanic plutons; 6,7. Late melts, mainly mafic, at depth and in shallow dikes; 8,9. Late melts, mainly mafic, in volcanoes and lava flows. Right: Alkalic rocks in folded mountains: I. 1. Mafic and ultramafic early melts at bottom of geosyncline (ophiolites, diabases, etc.) (*we now know that ophiolites are floor remnants of vanished oceans and they include diabase here separated by Cloos!*); II. 5. Intermediate and felsic plutons of first, concordant, synorogenic main magmatism (*i.e., calc-alkalic arc-related magmatism in our present terminology*); III. 6. Mafic early magmas; 7,8,9. Intermediate and felsic plutons of second, discordant, late-orogenic main magmatism (*i.e., calc-alkalic late arc and collision-related magmatism in our present terminology*); 10. Late dikes; 11,12. Late-orogenic subvolcanic plutons and volcanoes (*post-collisional i.e., Tibetan, and/or pre-collisional i.e., Altiplano-type plateau magmatism*); IV. 13,14. Post-orogenic magmatism in intramontane basins (*e.g., in Eastern Turkey: see Pearce et al., 1990; Yılmaz, 1990*); V. 15, 16 Postorogenic magmatism in the hinterland, partly becoming alkalic (*"orogenic collapse" magmatism: cf., Lorenz and Nicholls, 1976*).

# Hornorýnský prolom (impaktogén)

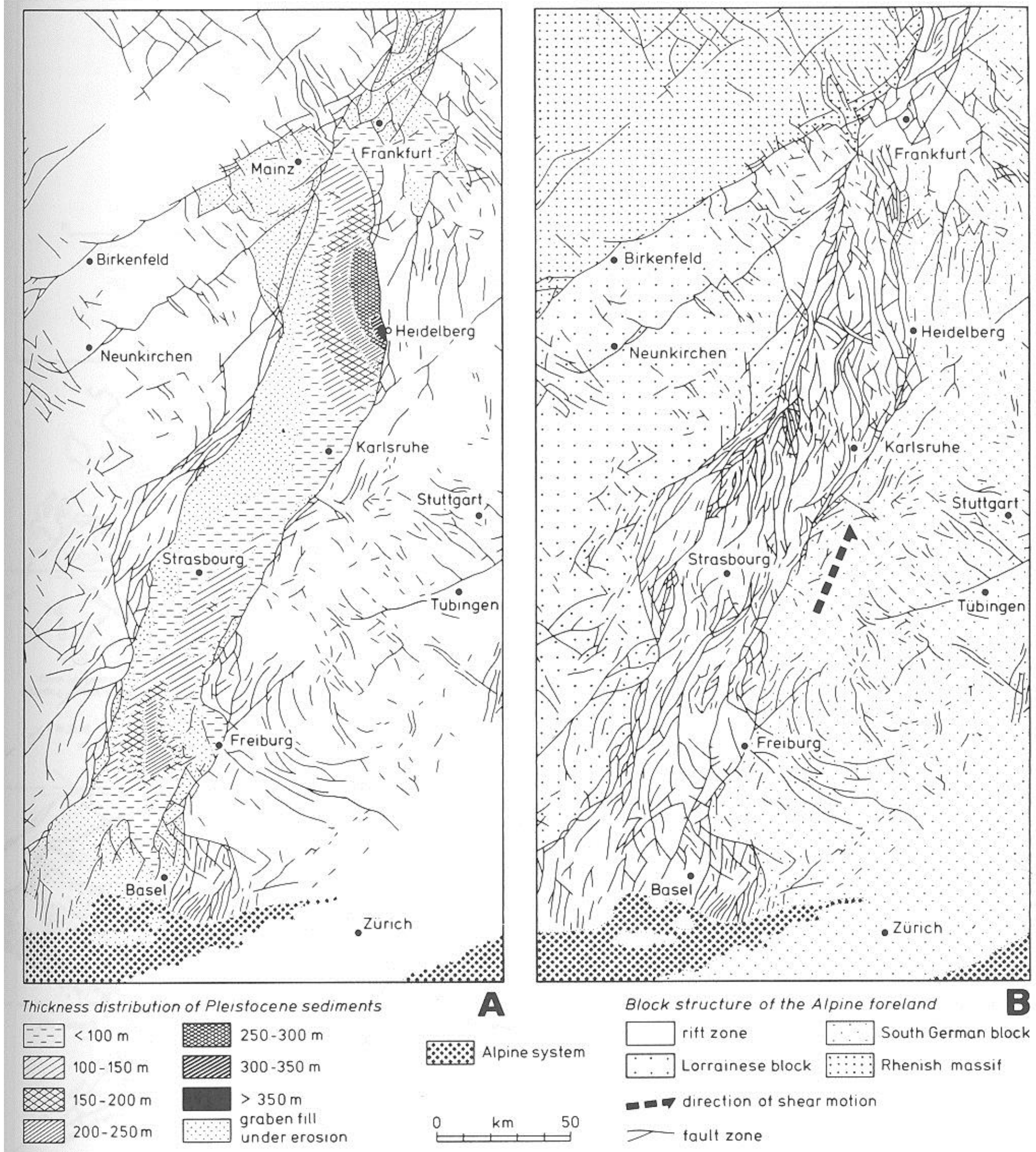


**Figure 2.9** The type impactogen, the Upper Rhine rift. **A.** Distribution of Pleistocene sediments outline modern Upper Rhine rift, and their thicknesses give an idea of activity of rift during Quaternary. (Reproduced with permission from Illies and Greiner, 1978, Fig. 7.) **B.** Modern Rhine rift is functioning as a sinistral strike-slip zone with local shortening in its middle segment, and extension in south and in north. This map illustrates distribution of Quaternary faults. (Reproduced with permission from Illies and Greiner, 1978, Fig. 7.)

**Typový impaktogén:**

**Hornorýnský prolom**

**A: distribuce pleistocénních sedimentů**

**B: převaha levostranných posunů, extenze na jihu a severu**

# Symetrický a asymetrický (half-) graben

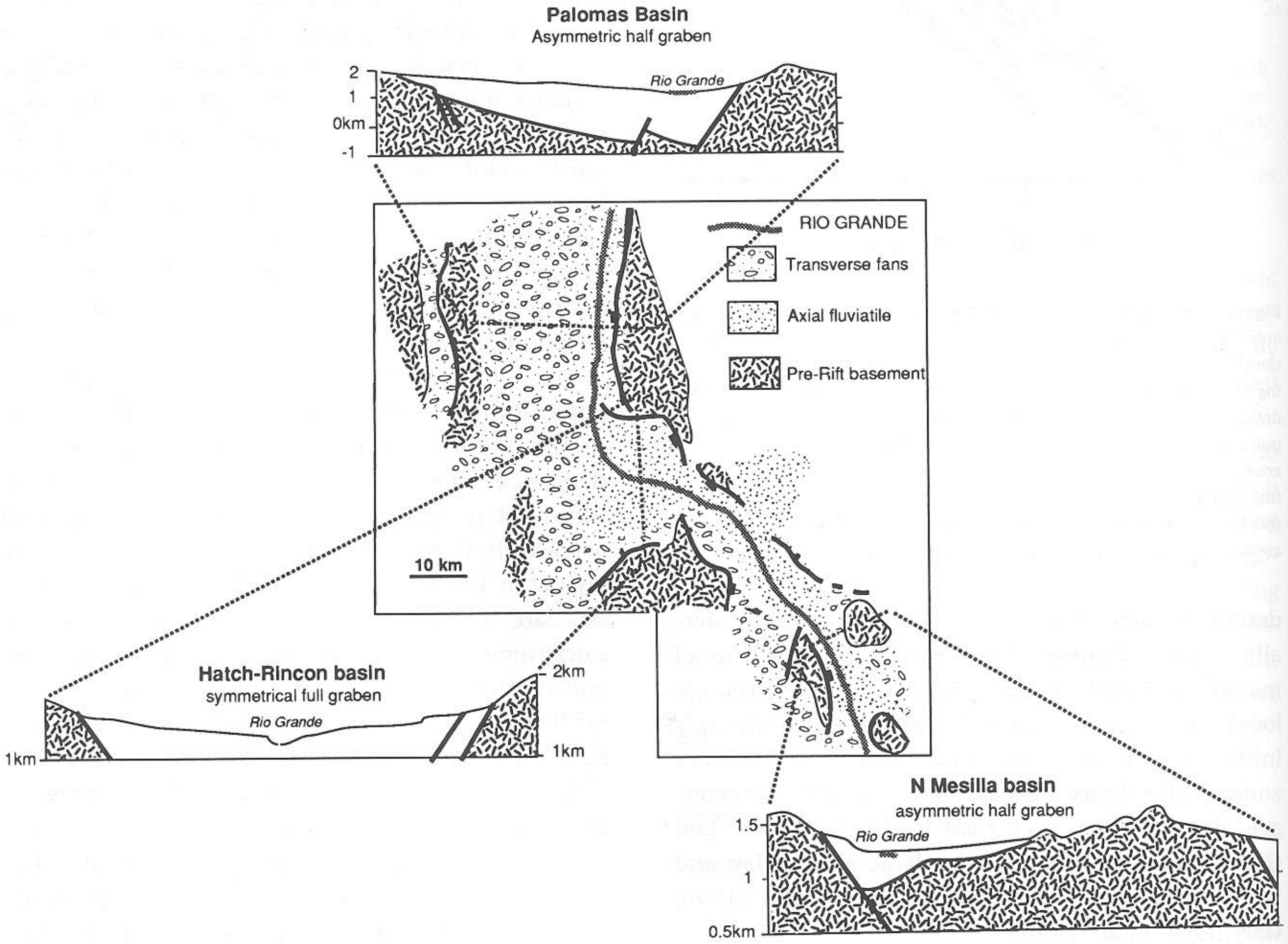


**Figure 3.29** Southern Rio Grande rift north of Las Cruces, New Mexico: a field test for alluvial architectural models (simplified after figures in Mack and Seager, 1990). In the asymmetrical Palomas and North Mesilla basins, the axial fluvial facies is characterized by multistorey channel sand and is concentrated near the locus of maximum subsidence within a few kilometers of the footwall scarp. Fanglomerates derived from the footwall drainage basins extend only a few kilometers or less from the scarp, whereas alluvial-fan facies deposited on the hanging-wall dipslope occupy a much wider outcrop belt. In the symmetrical Hatch-Rincon basin, the axial-fluvial facies extends to within a few kilometers of both the northern and southern basin margins, indicating that the axial channels could migrate uncontrolled by tectonic bias. There is also a much higher percentage of fine-grained overbank deposits separating the channel facies, some of which contain calcareous paleosols.

# Klastická sedimentace na half-grabenu

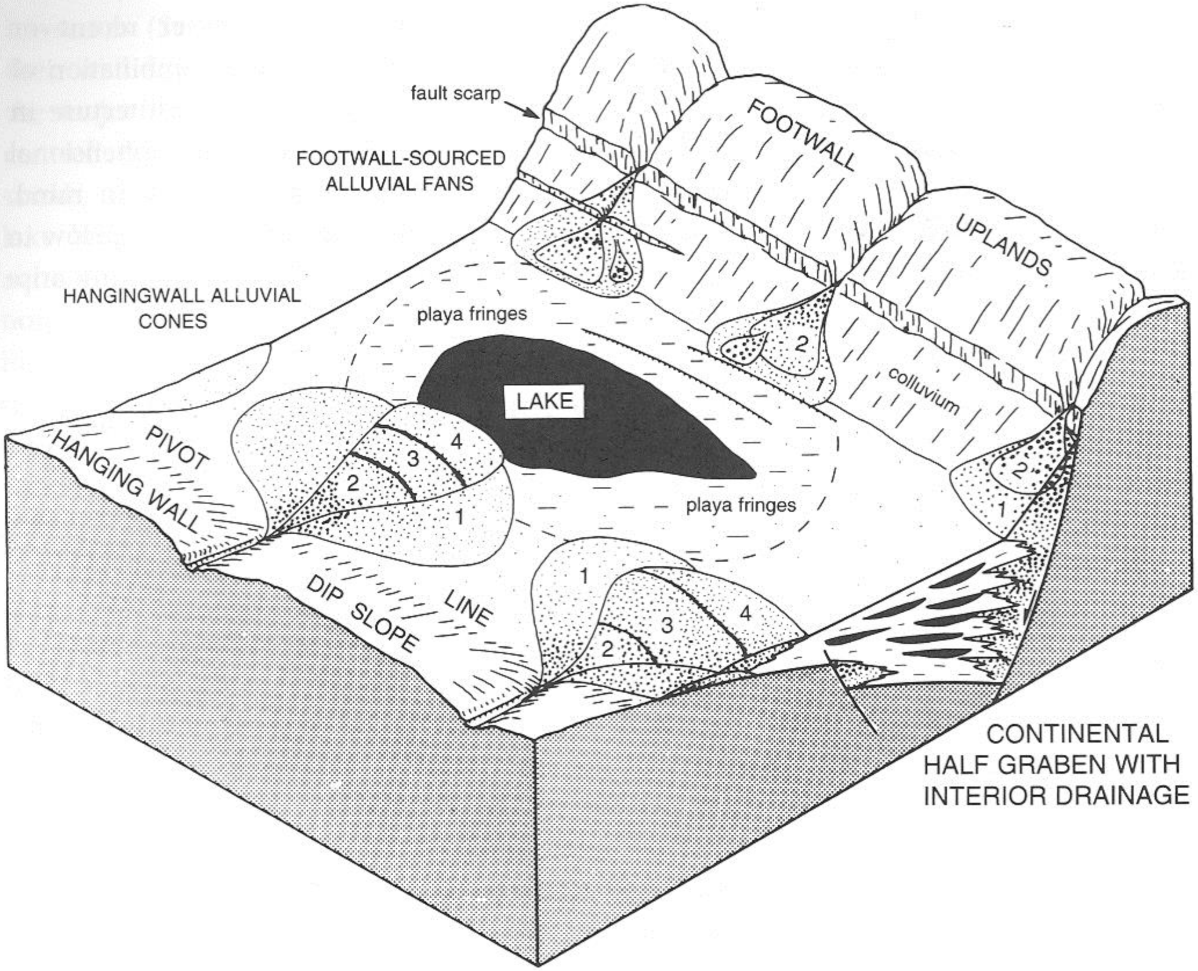


**Figure 3.32** Block diagram to summarize the major clastic environments present in closed continental half grabens with interior drainage (after Leeder and Gawthorpe, 1987).

# Karbonátová sedimentace na half-grabenu

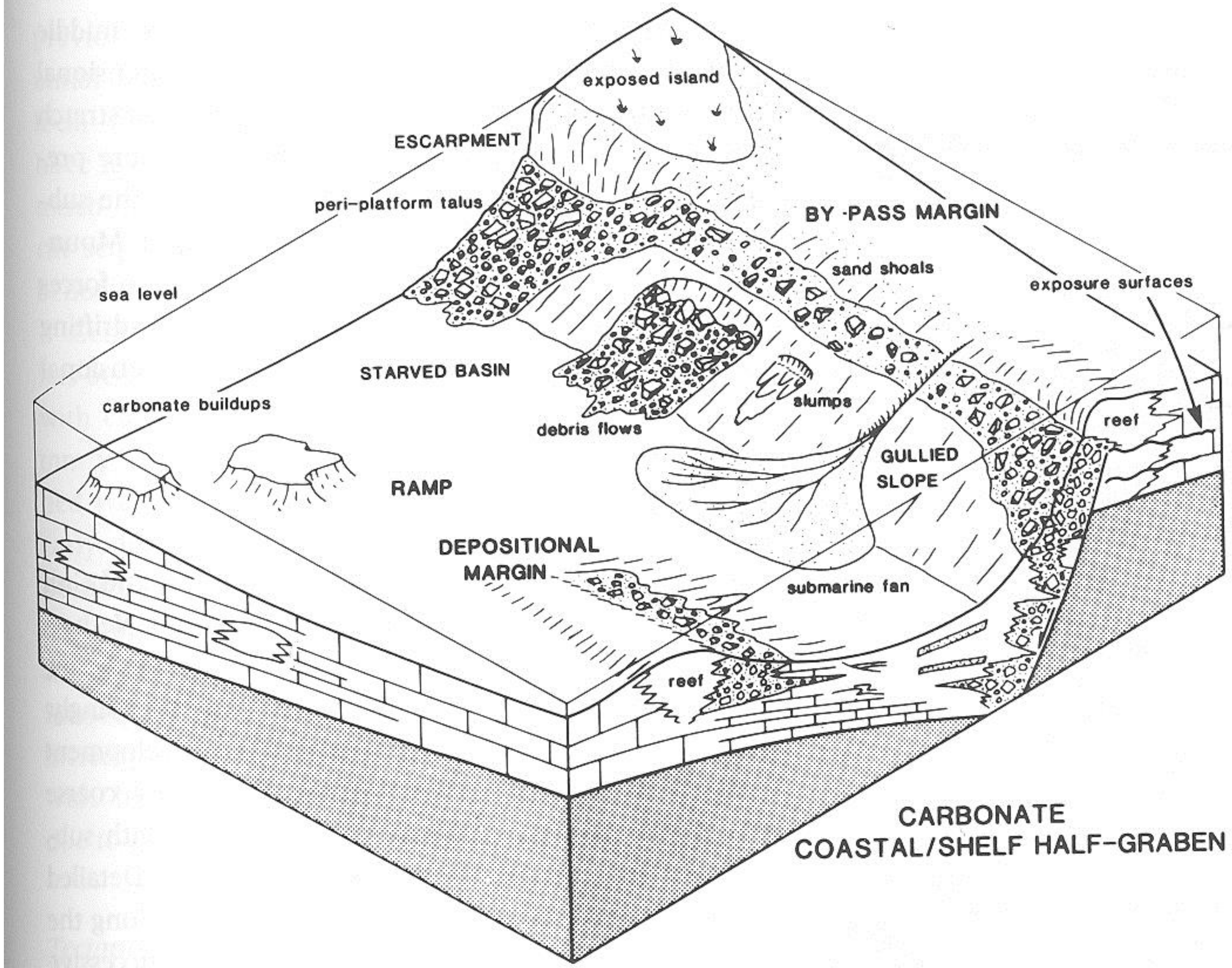


**Figure 3.36** Block diagram summarizing the major carbonate environments present in coastal/shelf half grabens (after Leeder and Gawthorpe, 1987).

# Pasivní okraj

- **synriftová fáze** - izostatická subsidence, half-grabeny, sedimentární klíny, vhodné klima - evapority (mexický záliv, východoafrický rift)

  **diskordance**
- **raná postriftová fáze** - termální subsidence, klastická sedimentace na ramenech dřívějšího riftu
- **pozdní postriftová fáze** - termální subsidence plus flexurální subsidence, velké mocnosti sedimentu - klastika, karbonáty

- **model subsidence**
  - pokračování riftingu, opakování riftingu – tektonická subsidence
  - termální subsidence
  - flexurální průhyb v důsledku zatížení sedimentem
  - příklady subsidenčních křivek

# Pasivní okraj

- **typy kontinentálních okrajů a sedimenty**
- **upbuilding** - agradace
- **outbuilding** - progradace - posun depocentra směrem do oceánu
- postriftové sedimenty

- Faciální modely
- facie příbřežních plošin
- příbřežní facie (přílivové plošiny, bariérové ostrovy)
- šelfové facie (tidální šelfy, bouřkové šelfy, zaříznutá údolí, kondenzační horizonty, říční delty)
- karbonátové systémy (lemové a izolované platformy)
- svahové facie (skluzy, úlomkotoky, svahový osyp, podmořské kaňony), karbonátové svahy - osypy, mud mounds
- facie úpatí (turbidity, podmořské vějíře - největší systémy Amazon, Mississippi, Rhóna, konturity), karbonátové systémy - osypy, malé vějíře, pelagické karbonáty
- kontinentální terasy - Blake Plateau
- jílové diapiry (mud diapirs)
- solná tektonika
- citlivě reagují na změny mořské hladiny

# Pasivní kontinentální okraje (Passive continental margins)

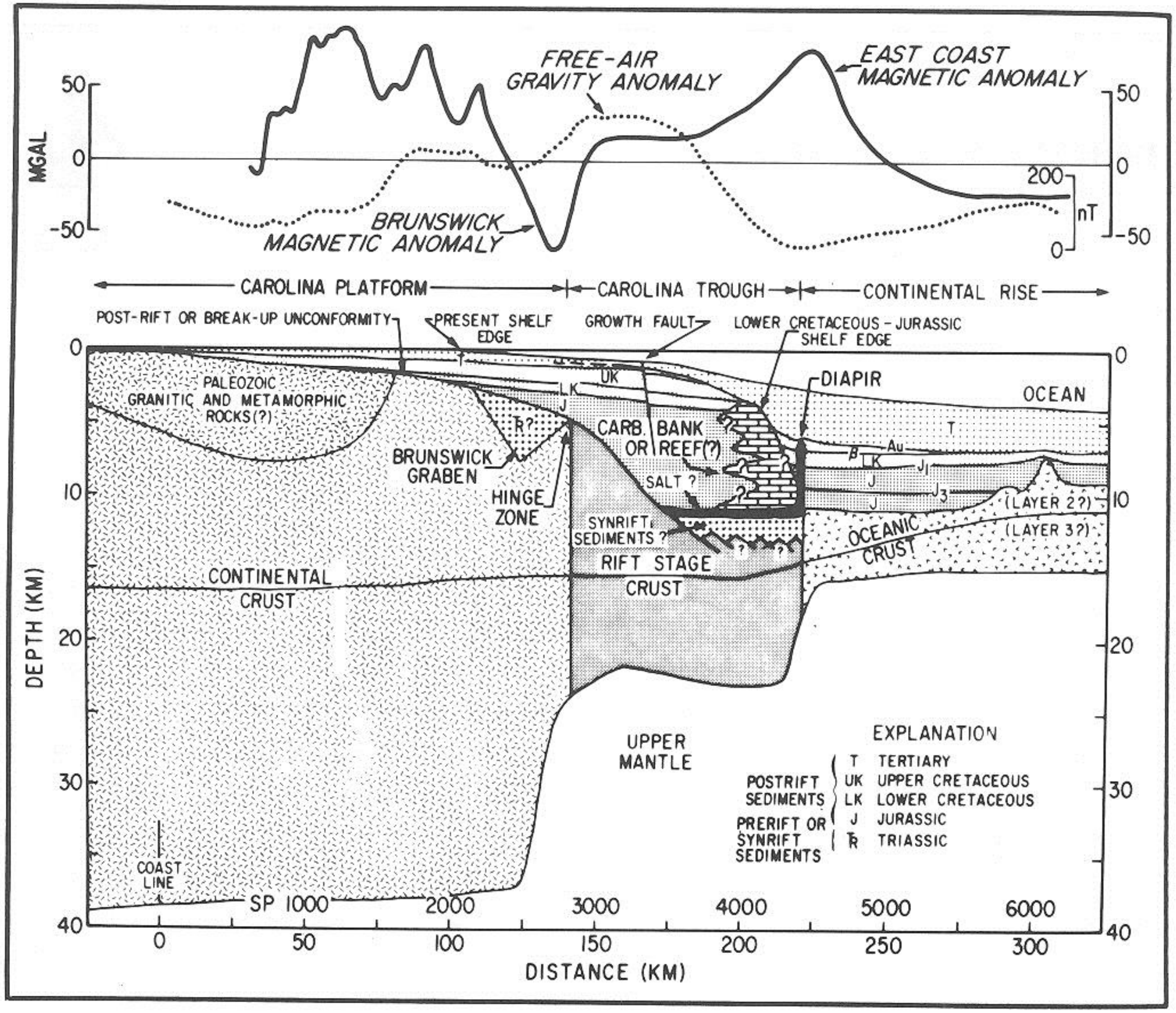
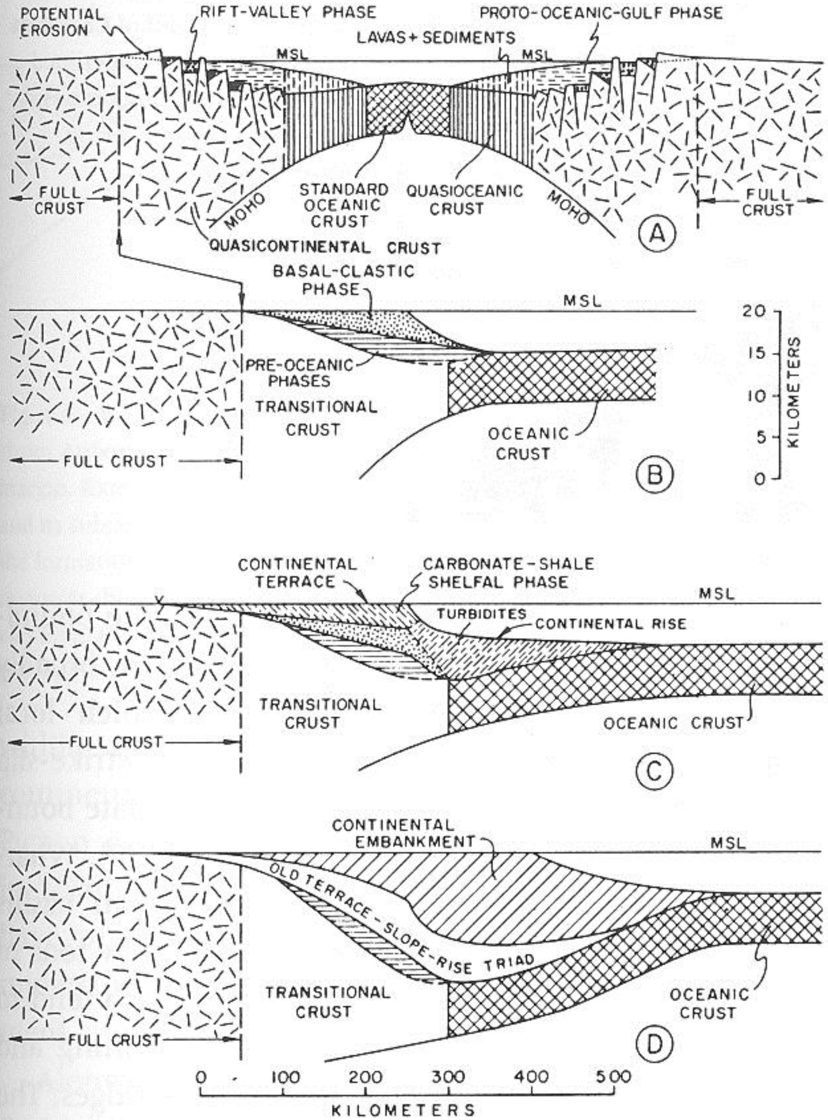


**Fig. 4.1** Cross section of modern passive margin off coast of North Carolina (Hutchinson et al., 1982). Rift stage crust is equivalent to transitional crust of Dickinson (1976a). SP refers to shot point.

*Continental Terraces and Rises Facing Obliquely: Opening*

# Pasivní kontinentální okraj



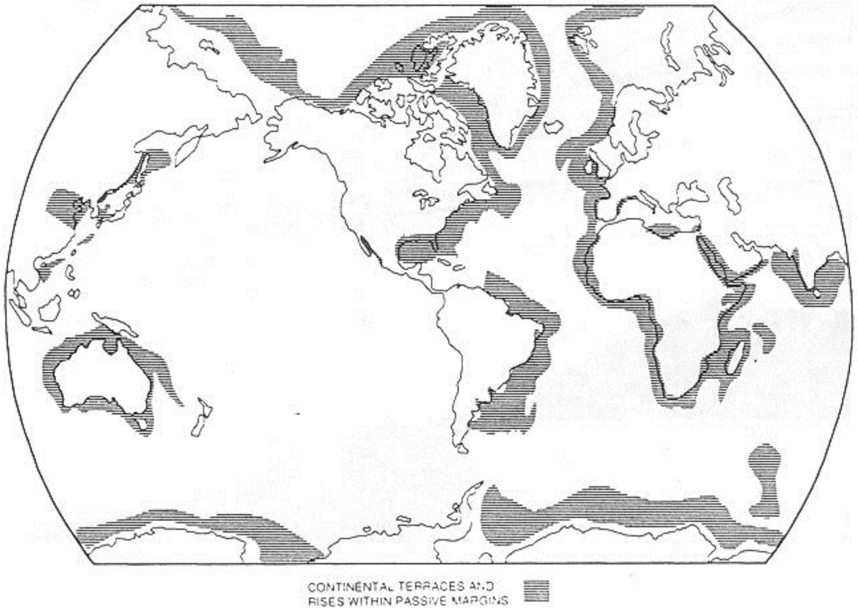


**Fig. 4.3** Distribution of continental terraces and rises, showing mainly those that face orthogonally opening ocean basins and that formed during breakup of Pangea (from Bally, 1979; Jolivet et al., 1989; Channell et al., 1991). Large segments of Cenozoic-Mesozoic (CZ-MZ) active margins also contain continental terraces and rises, especially in the western Pacific and in the Mediterranean. A system of continental terraces and rises also occurs in the obliquely opening Gulf of California.

influenced by motion along the transform boundary long after continental separation.

*Continental Terraces And Rises Facing*

# Rotace krustálních bloků

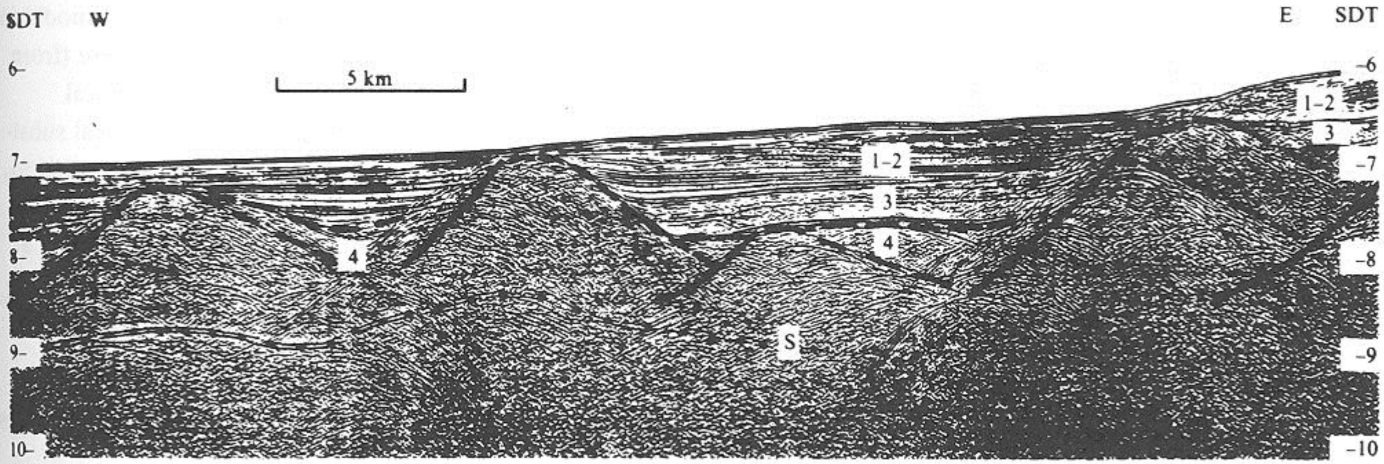
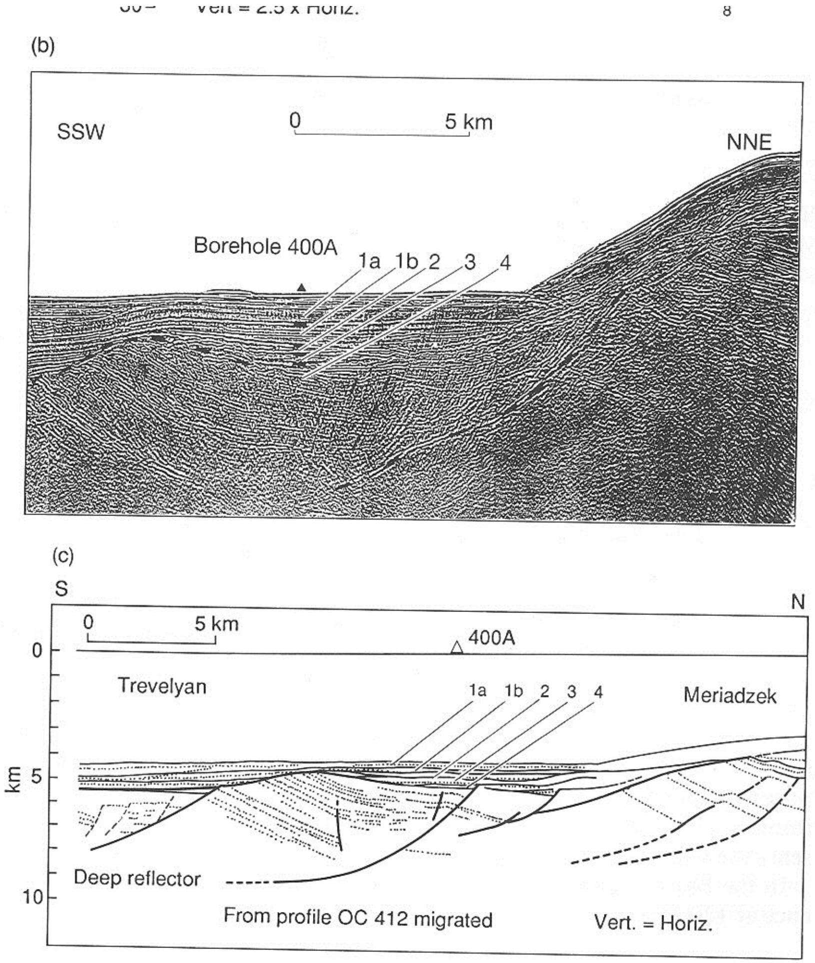
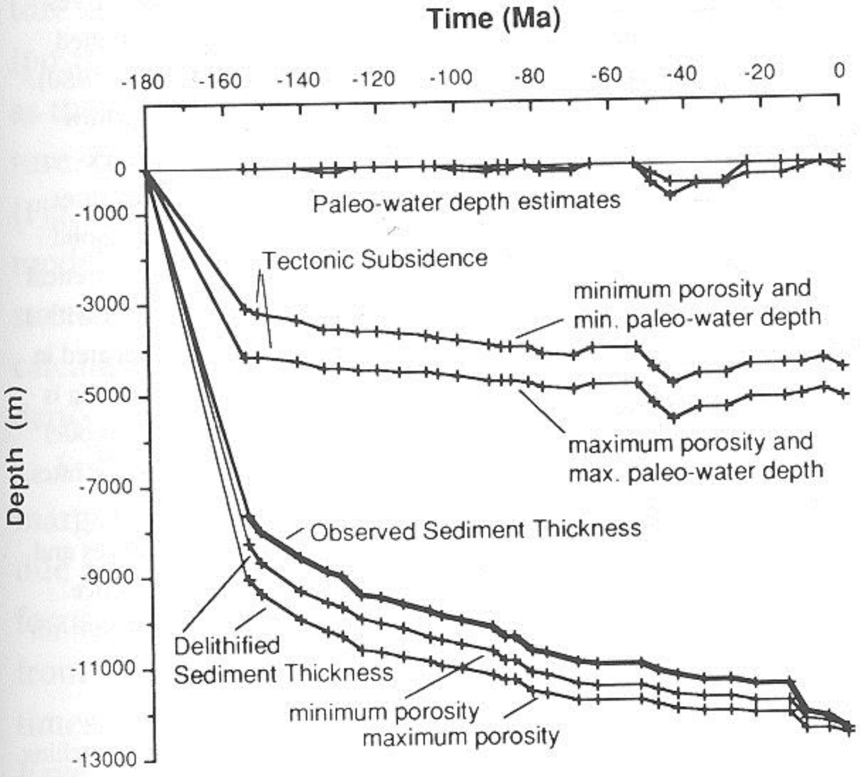


**Fig. 4.8** Rotated crustal blocks above listric normal faults in modified continental crust along continental terraces and rises. Seismic profile from just west of Galicia Bank (Spain), showing rotated basement blocks below sediment layer 3. Listric faults bounding these blocks appear to sole into a major crustal detachment fault inferred to lie along the reflector S. Vertical scale is in seconds and numbers 1 to 4 refer to stratigraphic intervals (from de Charpal et al., 1978).



. 3.32. (a) Profile across the
morican continental margin
wing the prominent tilted
lt blocks, based on the
ltichannel seismic reflection
ilts of Montadert *et al.*
79). The ocean–continent
isition occurs at a
sent-day water depth of
ut 5.2 km. (b) Detail of
d fault block geometry from
mic reflection profile OC 412
ntadert *et al.* 1977, Le
ion and Sibuet 1981) across
lower part of the Armorican
thern Bay of Biscay)
inental margin. After
itadert *et al.* (1979). (c) Line
ving interpretation of (b). 1a
uaternary to late Pliocene,
s Pliocene to early Miocene,
Miocene to late Palaeocene,
Maastrichtian to
panian, 4 is late Albian–late
an. After Montadert *et al.*
9).

# Subsidenční křivka na pasivním okraji



The equation for obtaining tectonic subsidence from a sedimentary basin:

$$T.S. = S^*\left(\frac{\rho_a - \rho_{s^*}}{\rho_a - \rho_w}\right) - \Delta SL\left(\frac{\rho_a}{\rho_a - \rho_w}\right) + WD$$

where:

$S^*$ = the decompacted sediment thickness
ρ = density
a = asthenosphere
w = water
ΔSL = change in sea-level
WD = paleo-water depth of the sediments
T.S. = tectonic subsidence, or the subsidence of the basin floor beneath water, without any sediment load. No sea-level correction has been made.

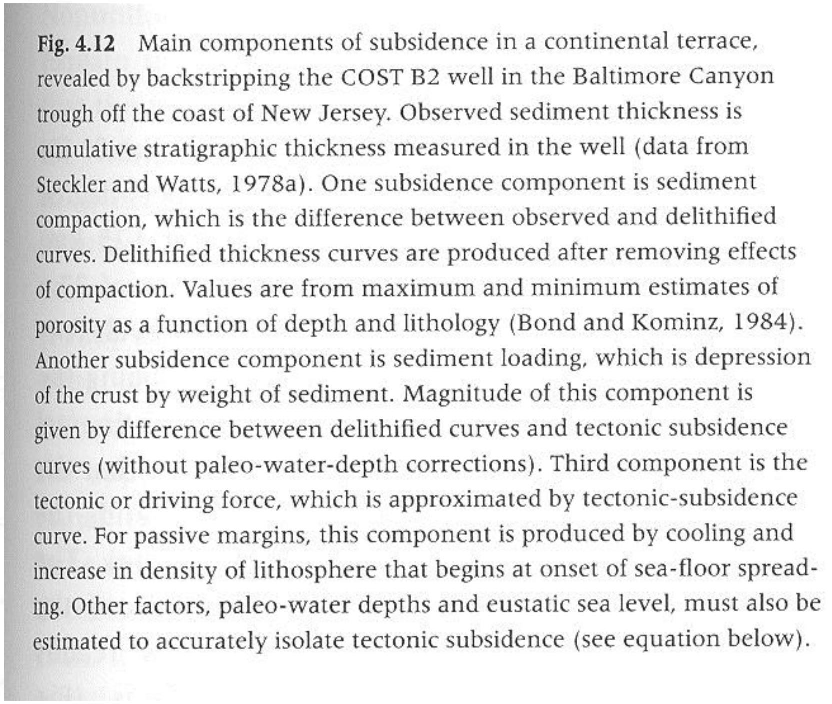


**Fig. 4.12** Main components of subsidence in a continental terrace, revealed by backstripping the COST B2 well in the Baltimore Canyon trough off the coast of New Jersey. Observed sediment thickness is cumulative stratigraphic thickness measured in the well (data from Steckler and Watts, 1978a). One subsidence component is sediment compaction, which is the difference between observed and delithified curves. Delithified thickness curves are produced after removing effects of compaction. Values are from maximum and minimum estimates of porosity as a function of depth and lithology (Bond and Kominz, 1984). Another subsidence component is sediment loading, which is depression of the crust by weight of sediment. Magnitude of this component is given by difference between delithified curves and tectonic subsidence curves (without paleo-water-depth corrections). Third component is the tectonic or driving force, which is approximated by tectonic-subsidence curve. For passive margins, this component is produced by cooling and increase in density of lithosphere that begins at onset of sea-floor spreading. Other factors, paleo-water depths and eustatic sea level, must also be estimated to accurately isolate tectonic subsidence (see equation below).

# Depoziční prostředí na pasivním okraji

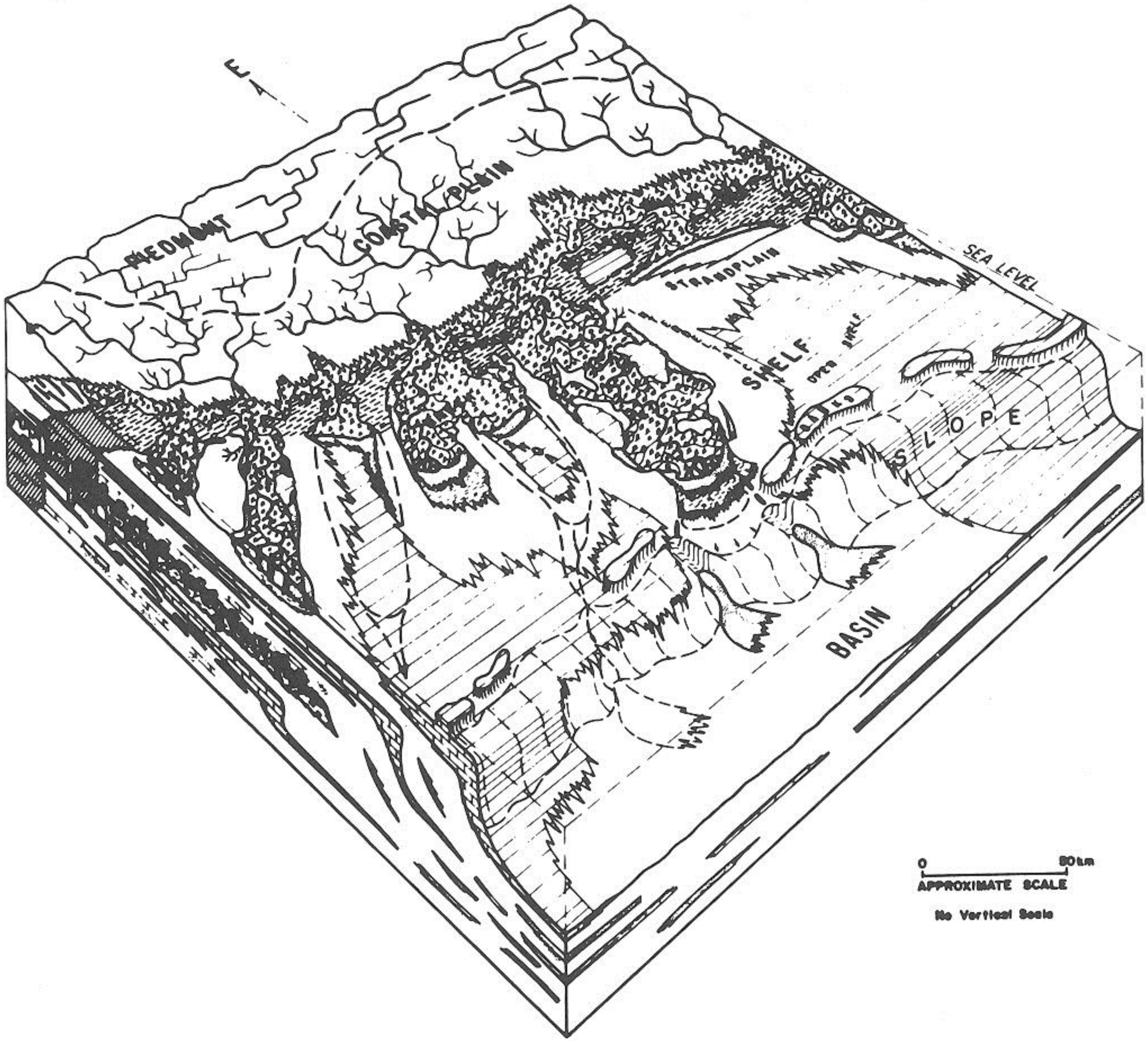


**Fig. 4.23** Block diagram showing typical depositional environments on passive margins, including nonmarine coastal plain, marine coastal, continental shelf, slope, and deep basin (from Brown and Fisher, 1977).

# Delta na pasivním okraji: nízký a vysoký stav hladiny moře

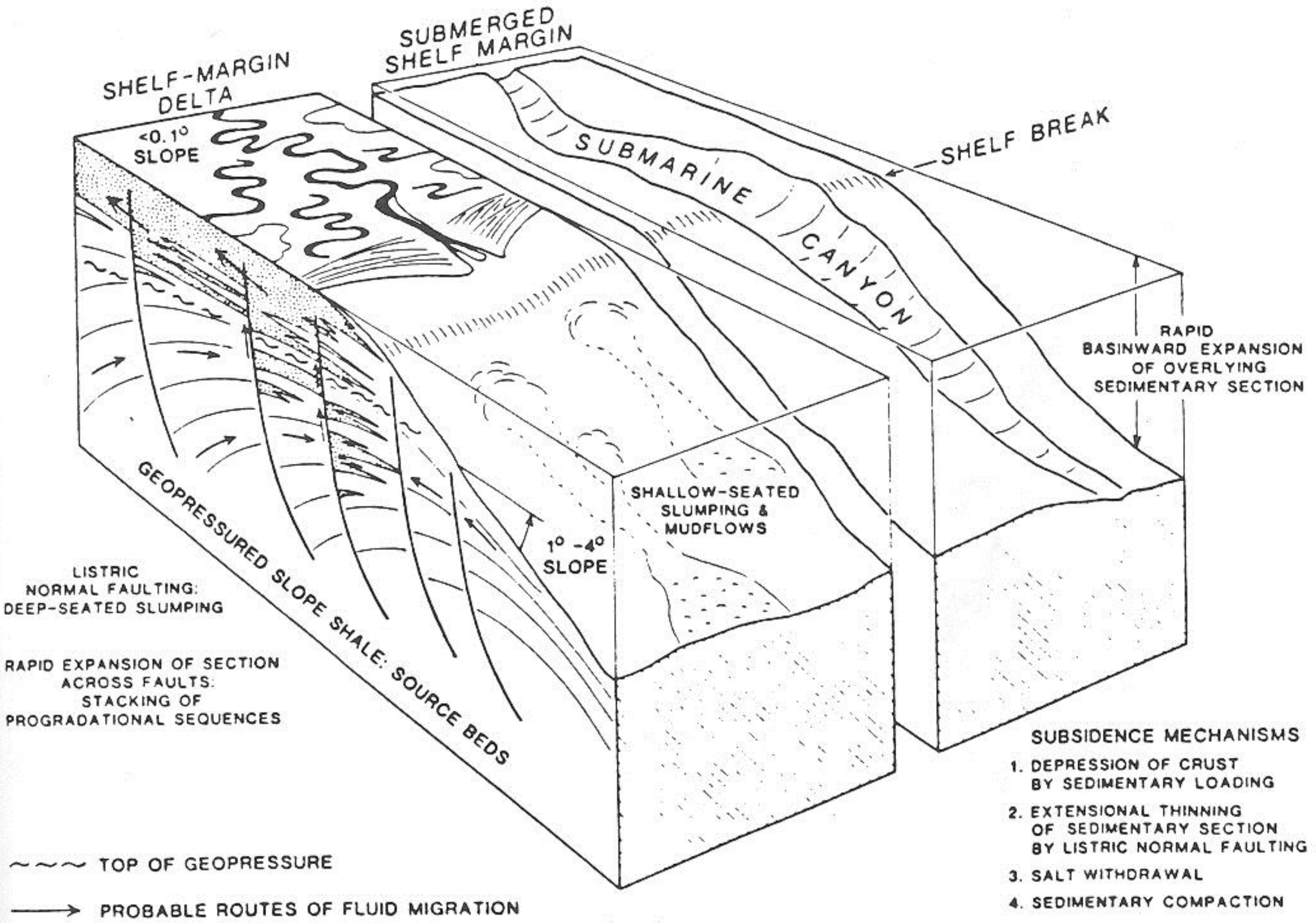
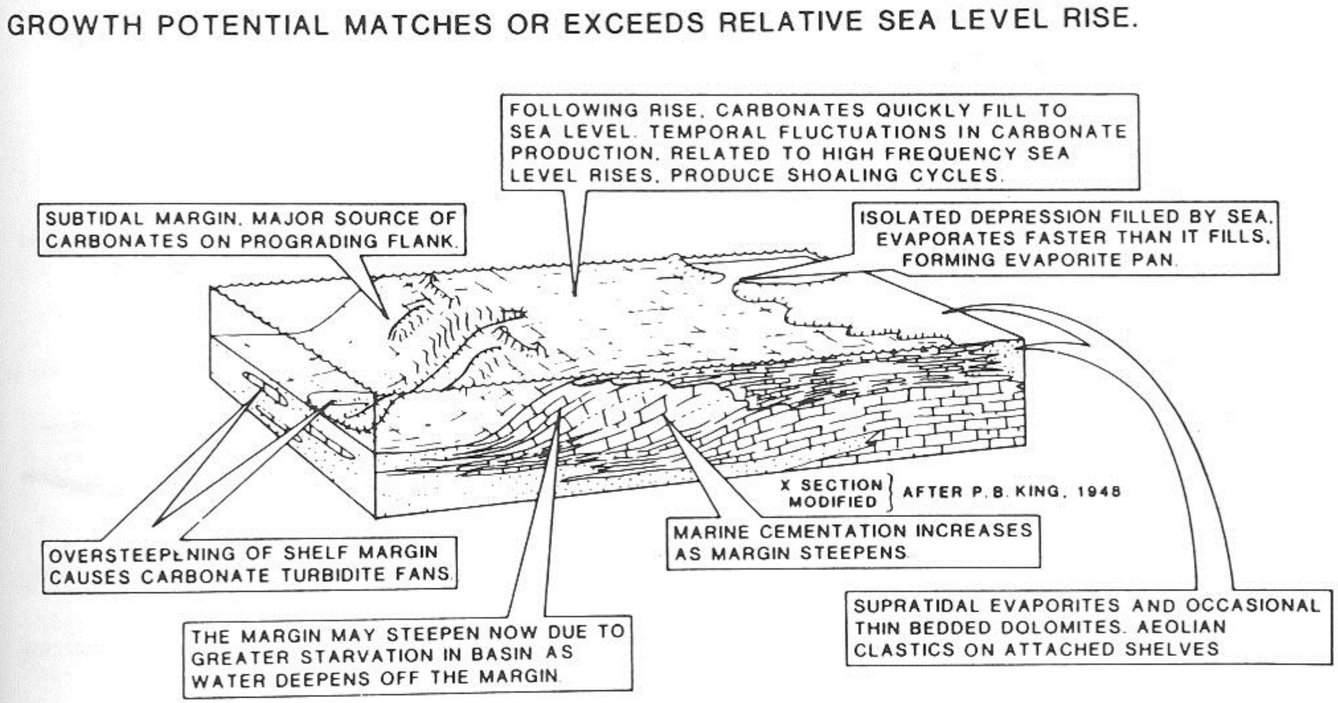


**Fig. 4.26** Block diagram model of a growth-faulted deltaic shelf margin during high and low stands of sea level (from Winker and Edwards, 1983).

slopes (Cook and Mullins, 1983). Large amounts of

# Karbonátový šelf



GROWTH POTENTIAL MATCHES OR EXCEEDS RELATIVE SEA LEVEL RISE.

FOLLOWING RISE, CARBONATES QUICKLY FILL TO SEA LEVEL. TEMPORAL FLUCTUATIONS IN CARBONATE PRODUCTION, RELATED TO HIGH FREQUENCY SEA LEVEL RISES, PRODUCE SHOALING CYCLES.

SUBTIDAL MARGIN, MAJOR SOURCE OF CARBONATES ON PROGRADING FLANK.

ISOLATED DEPRESSION FILLED BY SEA, EVAPORATES FASTER THAN IT FILLS, FORMING EVAPORITE PAN.

X SECTION MODIFIED } AFTER P. B. KING, 1948

OVERSTEEPENING OF SHELF MARGIN CAUSES CARBONATE TURBIDITE FANS.

MARINE CEMENTATION INCREASES AS MARGIN STEEPENS.

THE MARGIN MAY STEEPEN NOW DUE TO GREATER STARVATION IN BASIN AS WATER DEEPENS OFF THE MARGIN.

SUPRATIDAL EVAPORITES AND OCCASIONAL THIN BEDDED DOLOMITES. AEOLIAN CLASTICS ON ATTACHED SHELVES

**Fig. 4.27** Block diagram illustrating depositional environments of carbonate platform/platform margin, and off-bank basin (from Kendall and Schlager, 1981).

# Ropné pasti na pasivním okraji

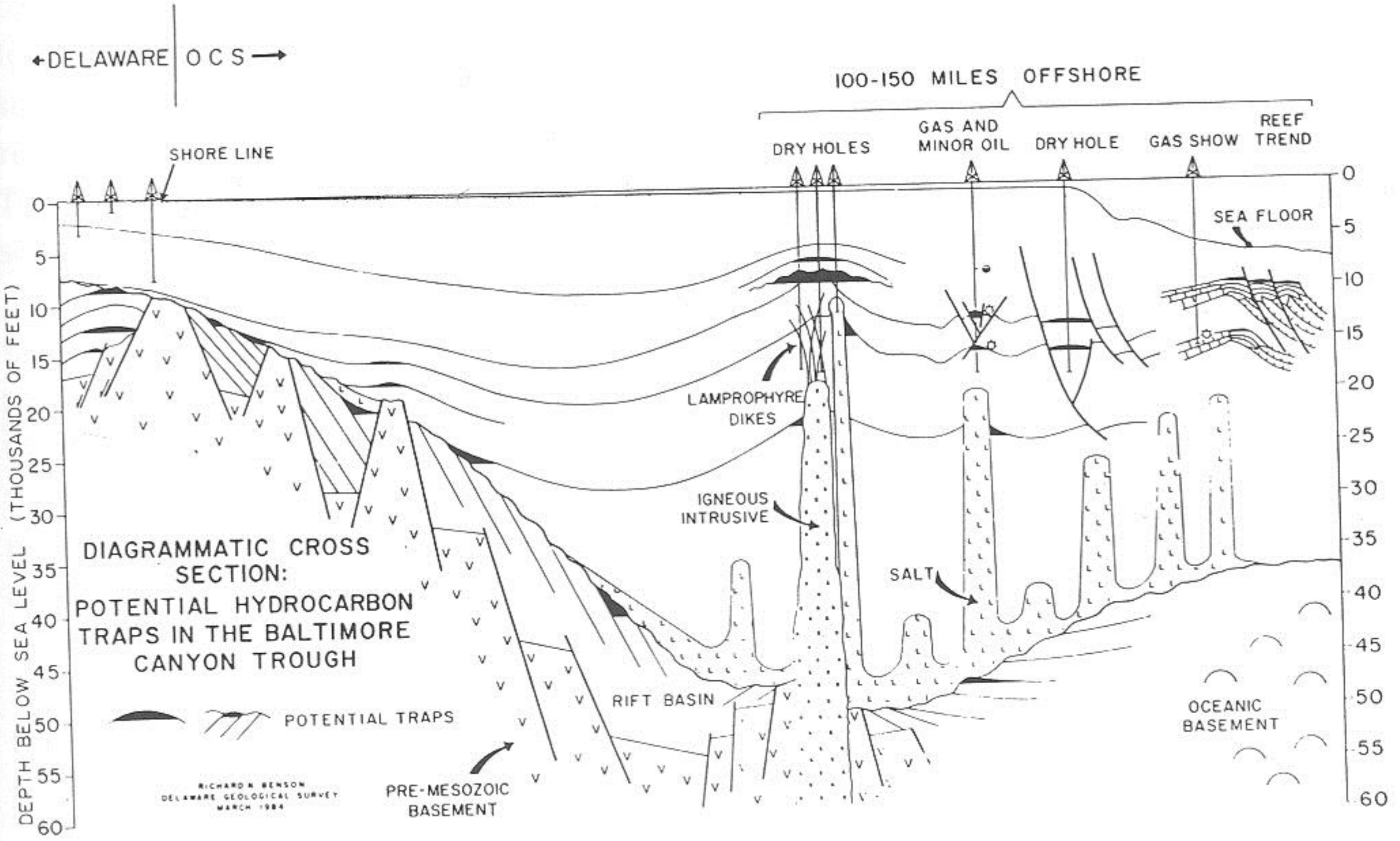


**Fig. 4.30** Schematic cross section of Baltimore Canyon trough, showing potential petroleum traps. Wells summarize exploration history (from Benson and Doyle, 1984).

# Hlubokomořské příkopy

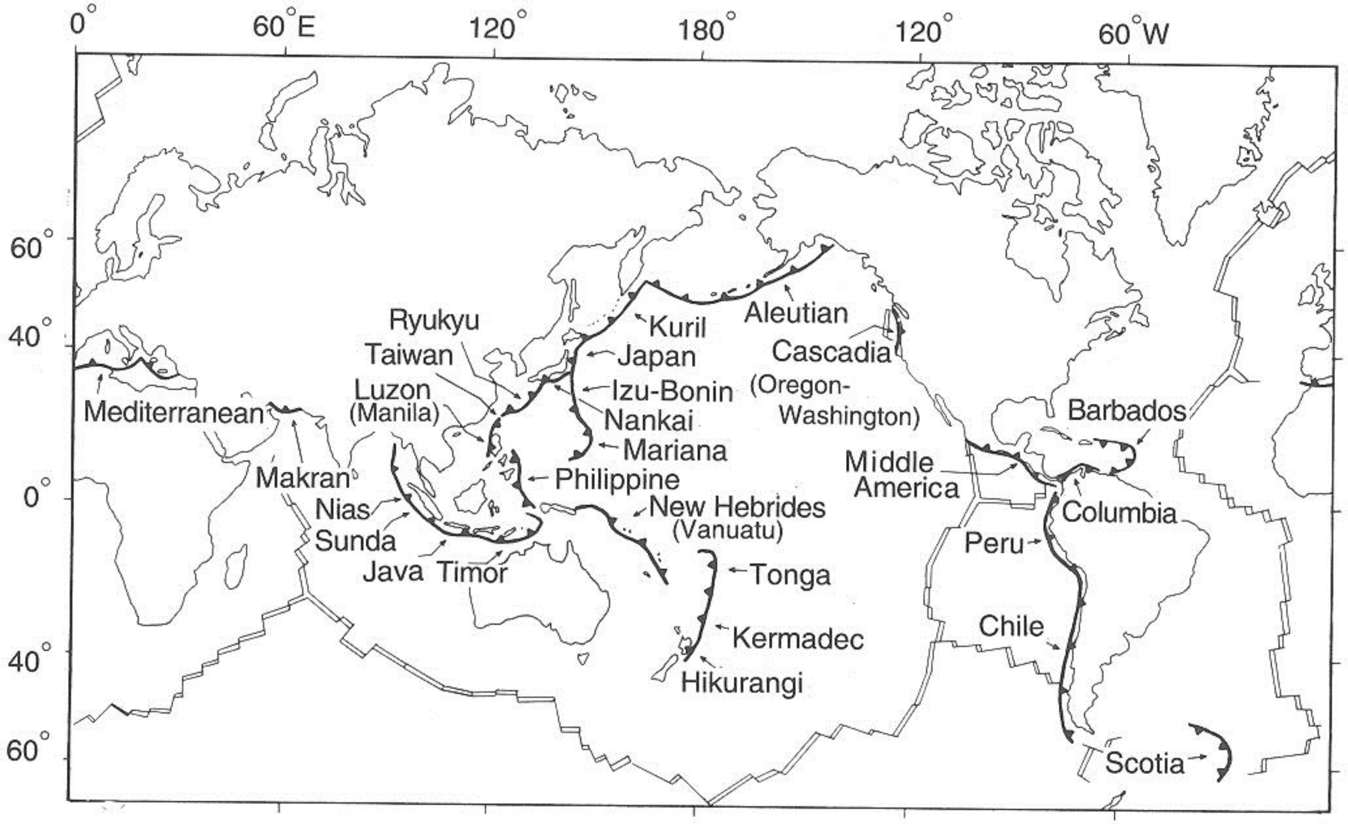


**Fig. 5.1** Global distribution of active oceanic subduction zones.

Rozmístění aktivních zón oceánské subdukce

# Hlubokomořské příkopy (Trench basin)

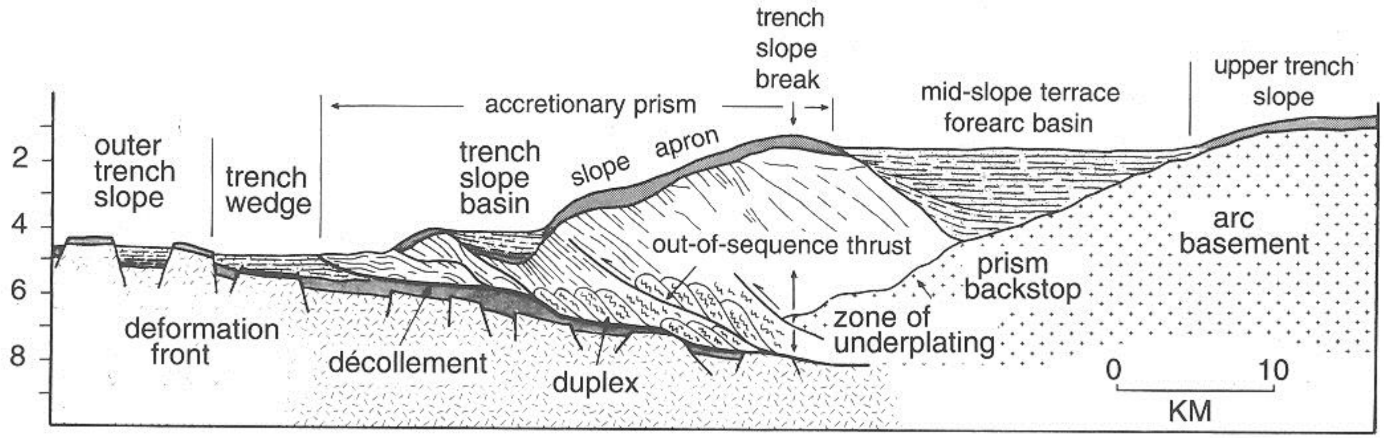


**Fig. 5.2** Schematic illustration of major bathymetric domains, regional-scale structural features, and sites of deposition within subduction zones.

Hlavní batymetrické zóny, regionální strukturně-tektonické parametry a akumulační oblasti na subdukčních zónách

- Slope apron – svahový osyp
- Forearc basin – předobolouková pánev
- Trench slope break – hrana svahu příkopu
- Trench slope basin – svahová pánev
- Trench wedge – sedimentační klín příkopu
- Decollement – hlavní zóna odlepení
- Out-of-sequence thrust – násun mimo sekvenci

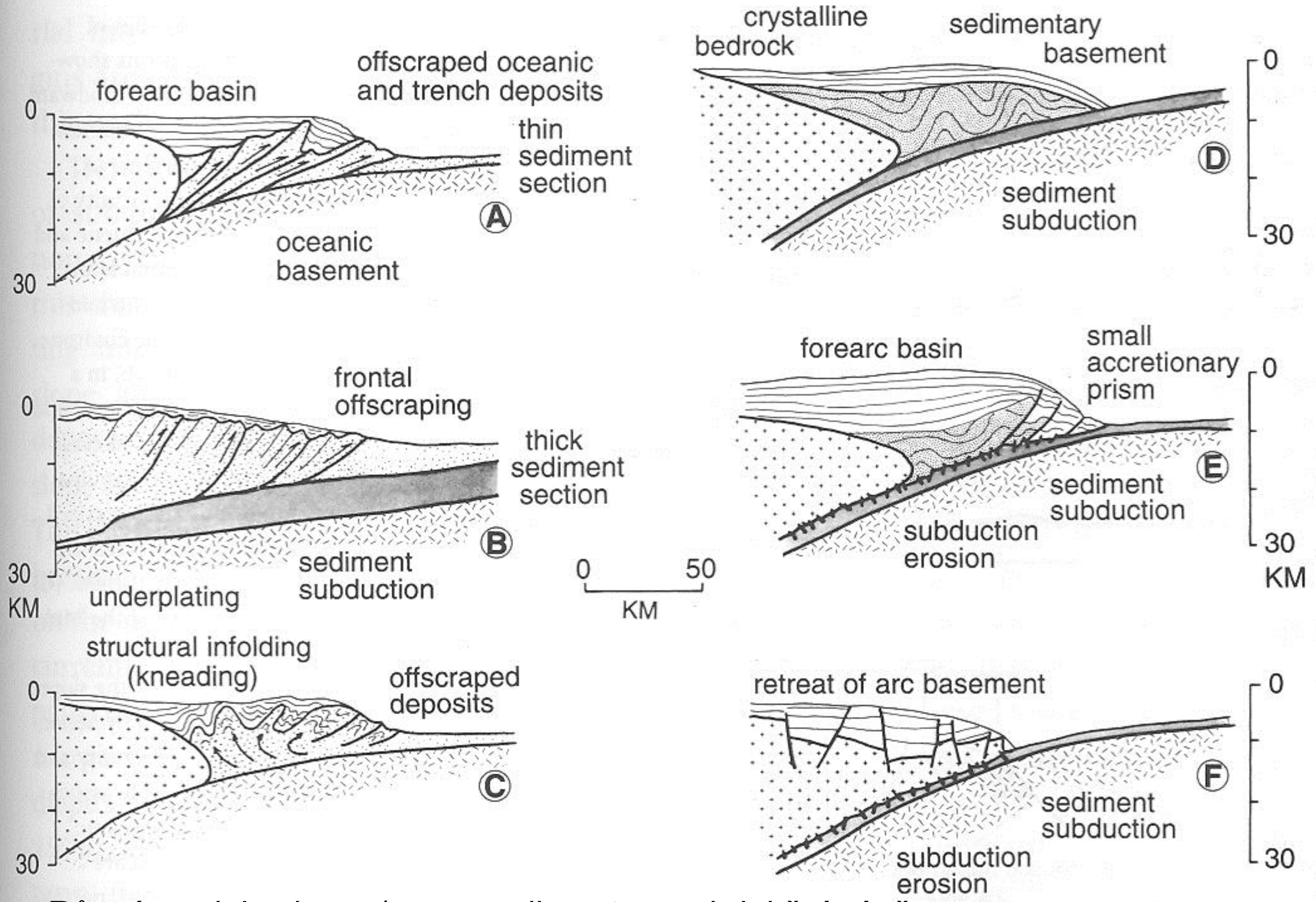


**Fig. 5.3** Conceptual models of accretion by offscrapping, sediment subduction, and subduction erosion (after Scholl et al., 1980). (A) Formation of accretionary prism by stacking of thrust slices derived from a relatively thin sequence of oceanic deposits. (B) Frontal offscrapping by imbricate thrusting within a thick sequence of oceanic and trench-wedge deposits; partial subduction and underplating are likely below the decollement. (C) Formation of structurally chaotic accretionary mass, together with structural infolding of trench-slope deposits (tectonic kneading). (D) Tectonic consumption of oceanic sediments beneath bedrock of a subduction margin; this model could be incorporated into models A or B, with structural partitioning along the decollement. (E) Subduction of oceanic deposits, mechanical erosion of the bedrock of the margin, and temporary outgrowth of a small accretionary wedge. (F) Advanced stages of subduction erosion, leading to retreat and exposure of igneous and metamorphic basement to volcanic arc or continental massif

Různé modely akrece/eroze sedimentu v subdukční zóně:

- „seškrabování“ /offscrapping/ tenkých šupin pelagických a příkopových sedimentů (A)
- Frontální seškrabování, imbrikace tektonických šupin (B)
- Strukturně chaotická akreční směs (C)
- Tektonická konzumace (subdukce) oceánských sedimentů (D)
- Subdukční eroze podloží aktivního okraje (bedrock) (E)
- Pokročilé stádium eroze aktivního okraje – ústup oblouku (F)

# Interpretace seismických profilů neakreční příkopy

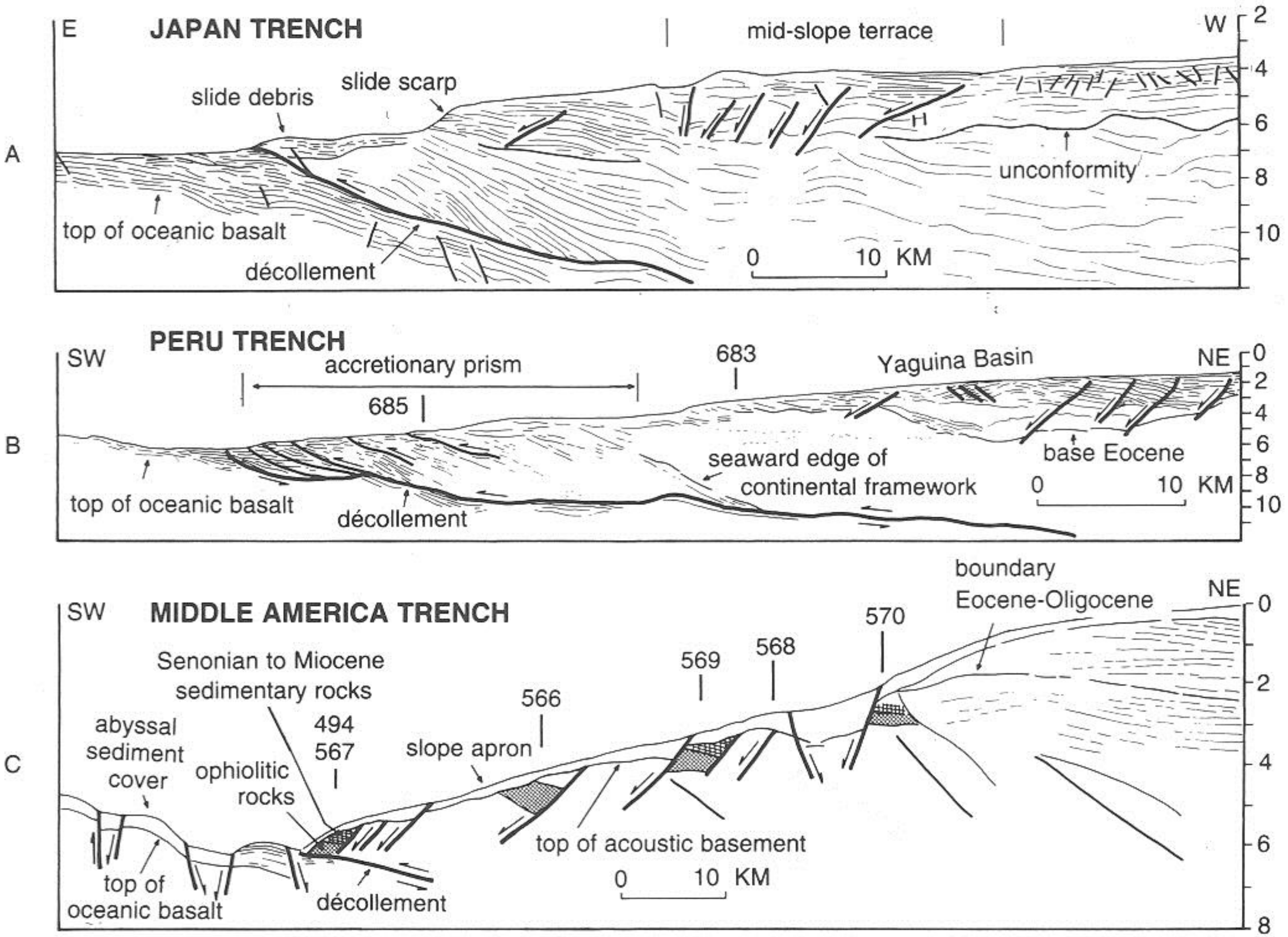


**Fig. 5.5** Line drawings of migrated depth sections showing trench wedges and landward trench slopes for nonaccretionary subduction margins. (A) Japan Trench in the vicinity of DSDP transects (von Huene and Culotta, 1989); normal faults occur mostly within the mid-slope and upper-slope environments. (B) Peru Trench, in a region of forearc subsidence and inferred tectonic erosion (von Huene et al., 1985a); Yaquina Basin (forearc) is characterized by normal faults, whereas the lower slope is cut by thrusts. (C) Guatemala segment of the Middle America Trench, where DSDP boreholes show the slope apron to be underlain by Senonian to Miocene sedimentary and ophiolitic rocks possibly associated with retreating oceanic basement of the island arc (Aubouin et al., 1985a); normal faults occur throughout this

A; Japonský příkop; Poklesové zlomy na svrchním a středním svahu

B, Peruánský příkop; poklesové zlomy ve svrchním svahu a v zóně subsidence v předpolní pánvi; násuny ve spodním svahu

C, středoamerický příkop (Guatemala); ústup oblouku, poklesové zlomy v celé subdukční zóně

# Faciální model Středoamerický trench

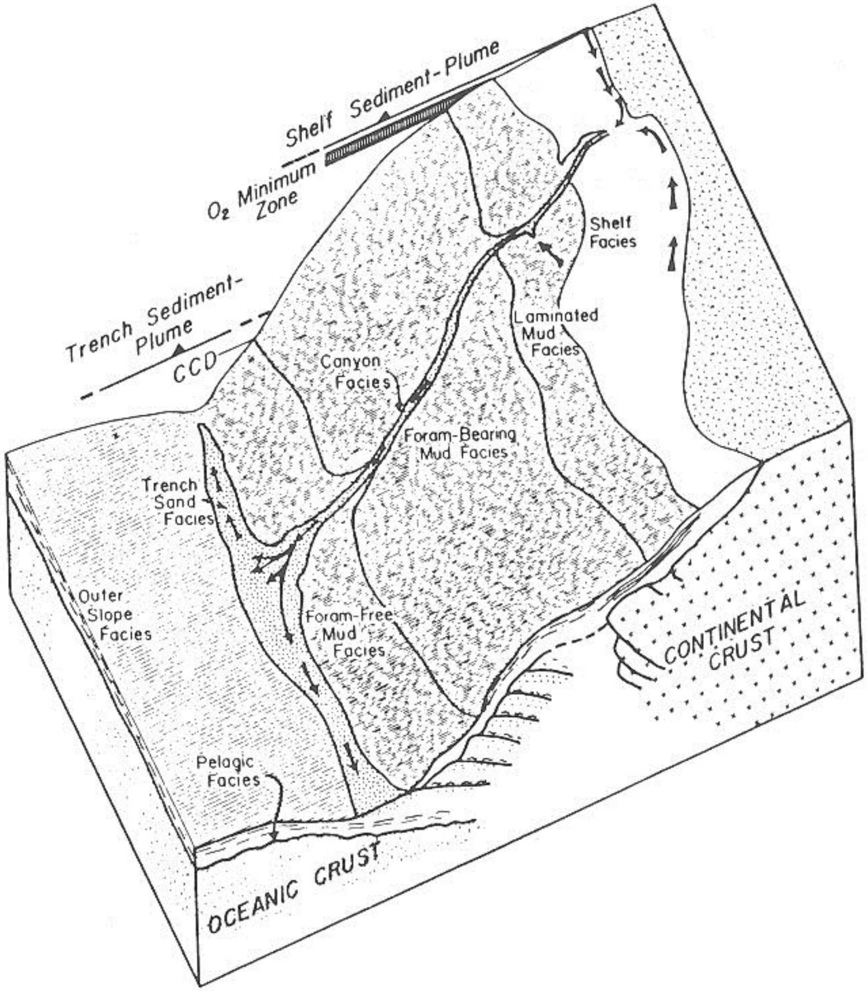


**Fig. 5.11** Sedimentary facies model for the northern Middle America Trench, offshore Mexico, showing the influence of Ometepec Canyon on forearc bypassing, the formation of a trench fan at the canyon mouth, and the development of a plume of suspended sediment rising several hundred meters above the trench floor. Foram-free mud facies corresponds to water depths below the calcite compensation depth (CCD). Laminated mud facies (minimal bioturbation) corresponds to water depths of the oxygen-minimum zone. (Modified from J.C. Moore et al., 1982a.)

Linárně protáhlý turbiditní vějíř

Osní transport turbiditních proudů a sedimentu

Poloha CCD

# Stratigrafický CU trend trench basins

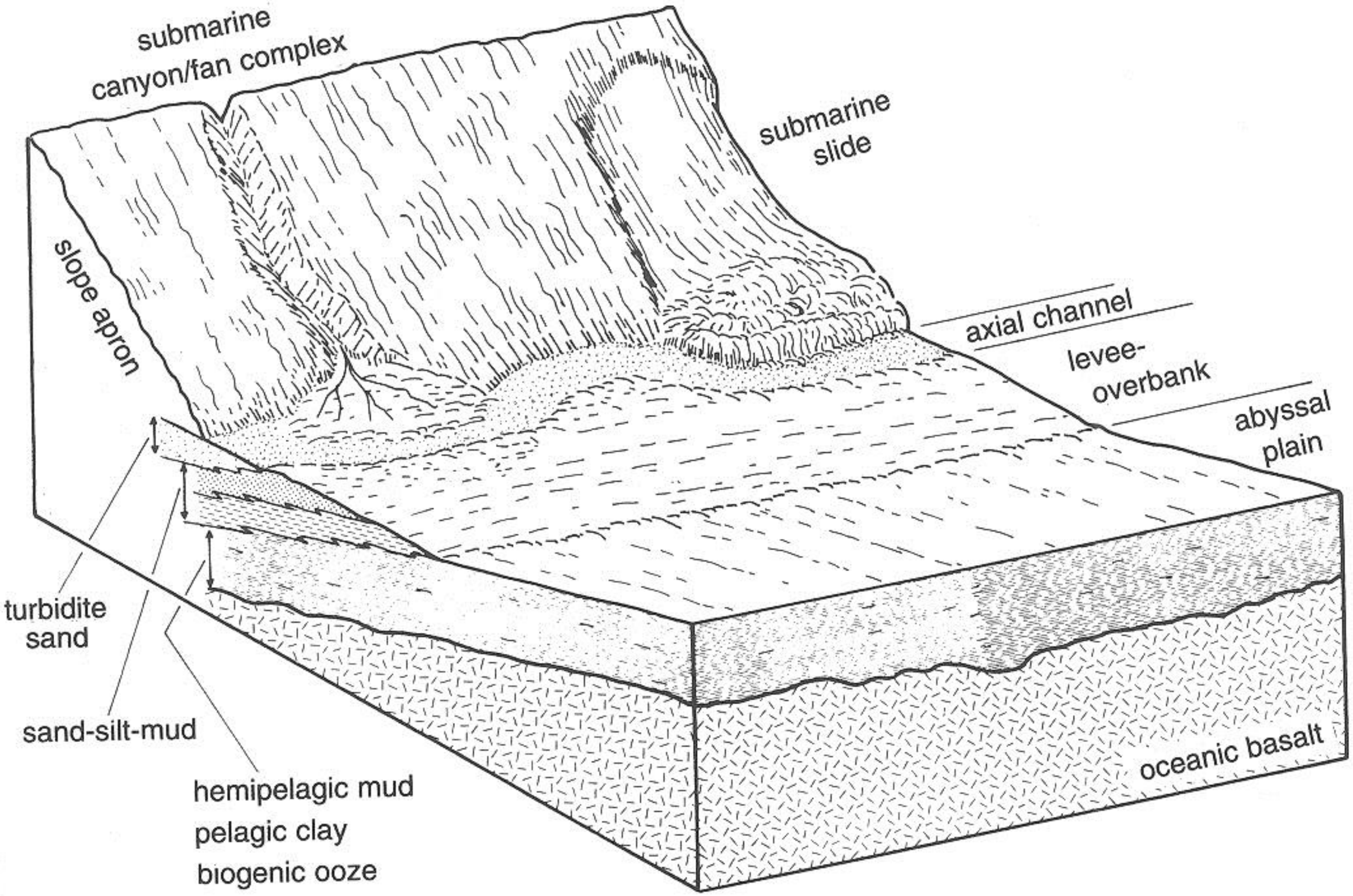
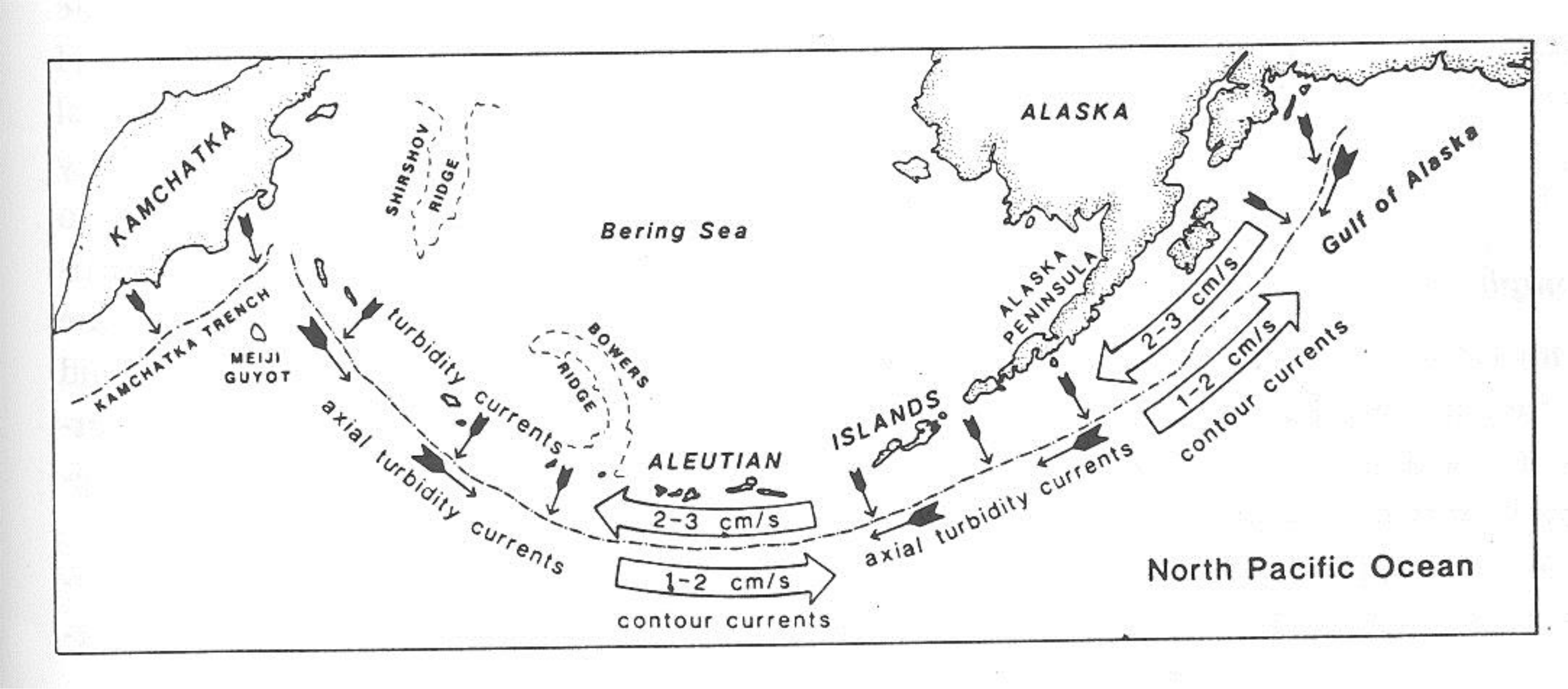


**Fig. 5.28** Paradigm upward coarsening stratigraphy outboard of the deformation front of a subduction margin, based largely on DSDP drilling data from the eastern Aleutian Trench. Modified from Piper et al. (1973).

- Nahoru-hrubnoucí stratigrafický trend – konvergence oceánského dna (kůry) s obloukem
- DSDP data z aleutského příkopu

# Aleutian trench



Parametry transportu v aleutském příkopu

- Rychlosti proudění vody při dně
- Konturové proudy
- Osní turbiditní proudy
- Směry šíření pelagického kalu v předobloukové pánvi Aleut

# Seismický profil, Aleutian trench

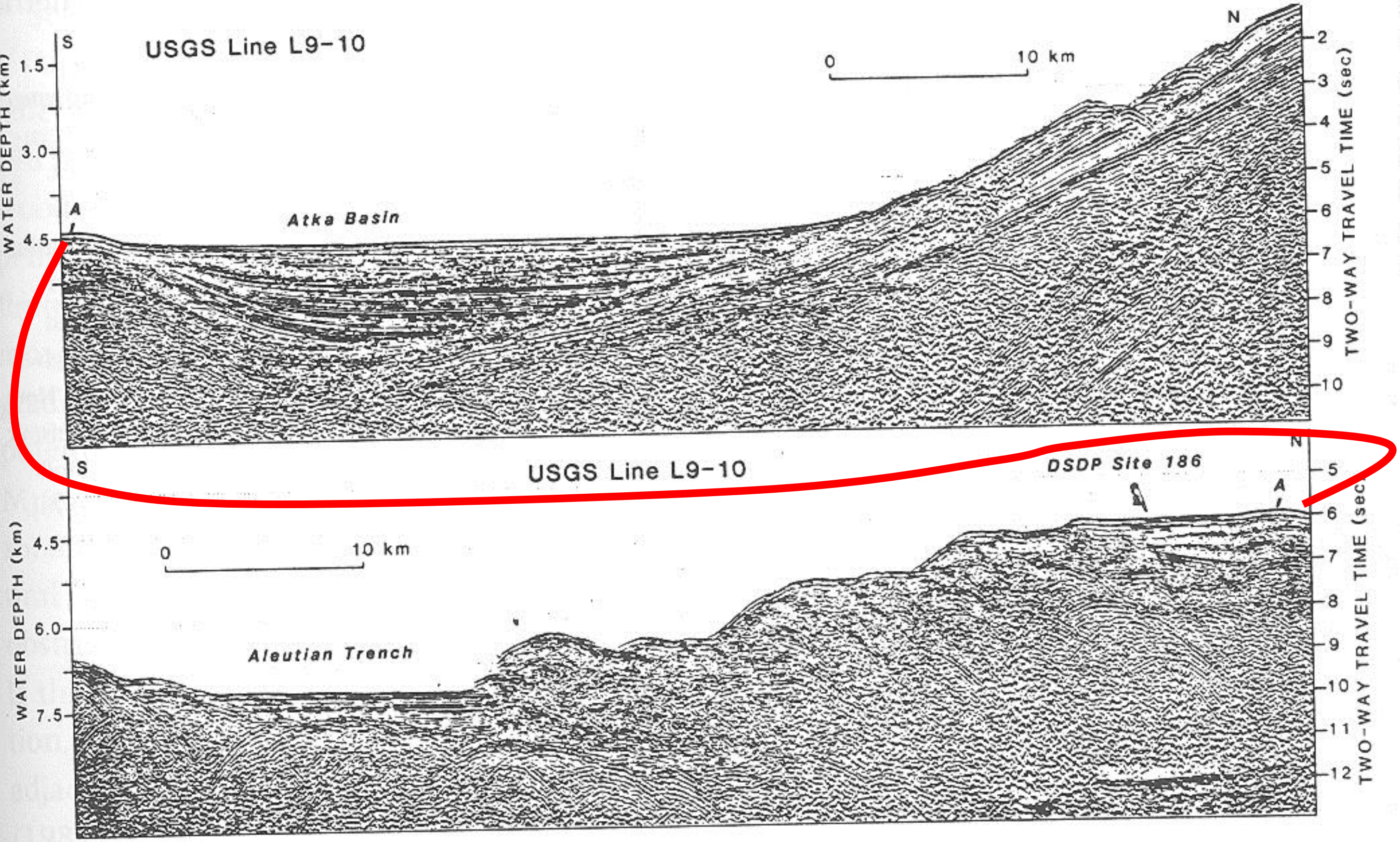


**Fig. 5.24** Unmigrated multichannel seismic profile through Atka Basin and the central Aleutian Trench. See Fig. 5.25 for location of trackline. The two segments of this profile join at point A. Note the position of DSDP Site 186. See Scholl et al. (1987b) for additional interpretation.

Horizontální reflektory v příkopu
Tektonické násuny v akrečním prizmatu

# Nankai Trough, CU trend

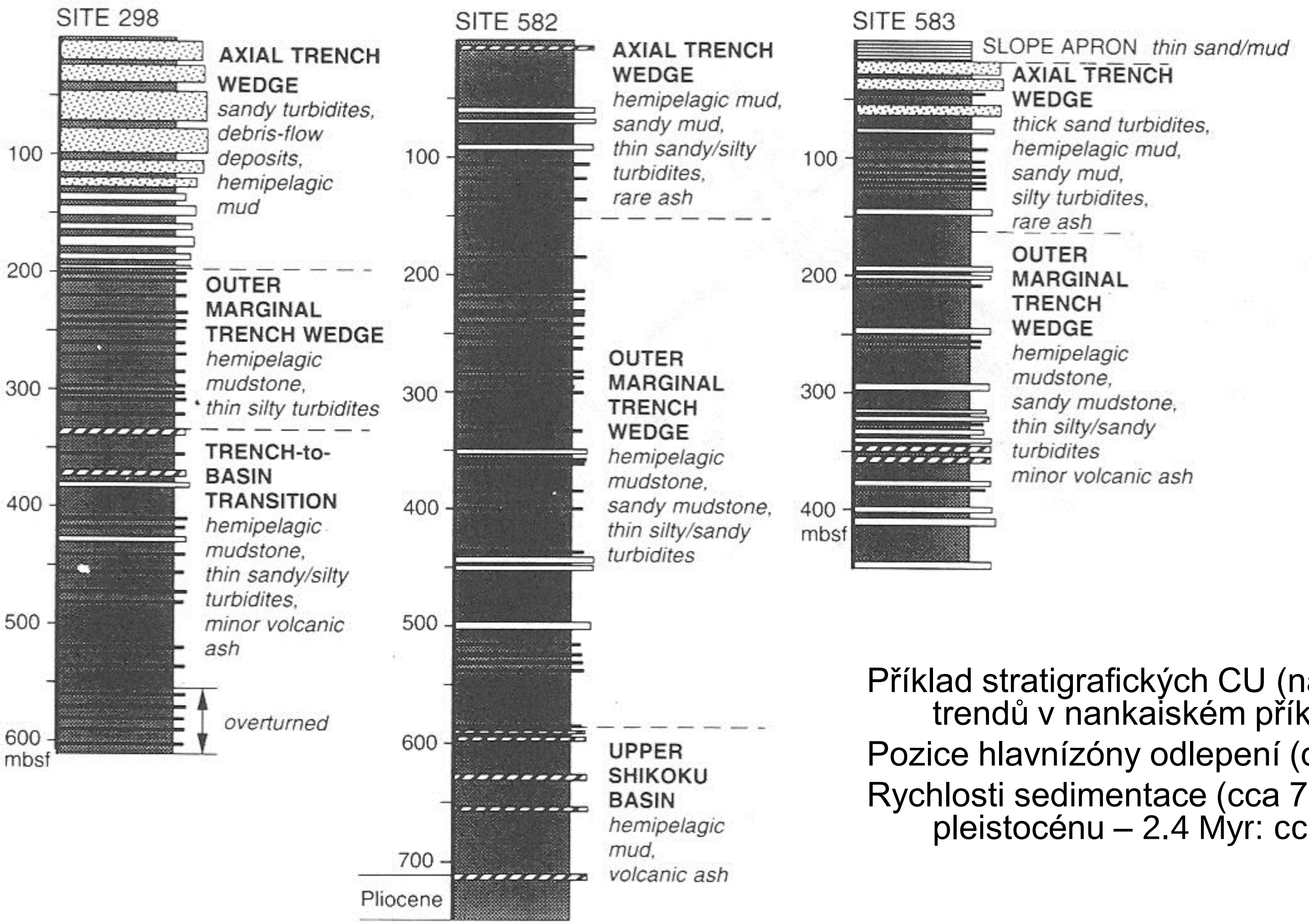


**Fig. 5.23** Simplified stratigraphic columns for DSDP and ODP boreholes near Nankai Trough (from Pickering et al., 1993). Note the complete upward coarsening cycle and the position of the decollement within the abyssal-plain (Shikoku Basin) section at Site 808. Compare this borehole stratigraphy with the seismic-reflection profile in Fig. 5.22.

Příklad stratigrafických CU (nahoru-hrubnoucích) trendů v nankaiském příkopu

Pozice hlavnízóny odlepení (decollement)

Rychlosti sedimentace (cca 700 m během pleistocénu – 2.4 Myr: cca 29 cm / kyr)

# Stratigrafie, trench basin

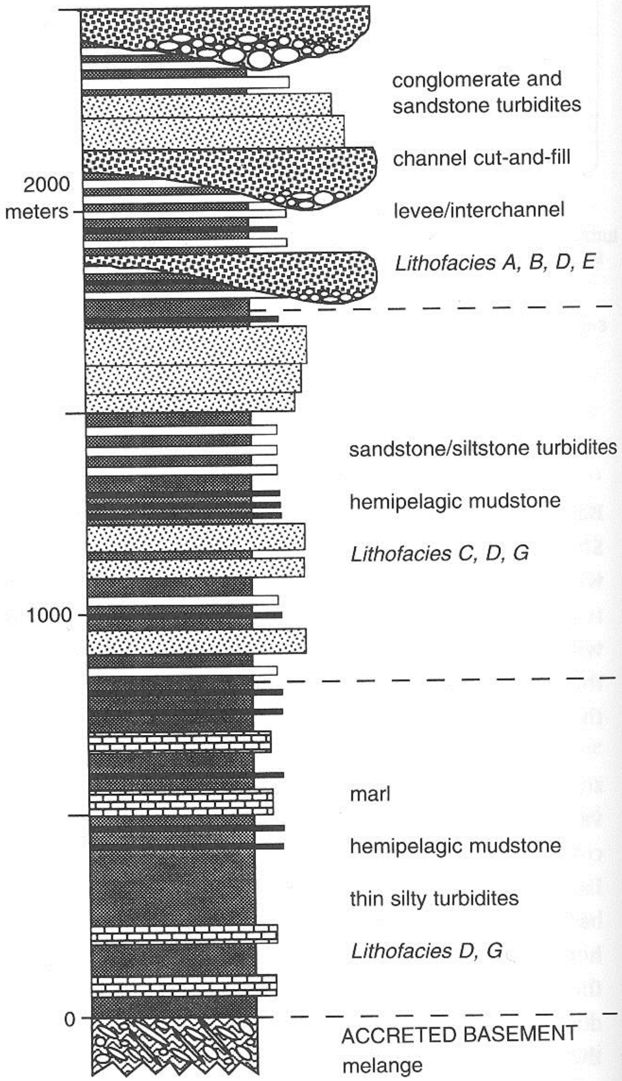


**Fig. 5.30** Hypothetical model for stratigraphic evolution of a trench-slope basin, based largely on the observations of Moore et al. (1980b) on Nias Island, Indonesia. See Table 5.2 for explanation of lithofacies designations. The upward coarsening and thickening megacycle is the result of basin uplift and temporal increases in terrigenous influx, as submarine canyons enhance the efficiency of transport from the continental shelf or arc platform. Smaller-scale cycles are due to progradation or lateral migration of depositional lobes (upward thickening) and migration/abandonment of channels (upward fining and thinning).

Hypotetický stratigrafický sled příkopových sedimentů

Nahoru hrubnoucí sekvence

Rostoucí kontinentální vliv

# Předobloukové pánve forearc basins

- pánve, kde sedimenty leží diskordantně na horninách ostrovního oblouku nebo oblouku kontinentálního okraje nebo na akrečním klínu

**modely subsidence**

- komplikovaná subsidenční historie
- zatížení sedimentem v depresi mezi obloukem a akrečním klínem
- izostatický pokles v důsledku podsunutí těžké oceánské litosféry
- chládnutí prohřáté nadložní desky v důsledku podsunutí chladné oceánské litosféry

**morfologie předobloukových pánví**

- **podsycené** (hladovějící), většinou ostrovní oblouky
- **přesycené**, většinou kontinentální okraje

**sedimentace**

- **terestrické prostředí** - fuviální a deltové sedimenty, aluviální vějíře, pyroklastika,
- **mělkomořské prostředí** - vysoký podíl vulkanoklastického materiálu, vysoký přísun sedimentu, málo biogenního materiálu (karbonáty)
- **turbiditní systémy** - nahoru hrubnoucí, vysoký podíl vulkanoklastik
- **sedimenty abysálních plošin** - jemnozrnné vulkanoklastika, vysoký podíl smektitové složky v jílech

# Předobloukové pánve (Forearc basins)

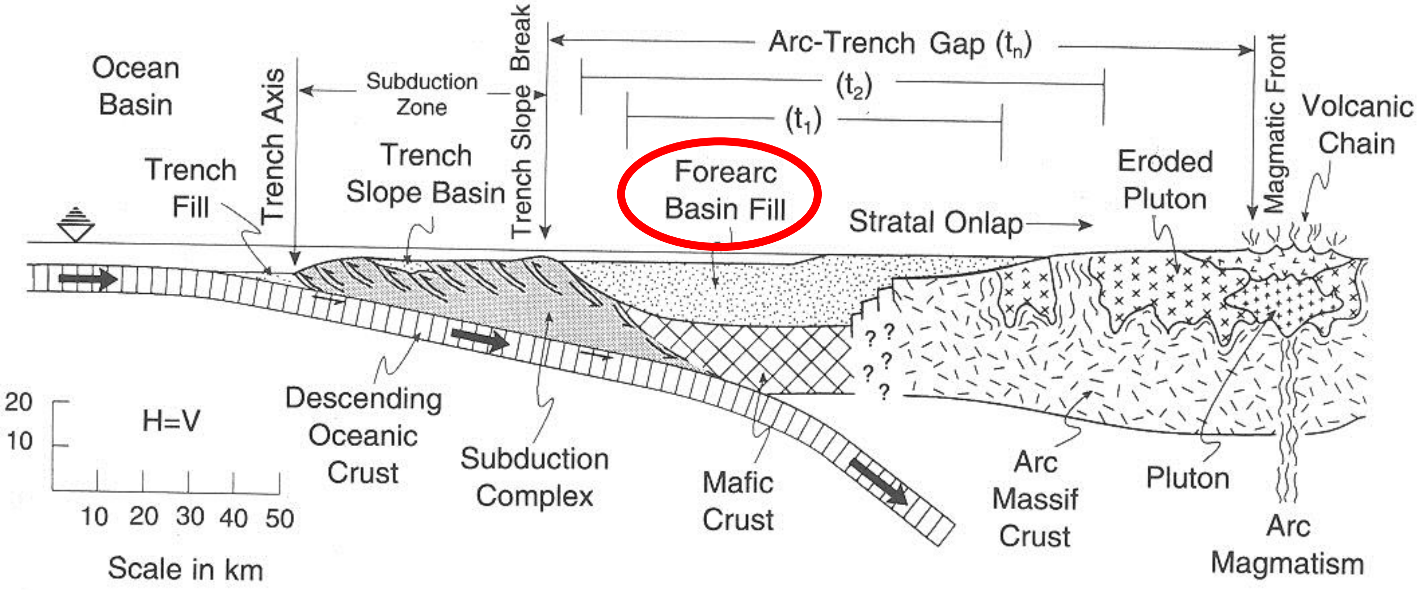


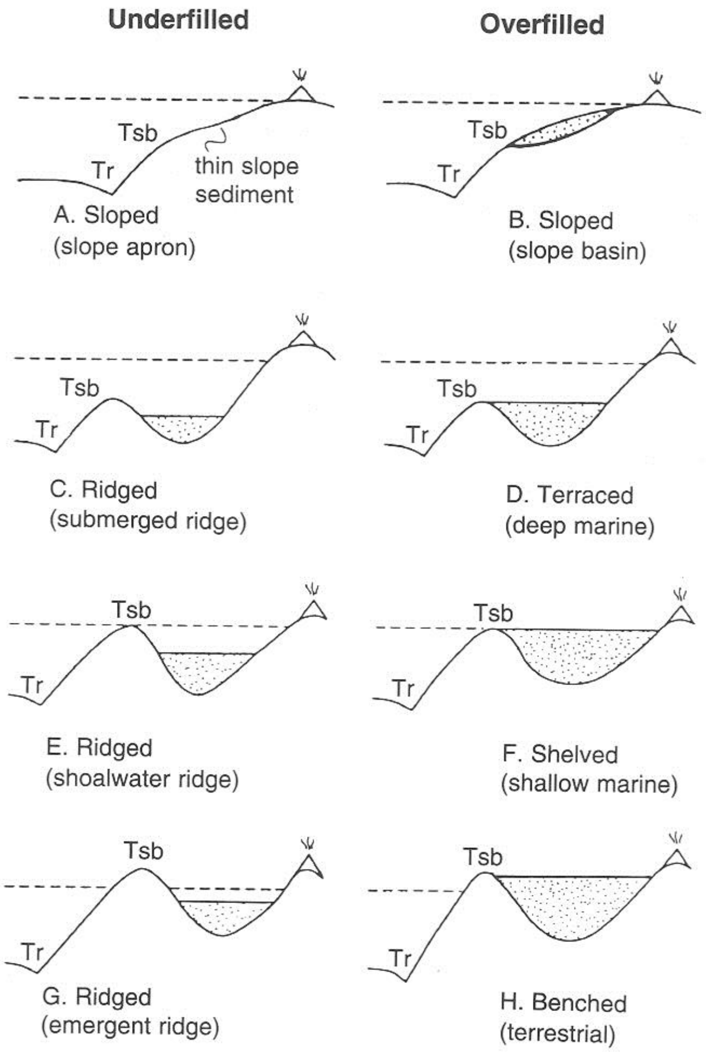
**Fig. 6.1** Geotectonic features of forearc basins in transverse profile. See Fig. 6.5 for internal structures of subduction complex and Fig. 6.6 for origins of forearc ophiolites (mafic crustal substratum). Stipples indicate undeformed sediment accumulations. Diagram shows ideal case for which sedimentary infilling of forearc basin keeps pace with accretionary growth of subduction complex, and omits potential faults (thrust, normal, strike-slip) that may cut forearc sediment prism. Cases lacking subduction complex not depicted (see text for discussion).

221

Idealizovaný profil předobloukovou pánví

Tečkovanou šrafou: nedeformované sedimenty předobloukové pánve

Idealizovaná situace, kdy výplň předobloukové pánve drží tempo s přírůstkem akrečního prizmatu; zlomová tektonika předobloukové pánve není zohledněna



A. Sloped (slope apron)

B. Sloped (slope basin)

C. Ridged (submerged ridge)

D. Terraced (deep marine)

E. Ridged (shoalwater ridge)

F. Shelved (shallow marine)

G. Ridged (emergent ridge)

H. Benched (terrestrial)

**Fig. 6.4** Morphologic variants of forearc basins, with basin fill stippled and vertical exaggeration for clarity: left, "underfilled" (most common for island arcs); right, "overfilled" (most common for continental margins). Symbols: dashed lines = sea level, Tr = trench, Tsb = trench-slope break (coincides with shelf-slope break for shelved forearcs). Modified after Seely (1979) and Dickinson and Seely (1979). Distribution of morphologic types in modern arc-trench systems indicated by Table 6.1.

Morfologická variabilita předobloukových pánví:

„podsycené“ – typické pro ostrovní oblouky

„přesycené“ – typické pro aktivní kontinentální okraje:

Tr – příkop

Tsb – hrana svahu příkopu

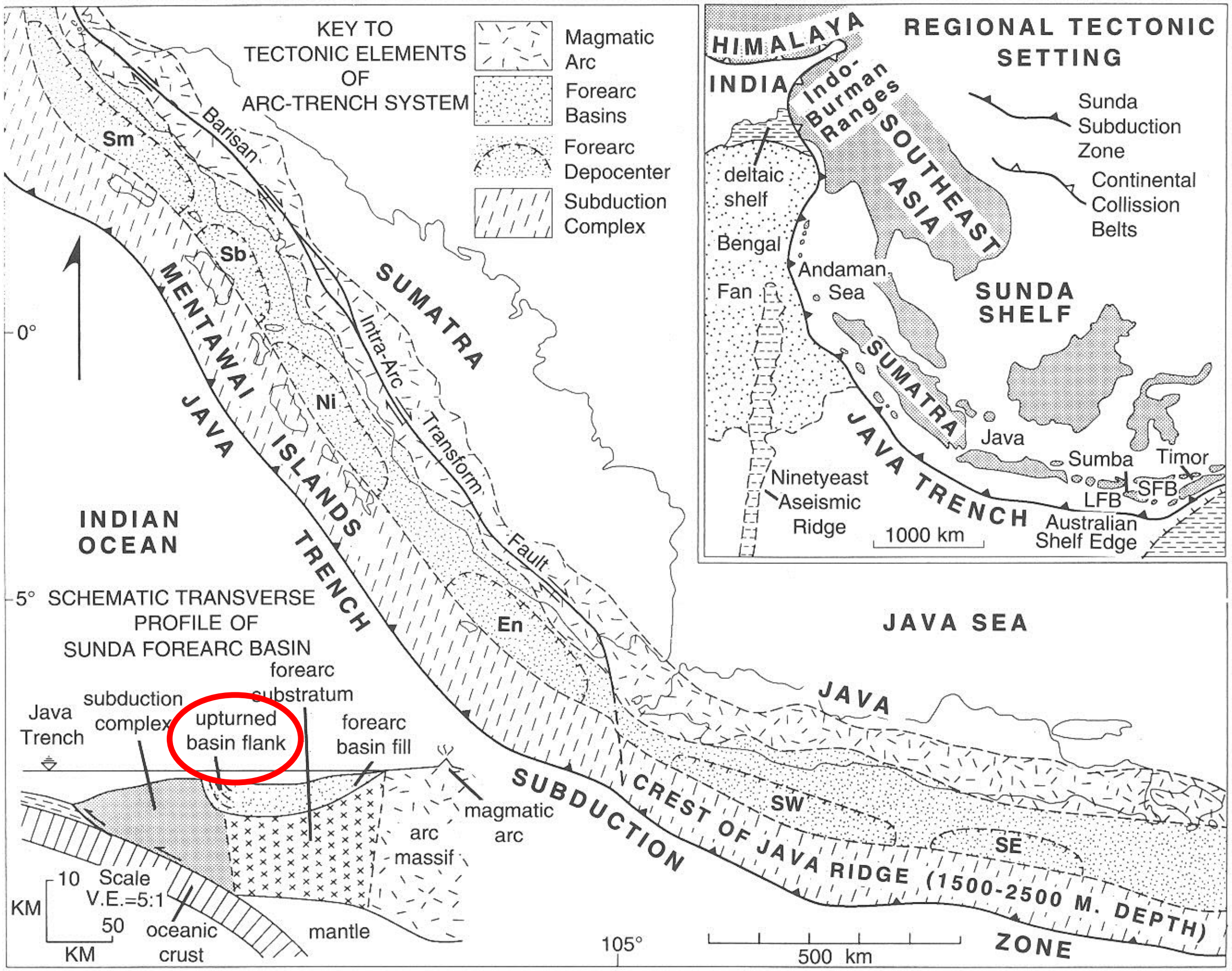


**Fig. 6.10** Configuration of elongate forearc basin, with multiple depocenters, in Sunda arc-trench system of Sumatra and Java (Hamilton, 1979; Karig et al., 1979, 1980a; Kieckhefer et al., 1981). Inset shows relation of Sunda subduction zone (note position of Sumatra and Java) to Himalayan suture belt and incipient arc-continent collision at Timor (LFB, Lombok forearc basin; SFB, Savu forearc basin). Forearc depocenters off Sumatra-Java (Table 6.1, III): Sm, Simeulue; Ni, Nias; Sb, Siberut; En, Enggano; SW, southwest Java; SE, southeast Java.

Protáhlá předoblouková pánev s množstvím dílčích depocenter (Sumatra, Jáva):

Předobloukové pánve:

p.p. Lombok (LFB)

p.p. Savu (SFB)

# Aljašské a Aleutské předobloukové pánve

Aleuty: terasové p. pánve (At, Un)

Aljaška: šelfové p. pánve (Sa, Sh, Tu, Al, St)

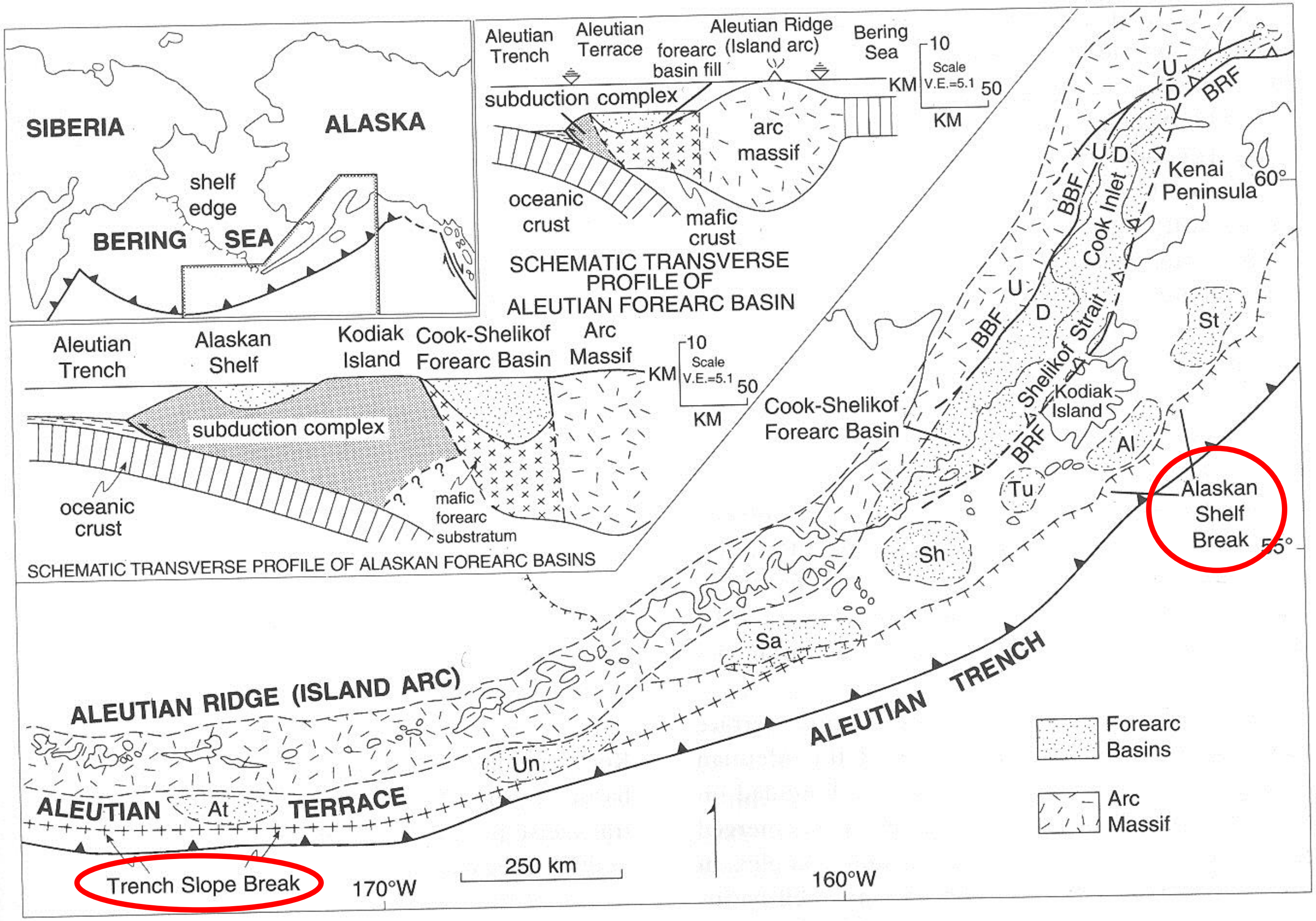
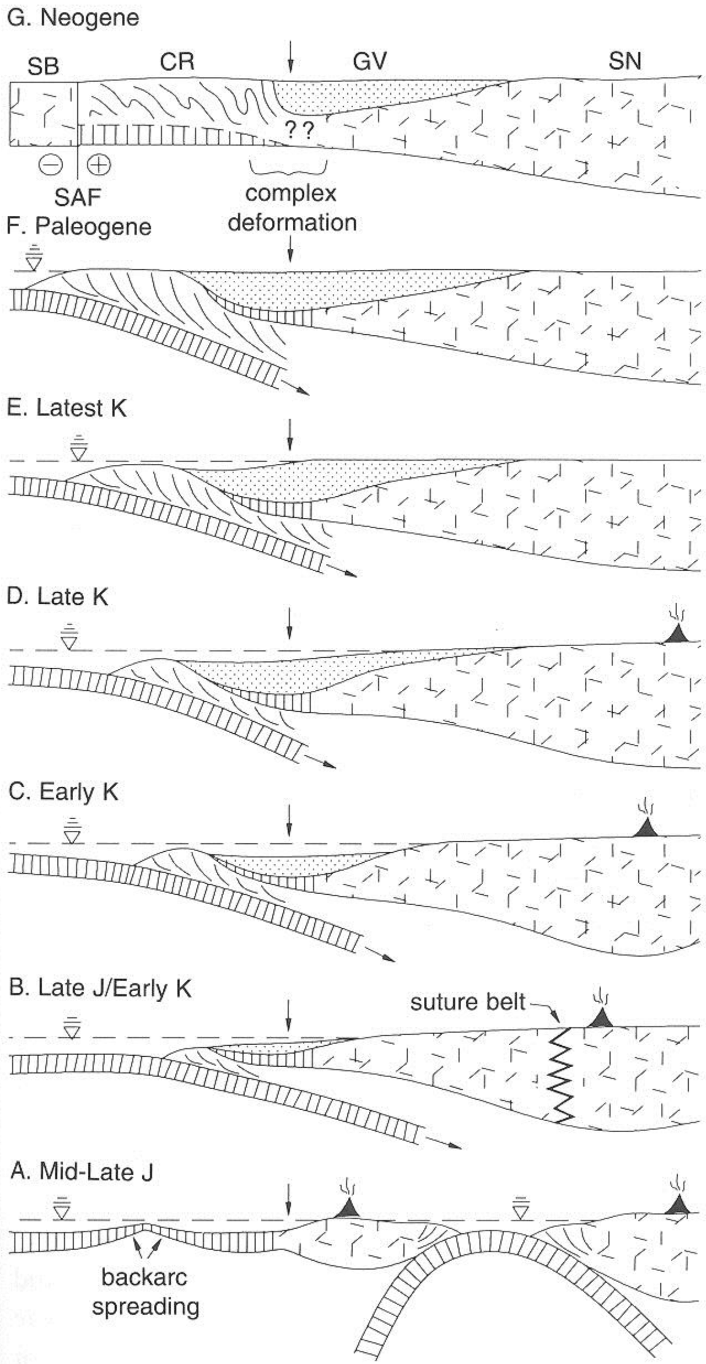


**Fig. 6.16** Relations of multiple Alaskan and Aleutian forearc basins (Bruns et al., 1987; Fisher et al., 1987; Scholl et al., 1987b; von Huene et al., 1987): Aleutian terrace basins (At, Atka; Un, Unalaska), Alaskan shelf basins (Sa, Sanak; Sh, Shumagin; Tu, Tugidak; Al, Albatross; St, Stevenson), and Cook-Shelikof basin (Table 6.1, I, II, IV; Kanaga basin is west of edge of map); inset map shows relations to continental blocks and linked transform system along continental margin. Mafic crust beneath Aleutian forearc basins can be regarded as buried flank of arc massif (Geist et al., 1988). BBF, Bruin Bay fault; BRF, Border Ranges fault.

Viz pozice

- hrany šelfu (Aljaška) – šelfové pánve
- Hrany svahu příkopu (Aleuty) – terasové pánve



Vývoj předobloukové pánve Great Valley, Kalifornie

SAF – zlom San Andreas

GV – Great Valley

SN – Sierra Nevada

CR – pohoří California Coast Range

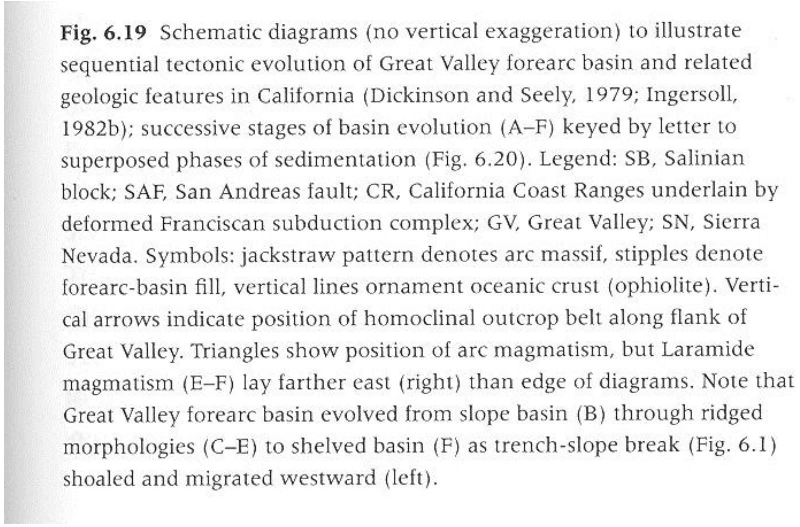


**Fig. 6.19** Schematic diagrams (no vertical exaggeration) to illustrate sequential tectonic evolution of Great Valley forearc basin and related geologic features in California (Dickinson and Seely, 1979; Ingersoll, 1982b); successive stages of basin evolution (A–F) keyed by letter to superposed phases of sedimentation (Fig. 6.20). Legend: SB, Salinian block; SAF, San Andreas fault; CR, California Coast Ranges underlain by deformed Franciscan subduction complex; GV, Great Valley; SN, Sierra Nevada. Symbols: jackstraw pattern denotes arc massif, stipples denote forearc-basin fill, vertical lines ornament oceanic crust (ophiolite). Vertical arrows indicate position of homoclinal outcrop belt along flank of Great Valley. Triangles show position of arc magmatism, but Laramide magmatism (E–F) lay farther east (right) than edge of diagrams. Note that Great Valley forearc basin evolved from slope basin (B) through ridged morphologies (C–E) to shelved basin (F) as trench-slope break (Fig. 6.1) shoaled and migrated westward (left).

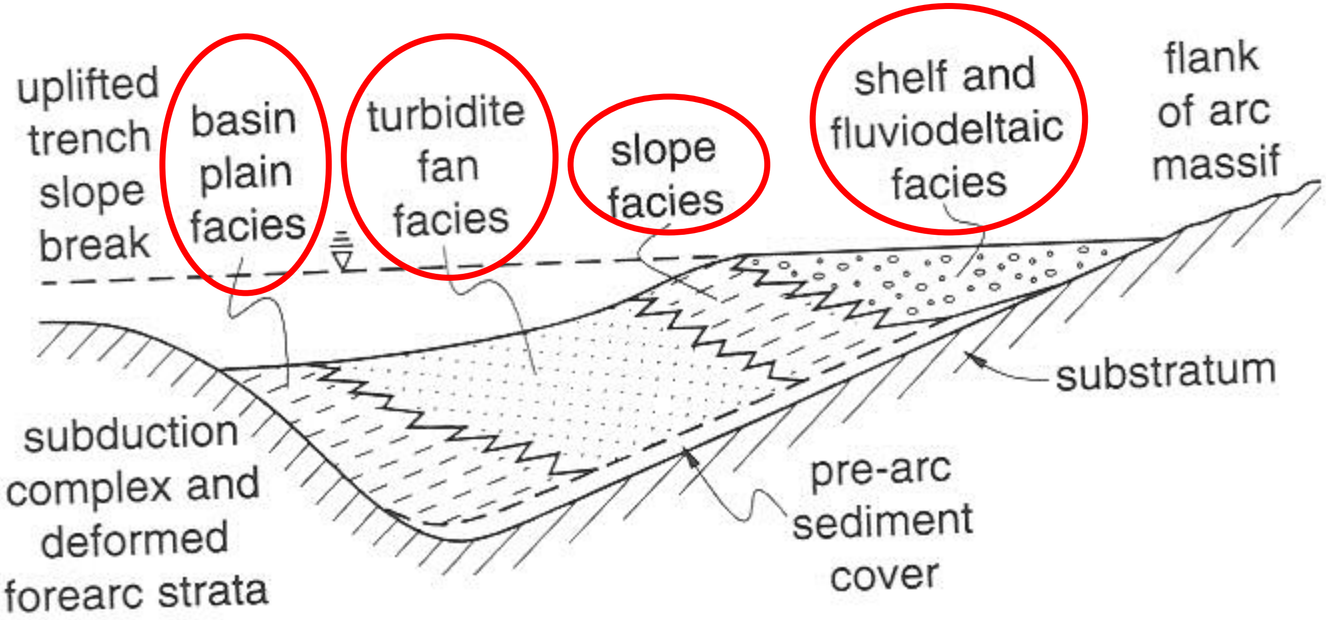


**Fig. 6.8** Facies framework of ideal forearc basin shown in transverse profile (not to scale); character of depositional systems and widths of facies tracts highly variable (see text); pre-arc sediment cover may range from oceanic pelagite and hemipelagite to foundered shelf deposits; influence of intrabasinal structures not depicted.

Distribuce facií v na příčném profilu idealizované předobloukové pánve

Progradace kontinentálních klastických sedimentů

# Zaobloukové pánve
# Backarc basins

- **ZP na kontinentálních okrajích** - extenze vázaná na subdukční systémy (Altiplano v Bolívii)
- **ZP na ostrovních obloucích** - extenze se spreadingovým centrem (Andamanské moře, tyrhénské moře)

**extenze vyvolaná:**

- výstup astenosféry
- injekce plášťovým chocholem
- ústup desky v týlu subdukční zóny
- tok astenosféry - zpětné odtlačování

**modely subsidence**

- synrift - postrift fáze
- izostatický pokles
- zatížení sedimentem
- termální subsidence

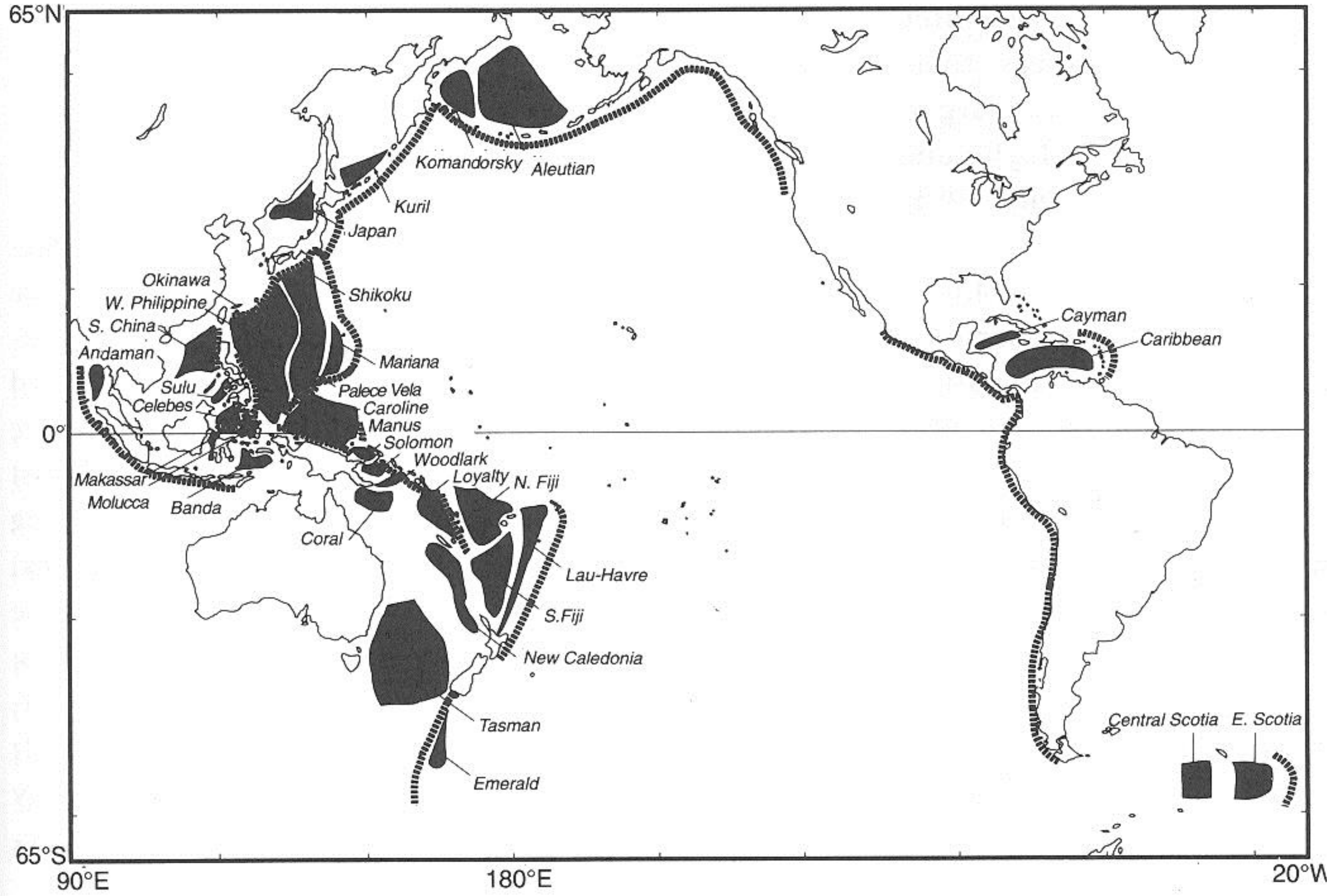
**opakované fáze zaobloukové extenze**

- aktivní a neaktivní oblouky

**sedimentace**

- oceánská sedimentace, pelagické sedimenty, vulkanoklastika

# Rozmístění příkopů a zaobloukových pánví v cirkumpacifickém regionu



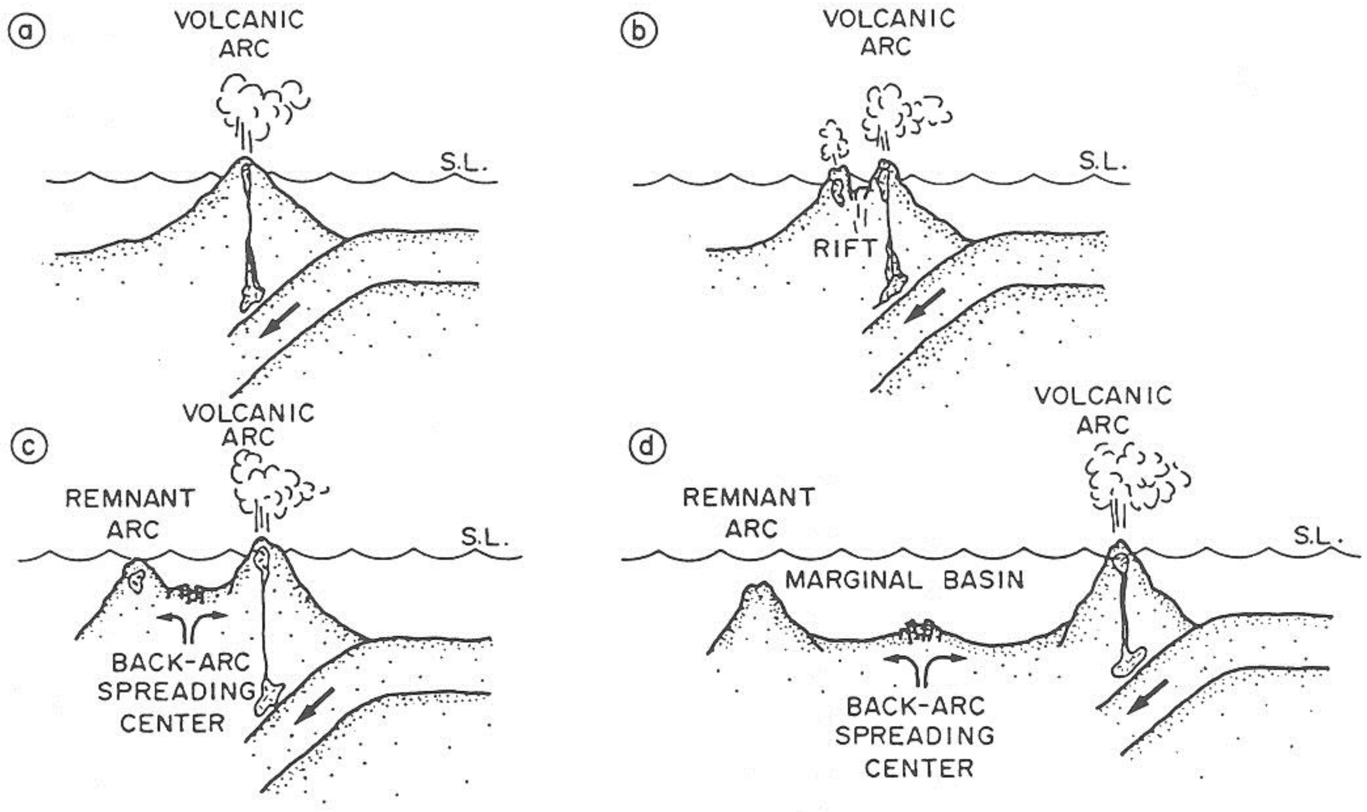
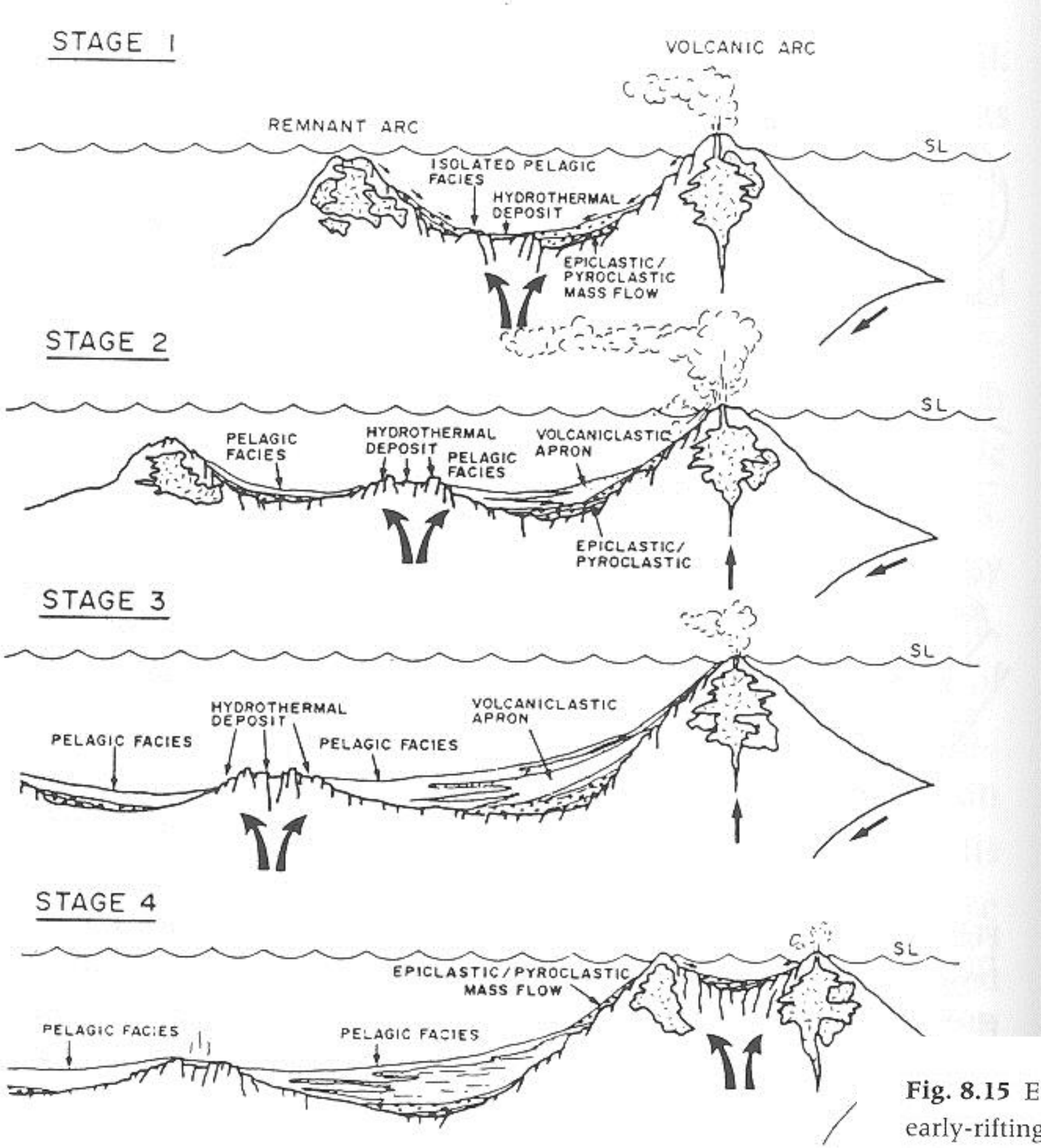


**Fig. 8.2** Generalized tectonic evolution of an intraoceanic backarc basin. From Carey and Sigurdsson (1984). After Karig (1971a,b).

Idealizovaný tektonický vývoj intraoceánské zaobloukové pánve
Volcanic arc – magmatický oblouk
Remnant arc – zbytkový oblouk



Idealizovaný vývoj sedimentace v intraoceánské zaobloukové pánvi

Pelagické facie

Hydrotermální depozita

Vulkanoklastické facie

STAGE 1: raný rifting, vysoký přísun vulkanoklastik

STAGE 2: rozpínání zaobloukové pánve, rychlý přísun vulkanoklastik

STAGE 3: uklidnění vulkanické aktivity, pokrývka pelagickými sedimenty

STAGE 4: ukončení rozpínání na oceánském hřbetu

**Fig. 8.15** Evolutionary model of backarc-basin sedimentation. During early-rifting stage (1) and backarc-spreading stage (2), there is a high influx of volcaniclastic material. The volcaniclastic apron produced during Stages 1 and 2 is draped by pelagic sediments as the basin matures and volcanism wanes in Stage 3. In Stage 4, the spreading axis becomes inactive and extension within the volcanic arc signals a second phase of backarc-basin formation. From Carey and Sigurdsson (1984).

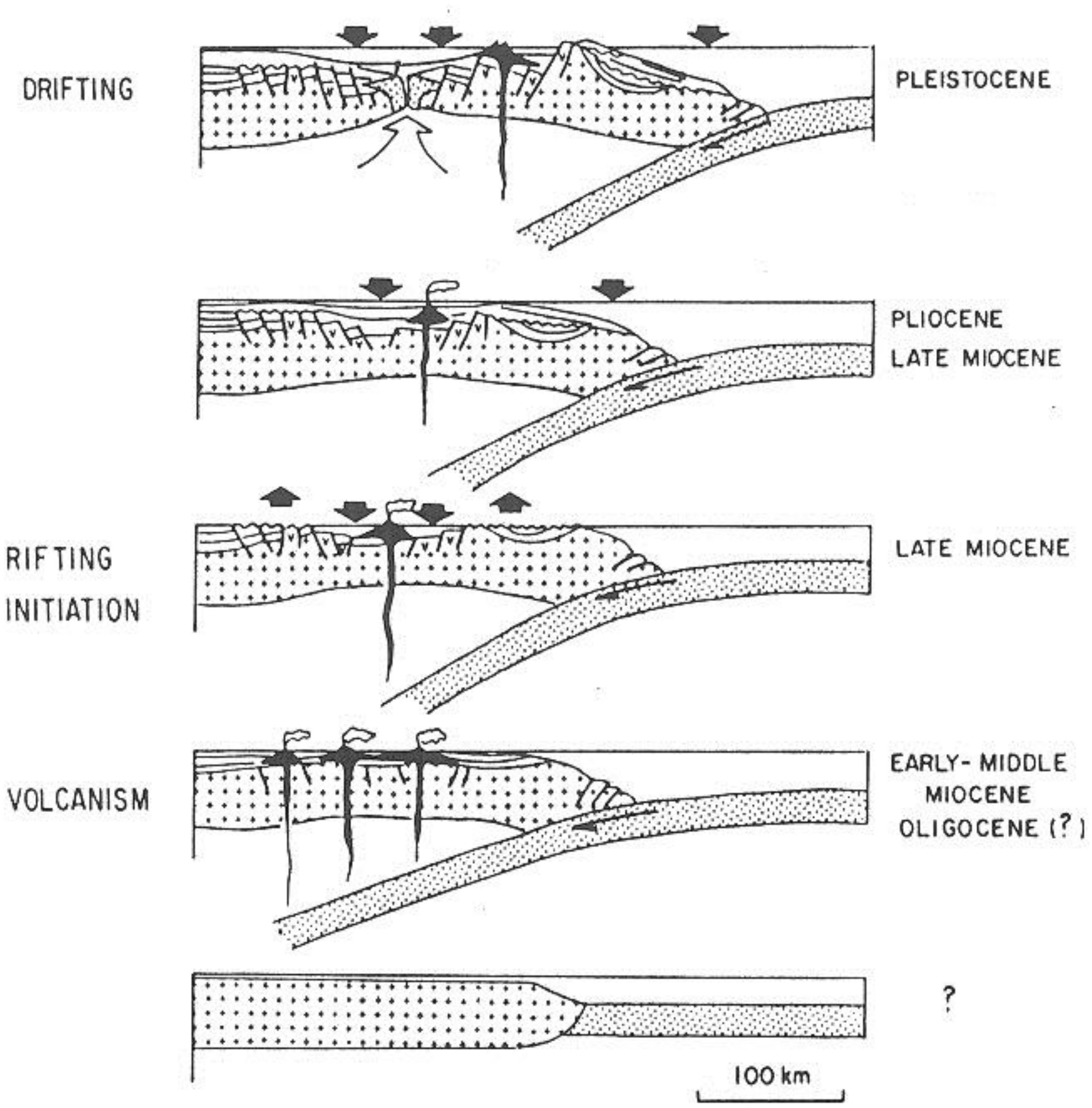
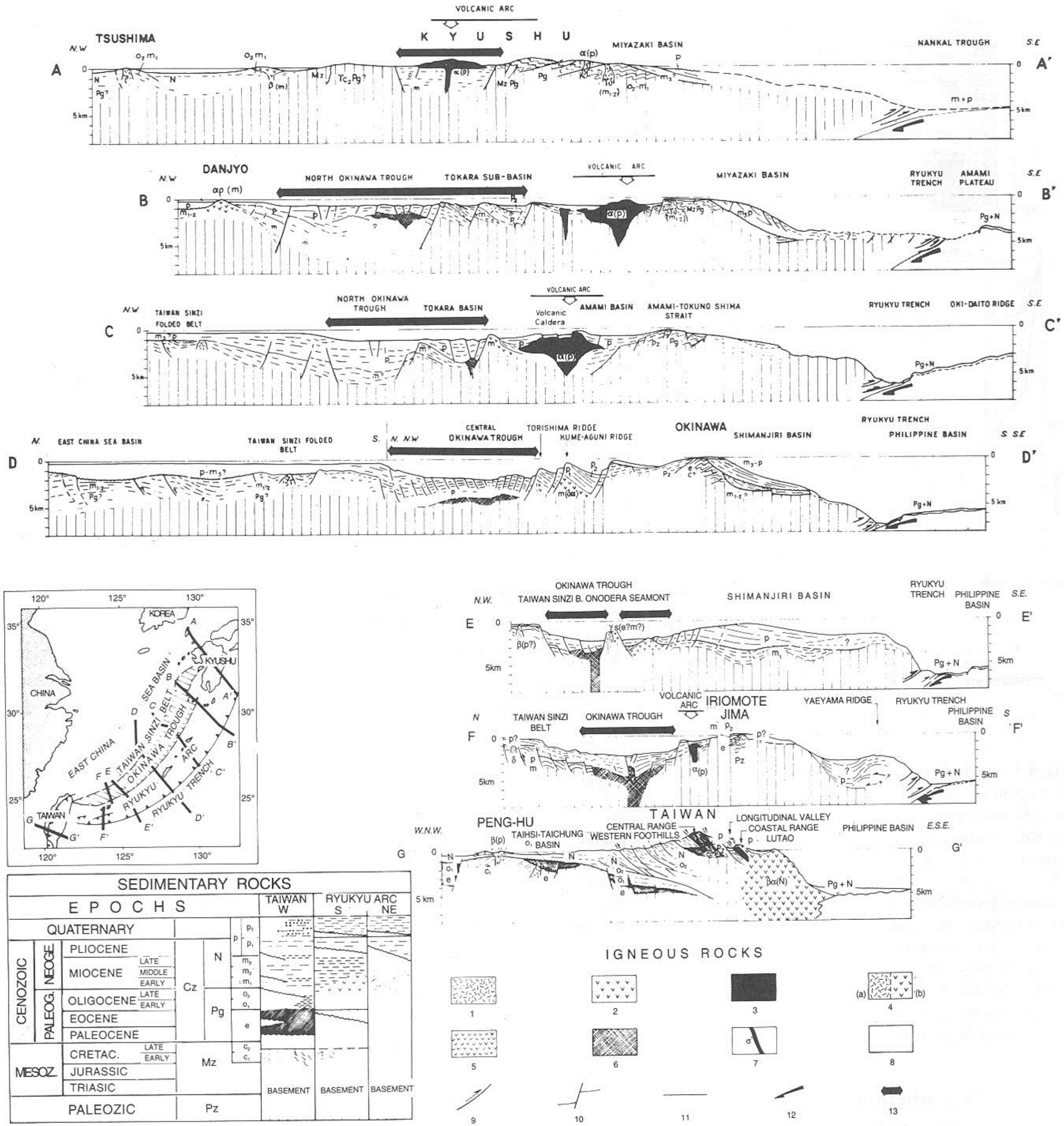


**Fig. 8.11** Tectonic evolution of the Okinawa Trough. From Letouzey and Kimura (1985).

**Kontinentální zaobloukové pánve:**

Tektonický vývoj Okinawského trogu



Příčné profily okinawským trogem (zaoblouková pánev v týlu oblouku Ryukyu)

Basement tvořený kontinentální litosférou

Různá míra extenze podél poklesových zlomů

**Oceánské zaobloukové pánve**

Diagram stáří vs. hloubka podloží (mocnost výplně) okrajových pánví filipínského moře (zaoblouková pánev) a normální oceánské kůry

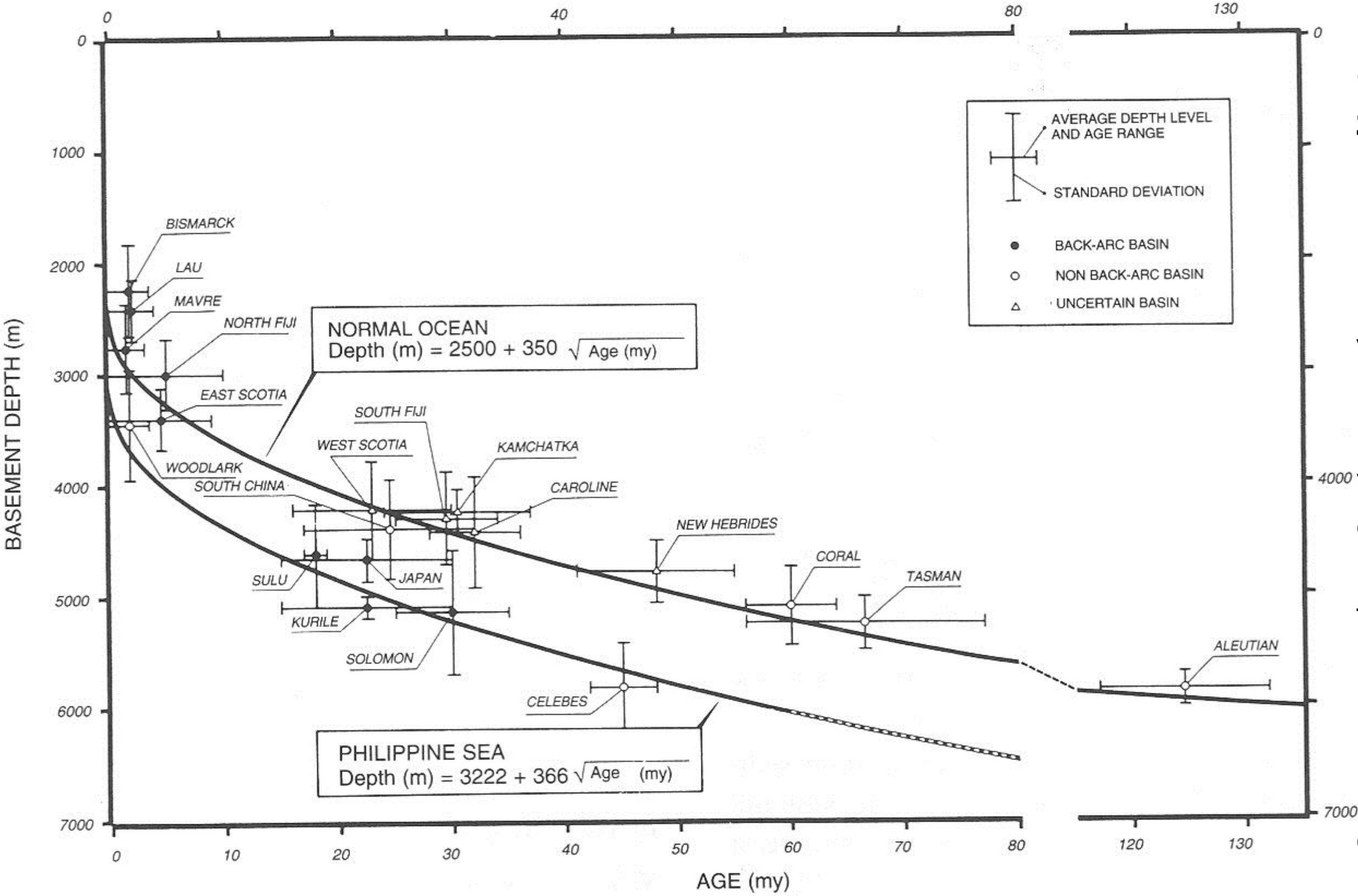


**Fig. 8.10** Age-versus-depth plot, comparing data for selected marginal basins to curves for Philippine Sea backarc basins and normal ocean crust. "Non back-arc basins" are those floored by oceanic crust not produced by sea-floor spreading behind an active arc-trench system. From Park et al. (1990).

Zjednodušený příčný profil, stratigrafické profily a subsidenční křivky riftu Sumisu v týlu oblouku Izu-Bonin (jižně od Japonska)

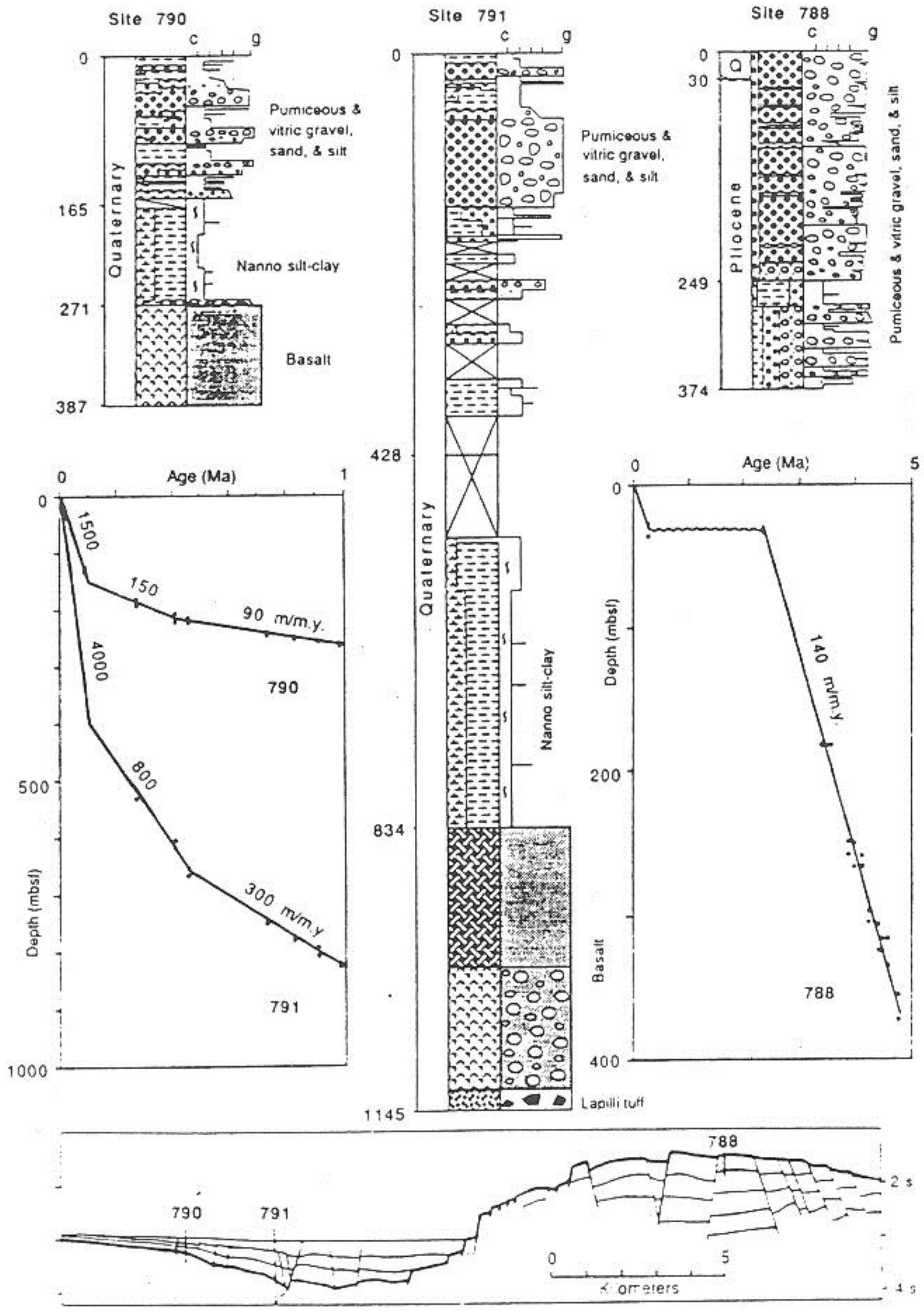
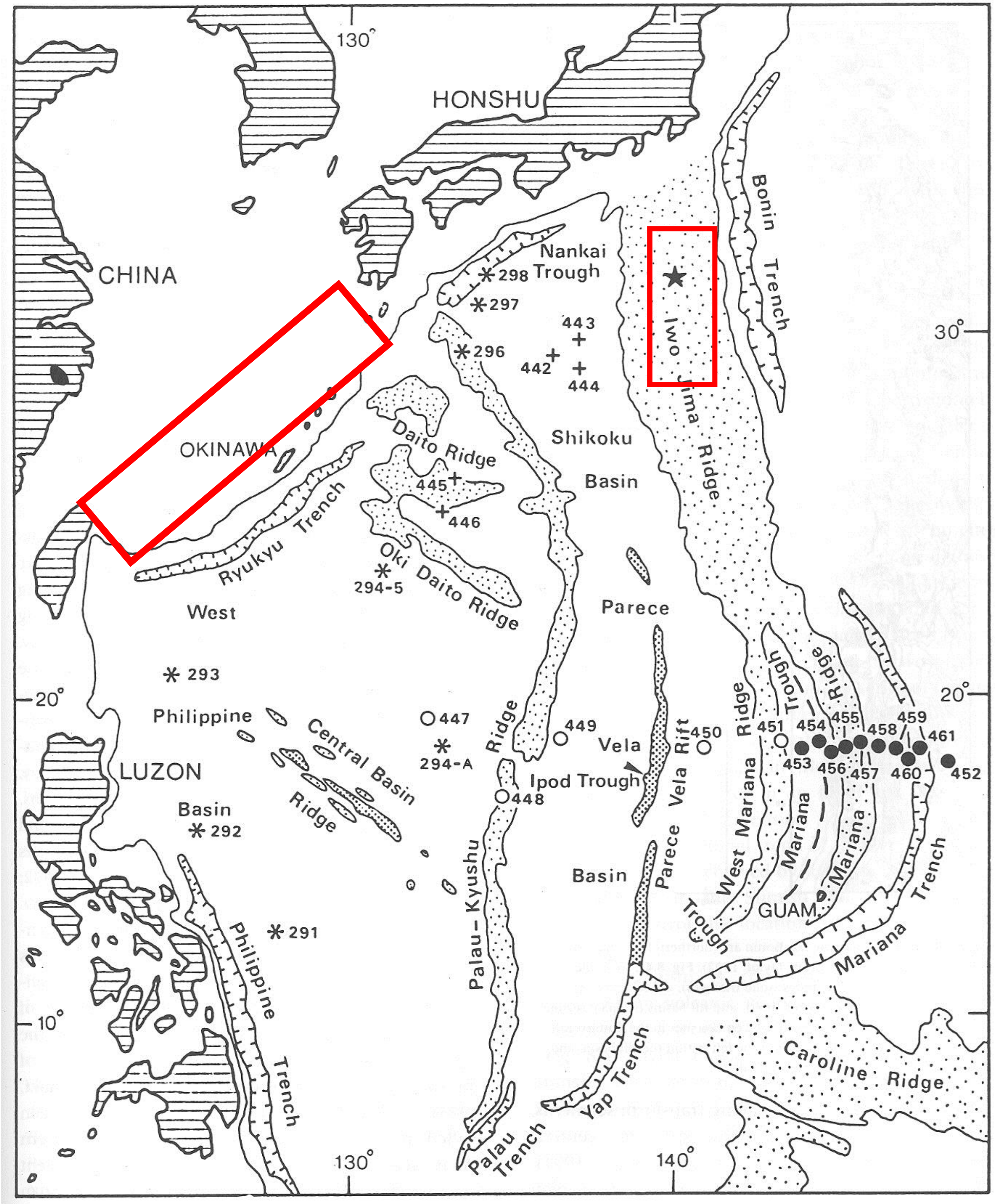


**Fig. 8.9** Simplified cross section, stratigraphic columns and age-versus-depth plots for ODP Leg 126 Sites 788, 790, and 791 in the Sumisu Rift. Site 788 is located on the rift flank, and Sites 790 and 791 in the inner rift. Cross section based on interpretation of an east-west seismic profile at approximately latitude 31°N. Stratigraphic columns indicate lithology (dash, clay to silt; barbed dash, nannofossils; and black dots, sand/sandstone and gravel/conglomerate). Patterns at base of Sites 790 and 791 refer to basaltic breccias and flows. Xs in columns mark intervals with no recovery. Grain size ranges from clay(c) to gravel(g). Wavy vertical lines indicate bioturbation. Slope of age-versus-depth plots gives apparent sediment accumulation rates in meters/million years (m/my). Data points based on paleontologic data. Wavy line in Site 788 plot indicates unconformity. From Taylor et al. (1991), Klaus et al. (1992) and Taylor (1992).

Zaobloukové pánve a zbytkové oblouky filipínského moře



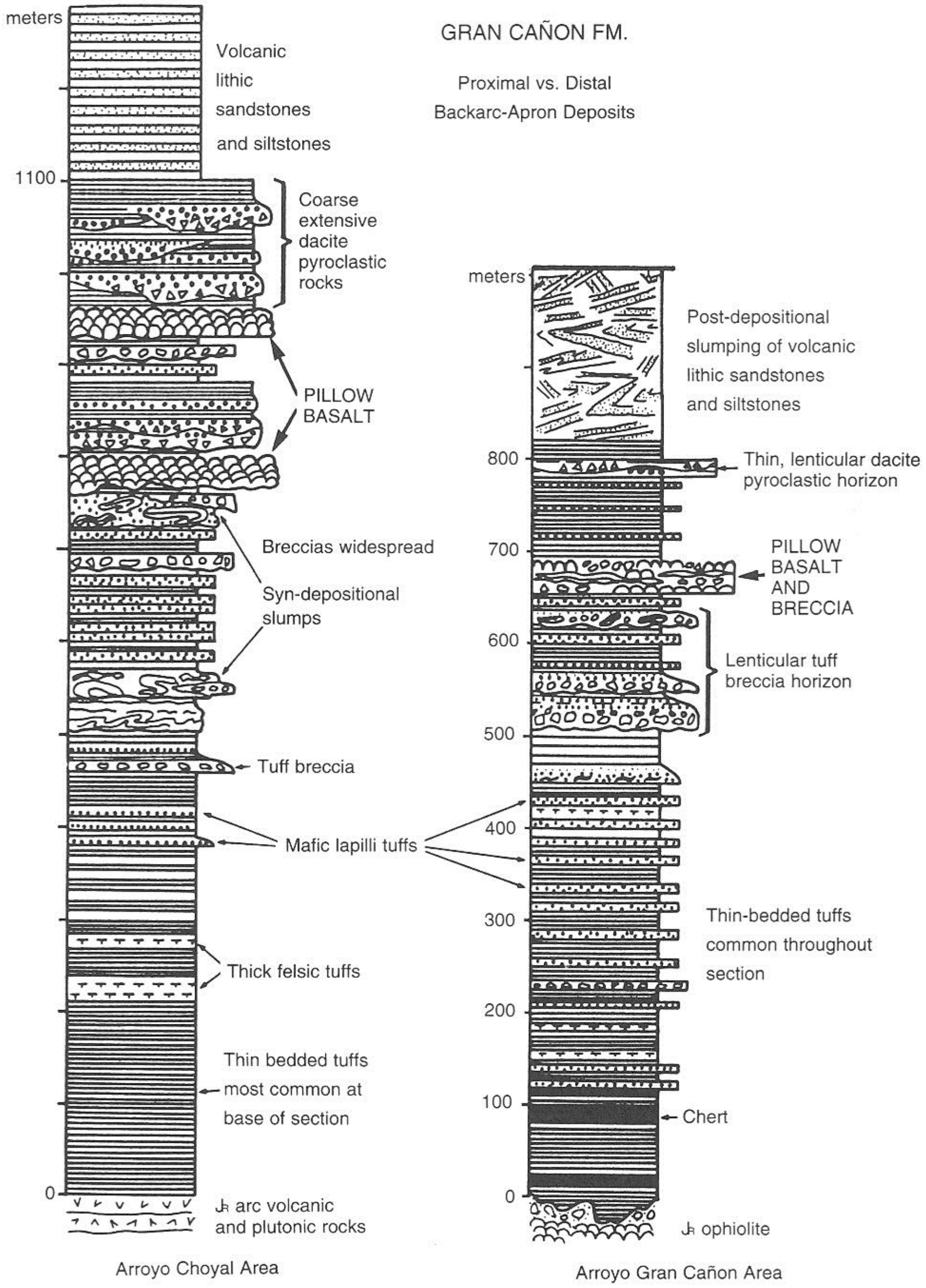


**Fig. 8.17B** Representative measured sections for the Gran Cañon Formation, Cedros Island. From Busby-Spera (1988a).

Reprezentativní stratigrafické kolonky Gran Cańon formation, ostrov Cedros, Baja California, Mexico

Střední jura

Progradace riftového vulkanického komplexu na basement oceánské kůry zaobloukové pánve

# Předpolní pánve v týlu magmatického oblouku (Retroarc foreland basins)

Schématický blokdiagram konvergentního kontinentálního okraje:

3 typy konfigurace týlu oblouku (jihoamerické Andy) v závislosti na úhlu subdukce

Sever: asymetrická týlová předpolní pánev, thin-skinned tectonics

Střed: plochá subdukce, kombinace pánví a hrástí omezených násunovými zlomy (broken foreland)

Jih: předpolní pánev v kombinaci s alkalickými bazalty, slabá tektonická extenze

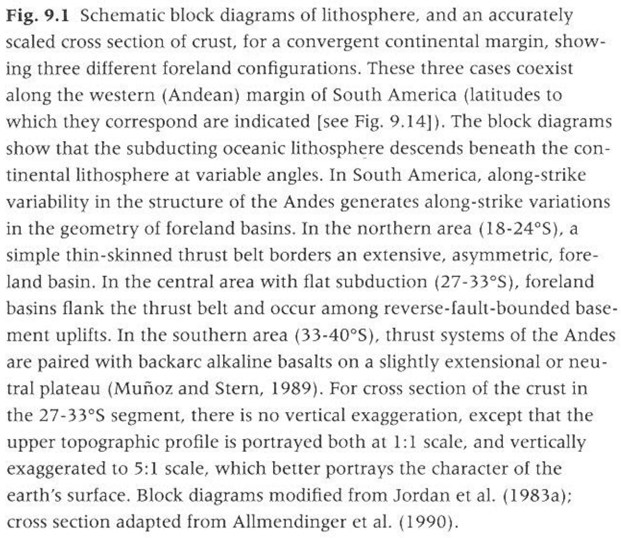
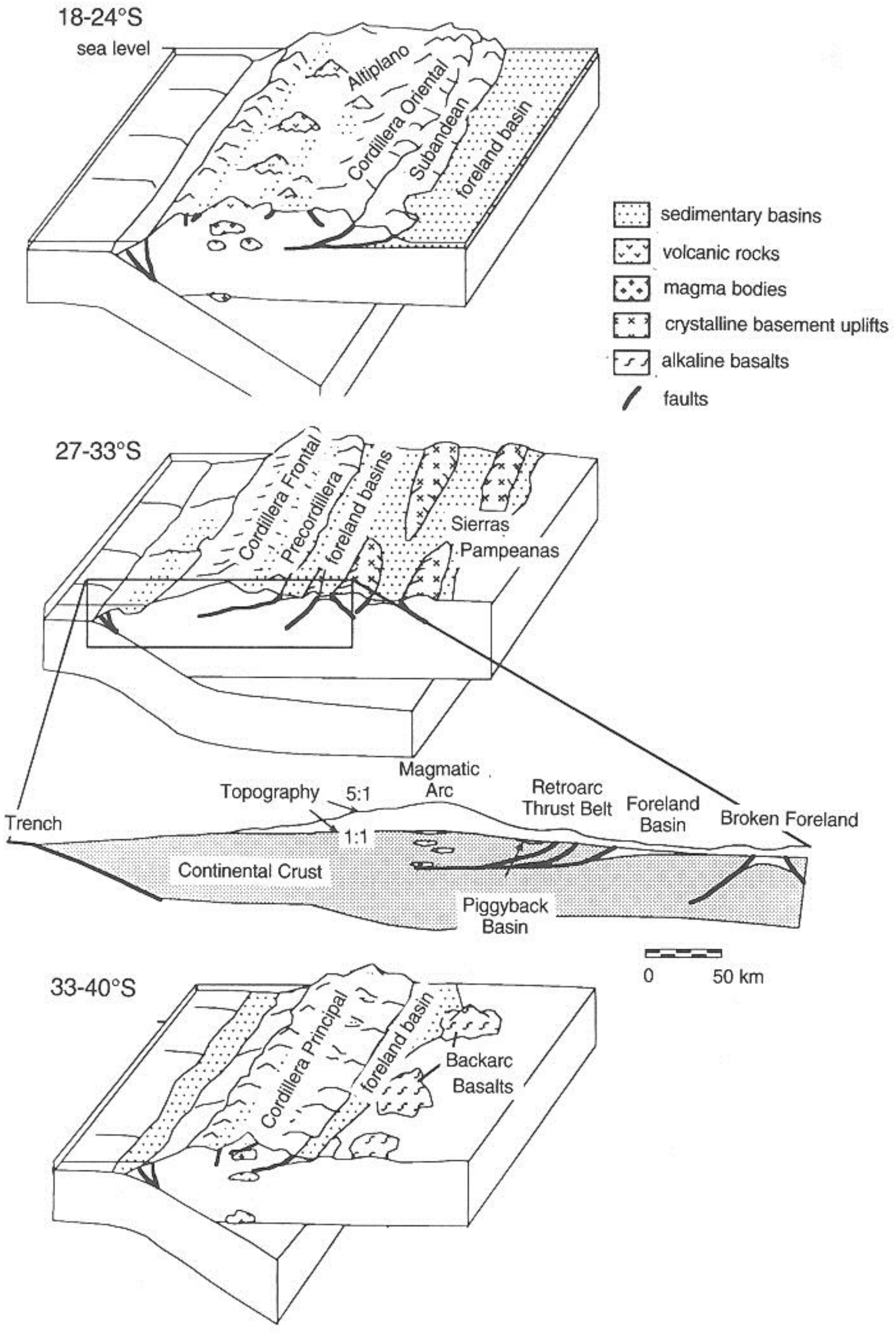


**Fig. 9.1** Schematic block diagrams of lithosphere, and an accurately scaled cross section of crust, for a convergent continental margin, showing three different foreland configurations. These three cases coexist along the western (Andean) margin of South America (latitudes to which they correspond are indicated [see Fig. 9.14]). The block diagrams show that the subducting oceanic lithosphere descends beneath the continental lithosphere at variable angles. In South America, along-strike variability in the structure of the Andes generates along-strike variations in the geometry of foreland basins. In the northern area (18-24°S), a simple thin-skinned thrust belt borders an extensive, asymmetric, foreland basin. In the central area with flat subduction (27-33°S), foreland basins flank the thrust belt and occur among reverse-fault-bounded basement uplifts. In the southern area (33-40°S), thrust systems of the Andes are paired with backarc alkaline basalts on a slightly extensional or neutral plateau (Muñoz and Stern, 1989). For cross section of the crust in the 27-33°S segment, there is no vertical exaggeration, except that the upper topographic profile is portrayed both at 1:1 scale, and vertically exaggerated to 5:1 scale, which better portrays the character of the earth's surface. Block diagrams modified from Jordan et al. (1983a); cross section adapted from Allmendinger et al. (1990).



Předpolní pánev amerického středozápadu (Western Interior), svrchní křída

Klastické sedimenty na západním okraji pánve představují vlastní výplň předpolní pánve

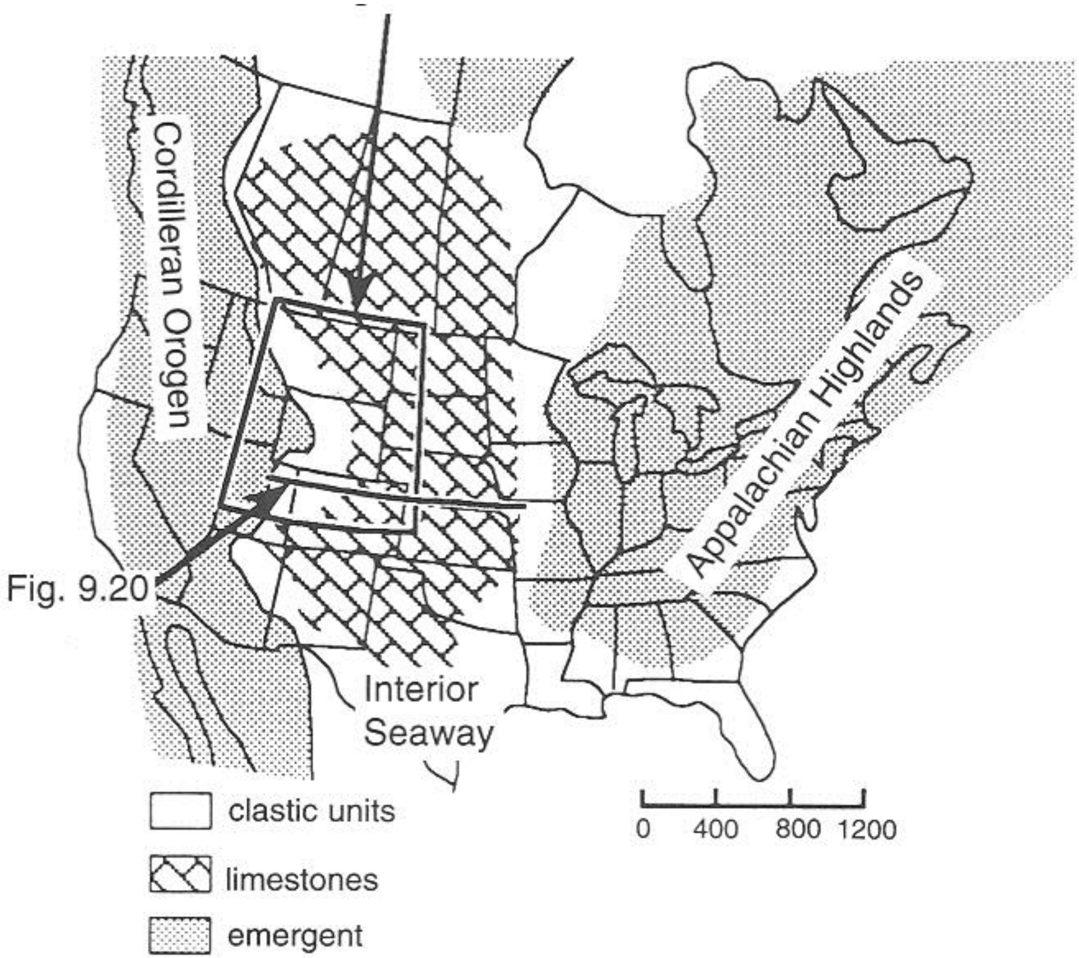


**Fig. 9.18** Extent of the late early Turonian sea in the Western Interior Seaway near the time of maximum marine flooding (after Williams and Stelck, 1975), and distribution of clastic-rich and lime-rich facies (after Kauffman, 1984). The clastic units along the western margin of the basin constitute the principal foreland-basin fill; these grade eastward into thinner, deeper-water limestones.

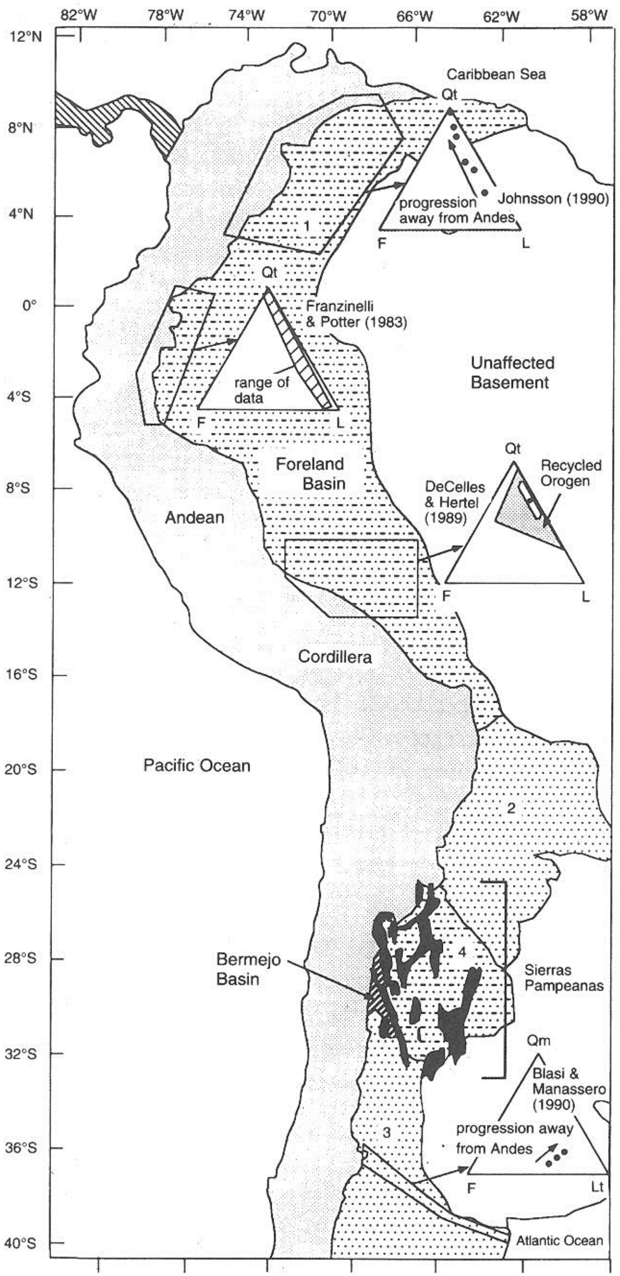


**Fig. 9.14** Distribution of Quaternary foreland basins of the Andes Mountains and Holocene sand compositions (in triangles). Map distinguishes foreland basins with contrasting drainage styles. 1. Foreland basin in a tropical climate drains through Orinocco and Amazon rivers. 2. An overfilled foreland basin in a drier climate, in which nearly all of the sediment appears to be trapped in the basin, although some of water drains to Paranà River. 3. Drainage basin in dry climate, whose rivers traverse the short distance to the Atlantic margin. In northern part of 3, most of the sediment is retained in the foreland basin, but in the southern part of 3, there is little documentation of foreland basins along the edge of the Andes. 4. Internally drained basins, receiving sediment from the Sierras Pampeanas broken foreland (uplifts shown in black) and the Andes Mountains. The Bermejo basin is an internally drained basin, receiving majority of its sediment from Andes, but whose structure is affected by the Sierras Pampeanas (see Fig. 9.15). Map based on DeCelles and Hertel (1989) and J. Damanti (unpublished drainage map). Sand composition data derived from areas enclosed in polygons. Compositions of modern sands for northern localities fall in the recycled-orogen category of Dickinson and Suczek (1979) (plotted for reference on composition triangle near 8° S latitude). Sand compositions for 36° S region are strongly influenced by volcanic arc. Methods varied among the four datasets that are available. DeCelles and Hertel (1989), Johnsson (1990), and Franzinelli and Potter (1983) counted thin sections, whereas Blasi and Manassero (1990) counted grain mounts. DeCelles and Hertel (1989) and Johnsson (1990) stained for calcium and potassium feldspars; Franzinelli and Potter (1983) stained for only potassium feldspar. DeCelles and Hertel (1989) used the Gazzi-Dickinson point-count method (Ingersoll et al. 1984); Johnsson (1990) and Franzinelli and Potter (1983) did not.

there are basement blocks bounded by reverse faults (Sierras Pampeanas) east of a thin-skinned thrust belt (Precordillera). The Sierras Pampeanas produce a set of broken-foreland basins and the Precordillera produces a standard foreland (Bermejo) basin. From 33 to 40° S, shortening is confined to a narrow thrust belt on the eastern flank of the Andes, and there is a transition in the foreland from basins in the north to a plateau further south, with backarc alkaline basalts on the plateau, and little deformation or very minor normal faulting (Muñoz and Stern, 1989). All of these Central Andean basins are now nonmarine and were nonmarine during most of their Mio-Pliocene development (N.M. Johnson et al., 1986; Jordan and

Kvartérní týlové předpolní pánve podél oblouku And

1: předpolní pánve v tropickém klimatu odvodňované Orinokem a Amazonkou

2: přesycené pánve v semiaridním klimatu, téměř veškerý sediment je zachycen v pánvi

3: aridní klima, veškerý sediment je zachycen v pánvích

Ternární diagramy ukazují provenienci z recyklovaného orogénu, na jihu ovlivněné vulkanickou aktivitou oblouku

# Sedimentační záznam předpolních pánví

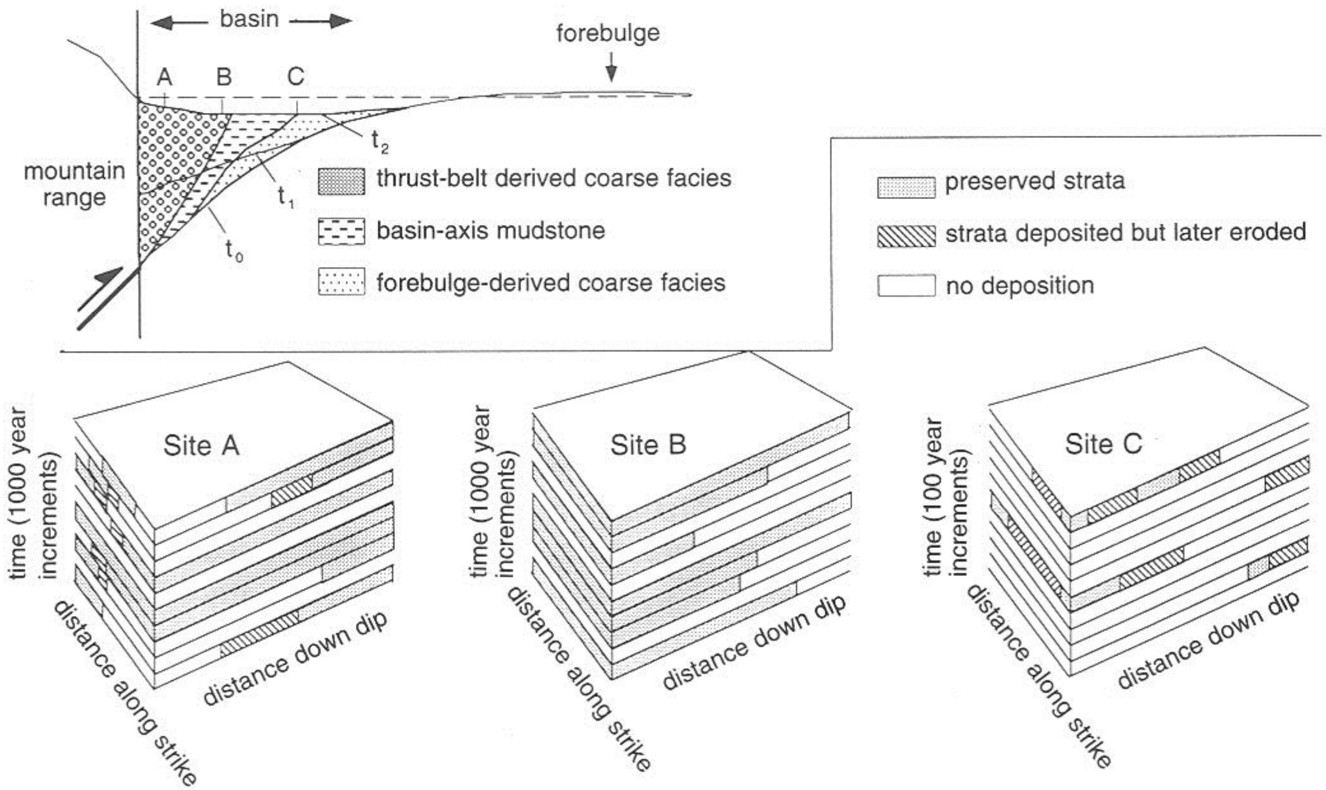


**Fig. 9.8** Foreland basins are unusually complete registers of geologic time in nonmarine environments. Block diagrams compare the record of time (in 1000-year increments) at three positions in a cross section of a foreland basin. Site A is in a proximal zone, with ample subsidence and sediment supply to capture most depositional events, but where a channelized depositional environment tends to limit the lateral distribution of depositional events and to subject those strata to subsequent erosion. Site B is slightly farther down depositional slope. It contains the most complete temporal record: there are ample subsidence and sediment supply, coupled with unchannelized deposition (hence little erosional power) in distal alluvial fans. Site C is a distal site, with a very incomplete stratigraphic record. The primary factor is the slow subsidence, which reduces the chance of deposition and increases the time during which a stratum remains at the surface to be subject to erosion by subsequent events. Based on Barrell (1917), Wheeler (1958), and McRae (1990), with time increment consistent with work of Beer (1990). $t_0$, $t_1$, and $t_2$ in reference cross section are successive time lines.

Předpolní pánve jsou dobrými archívy nemarinní sedimentace

Časový záznam sedimentace ve třech pozicích předpolní pánve

A: proximální zóna: subsidence + vysoký přínos materiálu, vysoká míra eroze díky fluviální činnosti

B: nejkompletnější záznam, subsidence + přísun sedimentu, distální prostředí

C: distální zóna, nekompletní stratigrafický záznam díky pomalé subsidenci (nesedimentace, eroze)

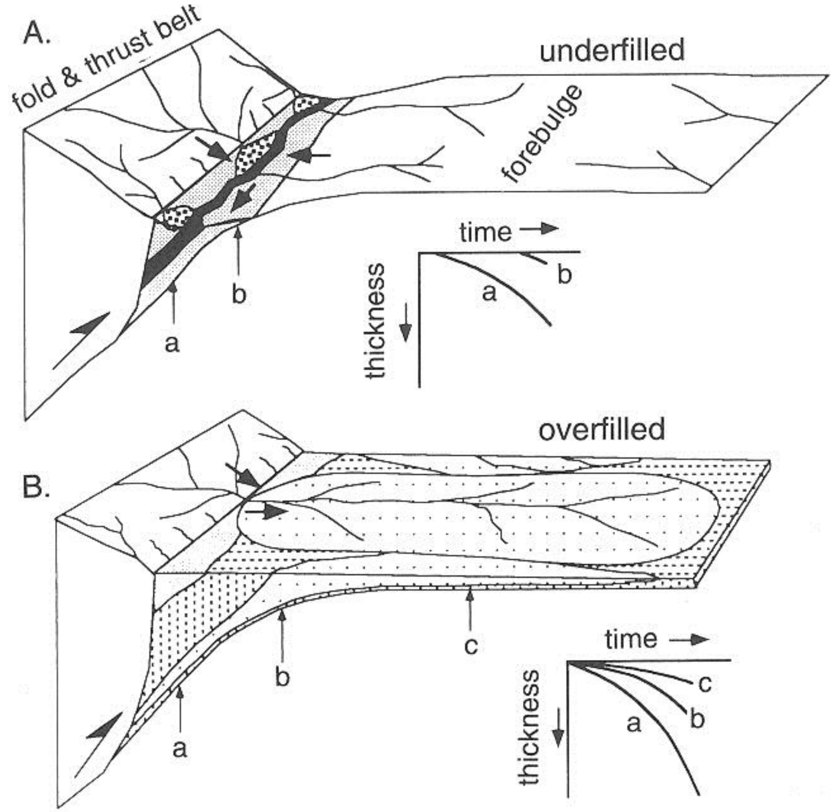


**Fig. 9.6** Comparison of the geometry and facies of underfilled and overfilled foreland basins. Based on steady-state model of Flemings and Jordan (1989). A) The underfilled basin forms a valley, and receives sediment from both the thrust belt and peripheral bulge (forebulge). B) In the overfilled basin, the peripheral bulge receives sediment from the thrust belt and is expressed only by slower accumulation and thinner strata than in the proximal zone. Insets show the accumulation history at increasing distances from the thrust front, revealing that the accumulation rate is slower in distal sites compared to proximal sites. Although the tectonic-subsidence histories may be identical for these two basins, the accumulation histories of the underfilled and overfilled cases are quite different (see text).

Geometrie a facie přesycené a podsycené týlové předpolní pánve:

Forebulge („výduť“) v předpolí pánve díky flexurálnímu průhybu podložní litosférické desky

-Eroze forebulge u podsycené pánvy

-Sedimentace na forebulge u přesycené pánve

-Tektonická subsidence může být stejná u obou pánví – rozhodující je kontrola přísunem sedimentu

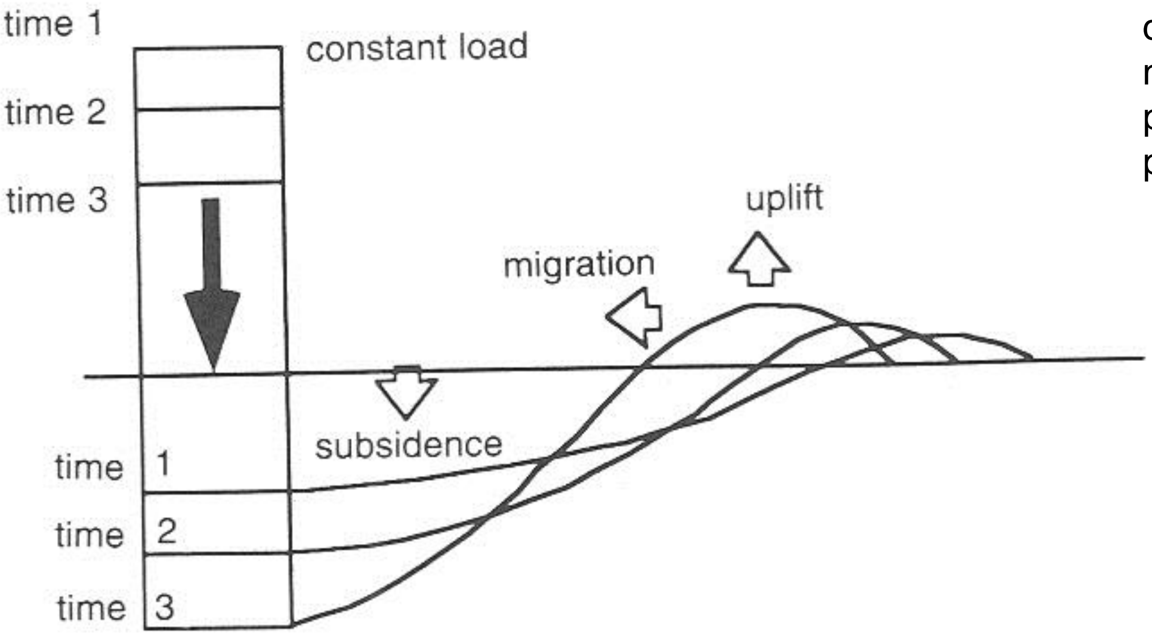


**Fig. 9.5** Cross section of a viscoelastic beam, adjusting to a constant load over a long period of time. The initial response (time 1) is regional flexure, as in Fig. 9.4, but the basin narrows progressively through time (after Quinlan and Beaumont, 1984).

Model viskózně elastické desky pod dlouhodobou zátěží – výzdvih a migrace forebulge směrem k předpolí a vývoj subsidence v předpolní pánvi

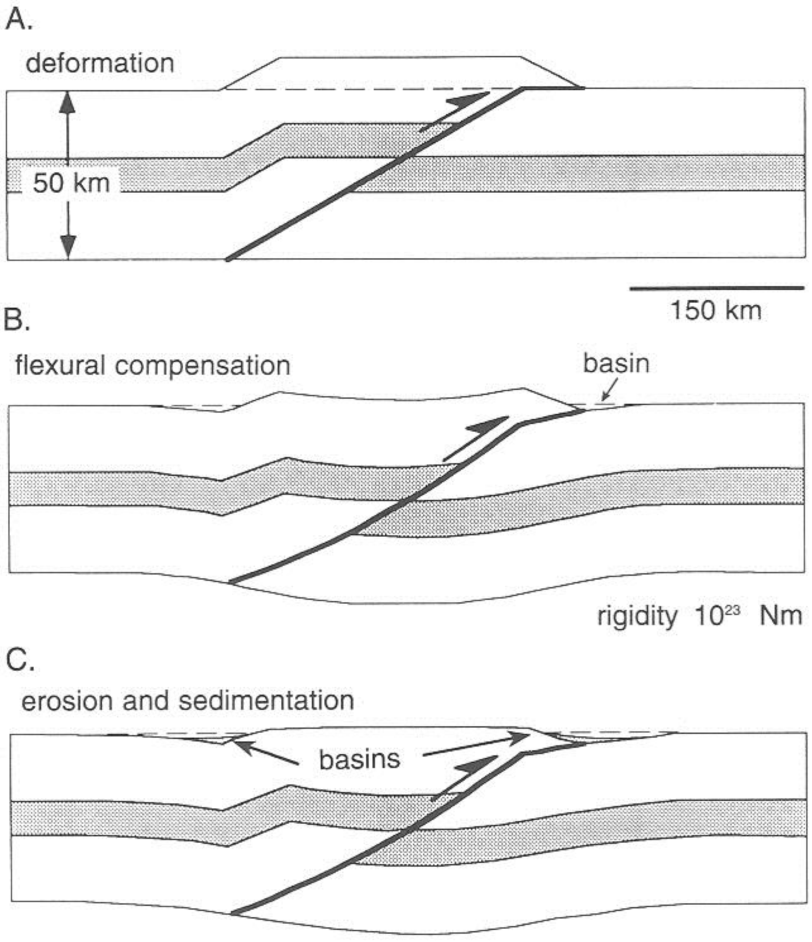


**Fig. 9.3** Three conceptual steps in formation of sedimentary basins flanking a thrust belt (vertical exaggeration 3×). A) Shortening causes thickening above a ramp, which acts as a load. B) Regional compensation of the load deflects lithosphere (note smooth arc at base of profile), producing basins at flanks of mountain range. C) Surface processes strip material from the mountain range and transfer it to the tectonic basins. Flexural compensation for erosion and deposition causes the basins in C to be wider than in B. Simplified model treats thickening in an orogenic belt as the result of shortening along one master fault that penetrates the crust; middle patterned layer is a marker horizon. Dashed line shows initial elevation of upper surface of crust (after Flemings and Jordan, 1990).

Tři fáze vývoje předpolních pánví:

A) Zkrácení vede k ztluštění litosféry – zátěž

B) Regionální kompenzace zátěže – flexurální subsidence

C) Eroze materiálu z vyzdvižené oblasti (pohoří) a transport do tektonických pánví na okraji pohoří, pokročilá flexurální subsidence

# Zbytkové pánve (Remnant basins)

- **ZBYTKOVÉ PÁNVE**
- **modely subsidence**
- **zbytková pánev**
- počáteční hloubka oceánského dna je funkcí stáří oceánské litosféry
- termální subsidence
- zatížení sedimentem
- subsidenční křivky jsou v podstatě nesetrojitelné, subdukce, pohlcení, tektonika
- flyš,
- časová polarita sedimentace - zmlazování směrem k předpolí
- **sedimentace**
- flyšové systémy
- švýcarské flyšové pánve
- pohoří Marathon - Quachita
- kulm ?
- svahové osypy, turbiditní vějíře, malé nebo velké, osní distribuce sedimentu
- typická sukcese sedimentace
- oceánské sedimenty a vulkanity - černé břidlice - pelagity - distální flyš - proximální flyš - molasa

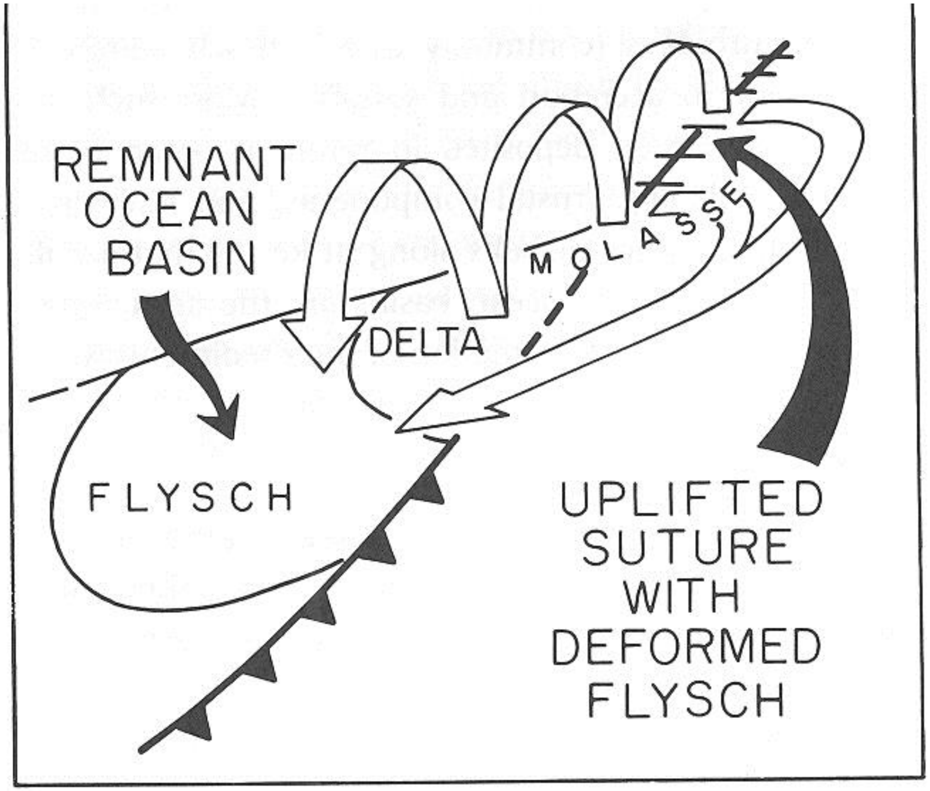
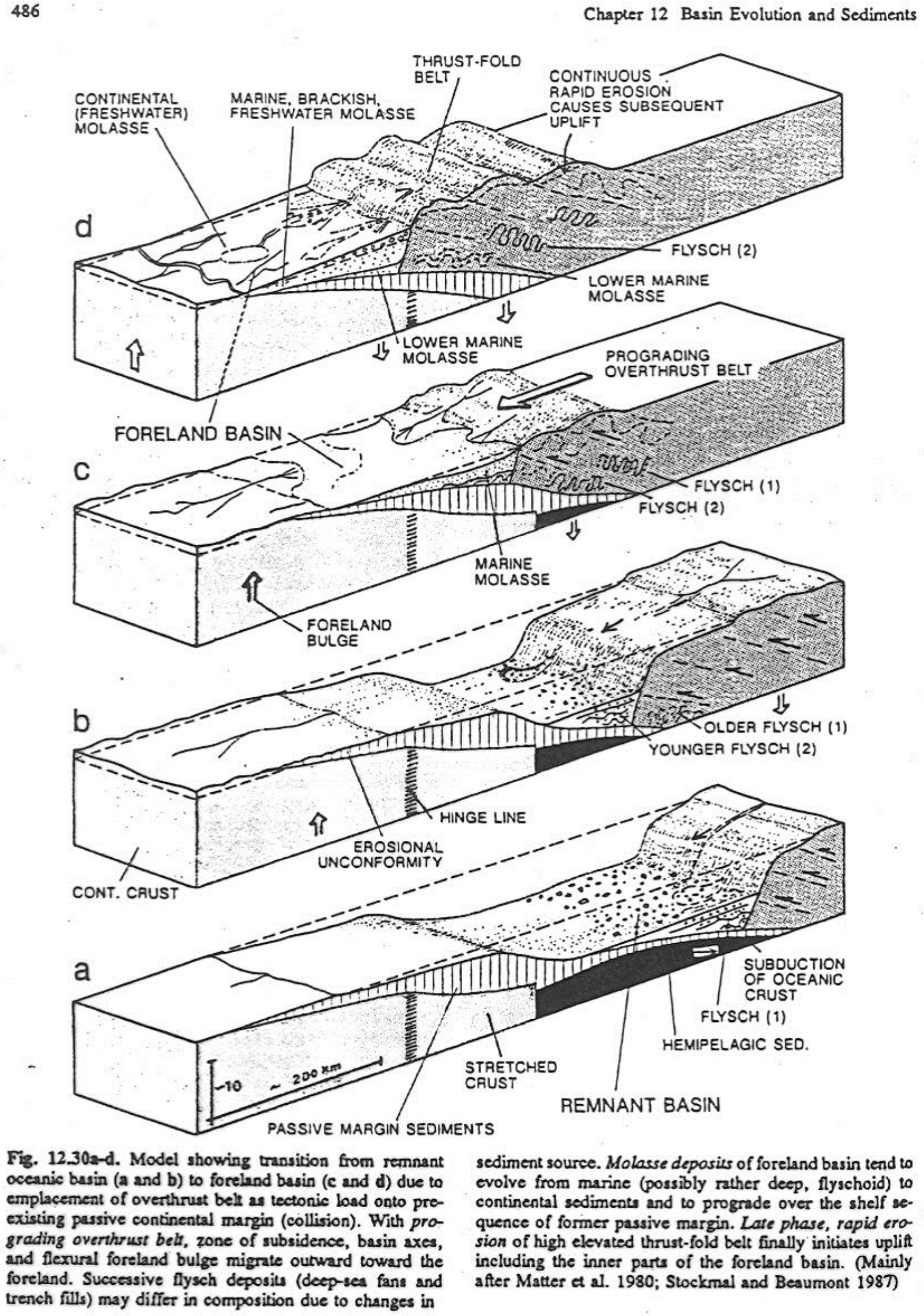


**Fig. 10.1** Conceptual diagram to illustrate progressive incorporation of synorogenic flysch within an orogenic suture belt by sequential closure of remnant ocean basin. From Graham et al. (1975).

Progresivní začleňování synorognního flyše do orogenního pásma postupným uzavíráním zbytkové oceánské pánve



486 Chapter 12 Basin Evolution and Sediments

**Fig. 12.30a-d.** Model showing transition from remnant oceanic basin (a and b) to foreland basin (c and d) due to emplacement of overthrust belt as tectonic load onto pre-existing passive continental margin (collision). With *prograding overthrust belt*, zone of subsidence, basin axes, and flexural foreland bulge migrate outward toward the foreland. Successive flysch deposits (deep-sea fans and trench fills) may differ in composition due to changes in sediment source. *Molasse deposits* of foreland basin tend to evolve from marine (possibly rather deep, flyschoid) to continental sediments and to prograde over the shelf sequence of former passive margin. *Late phase, rapid erosion* of high elevated thrust-fold belt finally initiates uplift including the inner parts of the foreland basin. (Mainly after Matter et al. 1980; Stockmal and Beaumont 1987)

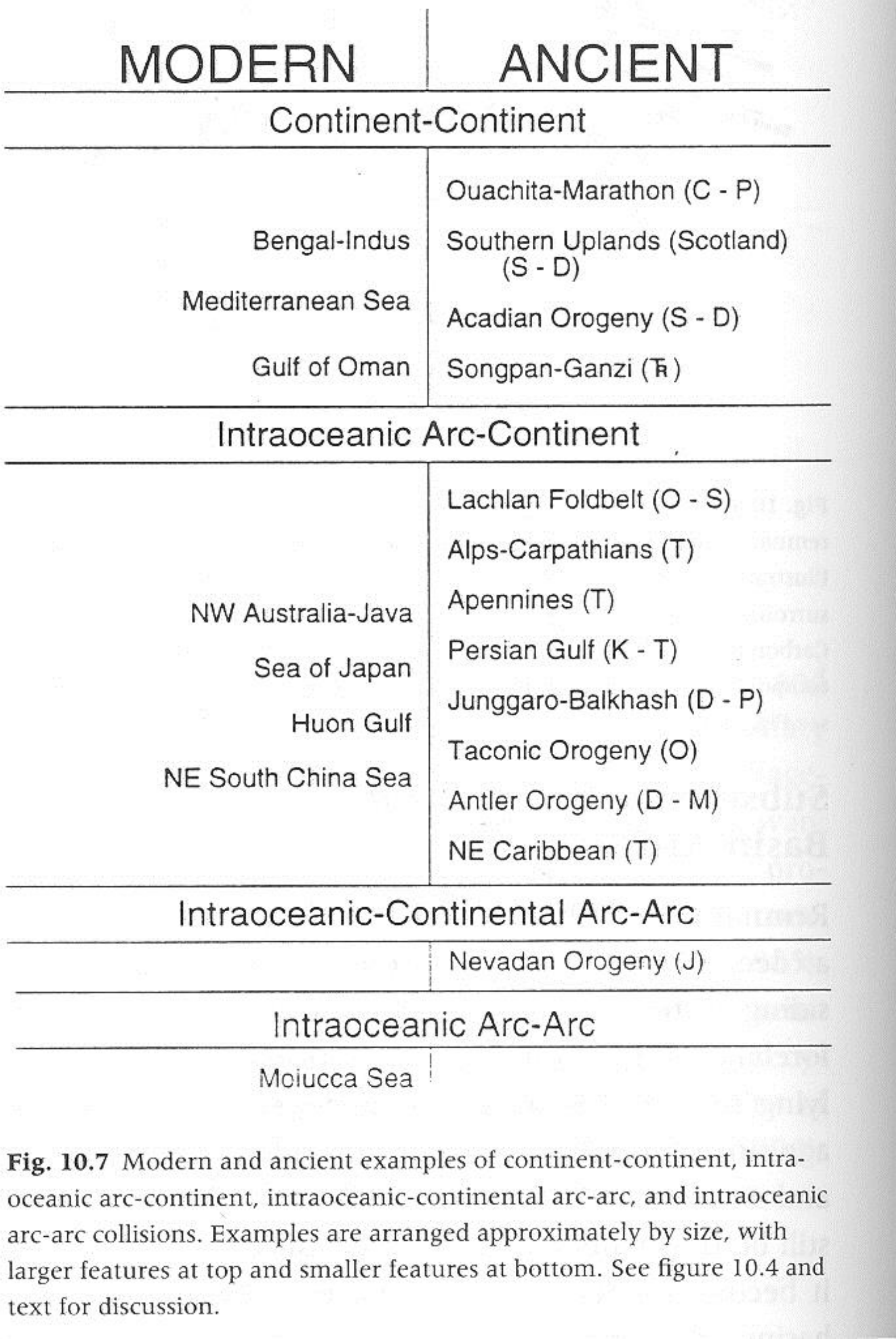
Postupný přechod od zbytkové pánve do periferní předpolní pánve

Migrace osy pánve směrem do předpolí

Změna provenience flyšových jednotek

Vývoj molasových pánví od marinních do kontinetálních

# Kolizní systémy



| MODERN | ANCIENT |
|---|---|
| **Continent-Continent** | |
| | Ouachita-Marathon (C - P) |
| Bengal-Indus | Southern Uplands (Scotland) (S - D) |
| Mediterranean Sea | Acadian Orogeny (S - D) |
| Gulf of Oman | Songpan-Ganzi (TR) |
| **Intraoceanic Arc-Continent** | |
| | Lachlan Foldbelt (O - S) |
| | Alps-Carpathians (T) |
| NW Australia-Java | Apennines (T) |
| Sea of Japan | Persian Gulf (K - T) |
| Huon Gulf | Junggaro-Balkhash (D - P) |
| NE South China Sea | Taconic Orogeny (O) |
| | Antler Orogeny (D - M) |
| | NE Caribbean (T) |
| **Intraoceanic-Continental Arc-Arc** | |
| | Nevadan Orogeny (J) |
| **Intraoceanic Arc-Arc** | |
| Molucca Sea | |

**Fig. 10.7** Modern and ancient examples of continent-continent, intraoceanic arc-continent, intraoceanic-continental arc-arc, and intraoceanic arc-arc collisions. Examples are arranged approximately by size, with larger features at top and smaller features at bottom. See figure 10.4 and text for discussion.

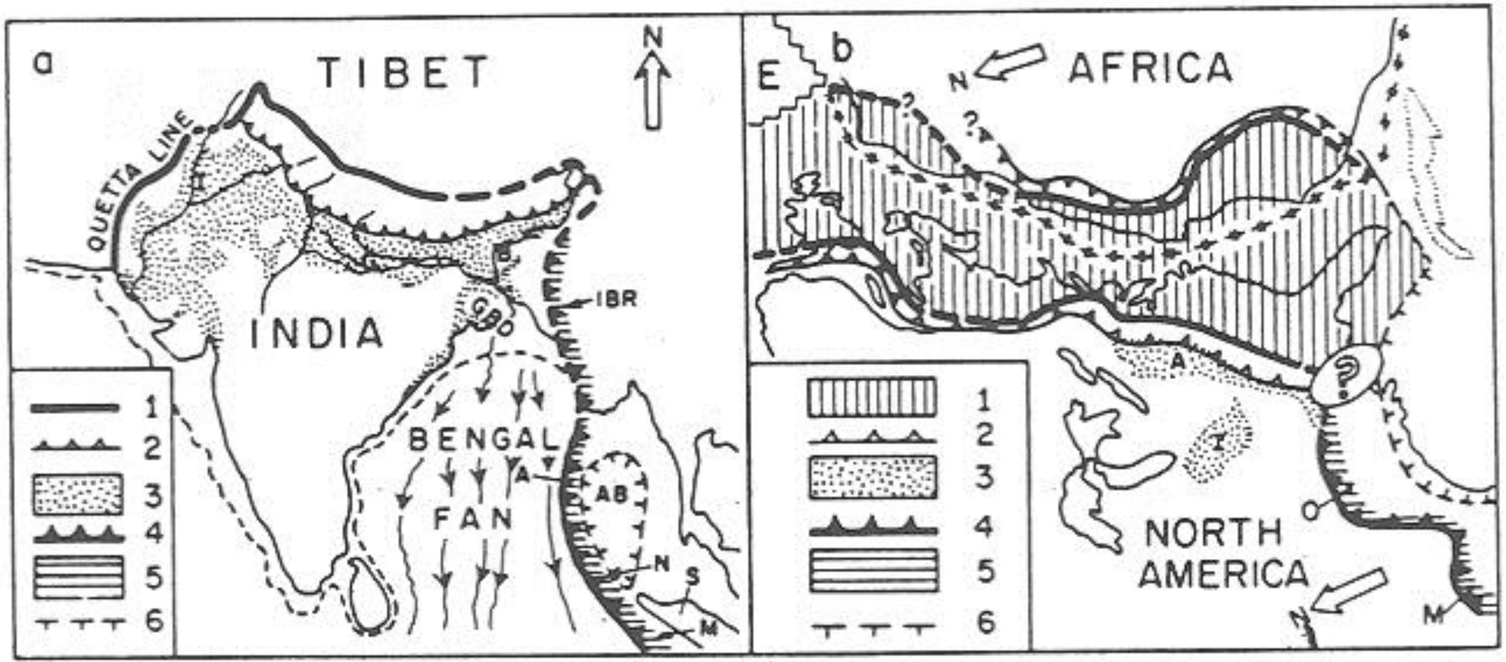


**Fig. 10.2** Main tectonic elements of Himalayan-Bengal (A) and Appalachian-Ouachita (B) regions at same scale. Symbols: A. 1, Himalayan suture belt between India and Eurasia; 2, Main Boundary fault (thrust) of Himalayan foothills; 3. Quaternary alluvium of Indus (I), Ganges (G) and Brahmaputra (B) river systems; arrows denote channel trends on subsea Bengal Fan with head near Ganges-Brahmaputra Delta (GBD); 4, Indoburman-Sunda subduction zone, dashed where inactive; 5, melanges and deformed flyschoid rocks of Indoburman Ranges (IBR), Andaman (A) Nicobar (N) insular ridge, and Mentawai (M) Islands off Sumatra (S); 6, schematic margin of extensional Andaman basin (AB). Dashed line is 1,000 m isobath of continental slope off India. B. 1, Complex belt of multiple Paleozoic suturing between North America and West Africa cratons shown joined (E is Europe) prior to Mesozoic opening of the Atlantic Ocean approximately along the stitched line; 2, fronts of foreland fold-thrust belts of Appalachian Valley and Ridge province (American side) and Mauritanides (African side); 3, coarse Carboniferous clastic strata, terrestrial and littoral, of Appalachian (A) and Illinois (I) basins; 4, frontal thrusts and folds of Ouachita system; 5, outcrop and known subcrop of Ouachita system; 6, schematic extensional margin of Mesozoic Gulf of Mexico (present position of Cuba shown in dotted outline). Question mark shows location of Black Warrior basin at transition from Appalachian foreland to Ouachita remnant ocean basin. From Graham et al. (1975).

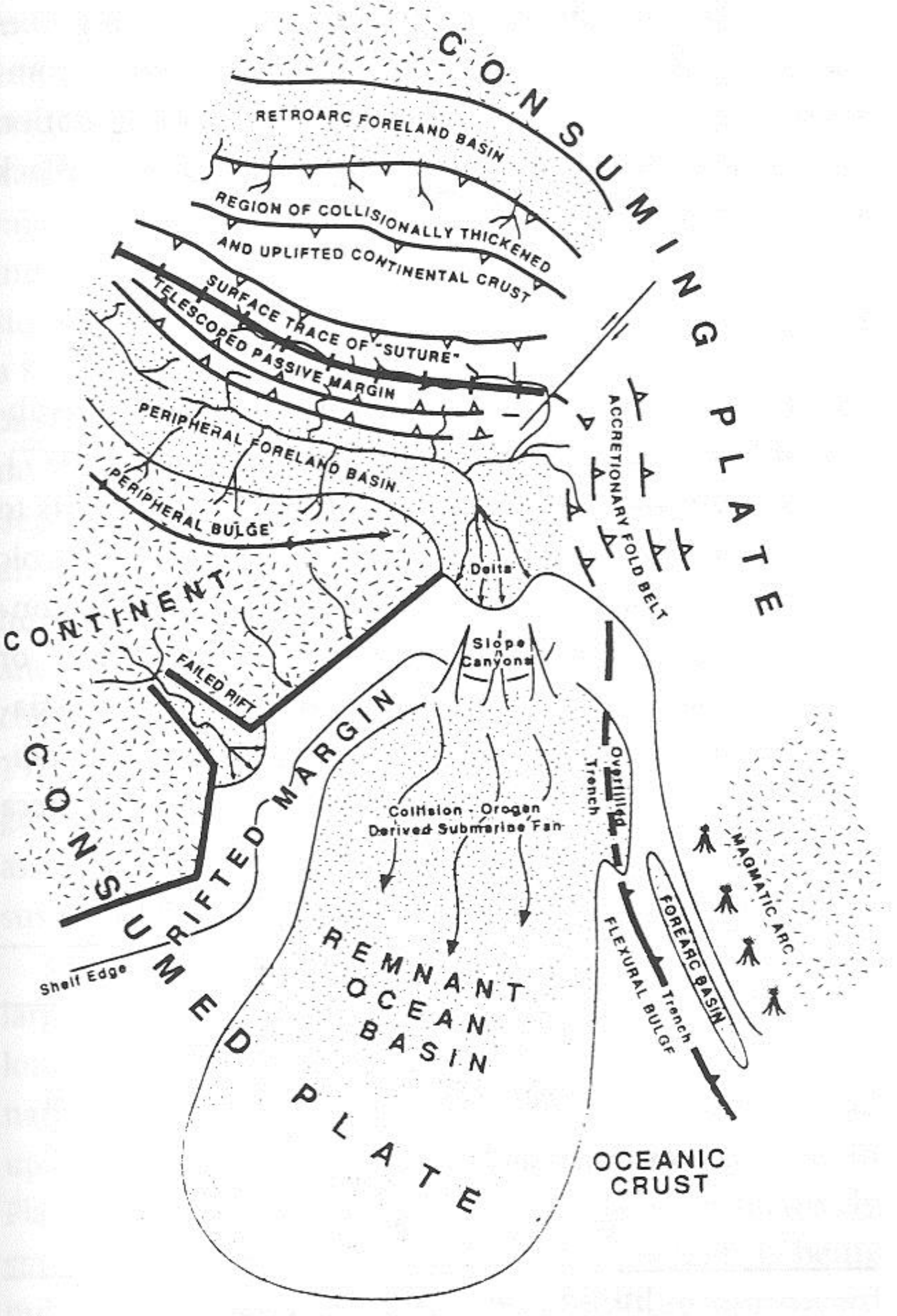


**Fig. 10.6** Morphotectonic map showing most components of typical remnant ocean basins closing sequentially between colliding continents. Illustrated geography is analogous to the modern Bay of Bengal and surrounding areas (compare to Figs. 10.5 and 10.8), and to inferred Carboniferous of the Ouachita area (compare to Fig. 10.16). Details of components may be modified in many ways, as discussed in text (e.g., see Fig. 10.4).

# Subsidenční křivky

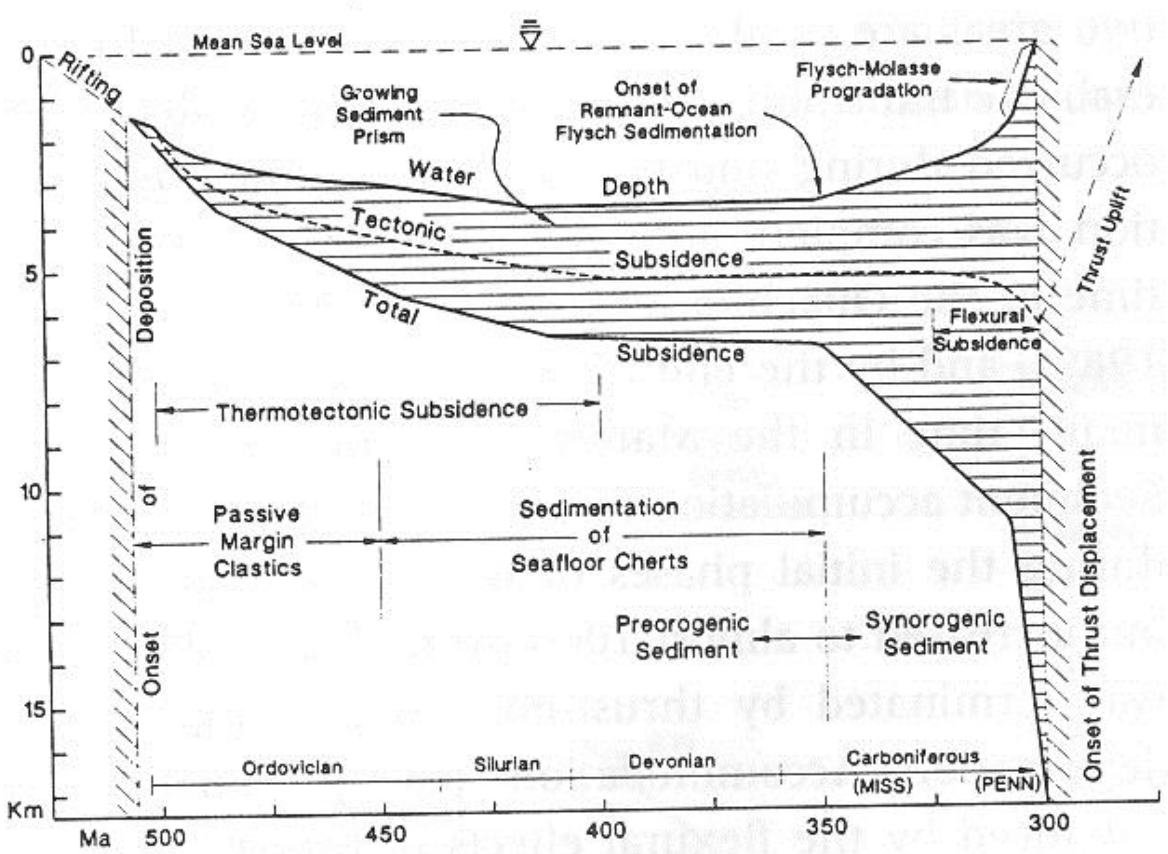


**Fig. 10.18** Hypothetical geohistory diagram for Ouachita succession of Ouachita Mountains (see Fig. 10.16). Thicknesses from Lowe (1989) and Morris (1989), and ages from Ethington et al. (1989) using DNAG time scale (Palmer, 1983). Thermotectonic subsidence constrained to rates established for cooling of oceanic lithosphere (350 m times square root of elapsed time in million years after rifting) for a period of 100 my after rifting, with no tectonic subsidence thereafter until onset of flexural subsidence under influence of structural loading by thrust sheets of Ouachita allochthon. Flexural subsidence constrained with flexural geometry inferred by Goebel (1991), assuming allochthon movement of 10 km/my (faster rate of 100 km/my would confine flexural subsidence to last 2.5 my of depositional history, and would smooth elbow of water-depth curve at transition from aggradational to progradational phases of flysch sedimentation, but would also sharpen corresponding elbow in curve for total subsidence of substratum). Backstripping constrained by net sediment densities inferred from equations for depth-porosity relations given by Dickinson et al. (1987).

# Orogenní pásmo Quachita

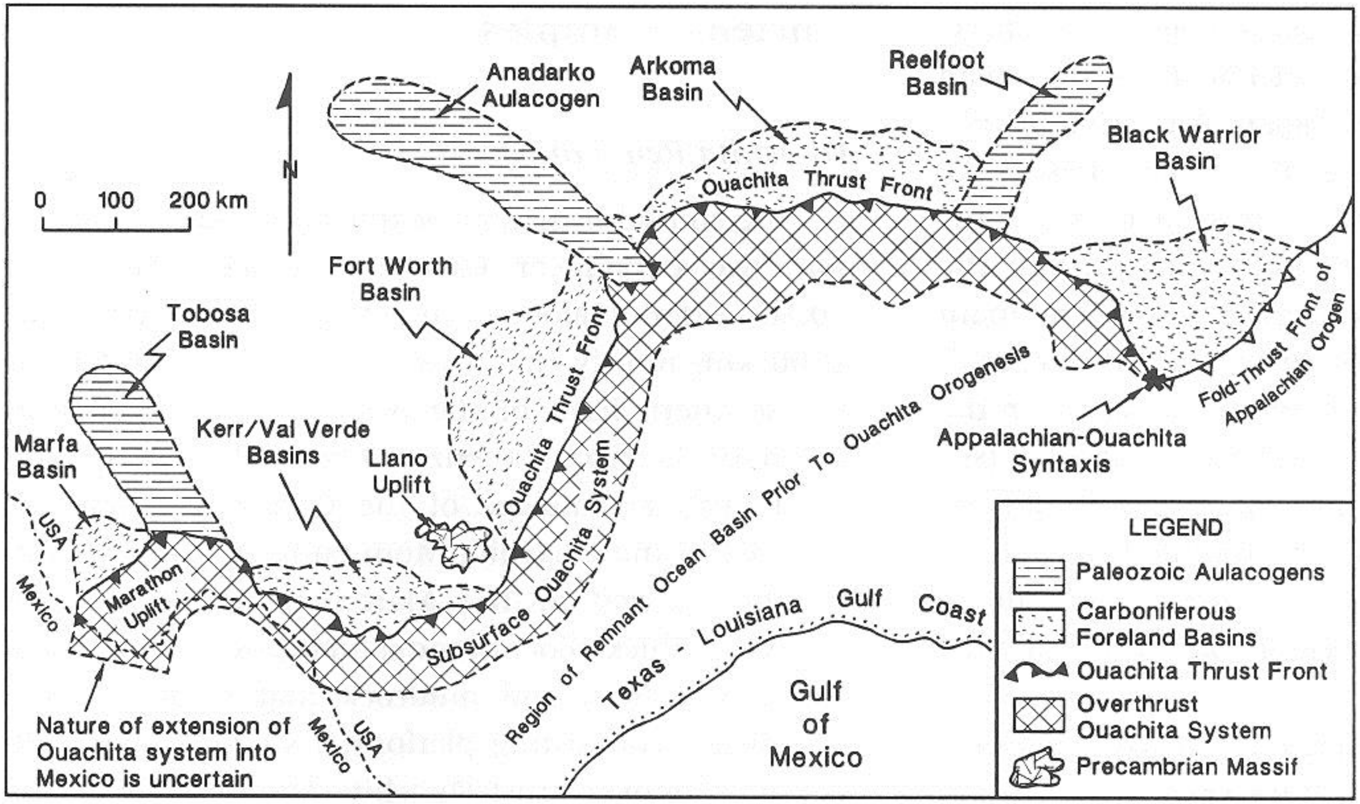


**Fig. 10.16** Regional tectonic relations of Ouachita orogenic belt. See text for discussion. Modified after Thomas (1989b).

# Idealizovaný sled sedimentace

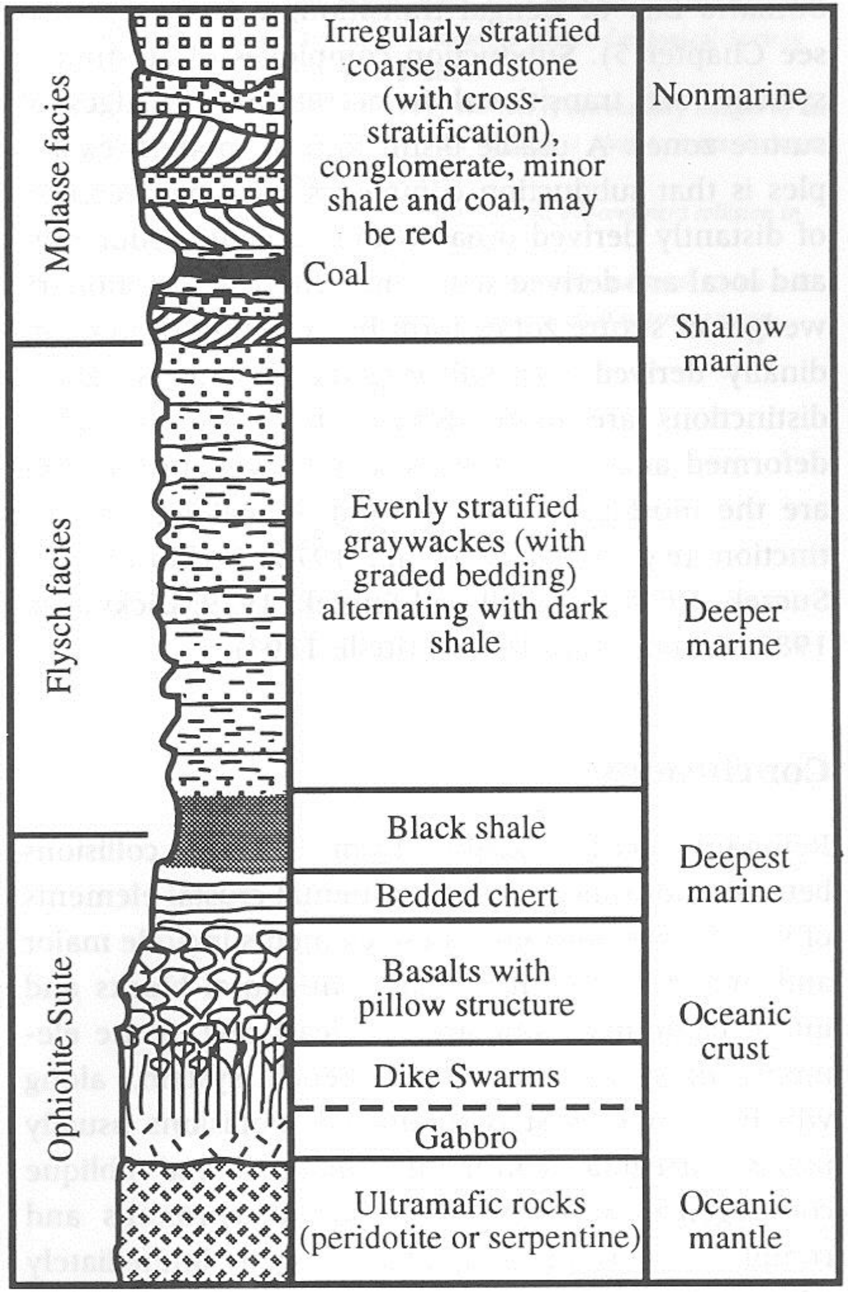


**Fig. 10.23** Idealized vertical sequence from oceanic igneous rocks and chert (ophiolite sequence) upward through graptolitic-graywacke turbidite (flysch) strata to red clastic (molasse) deposits. Such successions are commonly seen in orogenic belts and represent a progression from deep-marine to nonmarine conditions. We now interpret this succession as typically resulting from closing of remnant ocean basins, accretion of turbidites into suture zones, and creation of foreland basins adjacent to the orogens. See text for discussion. Modified from Dott and Batten (1988).

# Papua-New Guinea, zbytková pánev, Šalamounovo moře

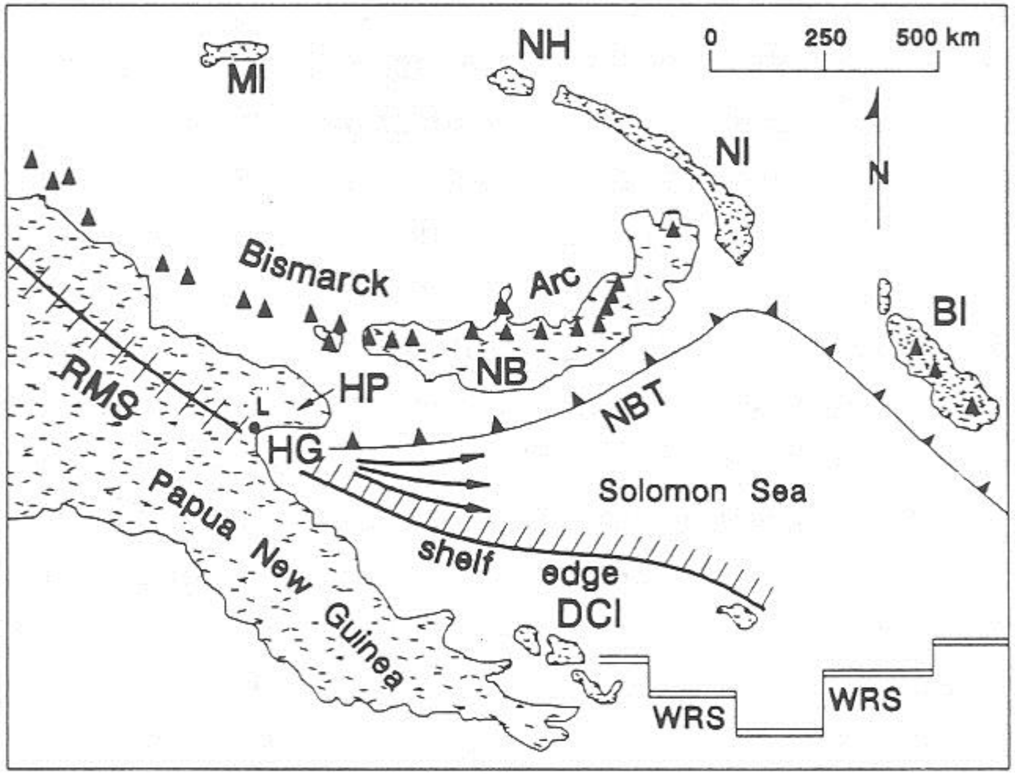


**Fig. 10.9** Setting of Solomon Sea remnant ocean basin in Papua New Guinea. Barbed line is New Britain Trench (NBT) and crossed line is Ramu-Markham suture (RMS) formed by collision of Bismarck arc with continental Papua New Guinea; NBT-RMS transition point is near Lae (L) at head of Huon Gulf (HG) beside accreted Huon Peninsula (HP). Black triangles are arc volcanoes and arrows denote flow paths of turbidity currents transporting clastic detritus longitudinally to deep seafloor. Other symbols: BI, Bougainville I. (of Solomons chain); DCI, D'Entrecasteaux Is.; MI, Manus I.; NB, New Britain; NH, New Hanover; NI, New Ireland; WRS, Woodlark rift system. Note scale (distance from Lae to Bougainville is comparable to distance from London to Warsaw, or from San Francisco to Denver). (Also see Fig. 11.20.)

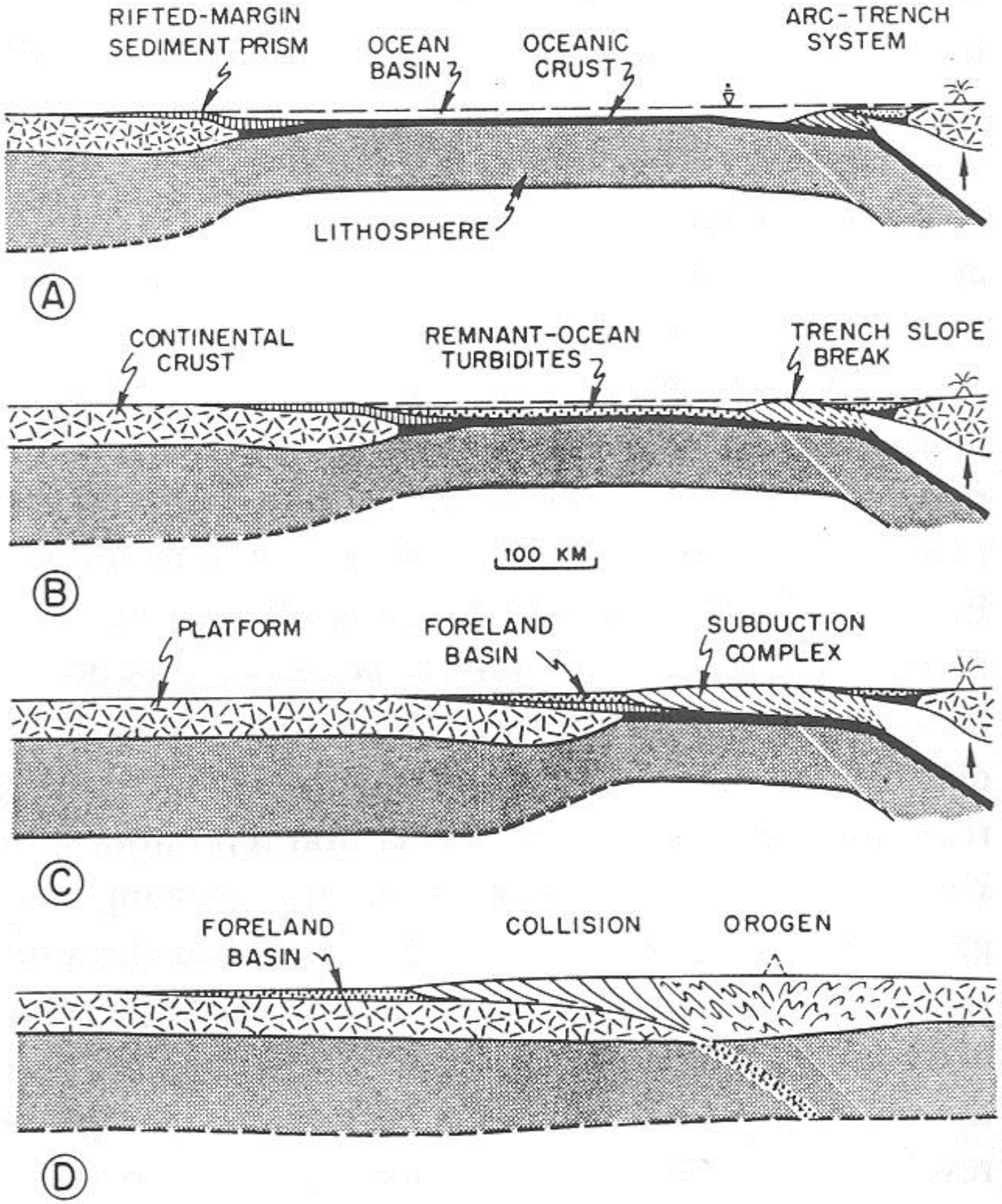


**Fig. 10.3** Idealized true-scale diagrams showing inferred evolution (A to D) of sedimentary basins associated with crustal collision to form a cryptic intercontinental suture belt within a collisional orogen. Diagrams represent a sequence in time at one place along a developing collisional orogen, or coeval events at different places along a suture belt marked by diachronous closure. Hence, erosion in one segment (D), where suture has formed, provides sediment that is dispersed longitudinally through a peripheral foreland basin, past a migrating transition point (B to C), to feed subsea fans in a remnant ocean basin (B) along tectonic strike. (See Figs. 10.1 and 10.6.) From Dickinson (1976a).

# Periferní předpolní pánve (Peripheral foreland basins)

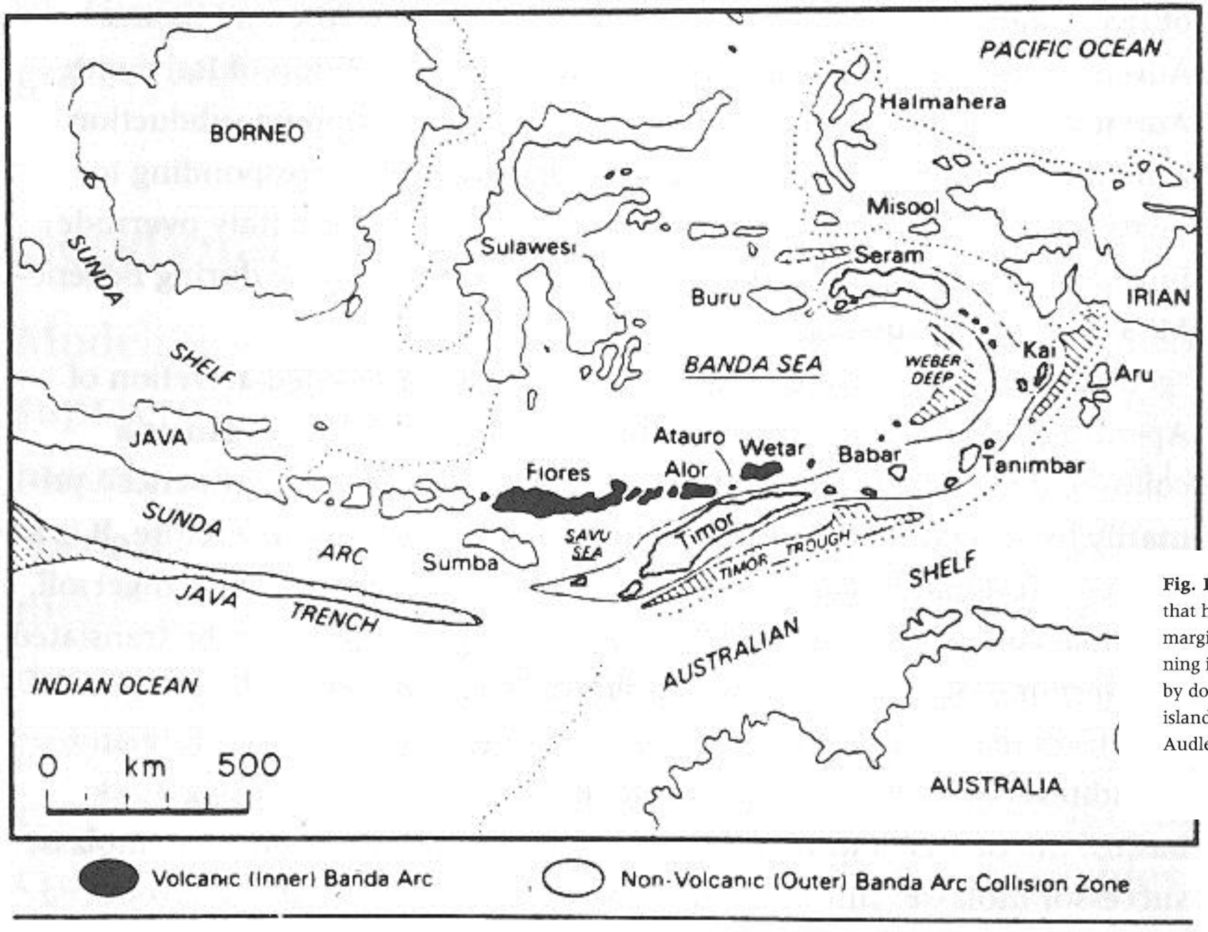


**Fig. 11.1** Tectonic setting of Timor Trough, a peripheral foreland basin that has been actively forming since collision of Australian continental margin with Banda arc along a north-dipping subduction zone, beginning in Pliocene. Northern edge of Australian continental crust is shown by dotted line, which underlies Australian shelf and includes continental islands of Irian and Halmahera (Reproduced with permission from Audley-Charles, 1986).

# Periferní předpolní pánve

- **předpolní pánve plus nesené „piggy-back“ pánve**
- Flexurální subsidence - reologický stav prohýbané litosféry - elastický model, viskózně-elastický model
- naložení předpolních pánví na bývalé pasivní okraje - progresivní zatěžování stále rigidnější litosféry
- subsidenční křivky -
- předmolasová fáze - křivka se podobá křivkám typických pasivních okrajů,
- molasová fáze - zrychlení subsidence (až 300 m/Ma celkové subsidence)
- desková kolize - ukončení konvergence a rychlé zpomalení subsidence
- **sedimentace**
- **raná fáze**: - podsouvání distálního pasivního okraje
- hlubokovodní sedimentace (podsycení)
- turbidity, flyš
- **pozdní fáze** - podsouvání prosimálního pasivního okraje
- mělkomořská a terestrická sedimentace (přesycení), klastika, méně často karbonáty - na podsouvané desce
- nahoru změlčující sekvence,
- forebulge - eroze

# Foreland basin

Onlap pánevní výplně na podložní desku

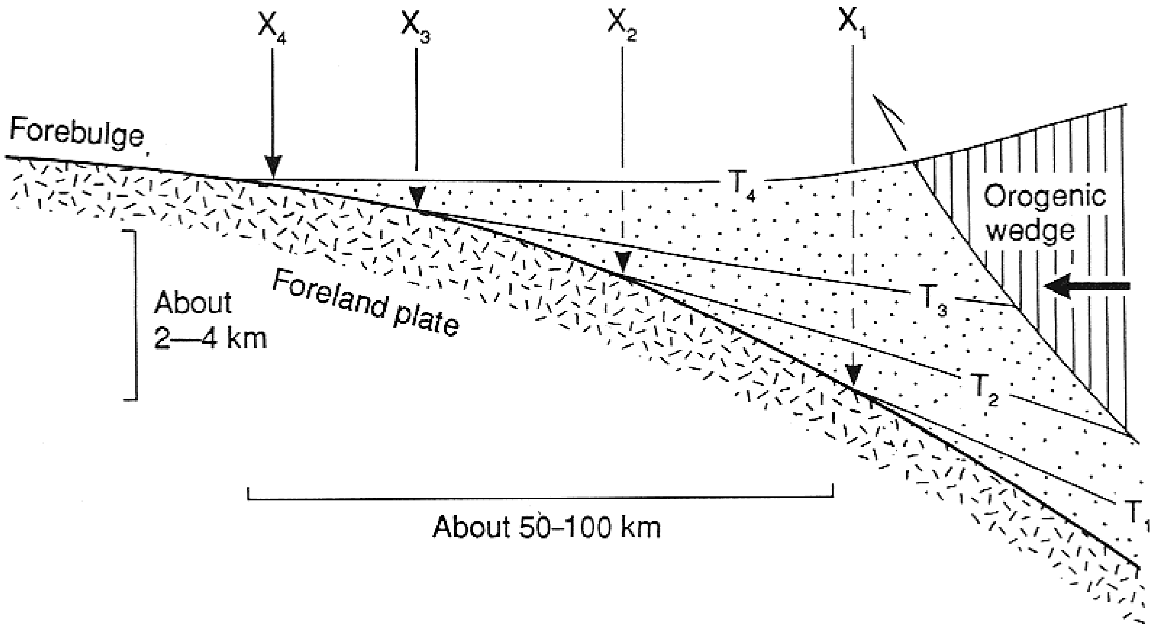


**Fig. 6.5.** Diagrammatic illustration of foreland basin stratigraphic pattern of onlap onto foreland plate. $x_1$ to $x_4$ show the successive positions of pinch-outs corresponding to the chronostratigraphic lines $t_1$ to $t_4$.

Předpolní pánev, Magallanova pánev, jih Jižní Ameriky

(b) Izopachy sedimentární výplně

(c) Interpretace seismického profilu, onlap progradačních klinoforem (fandelty)

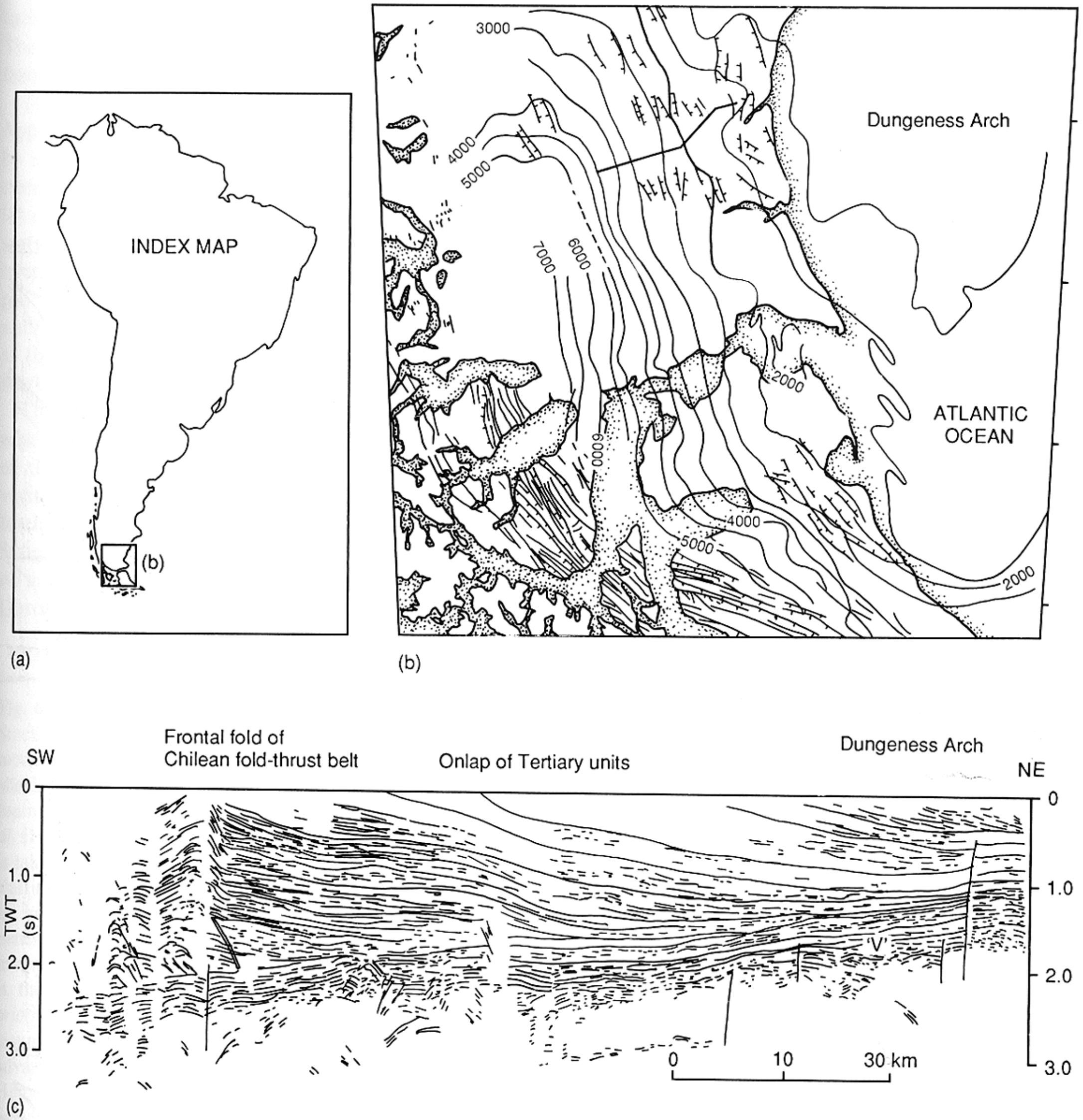
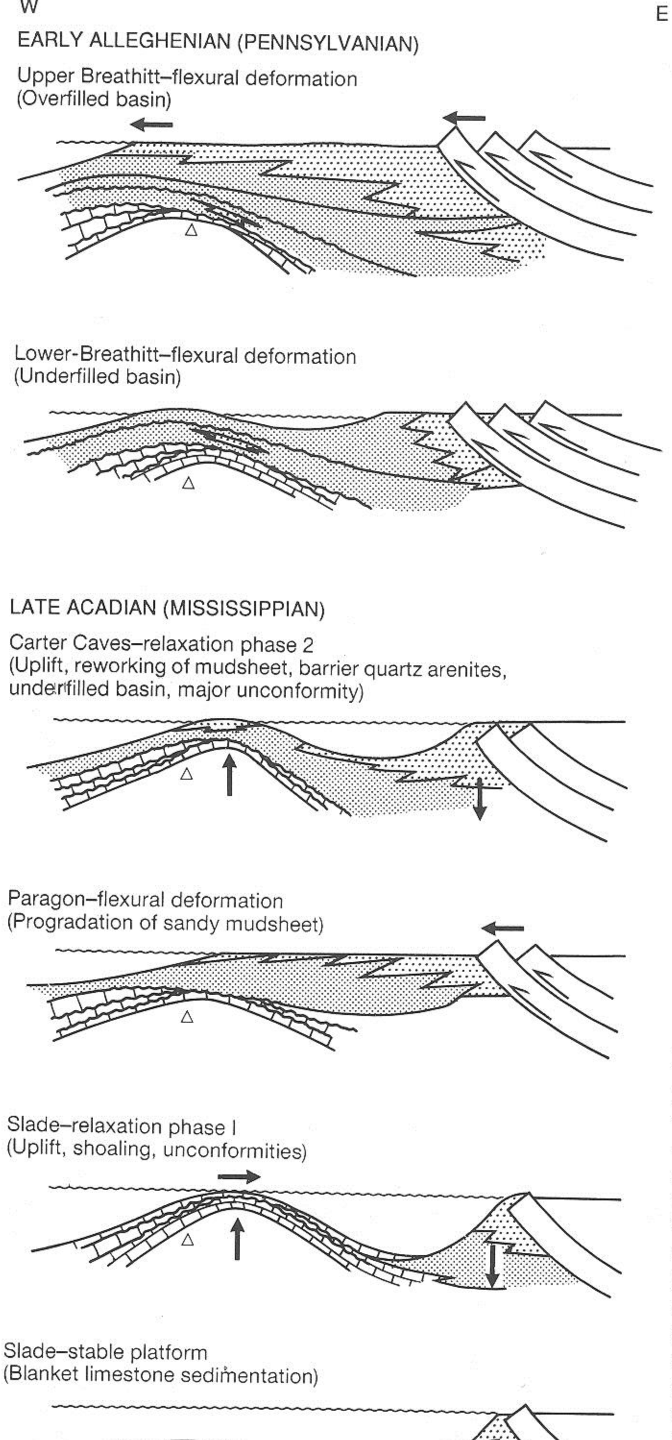


**Fig. 6.6.** The Magallanes Basin, southern South America (after Biddle *et al.* 1986). (a) Location map. (b) Isopachs (in m) of sedimentary fill of Magallanes Basin above the level of the Tobifera volcanics (representing the last stages of rifting prior to foreland basin flexure; Bruhn, Stern and De Wit 1978, Gust *et al.* 1985) showing thinning onto Dungeness Arch, and main structural lineaments, particularly the fold-thrust belt in the SW. The heavy solid line indicates line of section shown in (c). (c) Line drawing interpretation of seismic reflection record from the frontal fold of the Chilean fold-thrust belt to the flank of the Dungeness Arch. The Tertiary stratigraphic units show strong onlap on to the top of the Tobifera Volcanics (V). The progradational clinoforms are thought to be fan-deltas derived from the Andean mountain belt in the SW. They prograded into an environment of deep water shale deposition, which separated the fan-deltas from a zone of slow deposition of glauconitic sands close to and onlapping the basement high in the forebulge region.



EARLY ALLEGHENIAN (PENNSYLVANIAN)

Upper Breathitt–flexural deformation
(Overfilled basin)

Lower-Breathitt–flexural deformation
(Underfilled basin)

LATE ACADIAN (MISSISSIPPIAN)

Carter Caves–relaxation phase 2
(Uplift, reworking of mudsheet, barrier quartz arenites, underfilled basin, major unconformity)

Paragon–flexural deformation
(Progradation of sandy mudsheet)

Slade–relaxation phase I
(Uplift, shoaling, unconformities)

Slade–stable platform
(Blanket limestone sedimentation)

**Fig. 6.11.** Sequence of diagrammatic cross-sections of the Appalachian foreland basin to show the alternation of periods of flexural deformation caused by thrusting with periods of quiescence characterized by viscoelastic relaxation. The first diagram shows the Appalachian and Illinois basins 'yoked' together, the region being dominated by blanket shale and limestone deposition. The following diagrams show the responses of basin deepening and arch uplift/erosion during relaxation, and the shedding of clastic wedges during periods of active thrusting.

kj

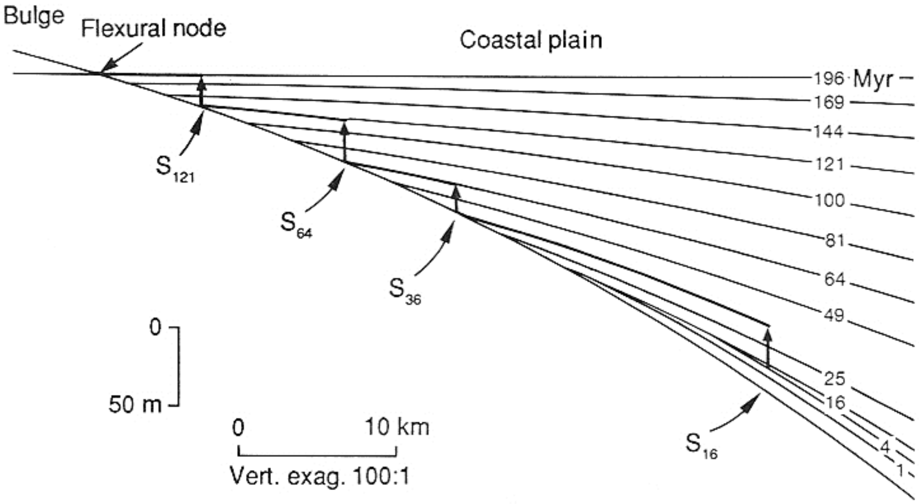


**Fig. 6.4.** Coastal plain and shelf stratigraphy using a thermal and mechanical model of a passive margin in which the tectonic subsidence of the margin is due to thermal contraction following heating and stretching of crust and lithosphere during rifting. Sediments rapidly infill the continental shelf, keeping a constant bathymetry with time. The sedimentary load flexes a cooling plate that increases in rigidity with time since heating. The initial lithospheric thickness is 125 km, initial crustal thickness 31.2 km, the coefficient of thermal expansion $3.4 \times 10^{-5}\,°C^{-1}$, the mantle temperature 1333 °C, initial densities of 2800 and 3330 kg $m^{-3}$ for crust and lithosphere respectively, and the uniform density of infilling material 2500 kg $m^{-3}$. The model calculations assume the stretch factor to be 3.0 and the equivalent elastic thickness to be given by the depth to the 450 °C isotherm.

Solid lines are the boundaries of stratigraphic units with ages indicated in Myr since the end of rifting. The effects of compaction have been ignored. The heavy line shows the amounts of coastal aggradation calculated using the method of Vail *et al.* (1977). After Watts (1982, p. 471).

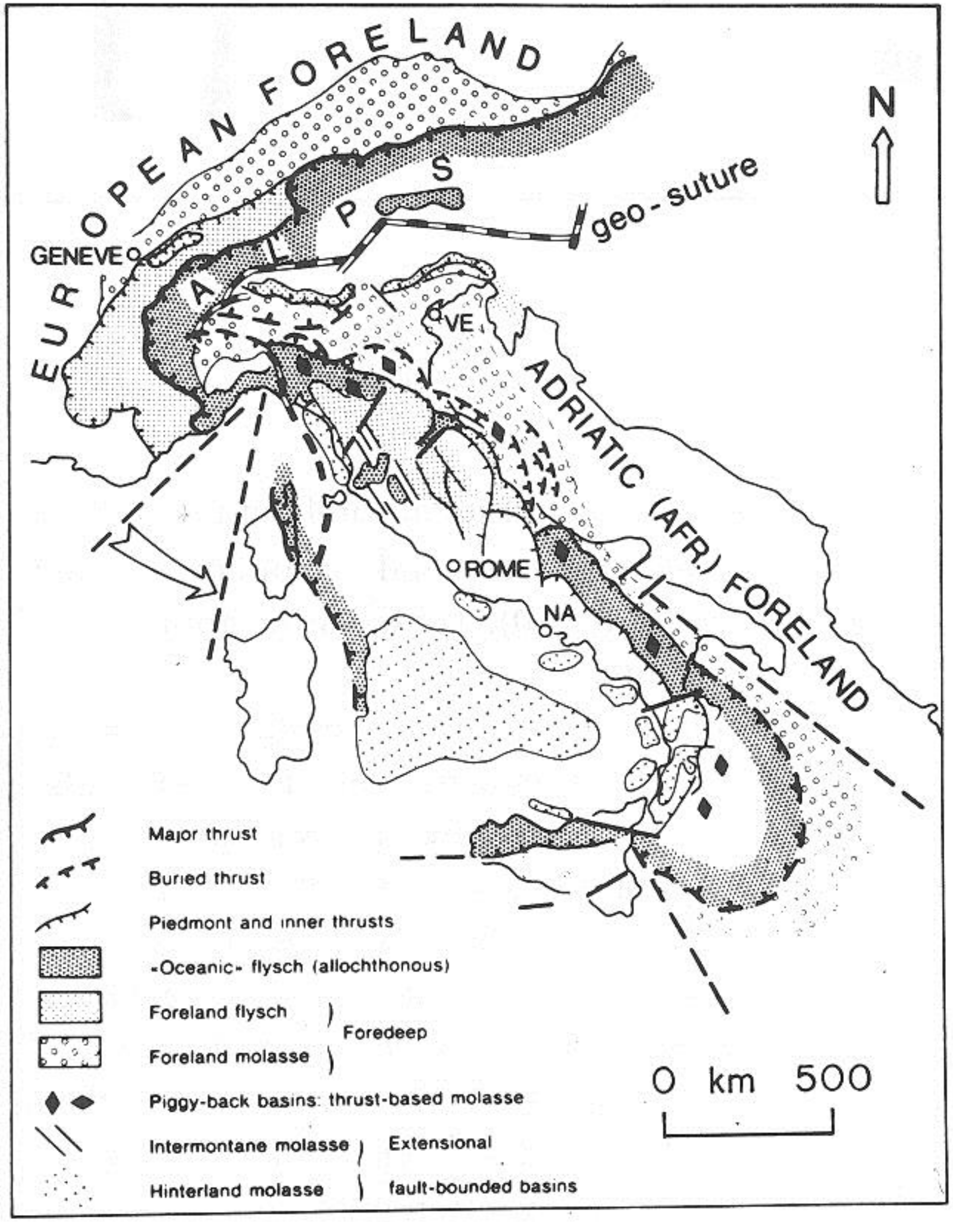


**Fig. 11.2** Tectonic framework of Switzerland and Italy, showing setting of two major Alpine and Apennine collision-related foreland basins. Adriatic foreland is a peripheral basin formed by collision of Italy with Adriatic-Yugoslavian continent along a southwest-dipping subduction zone during Oligocene-Recent. European foreland, corresponding to Swiss molasse basin, is a peripheral basin formed where Italy overrode European margin along a south-dipping subduction zone during Eocene-Miocene. Backthrusting on south side of Alps (south of "geo-suture" and north of VE [Venice]), in part, preceded accretion of Apennines. Therefore, Po Valley (north and west of VE) began as a collisional retroarc foreland (relative to Alps), but is now influenced primarily by Apennine compression (peripheral foreland). Therefore, it is a hybrid collisional foreland (both retroarc and peripheral) (R.V. Ingersoll, personal communication, 1994). Terminology of legend can be translated into terminology of this book as follows: "Oceanic" flysch (allochthonous): remnant-ocean turbidites; Foreland flysch: peripheral foreland turbidites; Foreland molasse: peripheral foreland molasse; Piggyback basins: thrust-based molasse: piggy-back molasse; Intermontane molasse: successor molasse; Hinterland molasse: backarc turbidites. (Reproduced with permission from Ricci-Lucchi, 1986.)

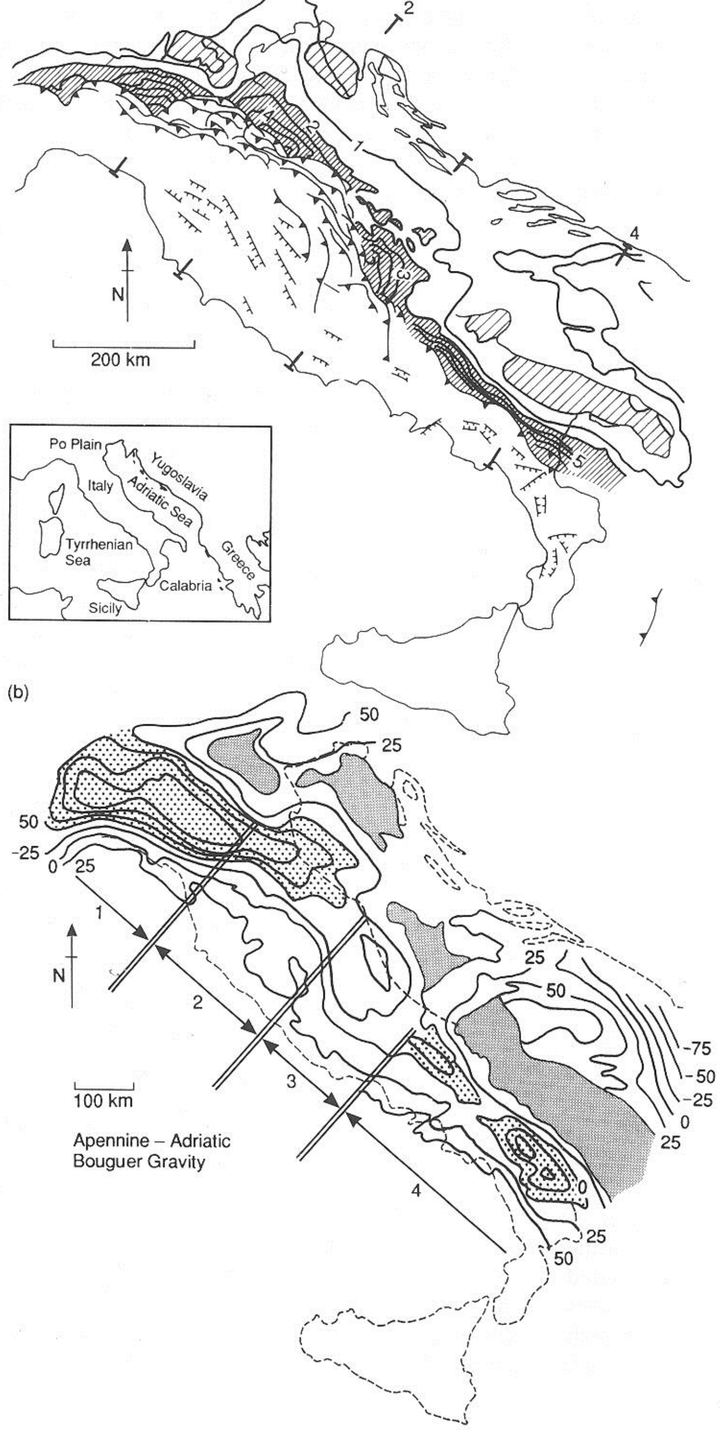


**Fig. 4.14.** (a) General map of the Apennine system showing depth to the base of the Pliocene in the Adriatic and Po Basins at a 1 km contour interval. There are four distinct outer-rise segments recognized in the basal Pliocene surface (shown in wide diagonal hatch). The narrow diagonal hatch shows the Apennine foreland basin and parts of the basal Pliocene surface that is below 2 km depth. (b) Simplified map of the Bouguer anomaly gravity field (milligal). Contour interval is 25 mgal. The four morphological outer rises correspond to Bouguer gravity highs, suggesting that they are maintained by regional flexure. The shaded areas represent anomalies of greater than 0 mgal in sectors 1 to 3 and 50 mgal in sector 4; stipple shows gravity anomalies less than − 50 mgal in sectors 1 to 3 and 0 mgal in sector 4. These sectors are believed to be bounded by major tears in the subducted plate, segmenting it at depth (after Royden, Patacca and Scandone 1987, compiled from Ogniben *et al.* 1985 and Morelli *et al.* 1975).

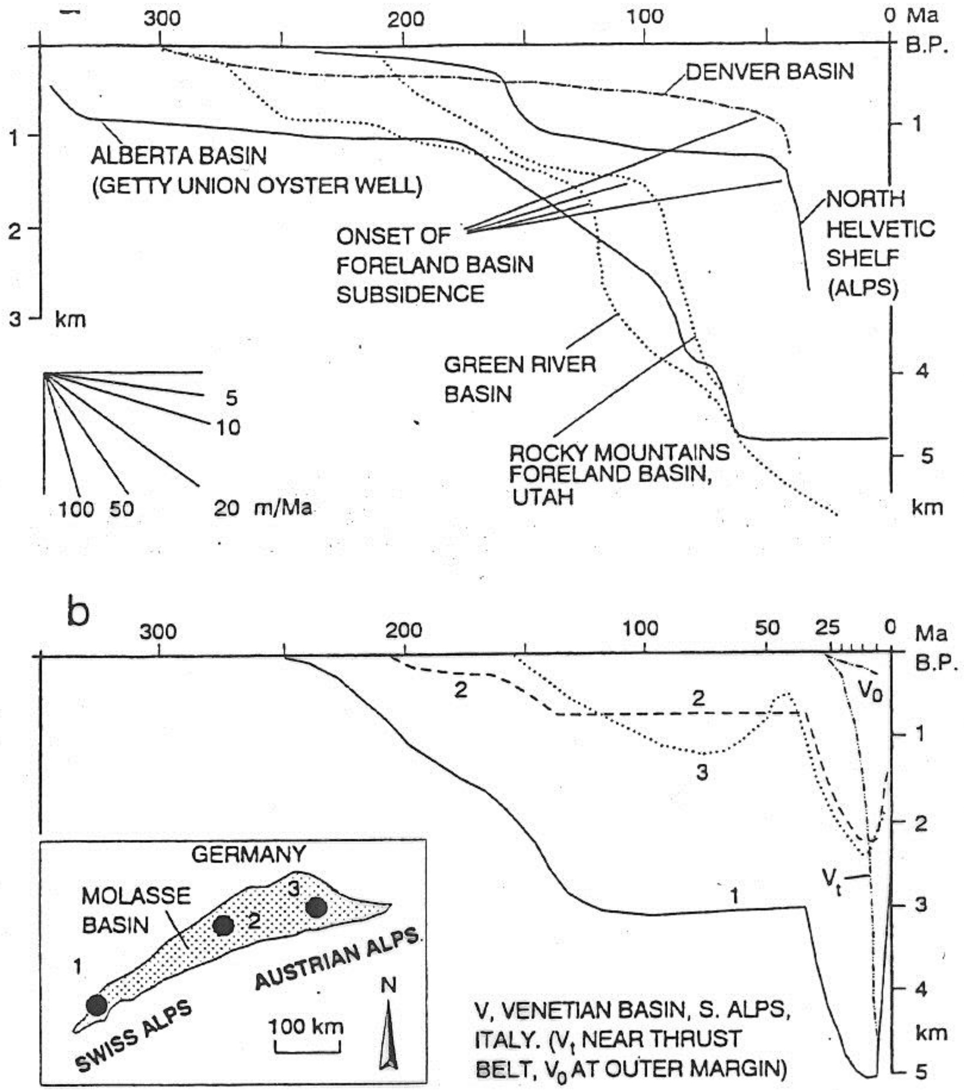


**Fig. 8.19a,b.** Subsidence histories of various foreland basins. All long-term curves show a pre-molasse phase, commonly characterized by slow to medium subsidence rates, and a molasse phase of rapid subsidence with the onset of foreland basin evolution. **a** Examples of the Rocky Mountains foreland in North America and the northern Helvetic zone of the Alps (Funk 1985). Note that Denver and Green River curves (Kominz and Bond 1986) indicate tectonic subsidence, while the other curves represent tota subsidence (Alberta curve corrected for compaction; Uta curve from Cross 1986). **b** Examples of total, uncorrecte subsidence curves from northern Alpine molasse basi (After Lemcke 1974) and Venetian basin, southern Alp (Massari et al. 1986). Note strong rebound, particularly i western portion of molasse basin in front of Swiss Alps

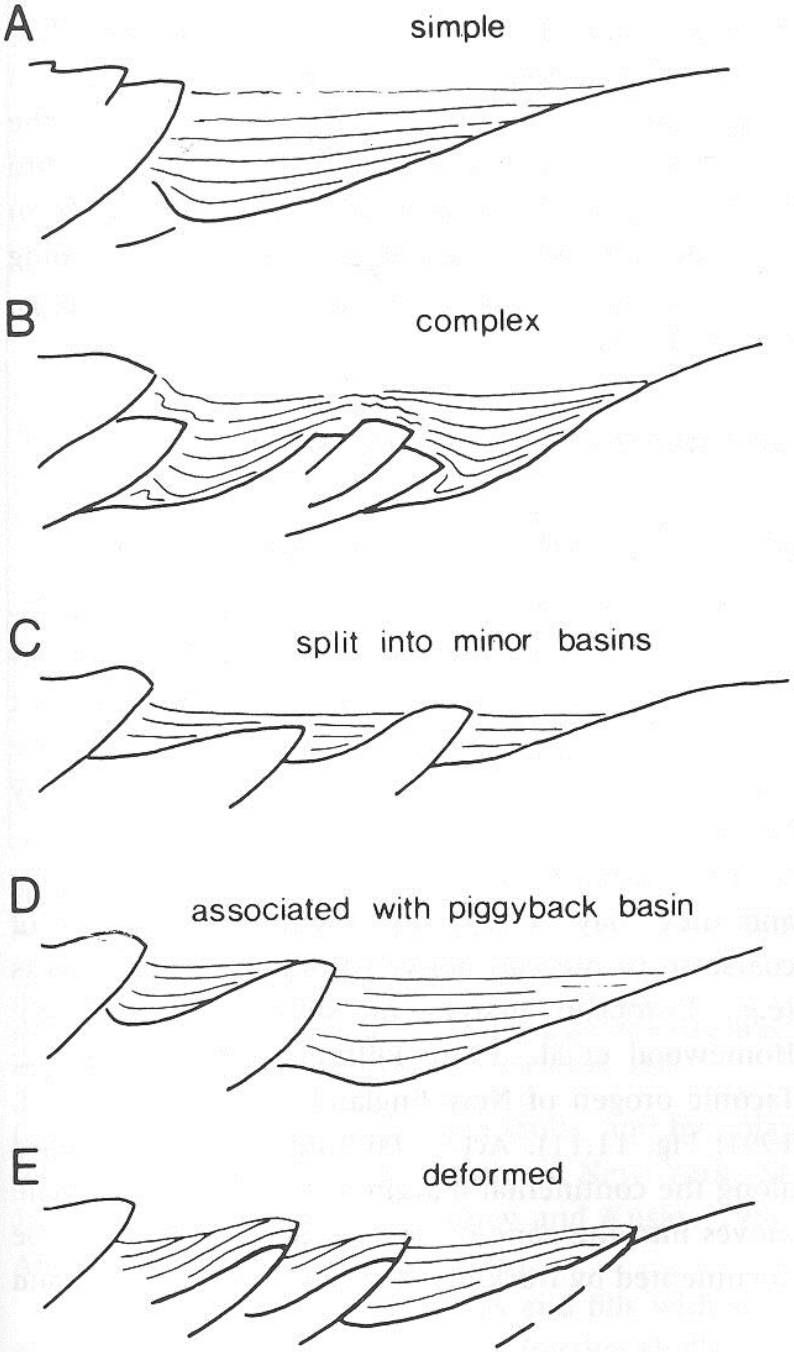
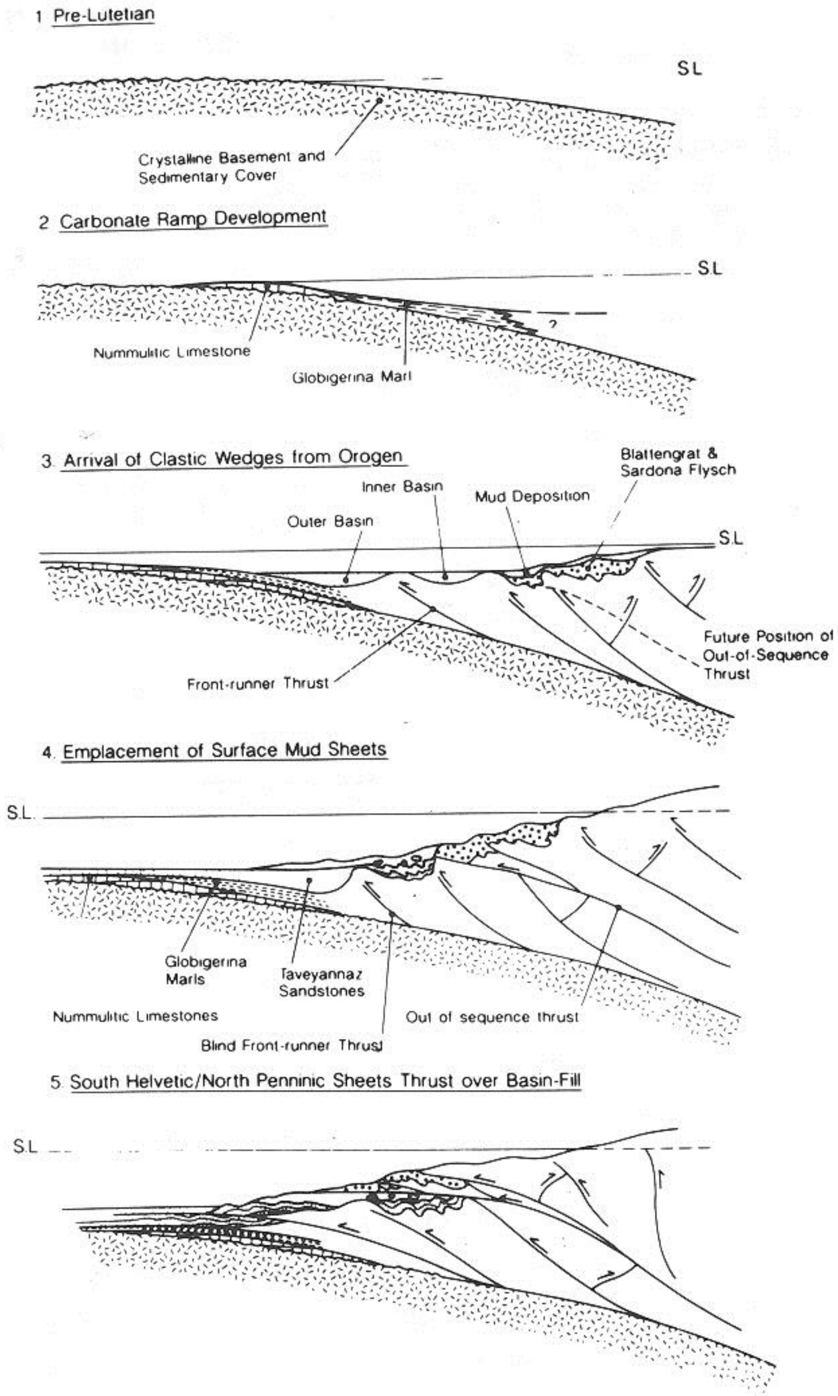


**Fig. 11.14** Variations in relationship between fold-thrust belt and foreland basin, based on seismic profiles. Minor basins and piggyback basins are varieties of satellite basins. (Reproduced with permission from Ricci Lucchi, 1986.)



1 Pre-Lutetian

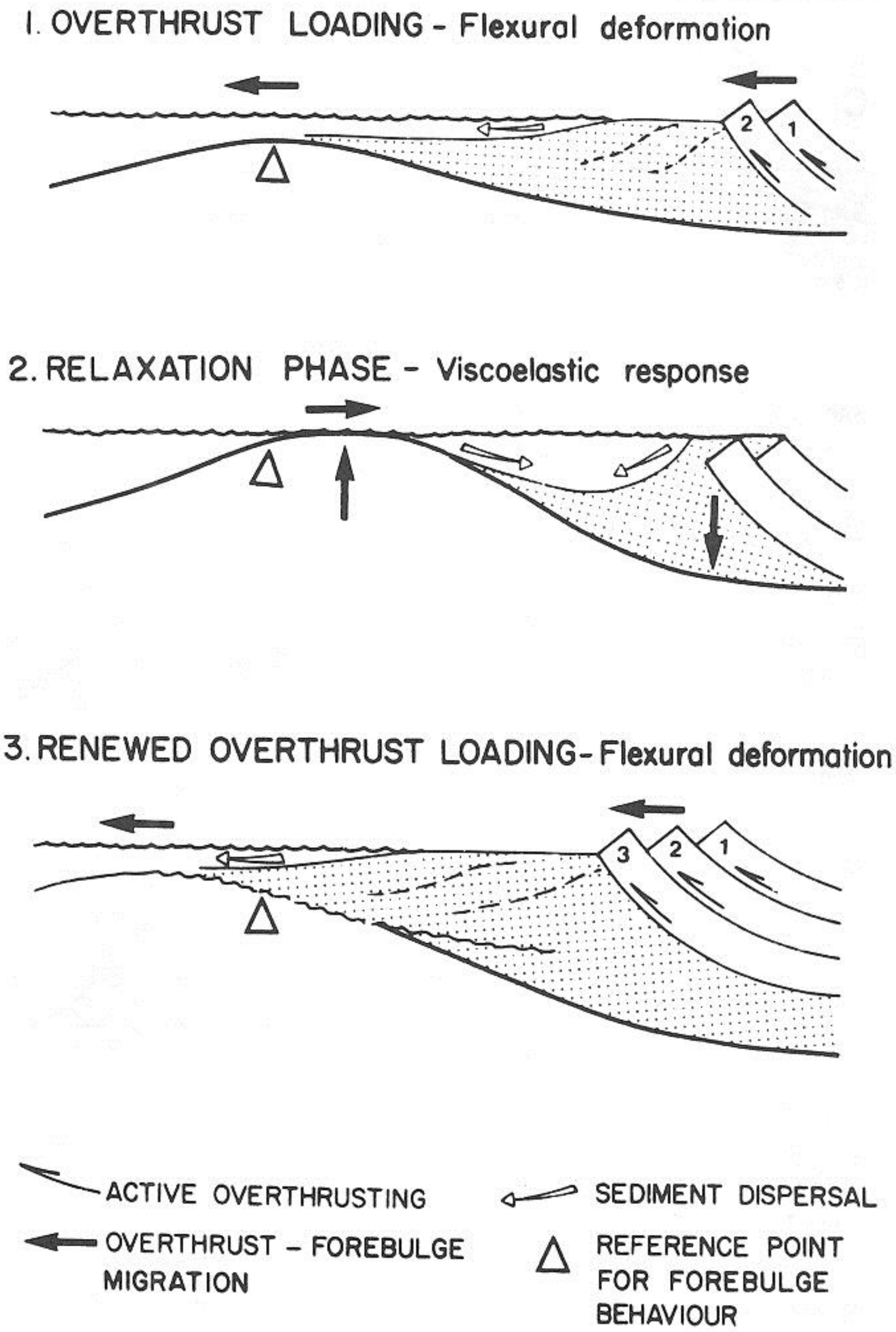
2 Carbonate Ramp Development

3. Arrival of Clastic Wedges from Orogen

4. Emplacement of Surface Mud Sheets

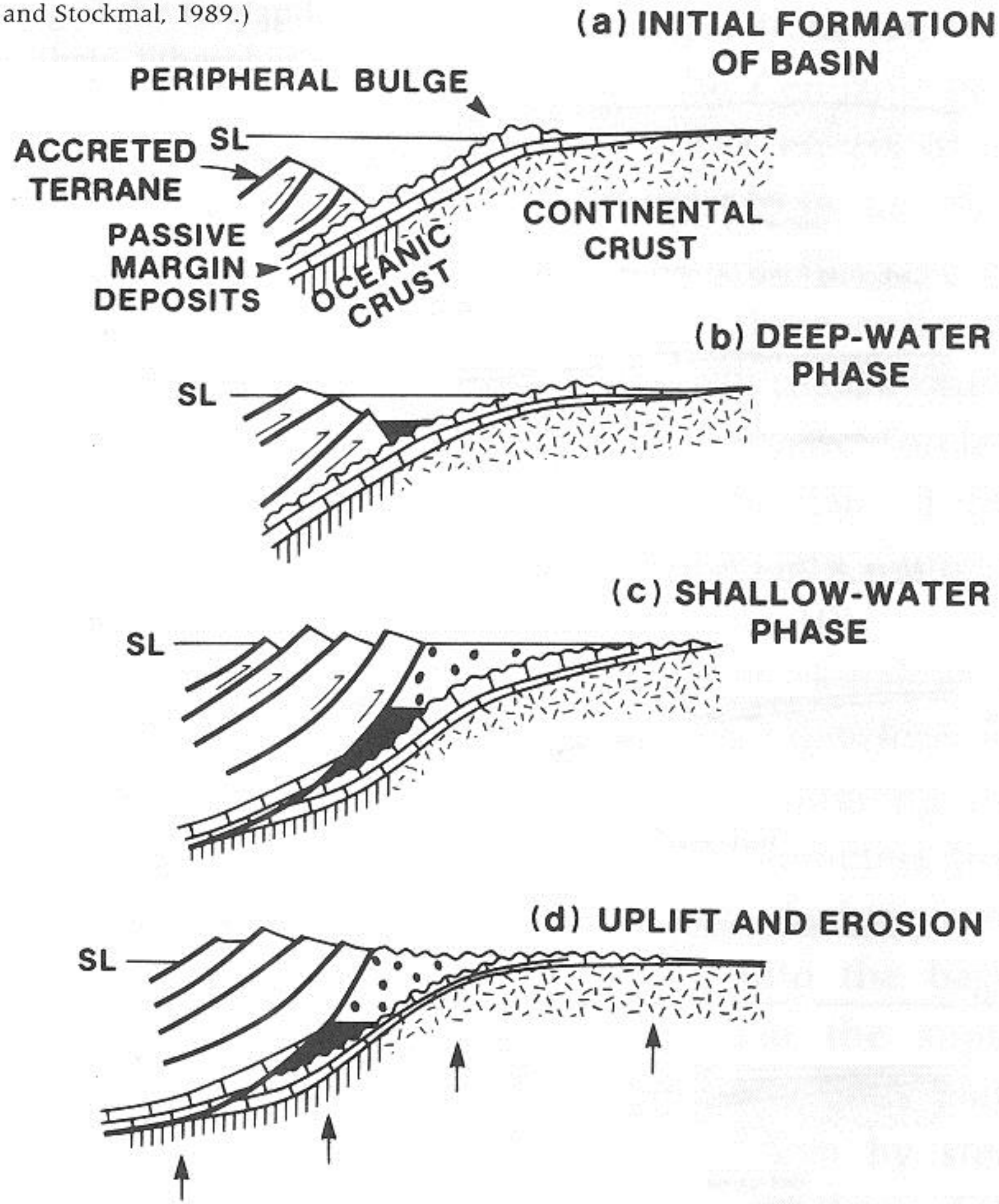
5. South Helvetic/North Penninic Sheets Thrust over Basin-Fill

**Fig. 11.7** Schematic evolution of North Alpine peripheral foreland basin, Switzerland, from initial uplift and erosion of forebulge on downgoing (European) plate in mid-Eocene (panel 1) to overthrusting from south in Oligocene (panel 5). (Reproduced with permission from Allen et al., 1991.)



ig. 11.22 Development and migration of a forebulge in response to ycles of deformation and tectonic quiescence. Forebulge develops as part f the flexural wave generated in the crust by loading (see Fig. 11.5). ollowing cessation of thrusting, there may be a viscoelastic relaxational esponse to loading, which leads to deepening and narrowing of the asin. In the case of an elastic crust this phase would not occur. The orebulge may be exposed to erosion, or become a shoal area within an therwise deeper-marine basin. With renewed crustal shortening, the orebulge migrates cratonward. Subsidence and uplift of the forebulge roduce onlap and wedge-out unconformities, respectively, on the flanks f the uplift. (Reproduced with permission from Tankard, 1986.)

**Fig. 11.6** Idealized model for terrane accretion, and development of sedimentary succession in a peripheral foreland basin. See text for discussion. (Reproduced with permission from Cant and Stockmal, 1989.)



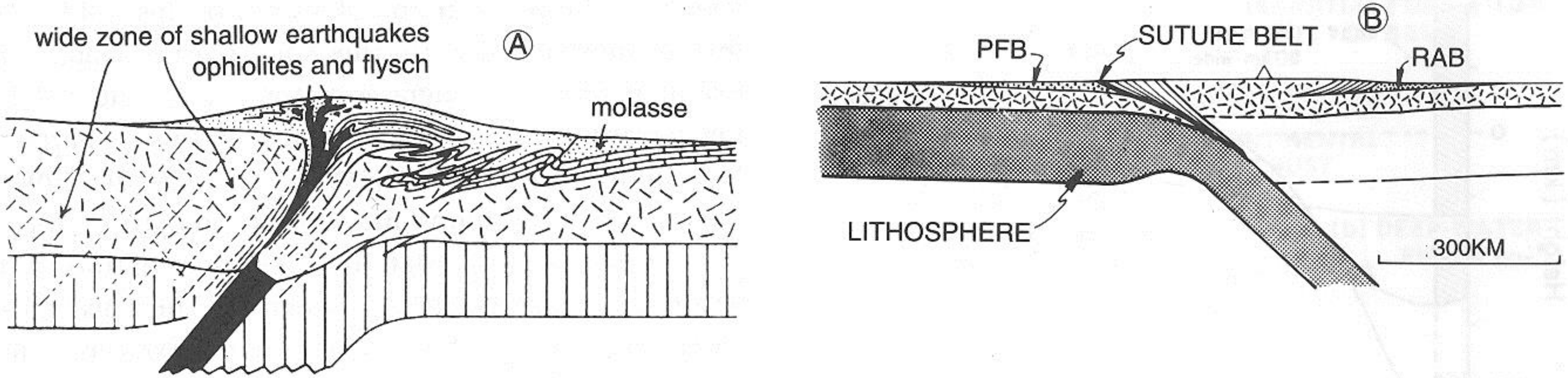


**Fig. 11.4** Schematic diagrams illustrating early plate-tectonic interpretations of foreland basins. (A) Development of orogenic welt and molasse wedge in adjacent foreland basin (reproduced with permission from Dewey and Bird, 1970).

(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.

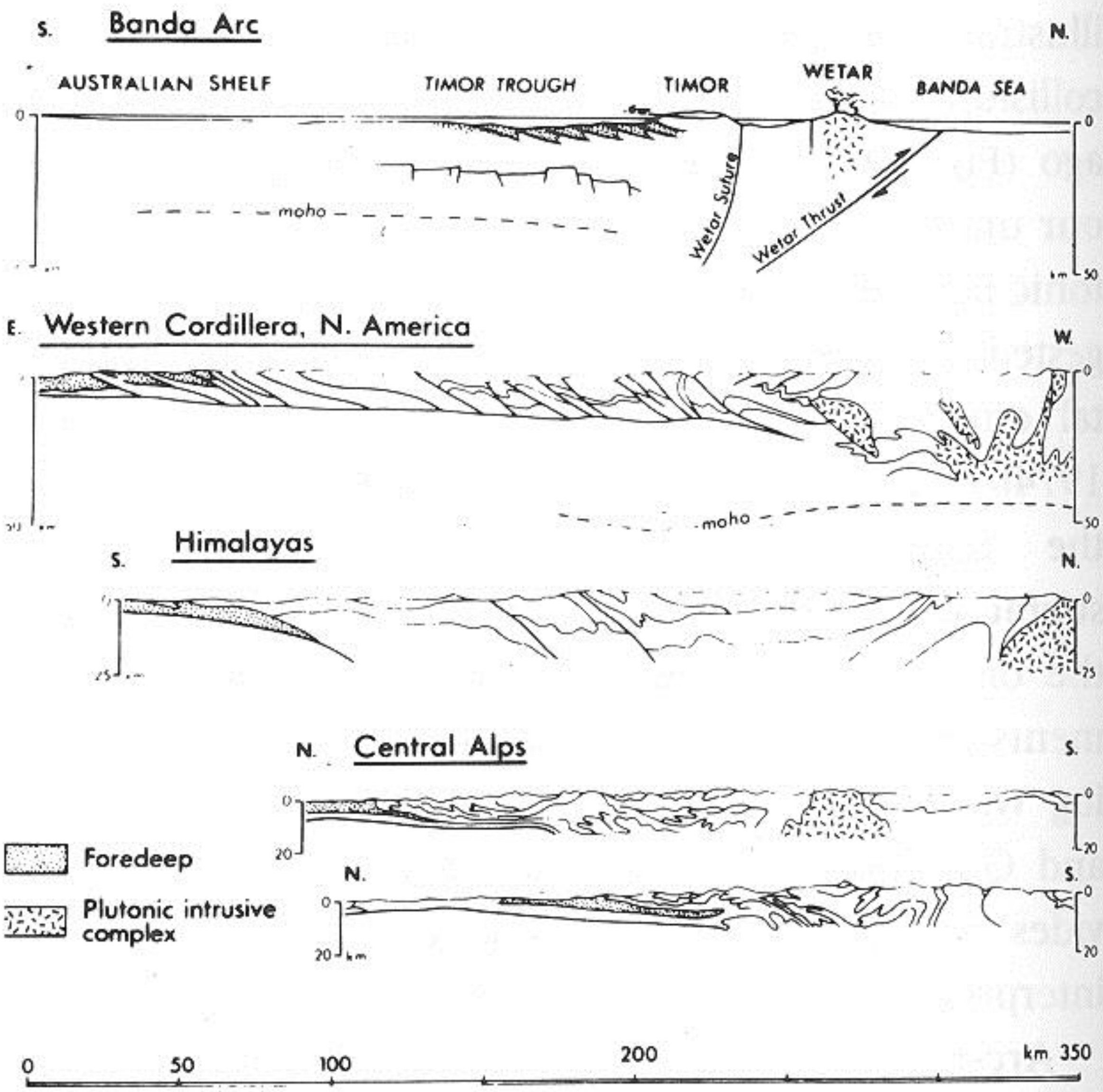


**Fig. 11.3** Comparative cross sections across four collisional orogens and their flanking foreland basins. Banda Arc section shows arc at Wetar overriding Australian continental margin, which is subducting northward as part of Indian plate (structural interpretation is controversial [see text], see Fig. 11.1). Western Cordilleran foredeep of North America is an example of a primarily retroarc foreland basin. Himalayan and Alpine basins are peripheral foreland basins developed on partially subducted continental crust (see Fig. 11.2). (Reproduced with permission from Audley-Charles, 1986.)

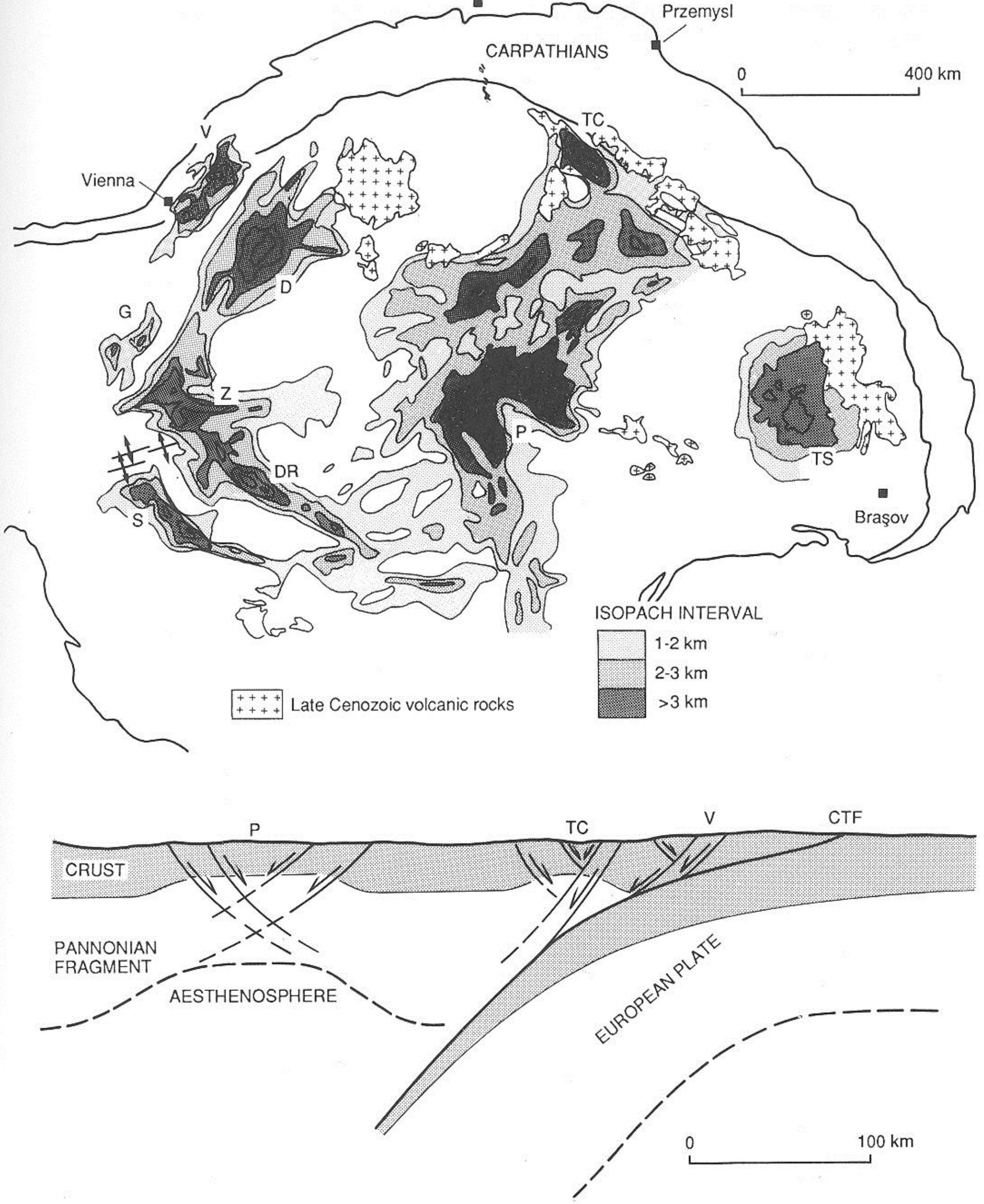


**Fig. 5.20.** Schematic cross-section to show the relationship of the Vienna Basin to other basins in the Carpathian–Pannonian system. The Vienna and Transcarpathian Basins are located on the leading (thin) edge of the Pannonian lithosphere and above the deflected European plate. The Pannonian Basin, however, is located entirely on the Pannonian lithosphere where it overlies aesthenosphere. Extension in the Pannonian Basin therefore involves mantle and the basin is consequently 'hot' compared to the 'cool' Vienna Basin (Royden *et al.* 1983). Inset shows

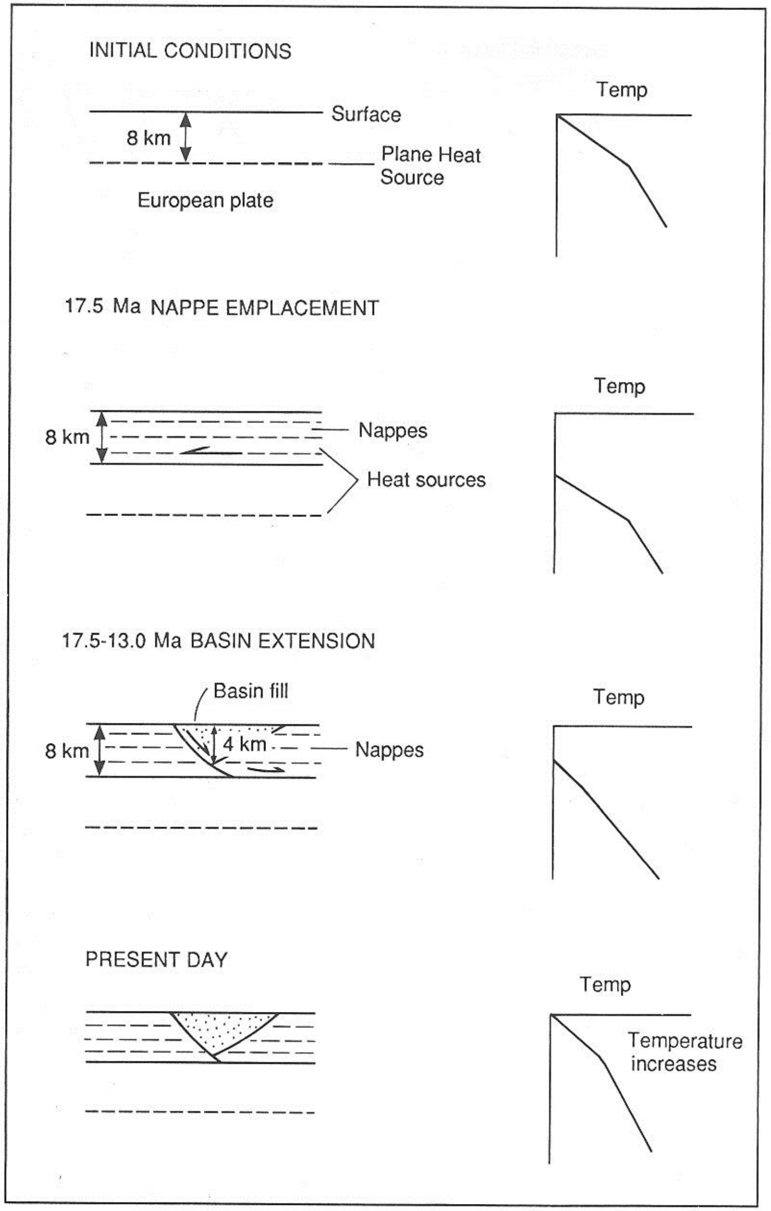
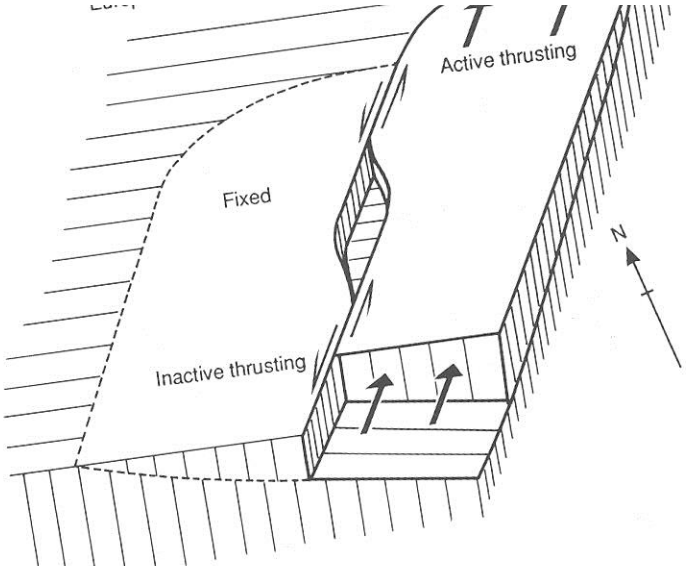


**Fig. 5.19.** Model used to calculate the thermal effects of nappe emplacement and thin-skinned extension of the Vienna Basin by Royden (1985). At initial conditions the European plate is at thermal equilibrium with a plane (radiogenic) heat source at 8 km depth. At 17.5 Ma (start of Karpatian stage) an 8 km thick thrust sheet with a temperature of 0 °C is emplaced over the European platform. Between 17.5 and 13.0 Ma (Karpatian–Badenian) the thrust complex is extended to form the Vienna Basin. The underlying autochthon is unaffected mechanically and thermally by the thin-skinned extension, and the temperature changes are solely due to conduction. Finally, temperatures in the basin increase by thermal conduction from the underlying European plate (after Royden 1985).



8. Schematic diagram te the relationship of ion in the Vienna Basin to slip faulting and mporaneous thrusting. In le Miocene times (17.5–13.0 the nappes to the west of the na Basin were fixed with ect to the European platform, lst nappes to the east were ng transported to the northeast er the European plate. This sulted in sinistral strike-slip eformation between the active an active nappes. Because the napp ad a basal detachment, the strike-slip deformation is confined largely to the allochthon. The Vienna Basin is situated at a left step (releasing bend) in this sinistr strike-slip system. It has a stretch rather than

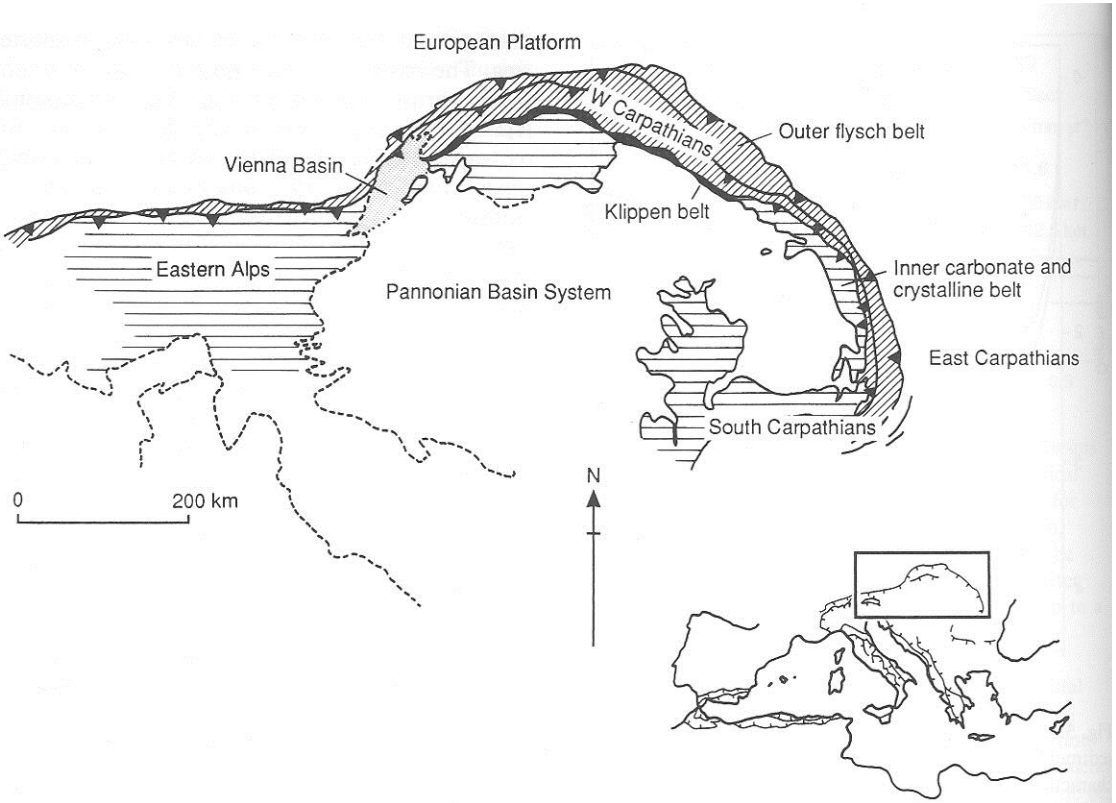
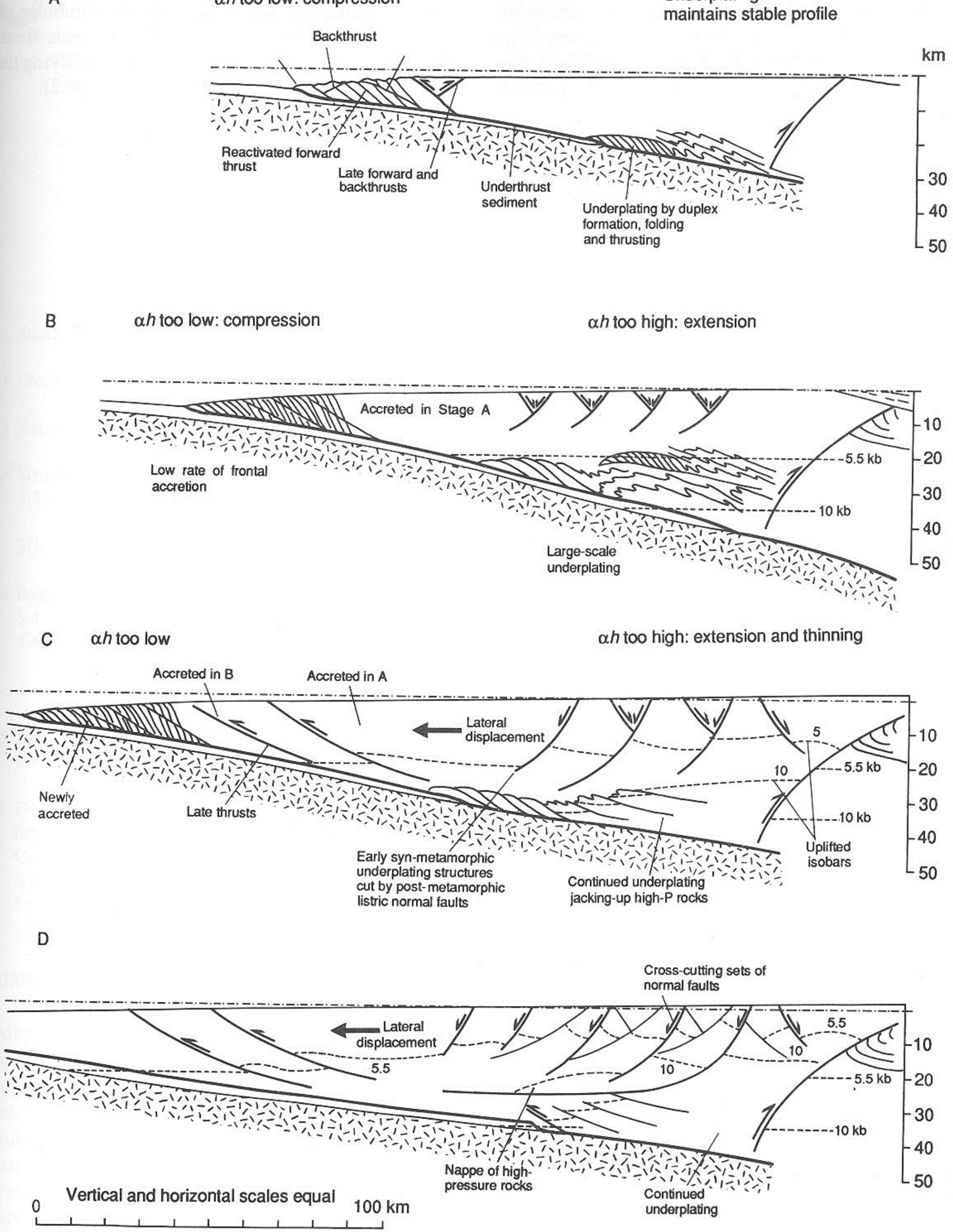


**Fig. 5.17** Location of the Vienna Basin in the Alpine-Carpathian System. The outer flysch belt was deformed in the Tertiary. The inner parts of the system (carbonate and crystalline belt) was deformed mainly in the Cretaceous. The Klippen belt separates the outer from the inner West Carpathians (after Royden 1985).


A
αh too low: compression
Underplating
maintains stable profile
km
Backthrust
Reactivated forward thrust
Late forward and backthrusts
Underthrust sediment
Underplating by duplex formation, folding and thrusting
30
40
50
B
αh too low: compression
αh too high: extension
Accreted in Stage A
Low rate of frontal accretion
Large-scale underplating
5.5 kb
10 kb
10
20
30
40
50
C
αh too low
αh too high: extension and thinning
Accreted in B
Accreted in A
Lateral displacement
Newly accreted
Late thrusts
Early syn-metamorphic underplating structures cut by post-metamorphic listric normal faults
Continued underplating jacking-up high-P rocks
Uplifted isobars
5
10
5.5 kb
10 kb
10
20
30
40
50
D
Cross-cutting sets of normal faults
Lateral displacement
5.5
10
10
5.5
5.5 kb
10 kb
Nappe of high-pressure rocks
Continued underplating
10
20
30
40
50
Vertical and horizontal scales equal
0
100 km

# Subsidence předpolních pánví

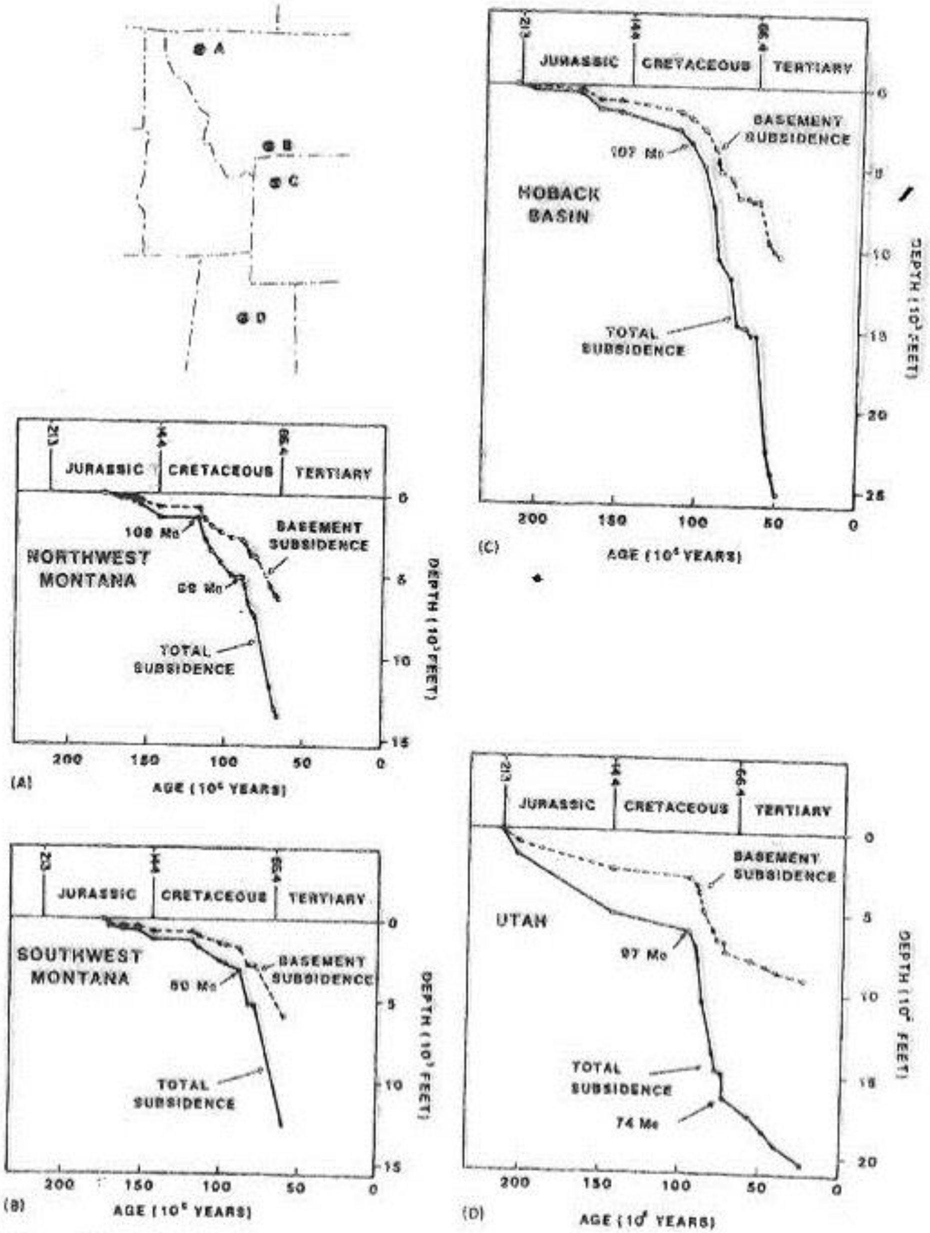


Fig. 7.26. Geohistory plots for four locations in the Mesozoic Sevier foreland basin of the western Un
States (Cross, 1986).

# „Strike-slip“ pánve

- obvykle malé rozměry
- vysoké rychlosti subsidence
- klasifikace:
  - transtenzní pánve
  - transrotační pánve
  - transpresní pánve (flower/palm tree structures)
- polygenetické pánve
- polyhistorické pánve
- extenzní subsidence

# Pánve na horizontálních posunech (Strike-slip basins)

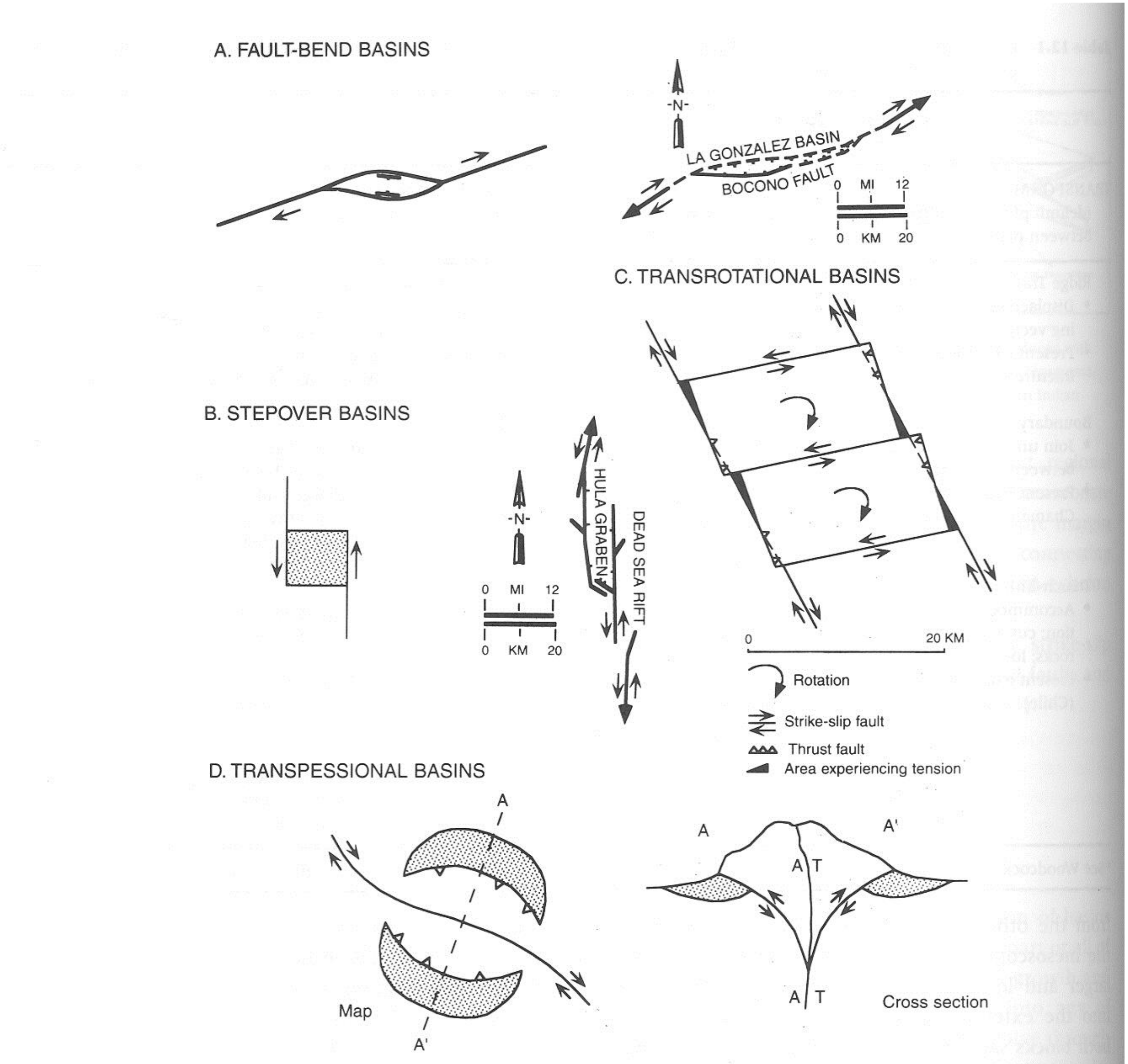
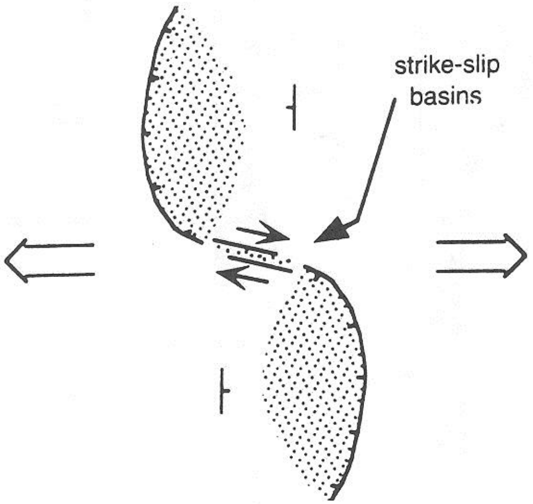
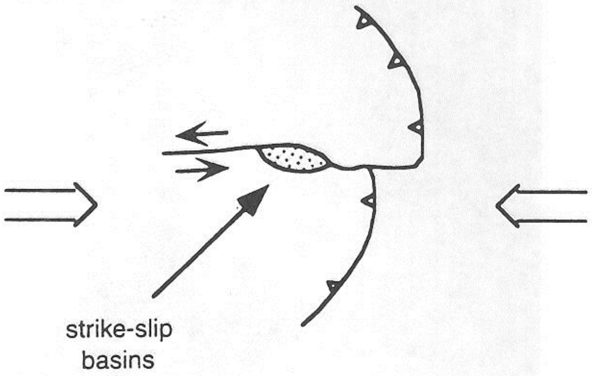


**Fig. 12.3** Diagrammatic maps of six strike-slip basin types: A) fault-bend basin (left) with map of La Gonzalez basin, Venezuela (right); B) stepover basin (left) with map of part of Dead Sea rift (right); C) transrotational basins (black areas); D) transpressional basins (dot pattern) in map view (left) and cross section (right); E) polygenetic basins (dot pattern) in regional extension (left) and in regional shortening (right); and F) polyhistory basins initiated as rift basin.

## E. POLYGENETIC BASINS

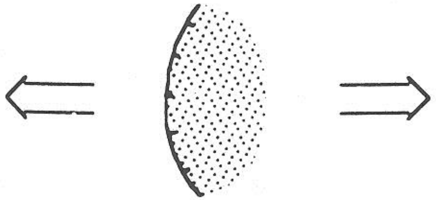


Regional Shortening

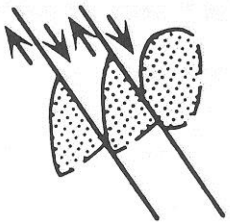


Regional Extension

## F. POLYHISTORY BASINS



Rift Basin
developed under
regional extension



Conversion to
strike-slip basins
by later right-slip

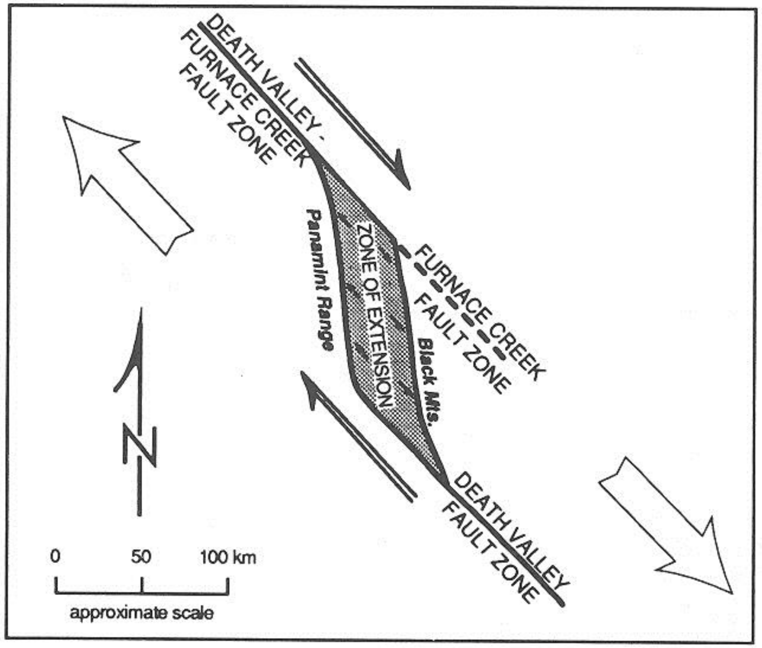


**Fig. 12-19** Diagrammatic sketch map of Death Valley "pull-apart." (Modified from Burchfiel and Stewart, 1966.)

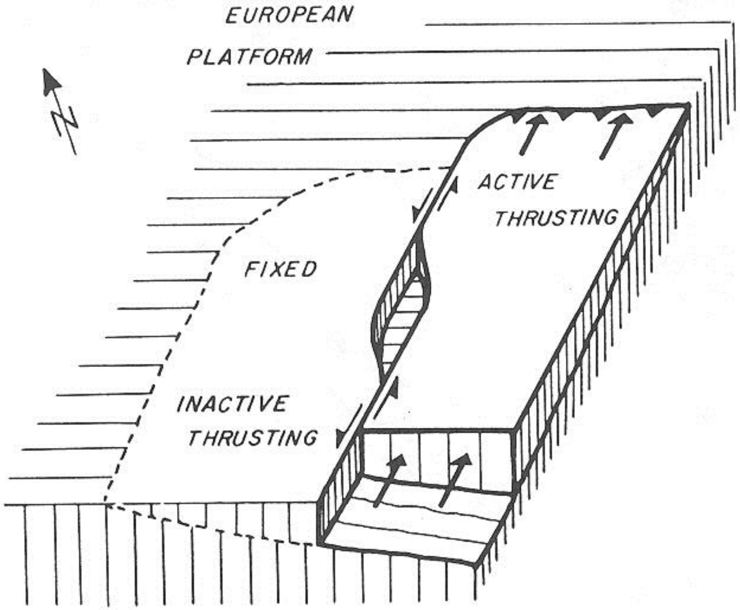


**Fig. 12.20** Schematic diagram of opening of Vienna basin as a fault-bend basin at a left step in a left-slip tear fault within an allochthon thrust northeastward onto the European platform (Reproduced with permission from Royden, 1985).

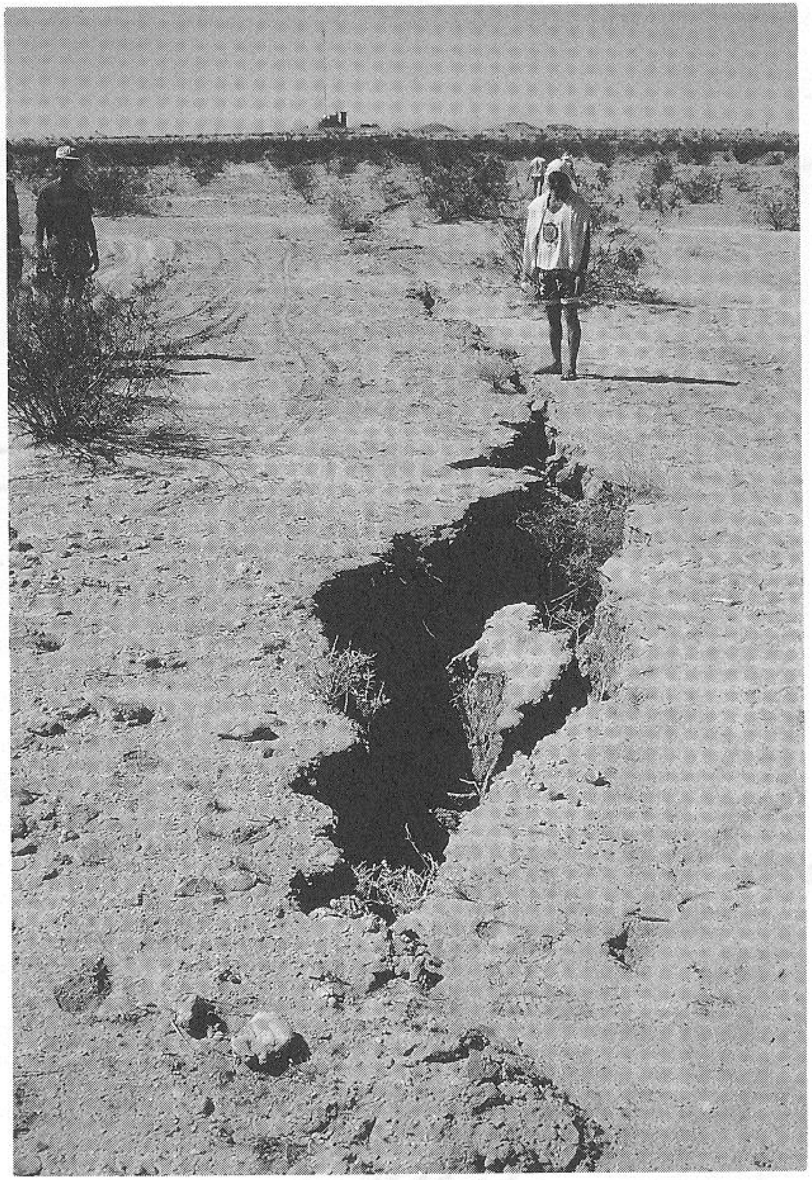


**Fig. 12.4** Small fault-bend basin from Superstition Hills earthquake zone. Fault strikes away from viewer, from bottom of photograph to tower on horizon. Axis of basin is about 25° to fault strike. Net right-lateral strike-slip at this site was 1.5 m (photograph by A. G. Sylvester).

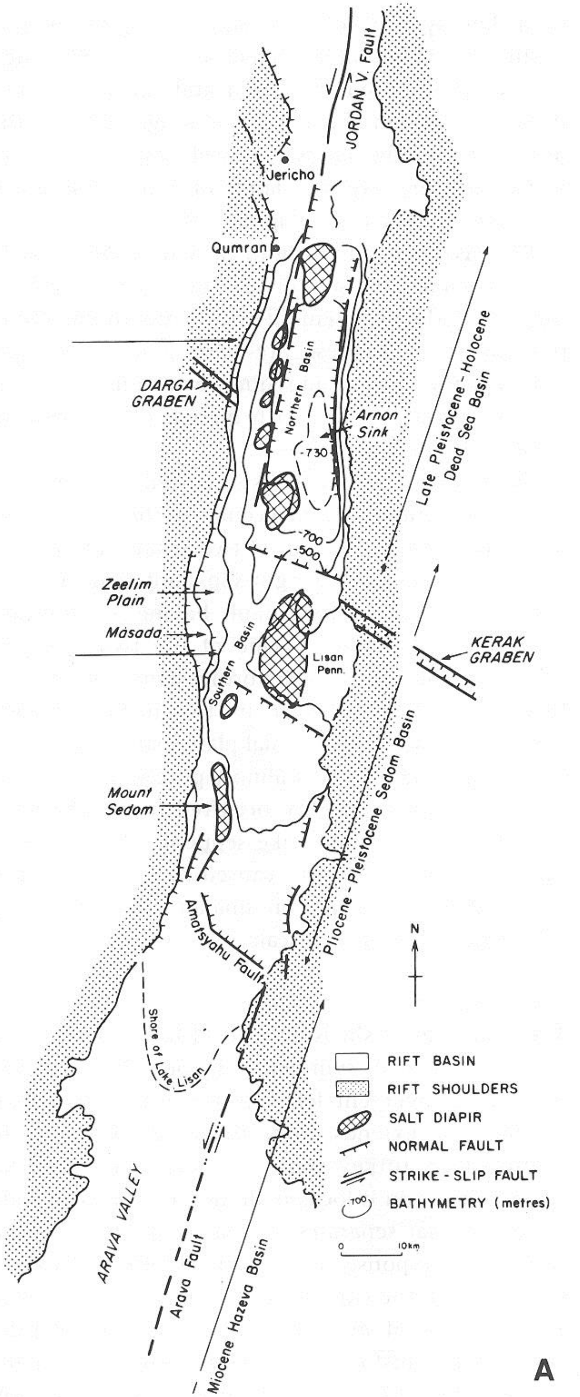


**Fig. 12.14** Geologic setting of Dead Sea basin. A) Geologic map of Dead Sea-Arava depression, illustrating tectonic elements, physiographic features, northward migration of depocenter, and basin asymmetry expressed by bathymetry (Reproduced with permission from Manspeizer, 1985). Early Miocene (25–14 Ma) strike slip of about 60–65 km opened Arava basin that filled with about 2 km of red beds during a pause in strike-slip displacement. Later displacement in last 4.5 my allowed deposition of more than 4 km of marine to lacustrine rock salt of the Sedom Formation, overlain by 3.5 km of lacustrine evaporitic carbonate and clastic sedimentary strata. B) Schematic block diagram of Dead Sea region, viewed to north, with generalized rift physiography, tectonic framework and depositional domains (Reproduced with permission from Manspeizer, 1985). Bedrock of different ages on rift shoulders, basin bathymetry and eastward thickening of strata illustrate tectonic asymmetry.

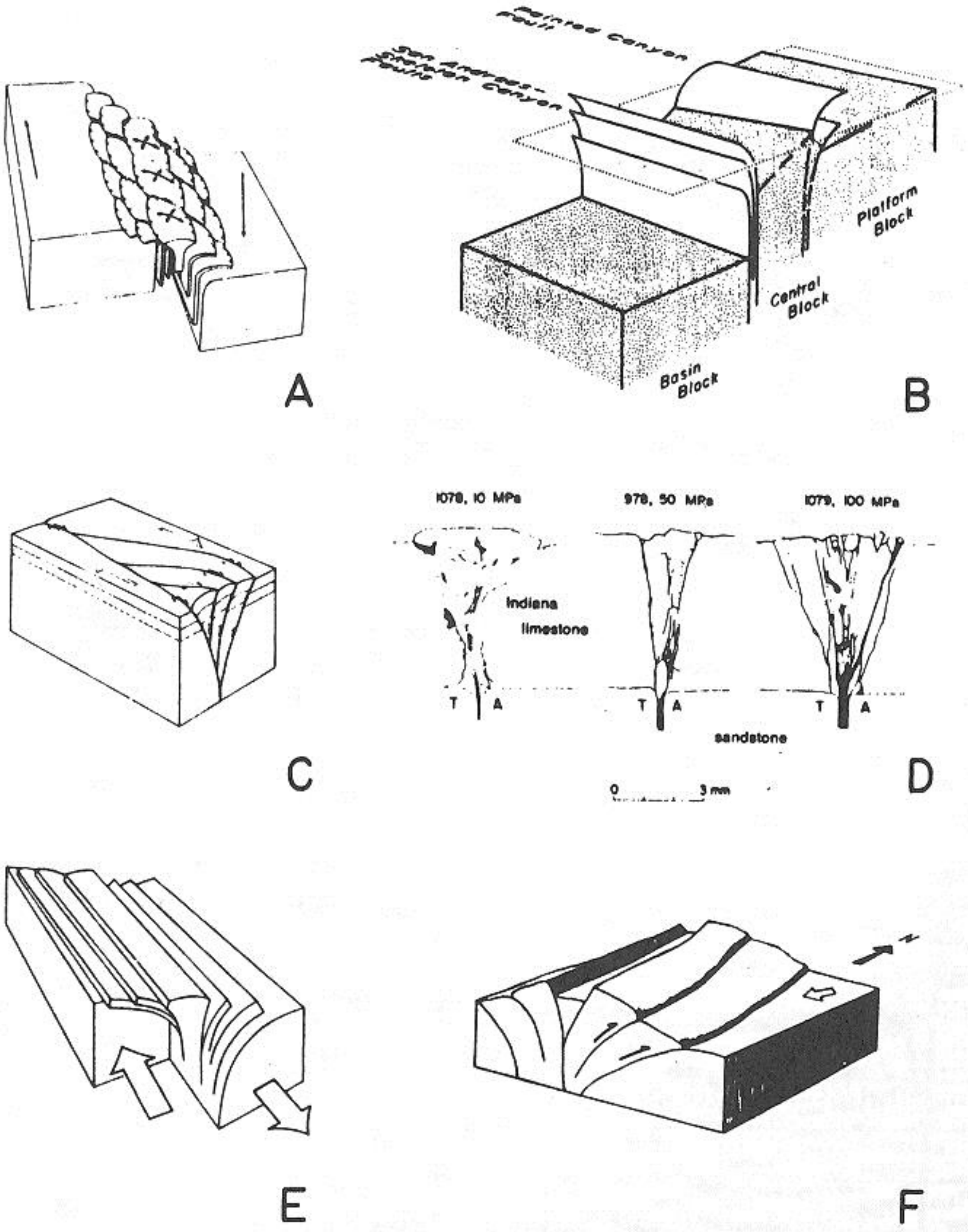


**Fig. 12.6** Conceptual diagrams of flower or palm-tree structures in right simple shear (from Sylvester, 1988): A) from Lowell (1972, p. 3099); B) from Sylvester and Smith (1976); C) from Woodcock and Fisher (1986); D) from Bartlett et al. (1981); E) adapted with modifications from Ramsay and Huber (1987, p. 529); and F) with axial graben from Steel et al. (1985).

the upper plate of allochthonous thrust sheets, yield

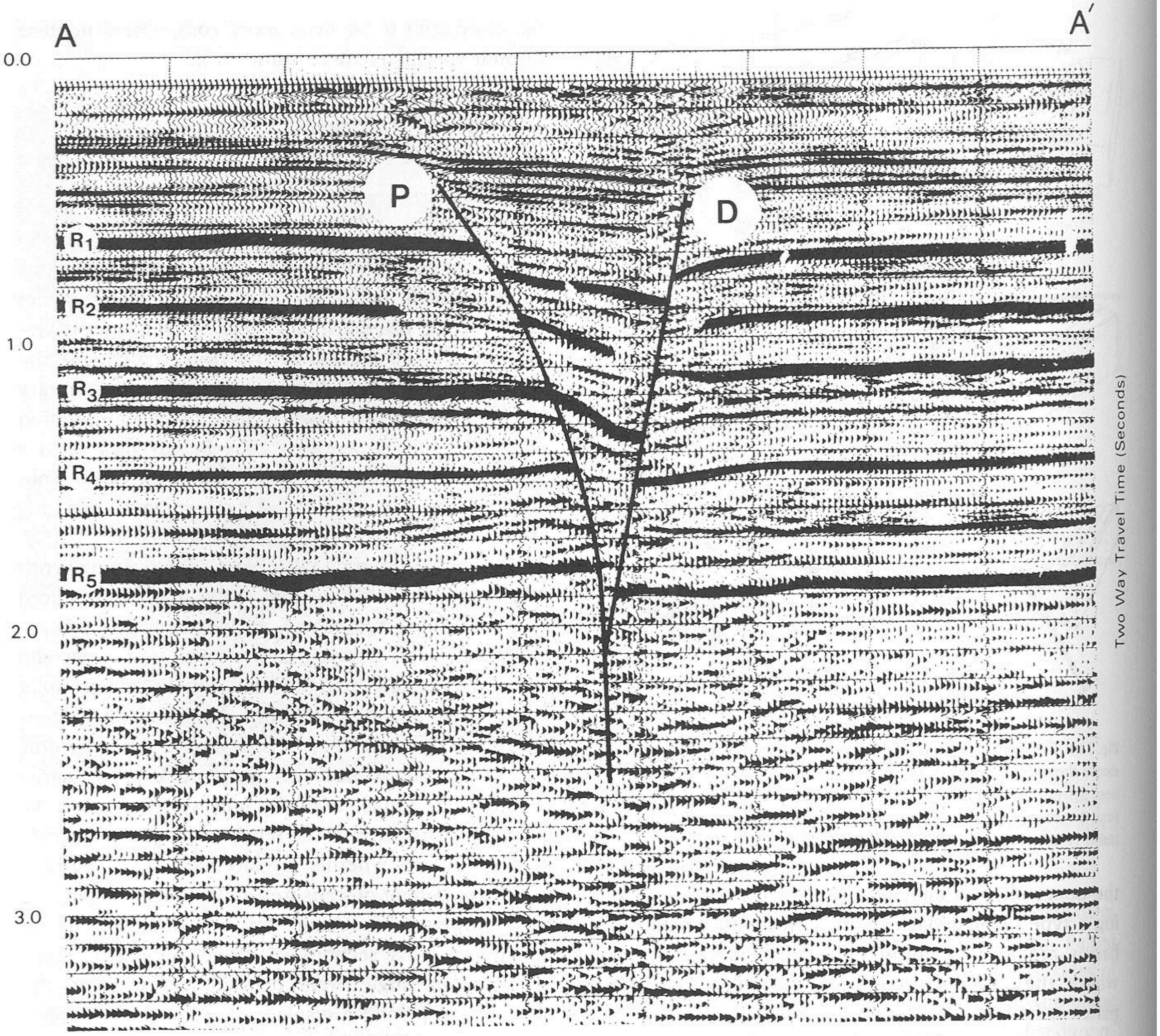


**Fig. 12.7** Seismic-reflection image of negative flower structure (Reproduced with permission from D'Onfro and Glagola, 1983). P and D indicate fault names.

# Intrakratonní pánve

- **INTRAKRATONNÍ PÁNVE (KONTINENTÁLNÍ PLATFORMY)**
- pomalá subsidence - v průměru 25 m/Ma,
- velké rozlohy
- dlouhodobá sedimentace (100 Ma až 1 miliarda let)
- **mechanismus subsidence**
  - velmi pomalá termální subsidence, absence extenzního natahování litosféry
  - možná fázová přeměna gabra na eklogit v nejspodnější kůře
  - možná předsubsidenční historie - prohřátí litosféry
- **příklady**
  - michiganská pánev (spodní paleozoikum)
  - sibiřská platforma
  - pánev jezera Chad
  - Eyrská pánev v Austrálii
  - sedimentace - mělkomořská nebo nonmarinní, časté hiáty a přerušení sedimentace - i dlouhodobé
  - Michiganská pánev - kambrium - jura, potom kvartér

# Intrakratonní pánve (Interior sag basins)

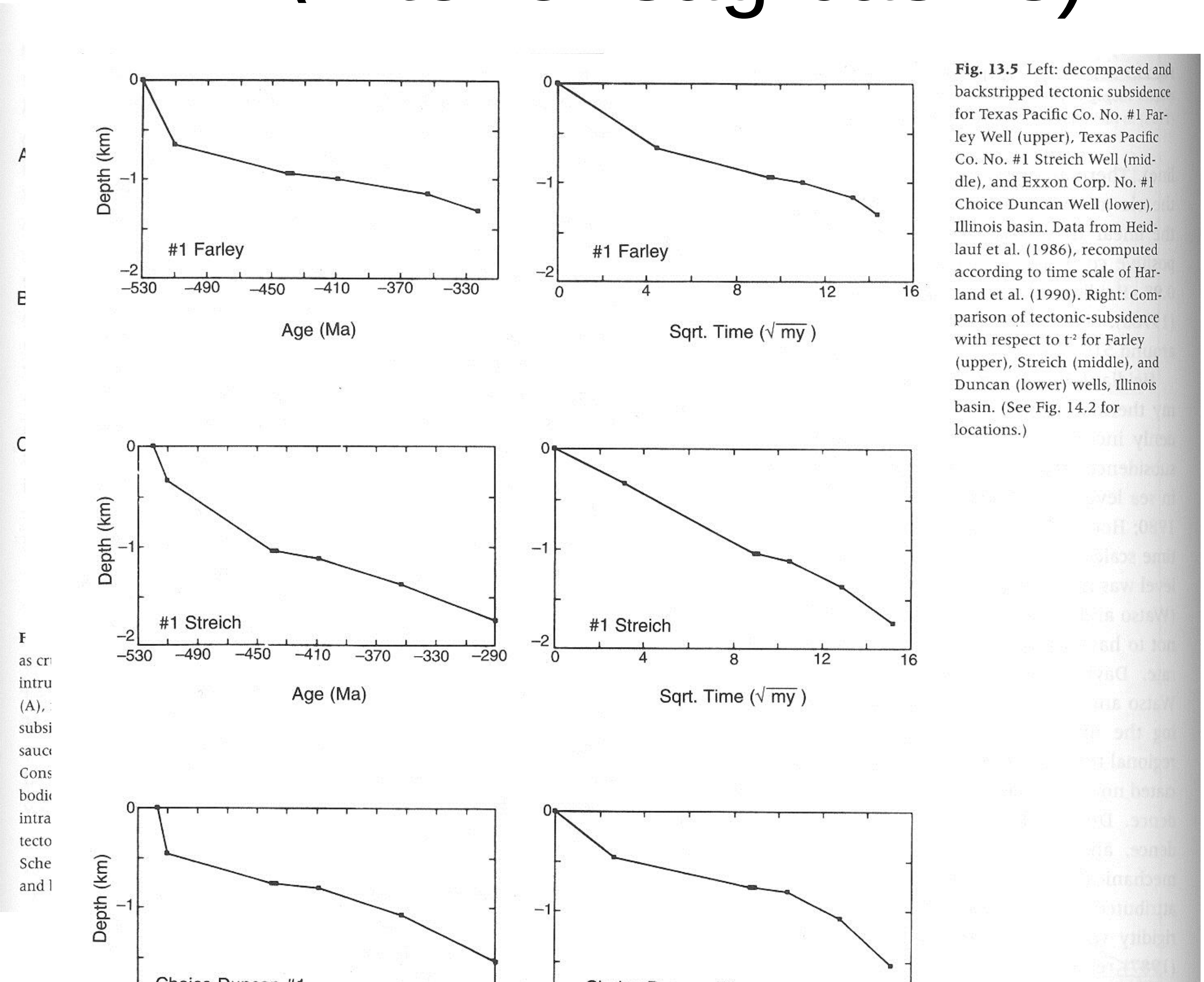


**Fig. 13.5** Left: decompacted and backstripped tectonic subsidence for Texas Pacific Co. No. #1 Farley Well (upper), Texas Pacific Co. No. #1 Streich Well (middle), and Exxon Corp. No. #1 Choice Duncan Well (lower), Illinois basin. Data from Heidlauf et al. (1986), recomputed according to time scale of Harland et al. (1990). Right: Comparison of tectonic-subsidence with respect to $t^{-2}$ for Farley (upper), Streich (middle), and Duncan (lower) wells, Illinois basin. (See Fig. 14.2 for locations.)

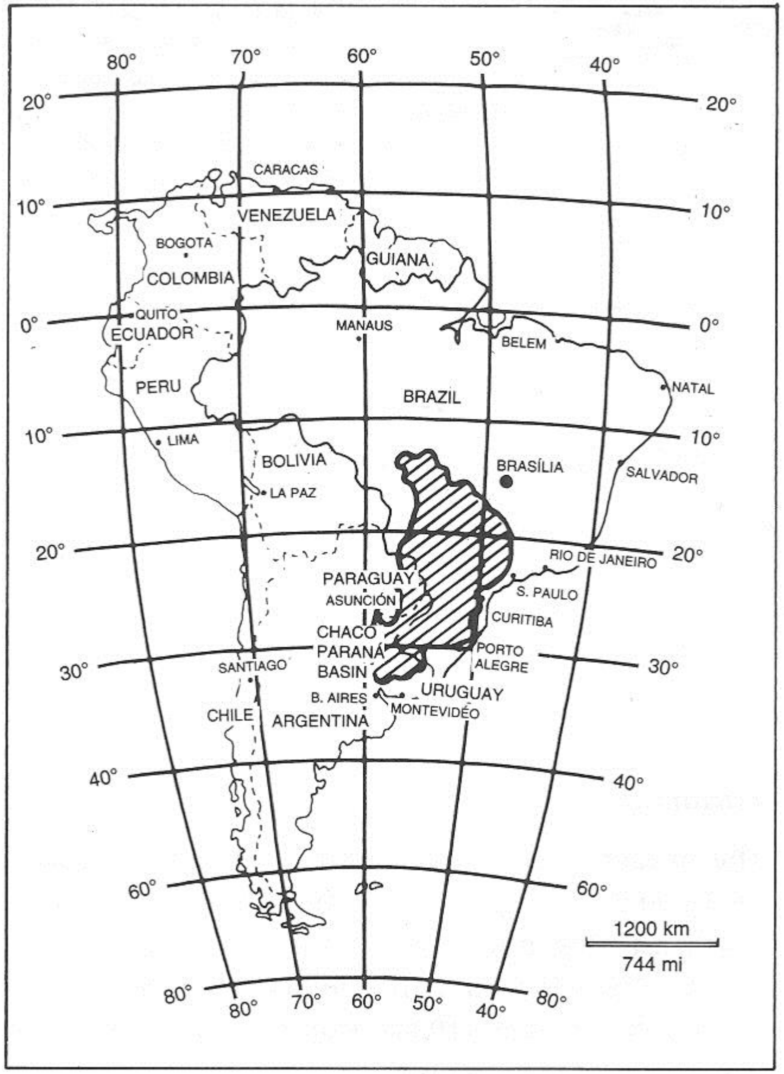


**Fig. 13.13** Index map of Brazil, showing location of Parana basin. (Redrawn after Zalan et al., 1990.)

(Fig. 13.15). Eruption of the lavas was associated with rifting of South America from Africa.

The basin is criss-crossed by regional normal faults and lineaments, some of which are known to extend into basement (DeBrito Neves et al., 1984; Zalan et al.,

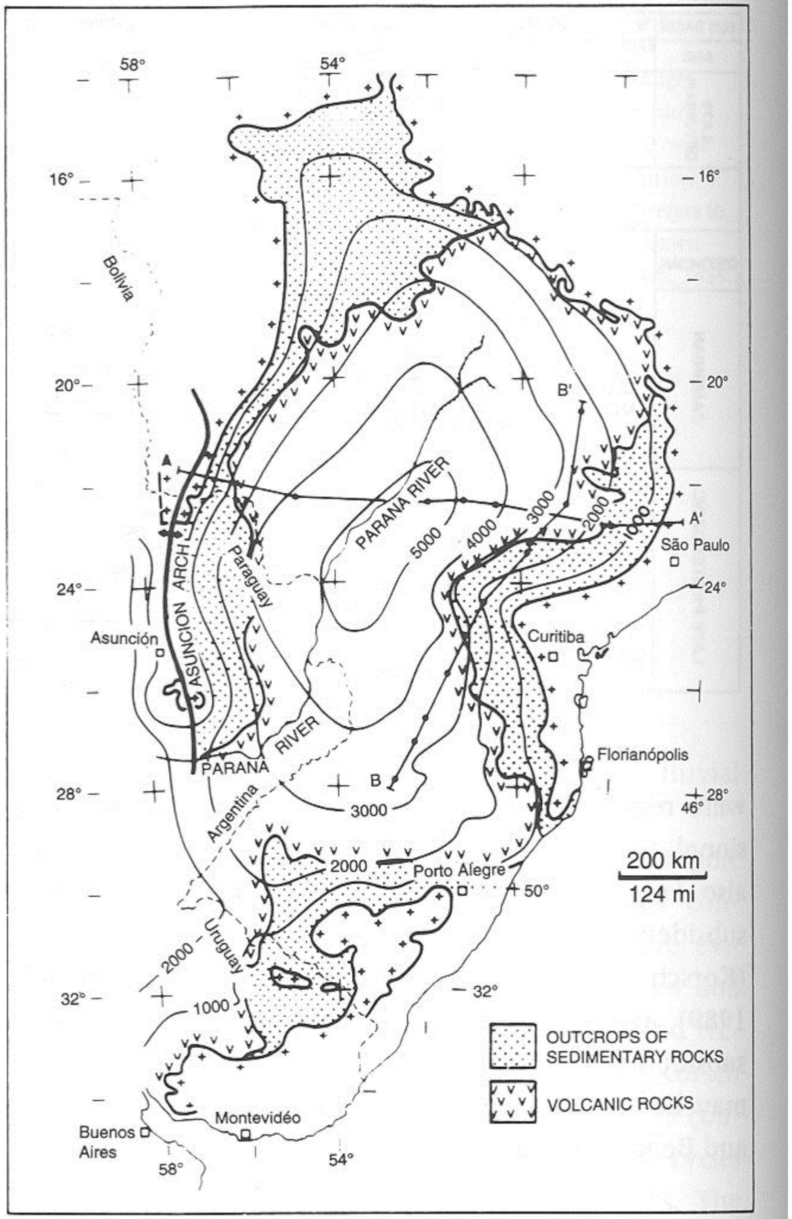


**Fig. 13.14** Isopach map, incorporating both sedimentary and volcanic basin fill, Parana basin, Brazil. (Redrawn after Zalan et al., 1990.)

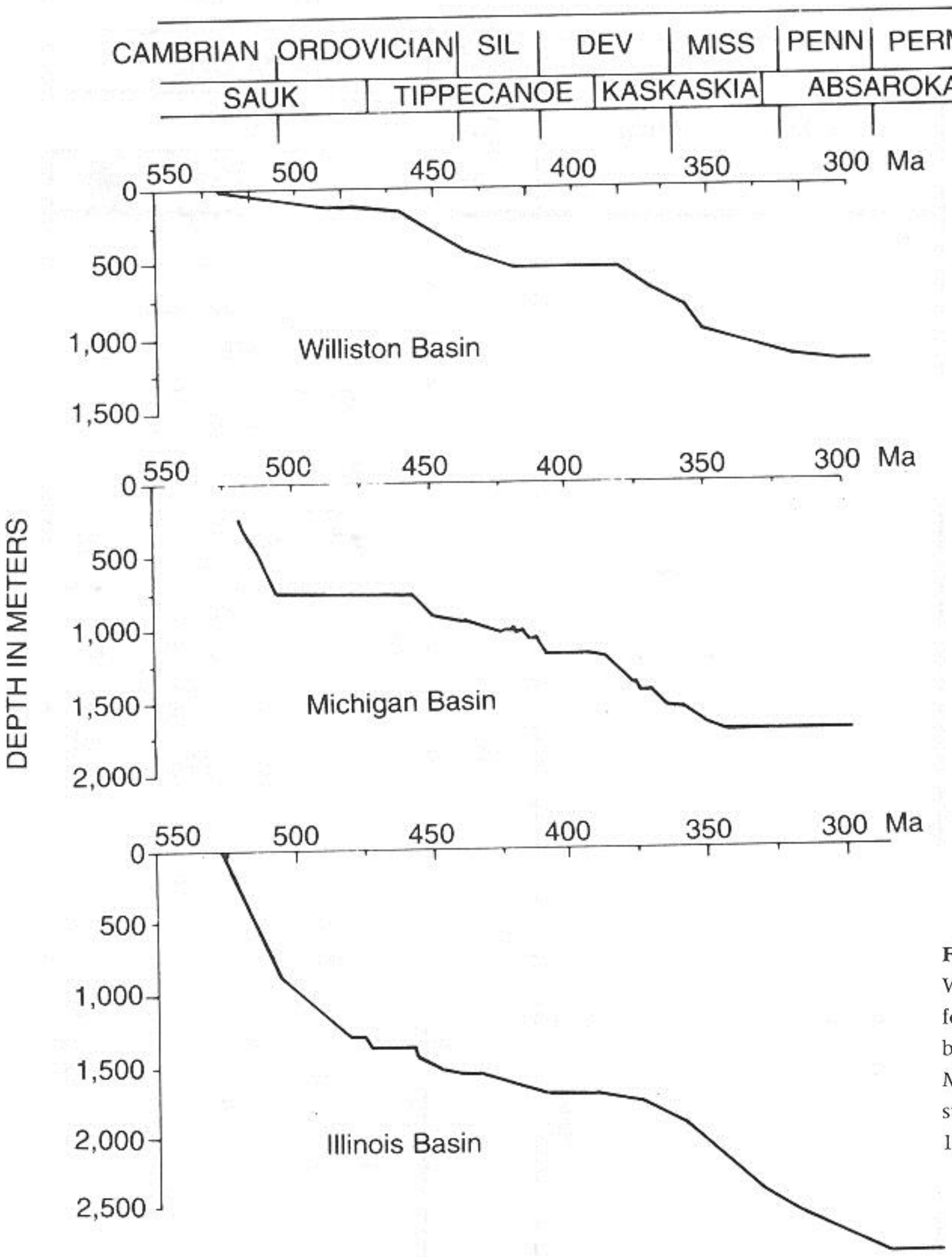


**Fig. 13.8** Backstripped and decompacted tectonic subsidence for the Williston, Michigan, and Illinois basins, showing similar time of basin formation around 550 to 530 Ma, and initiation of thermal subsidence between 530 and 500 Ma. Stratigraphic data for these curves came from McClure-Sparks Well in Michigan basin (Hinze et al., 1978), and regional stratigraphic summaries for other two basins (see Bond and Kominz, 1991, for details). (Redrawn from Bond and Kominz, 1991, Fig. 2E.)

# Tepelná historie sedimentačních pánví

# Kerogen a jehy typy

- **Kerogen:**
  - Kapalné a plynné uhlovodíky vznikají v průmyslově a ekonomicky zajímavých koncentracích výhradně teplotní přeměnou (alterací, konverzí, katagenezí, metamorfózou) organické hmoty rozptýlené v sedimentárních horninách. Tato organická hmota se nazývá kerogen a okolní hornina horninou zdrojovou.

- Existují tři hlavní typy kerogenu (kerogen I, kerogen II a kerogen III), které se odlišují z hlediska geneze, složení a také produkčního potenciálu uhlovodíků během konverze:
  - **kerogen typu I**

    akvatický, řasový kerogen s obsahem amorfních látek, produkuje nejvíce kapalných uhlovodíků, na uhlovodíky se mění až 65% výchozí hmotnosti,
  - **kerogen typu II**

    smíšený terestricko-akvatický kerogen, obsah pylových zrn, fragmentů bylin a minoritního podílu humusového materiálu vedle amorfních součástek a zbytků řas a dalších planktonických zbytků, produkuje kapalné i plynné uhlovodíky, konverzí se mění na uhlovodíky z 50%,
  - **kerogen typu III**

    terestrický kerogen, obsah bylinných i dřevných fragmentů i nestrukturních součástek, produkuje převážně plynné uhlovodíky, v rámci kterých výrazně převládá metan, na uhlovodíky se během konverze mění maximálně 30% původní hmotnosti.

# Tepelná přeměna organické hmoty

- *Fáze přeměny (alterace)*
- Proces konverze kerogenu na uhlovodíky generelně začíná při teplotách 50 respektive 60 oC (iniciační teplota), vrcholí kolem teplot 80 až 120 oC a rychle vyznívá při teplotách vyšších než 140 až 170 oC, přičemž existují v závislostech intenzity produkce uhlovodíků na teplotě mezi jednotlivými typy kerogenu rozdíly. S rostoucí teplotou nabývá na intenzitě dělení dlouhých řetězců alkanů, alkenů a izoprenoidních uhlovodíků (krakování). V teplotách nad ca 100 oC jsou dlouhodobě stabilní jen plynné uhlovodíky.
- Pro fázový charakter fluid má význam vedle teplot a tlaků také množství a látkové složení uhlovodíků.
- Zvyšování teplot expozice kerogenu v horninách je určováno zvyšováním úložných hloubek, zvyšováním mocnosti nadloží. Zvyšování mocnosti nadloží může být buď subsidenční (postupné „pohřbívání“ zdrojových hornin do větších hloubek pod rostoucí mocností ukládaných sedimentů) nebo tektonické (zvýšení hloubek uložení zdrojových hornin pod relativně náhle nasunutými příkrovy). V naší zájmové oblasti přicházejí v úvahu oba způsoby. Zjednodušeně lze chápat teplotu expozice jako funkci teplotního gradientu a expoziční hloubky ponoření sedimentu s korekcí o hodnoty teploty pro nulovou hloubku (průměrná povrchová teplota pod hranicí sezónních výkyvů, resp. teploty moře – ca 6 až 12 oC).
- Průběh konverze kerogenu všech typů závisí na kombinaci teplot a časů expozice. Přibližně platí, že rychlost procesů konverze kerogenu na uhlovodíky se s každým nárůstem teploty o 10 až 15oC zdvojnásobuje (Arrheniova rovnice pro kinetiku chemických reakcí). Stejný efekt v transformaci kerogenu trvající hypoteticky při teplotách 70 oC například 100 mil. let je dosažen již za ca 6 mil. let při teplotách 110 oC. Zároveň se však předpokládá, že při stálých teplotách transformace po 10 mil. bez dalšího zvyšování teplot ustává. Daná úroveň katageneze kerogenu může být dosažena v dřívějších etapách geologického vývoje oblasti (reliktní katageneze) nebo je zvyšována v současných hloubkách.
- Proces konverze kerogenu je nevratný. Může však být přerušován a znovu obnovován při zvýšení teplot, respektive při nástupu nových „teplotních impulzů“ (zvýšení úložných hloubek nebo gradientů, popřípadě úložných hloubek i gradientů). Rozhoduje celková teplotní dávka – sumární impulz tepla. O sumární impulz tepla se opírají veškeré současné modely vzniku uhlovodíků z kerogenu hornin. Bez ohledu na užité jednotky rozdělují obvykle konverzi na tyto hlavní fáze:
- fáze nezralého kerogenu - immature zone, vznik maximálně biogenního metanu,
- fáze rané konverze plynu a ropy - incipient mature zone,
- hlavní fáze vzniku ropy - mature zone, oil window, ropné okno,
- fáze tvorby plynokondenzátu - wet gas zone, plyn, kondenzát, vyznivání tvorby ropy,
- fáze tvorby suchého plynu - dry gas zone, vznik plynu transformací kerogenu i krakováním vyšších uhlovodíků, převah metanu,
- fáze vyčerpaného kerogenu - uhlovodíky již nevznikají.

Hloubkový profil odraznosti vitrinitu, Louisiana

Téměř linerární profil = geotermický gradient byl v průběhu sedimentace téměř konstantní

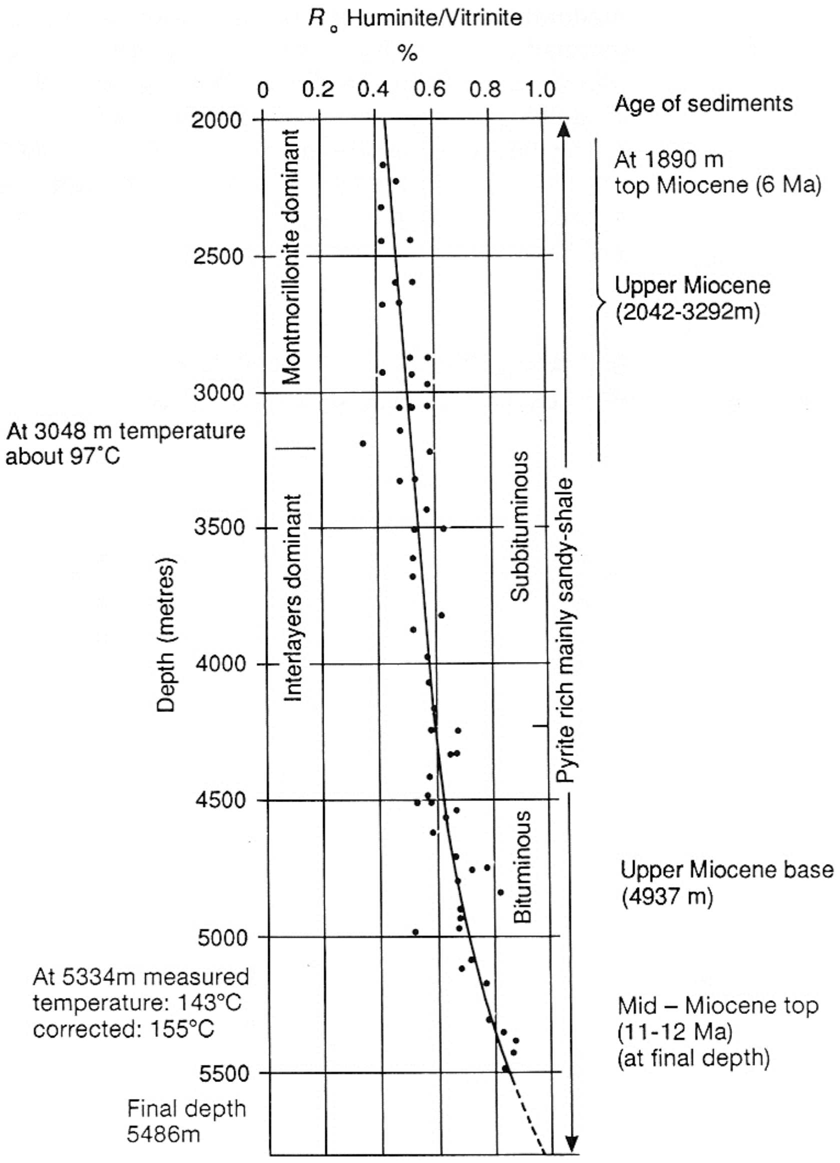


**Fig. 9.7.** Vitrinite reflectance profile for Terrebonne Parish, Point au Fer well in Louisiana. The profile is sublinear and continuous, suggesting a near constant geothermal gradient through time (after Heling and Teichmüller 1974).

Subsidenční historie a hloubkový profil odraznosti vitrinitu

Sydney Basin

Subsidence 0,073 mm/rok

Geotermický gradient: 50 ºC/km

Bowen Basin
Subsidence 0,073 mm/rok
Geotermický gradient: 44 ºC/km

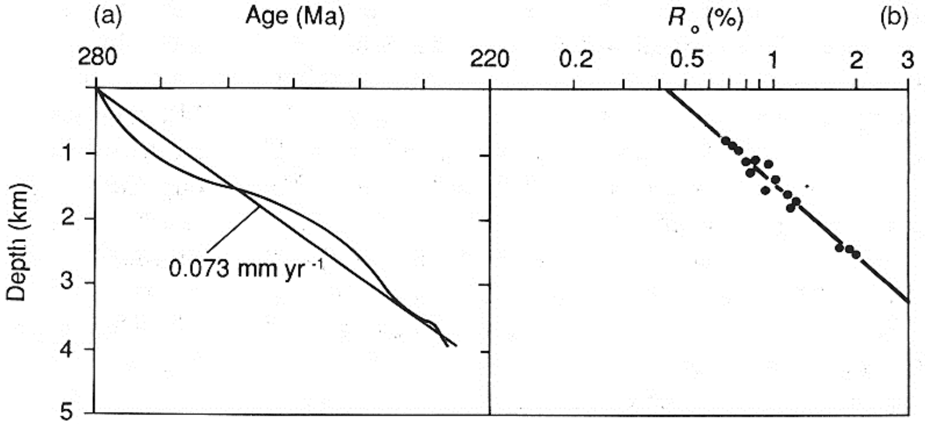


**Fig. 9.11.** Subsidence history (a) and reflectance profile (b) of the Howes Swamp 1 borehole in the Sydney Basin (Mayne *et al.* 1974). The subsidence curve gives a constant rate of 0.073 mm $\mathrm{yr}^{-1}$. In (b) black dots are reflectance measurements, and solid line is the curve resulting from the tectonic model A1 with a constant geothermal gradient of 50 °C $\mathrm{km}^{-1}$ (after Middleton 1982).

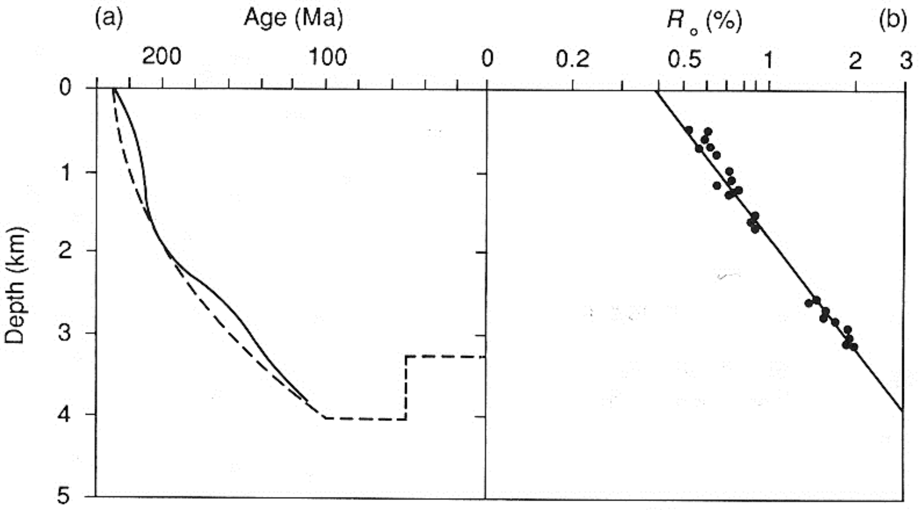


**Fig. 9.12.** Subsidence history (a) and reflectance profile (b) for the Windoan region of the Bowen Basin. The solid line in (a) is the observed basement subsidence, showing a rough $t^{1/2}$ relationship. The dashed line is the curve for the tectonic model A2 with a constant geothermal gradient of 44 °C $\mathrm{km}^{-1}$. (Shibaoka, Bennett and Gould 1973). In (b) the black dots are vitrinite reflectance measurements and the solid line is the curve for the A2 tectonic model (full details of parameter values in Middleton 1982).

**Nelineární průběh hloukové distribuce odraznosti vitrinitu**

Křivky odraznosti vitrinitu ve vrtech

Alsasko, rýnský prolom

Předoligocenní vysoký gradient = vysoký tepelný tok

Postoligocenní nízký gradient = nízký tepelný tok

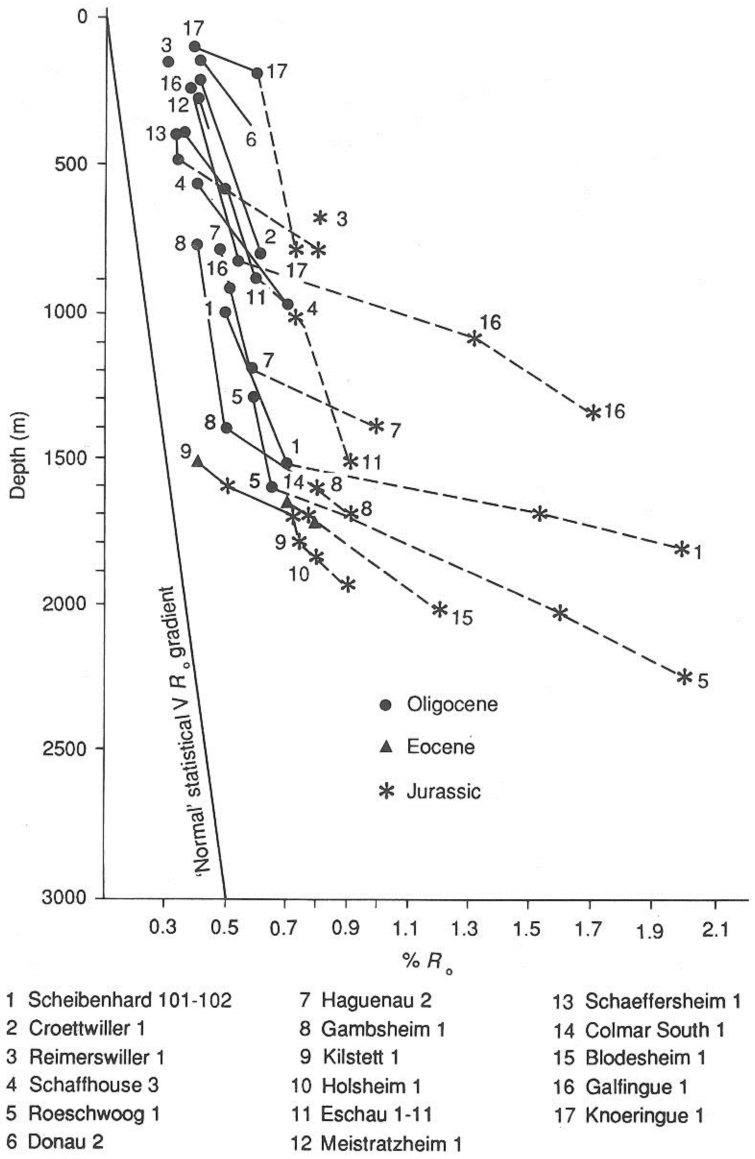


**Fig. 9.8** Reflectance profiles from a number of wells in the Alsace region of the Rhine Graben. In general, there are pronounced dog-legs in the $R_o$ profiles at about the age of the Eocene–Oligocene boundary. The post-Oligocene history shows a near 'normal' gradient, whereas the pre-Oligocene sediments have high reflectance values in relation to their depth of burial (after Teichmüller 1970).

Izolinie odraznosti vitrinitu (paleoizotermy)

Křížení s tektonickými strukturami

Posttektonické prohřátí

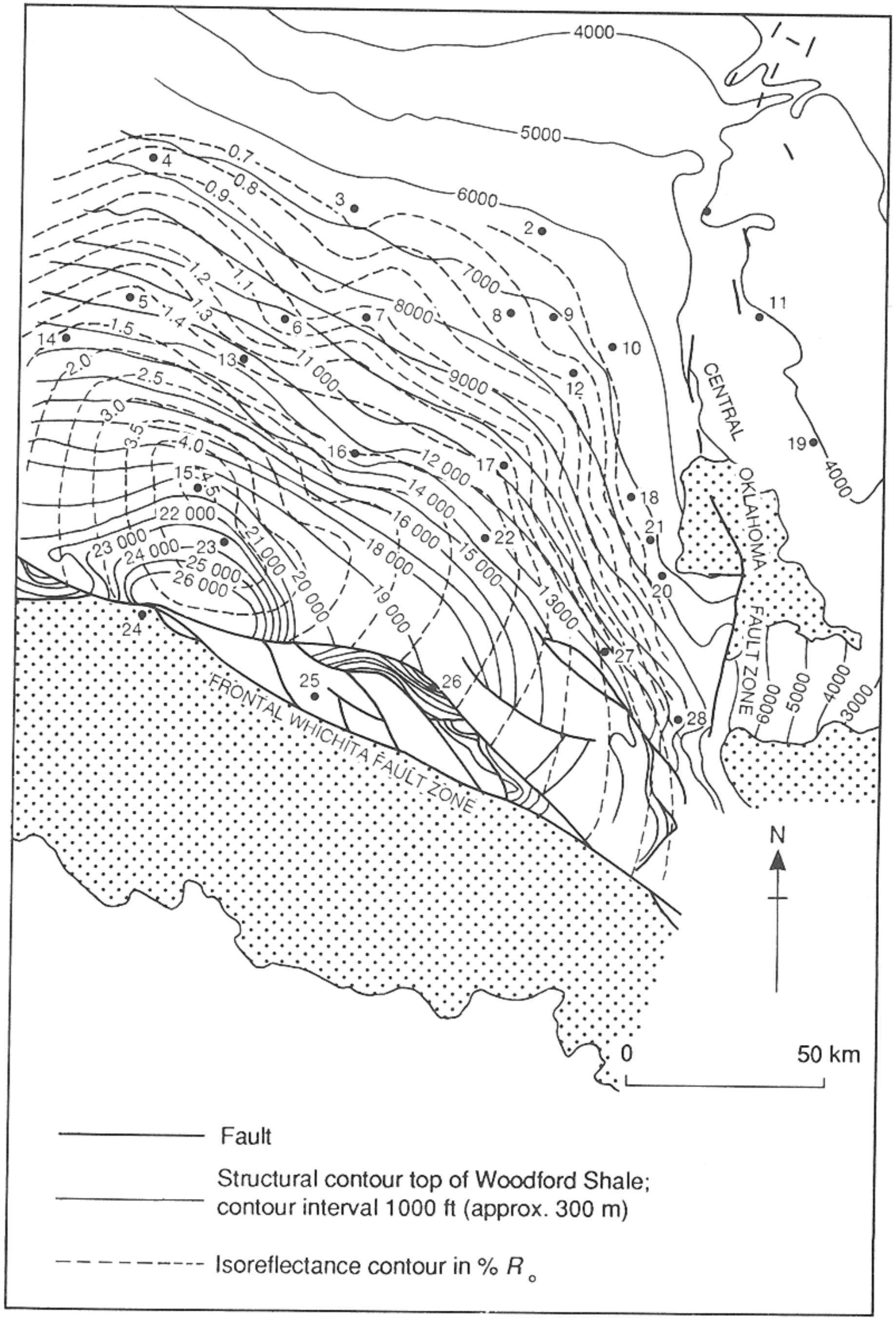


**Fig. 9.20.** Combined isoreflectance and structure map of the Woodford Shale in the Anadarko Basin of Oklahoma (after Cardott and Lambert 1985). Vitrinite reflectance values in general increase with depth of burial, but strong cross-cutting relationships of the isoreflectance and structure contours suggest that there may have been local thermal disturbances superimposed on the burial-related maturation.

# Vliv generovaného interního tepla v sedimentárním profilu H a tepelné vodivosti K na hloubkovou distribuci teplot (T(y))

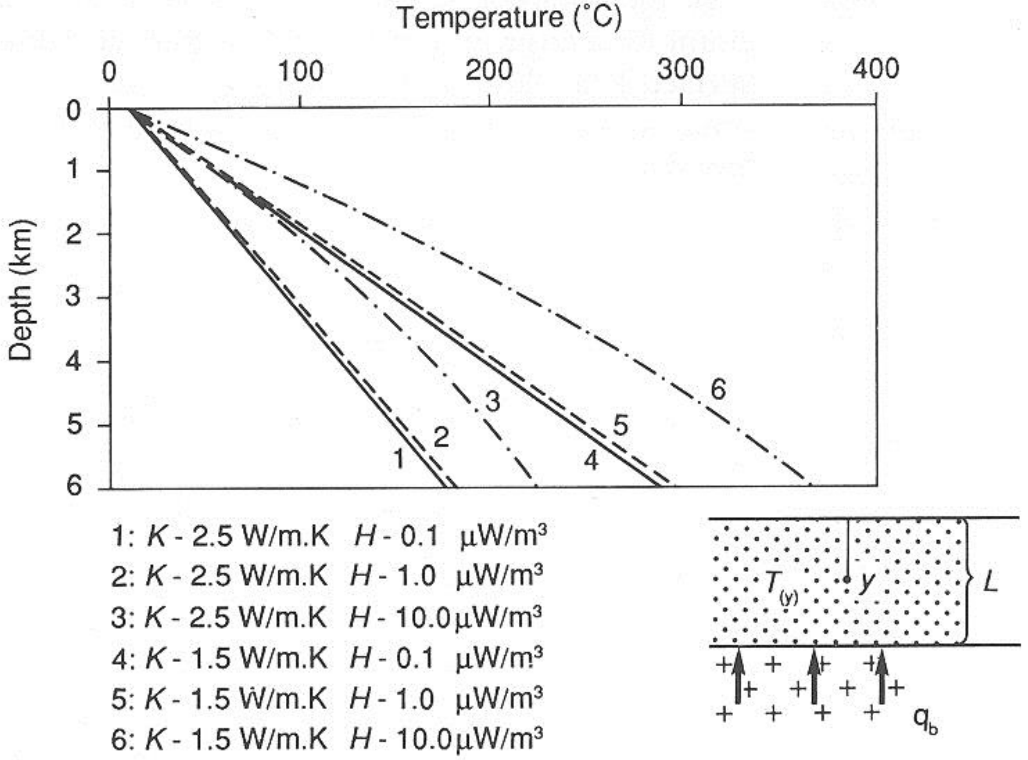


**Fig. 9.3.** The influence of internal heat generation in the sedimentary column *H* and the thermal conductivity *K* on the distribution of temperature with depth ($T(y)$). The different curves were calculated by Rybach (1986) for a thickness of the heat-producing zone of 6 km, a basal heat flux $q_b$ of 70 mW m$^{-2}$ and a surface temperature $T_0$ of 10 °C.

Vliv průtoku podzemní vody na povrchový tepelný tok v sedimentární pánvi

(a) mapa tepelného toku, Alberta, Kanada

Zóna doplňování akvifery (recharge zone) snižuje hodnotu tepelného toku

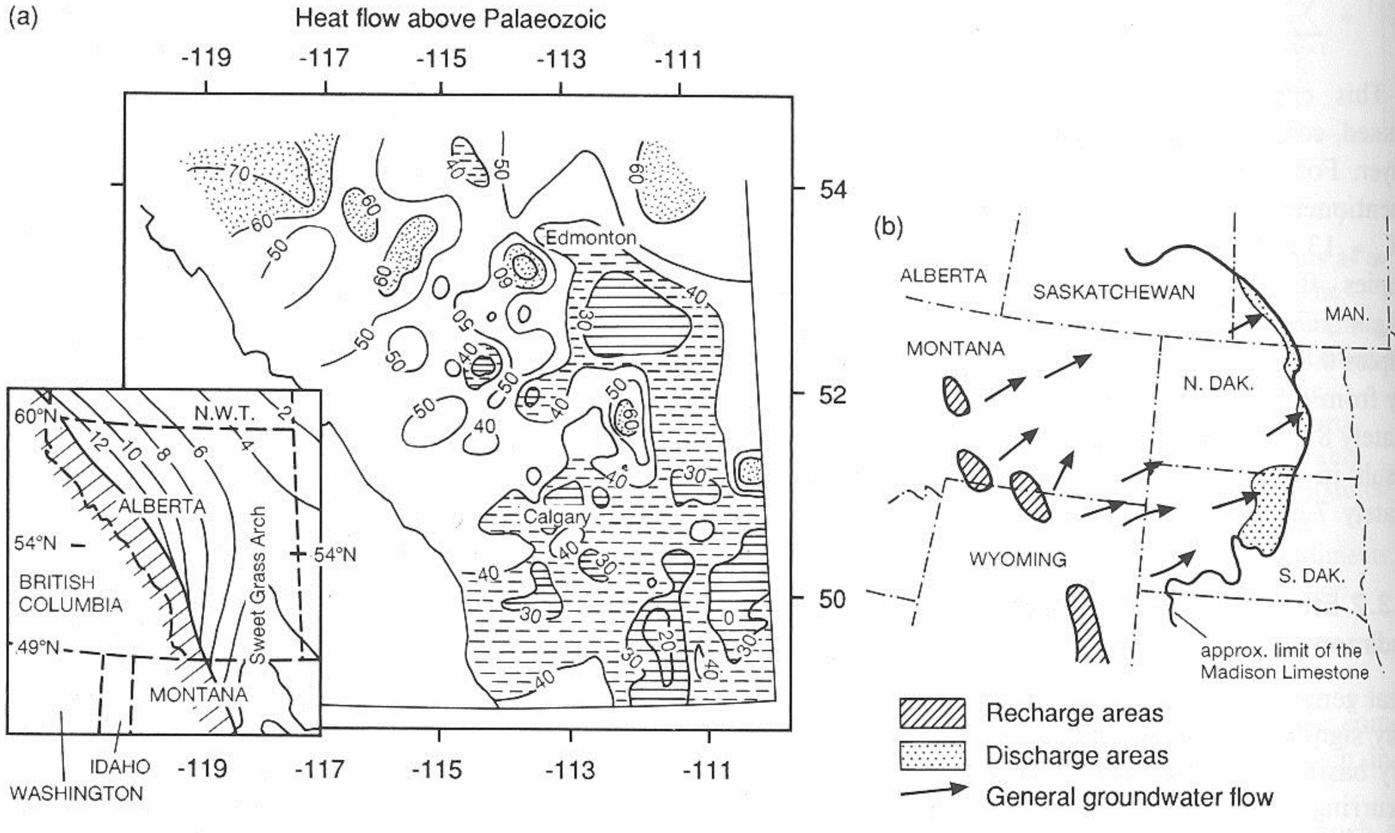


**Fig. 9.4.** Effects of groundwater flow on surface heat flows in sedimentary basins. (a) Heat flow map of southern and central Alberta, Canada based on estimated heat flow values (in mW $m^{-2}$) above the top of the Palaeozoic. These values are based on 33 653 bottom hole temperature data from 18 711 wells analysed by Majorowicz *et al.* (1984). The heat flows are strongly influenced by groundwater flow from recharge areas in structurally high regions such as the Sweet Grass Arch (inset), to discharge areas. (b) Pattern of recharge and discharge in the Great Plains, USA in the Mississippian (Lower Carboniferous) Madison Limestone aquifer (after Downey 1984).

Hloubková závislost indexu maturace organické hmoty (odraznost vitrinitu) pro kerogeny různých stáří

Starší kerogeny jsou zralejší než mladé kerogeny

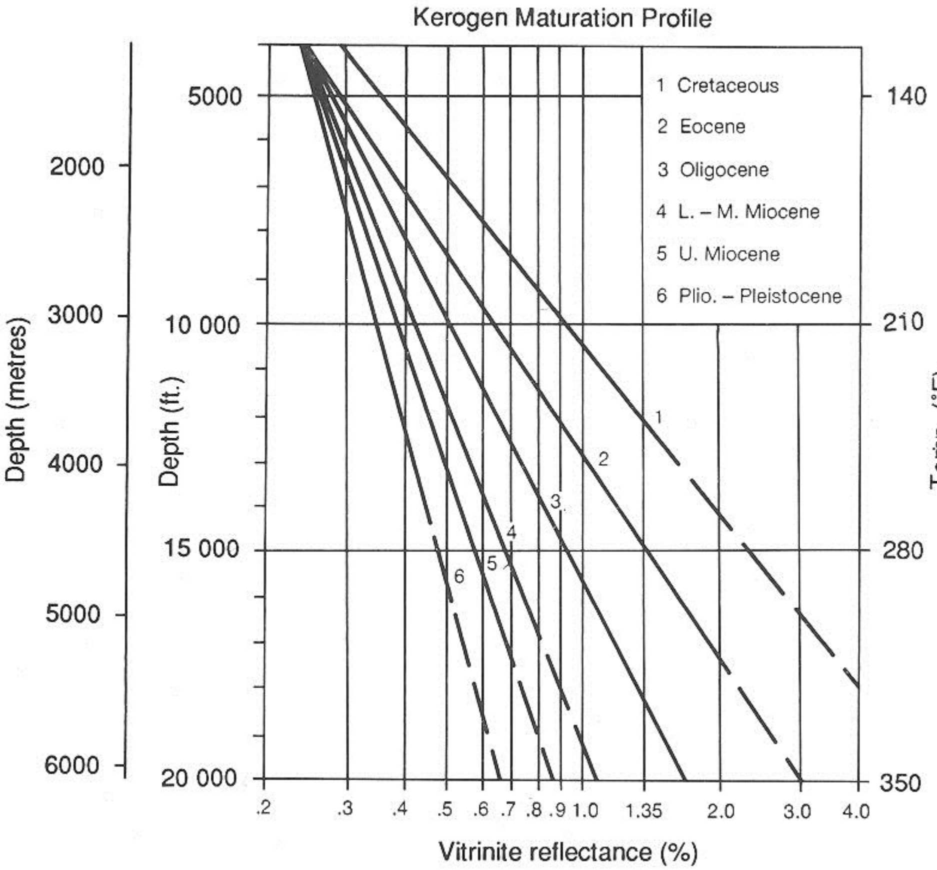


**Fig. 9.1.** Plot of depth versus an index of organic maturation (vitrinite reflectance) for kerogens of various ages (after Dow 1977). For the same depth of burial (and therefore for the same temperature at a constant geothermal gradient), older kerogens are significantly more mature than younger kerogens.