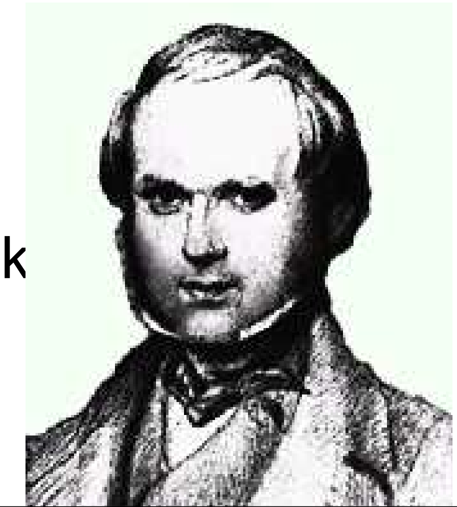
STRATIGRAFIE

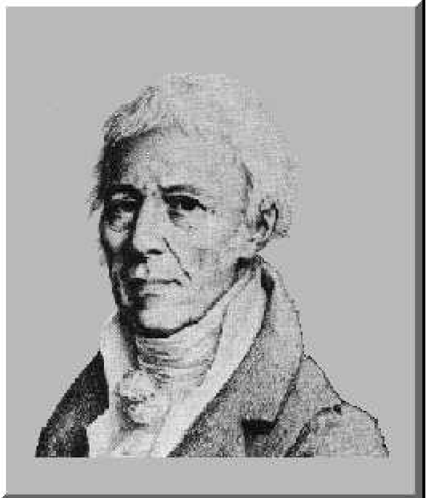
- „Nauka o vrstevních sledech“ (princip superpozice) Zabývá se relativním měřením času v geologii
- Studuje „horninové jednotky“ a interpretuje horninové sledy jako sled událostí v dějinách Země („klíč“ k pochopení historie planety Země)
- Součástí téměř všech geologických disciplín (stáří hornin je jednou ze základních informací, se kterou pracují všichni geologové)

Historie

- N. Steno, 1669, Princip superpozice a související principy
- “No geology existed prior to Hutton“
  J. Hutton, princip uniformity, uniformitarianismus

- Charles Lyell, Principles of Geology
- W. „Strata“ Smith, základy biostratigrafie, principle of faunal succession („stejných zkamenělin“)
- Lamarck, Darwin, evoluční teorie
- A. Gressley, pojem facie, interpretace
- horninových celků ve smyslu prostředí vznik





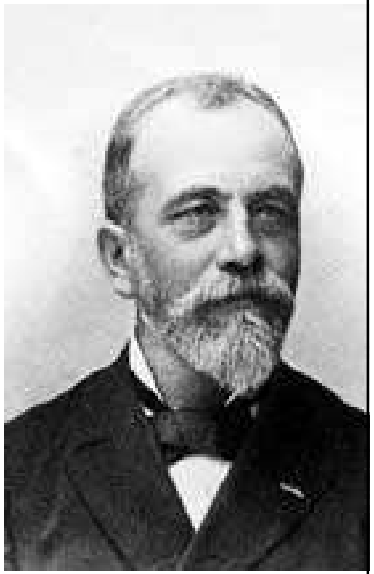
Charles Lyell (1797 - 1875)

- *The Principles of Geology* (1833 - 1875)

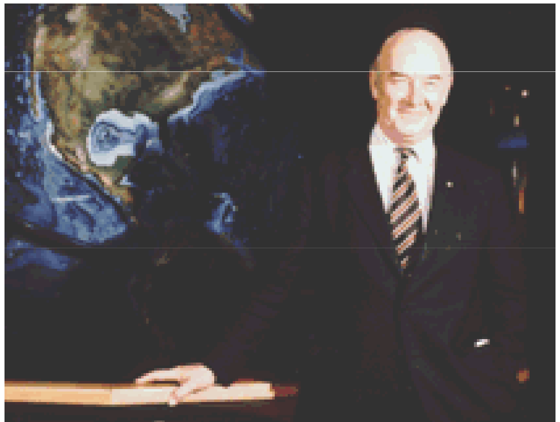
*A strong promoter of uniformitarian theory;

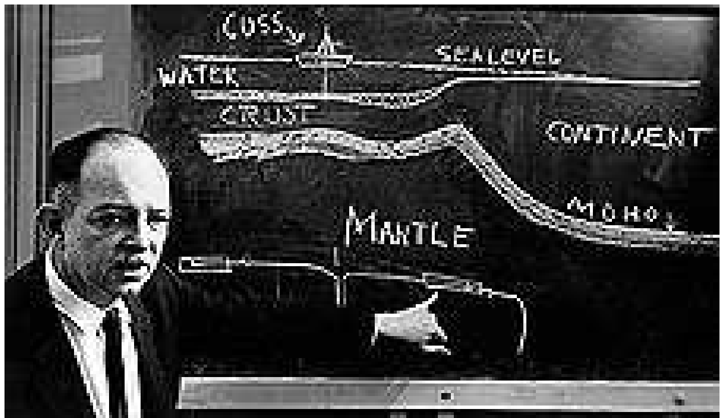
*A vehement opponent of catastrophism;

Geotektonické hypotézy



- J.D. Dana, J. Hall, geosynklinální hypotéza
- M. Bertrand, teorie příkrovů
- A. L. Wegener, kontinentální drift
- Harry Hess, sea-floor spreading
- J.Tuzo Wilson, transform faults, Wilson cycle





Datování hornin

- E. Rutherford, manželé Curieovi, objev radioaktivity, počátek 20. stol.
- W. F. Libby (Nobel prize 1960), ^{14}C dating

Chronostratigrafická škála

- Definice mnoha útvarů (Cambrian, Silurian, Devonian, Permian) v polovině 19. stol (R. Murchinson, A. Sedgwick)

- 2. pol. 19. stol., vytvoření chronostratigrafické škály

- Mezinárodní návody lito- a biostratigrafické klasifikace a nomenklatury, Hedberg 1976,

Basic stratigraphic principles

1. **The principle of superposition** - in a vertical sequence of sedimentary or volcanic rocks, a higher rock unit is younger than a lower one. "Down" is older, "up" is younger.
2. **The principle of original horizontality -** rock layers were originally deposited close to horizontal.
3. **The principle of original lateral extension -** A rock unit continues laterally unless there is a structure or change to prevent its extension.
4. **The principle of cross-cutting relationships -** a structure that cuts another is younger than the structure that is cut.
5. **The principle of inclusion -** a structure that is included in another is older than the including structure.
6. **The principle of "uniformitarianism" -** processes operating in the past were constrained by the same "laws of physics" as operate today.

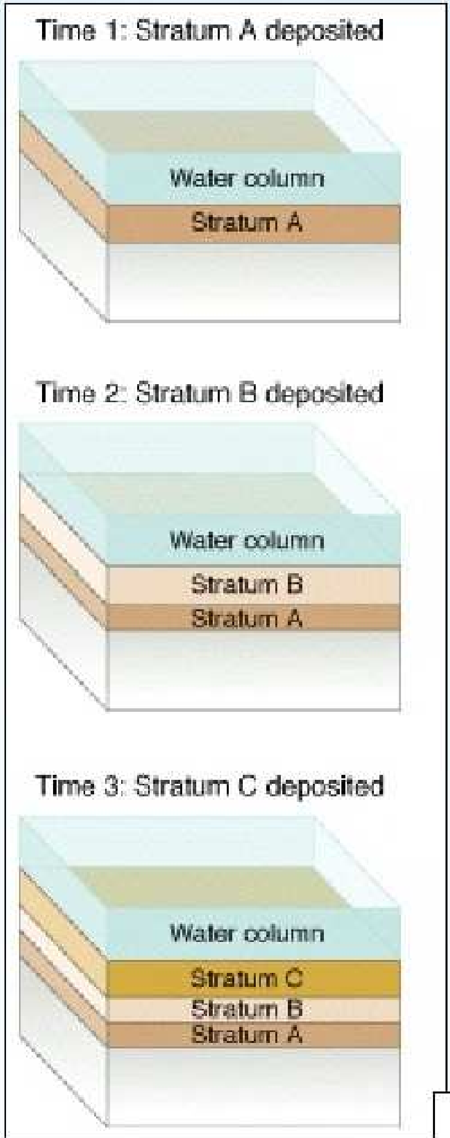


Fig 3-4

Reading the Record of Time in Sedimentary Rocks - Steno's Laws

- Law of Superposition
  - sediment deposited in layers on seafloor or land surface
  - each succeeding layer buries strata underneath
  - oldest stratum at bottom
  - youngest stratum at top

THE PRINCIPLE OF SUPERPOSITION

•In a sequence of strata, any stratum is younger than the sequence of strata on which it rests, and is older than the strata that rest upon it. "...at the time when any given stratum was being formed, all the matter resting upon it was fluid, and, therefore, at the time when the lower stratum was being formed, none of the upper strata existed." Steno, 1669.

Steno's Stratigraphic Laws

- Law of Superposition
  - strata are progressively younger from bottom to top of section
- Law of Original Horizontality
  - strata deposited in horizontal layers
  - tilted rocks have been deformed

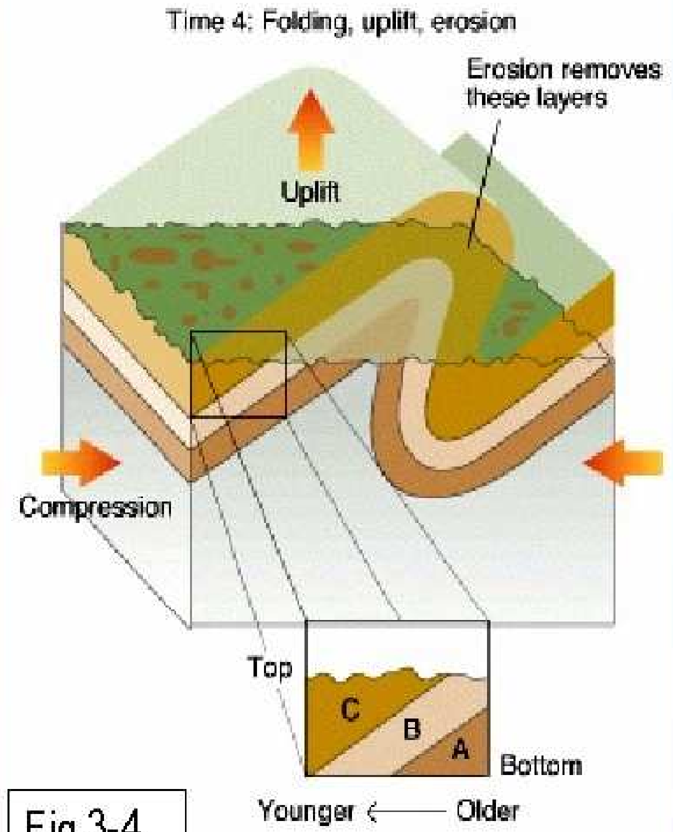


Fig 3-4

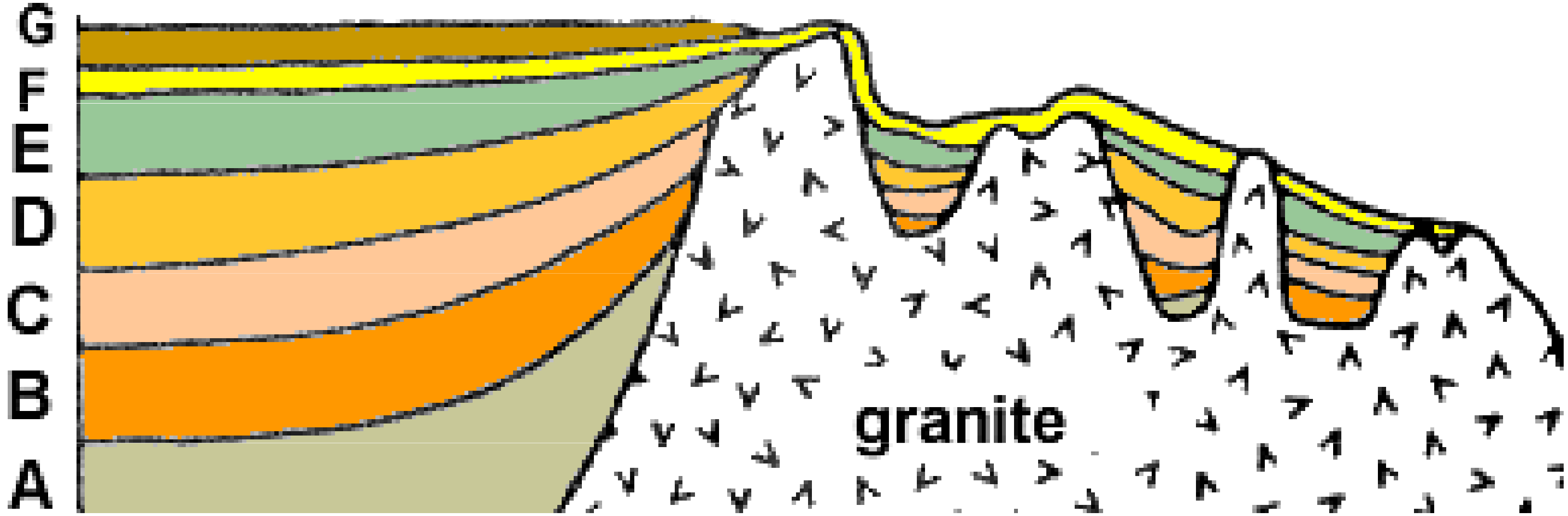
PRINCIPLE OF INITIAL HORIZONTALITY

•Strata are deposited horizontally and then deformed to various attitudes later. "Strata either perpendicular to the horizon or inclined to the horizon were at one time parallel to the horizon." Steno, 1669.

Nicholas Steno, a Danish physician living in Italy in 1669 proposed that the Earth's strata accumulated with three basic principles. Steno pointed out obvious, but overlooked principles of sediment accumulation. They included the **Principle of Original Horizontality**, **Principle of Superposition**, and **Principle of Original Continuity**. If sediments accumulate in a large basin, the laws of gravity will deposit the beds, horizontal to the surface of the Earth. Beds can "pinch out" along the sides of the basin as in the figure below.

The Principle of Superposition states that in a sequence of sedimentary rock layers, the bottom layers are older than the top layers. The bottom layers were deposited first. In the figure below A is the oldest bed and G is the youngest.

The Principal of Original Continuity states that the beds can be traced over a long interval if the basins were open. For instance, Bed F can be traced continuously to the smaller basin in the figure below. The other beds below F can then be correlated to Beds A-E.



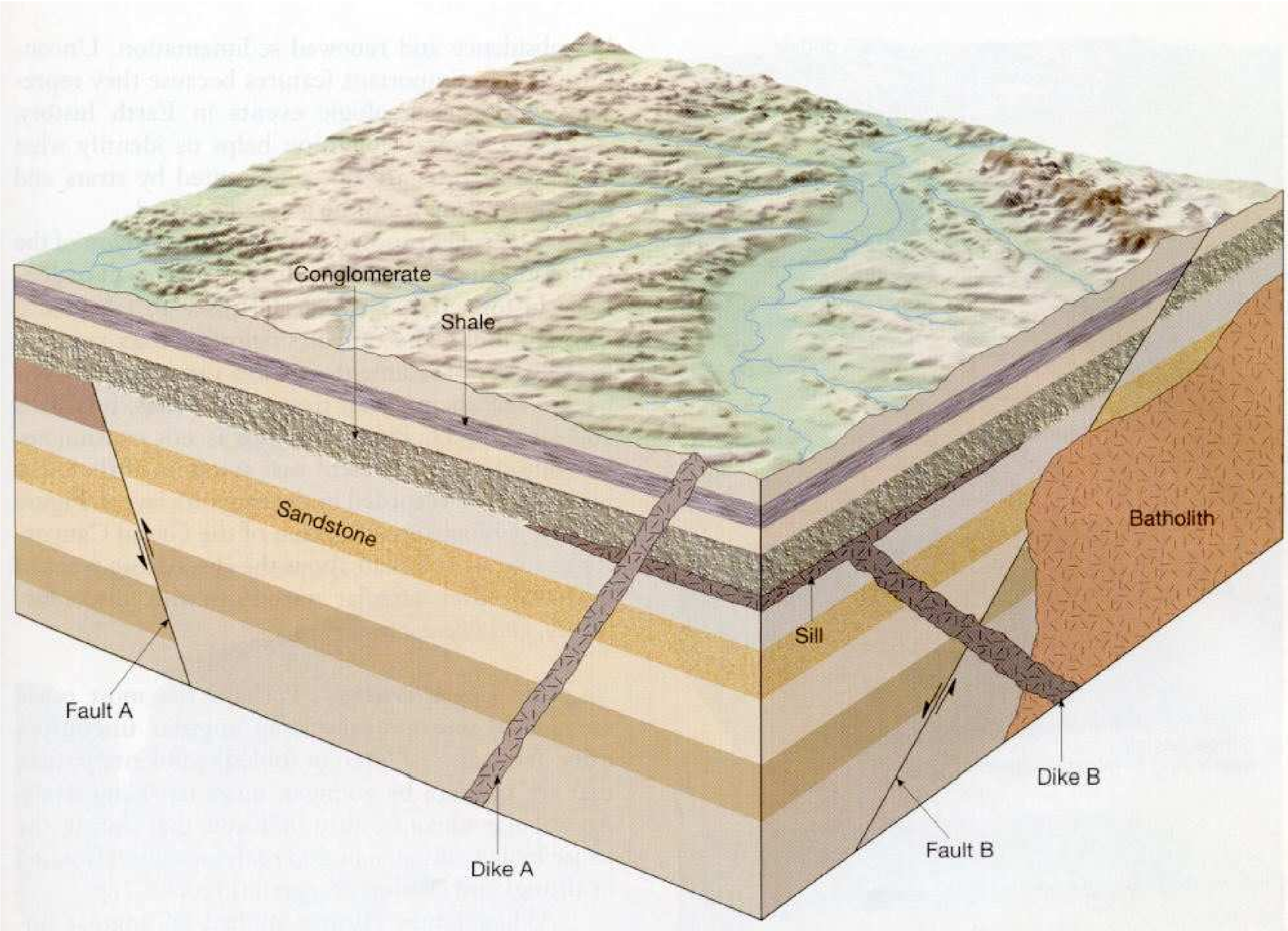
PRINCIPLE OF STRATA CONTINUITY

•Strata can be assumed to have continued laterally far from where they presently end. "Material forming any stratum were continuous over the surface of the Earth unless some other solid bodies stood in the way." Steno, 1669

Relativní datování: stratigrafická inkluze, stratigrafický průnik

PRINCIPLE OF CROSS CUTTING RELATIONSHIPS

***** Things that cross-cut layers probably postdate them. "If a body or discontinuity cuts across a stratum, it must have formed after that stratum." Steno, 1669

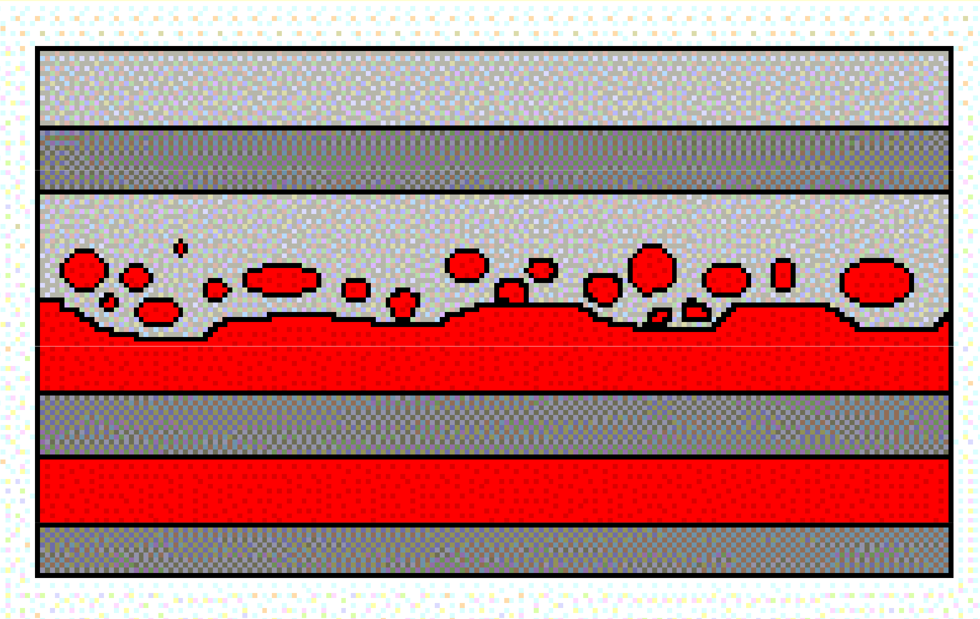


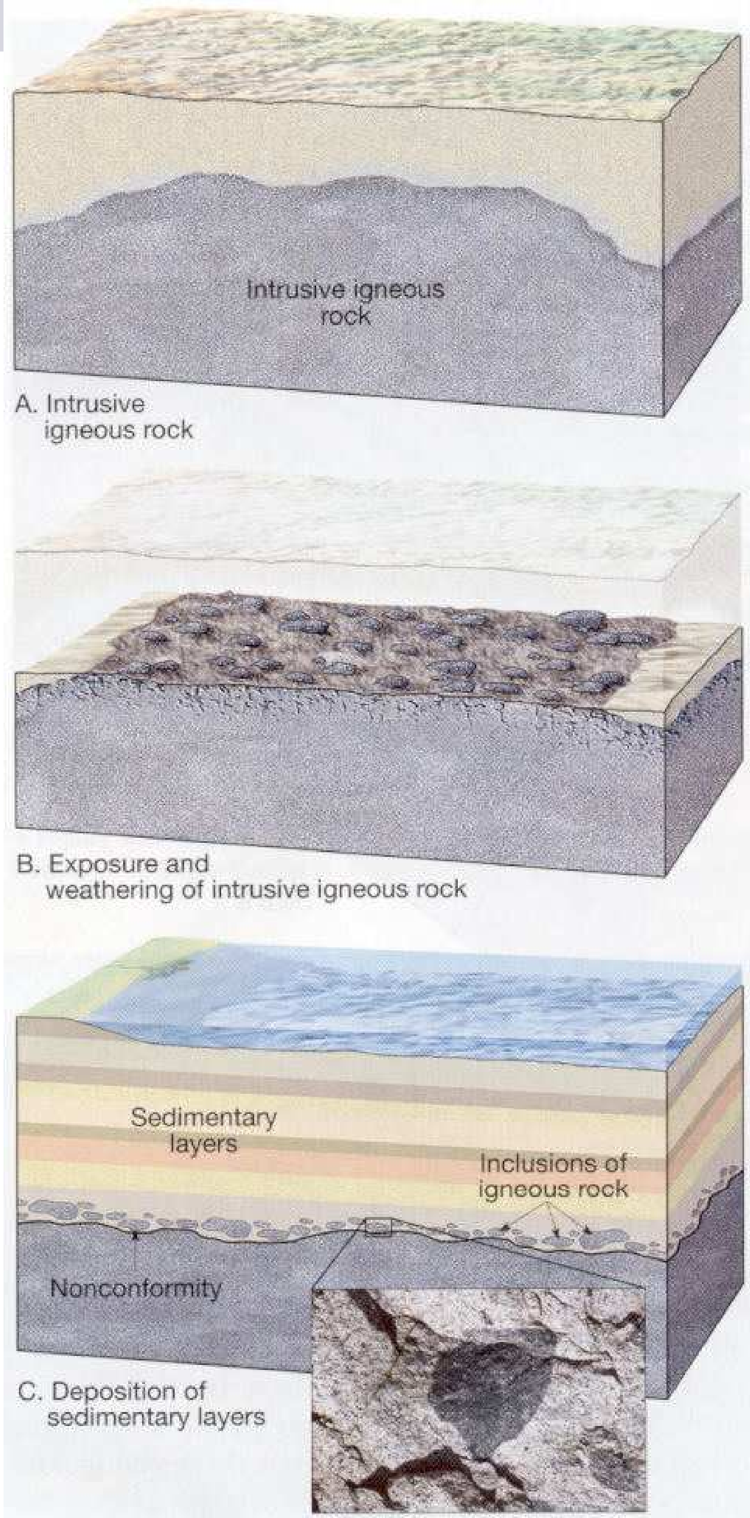
Relativní datování: stratigrafická inkluze, stratigrafický průnik

Principle of inclusions See Levin, 5th edition, p. 14-15

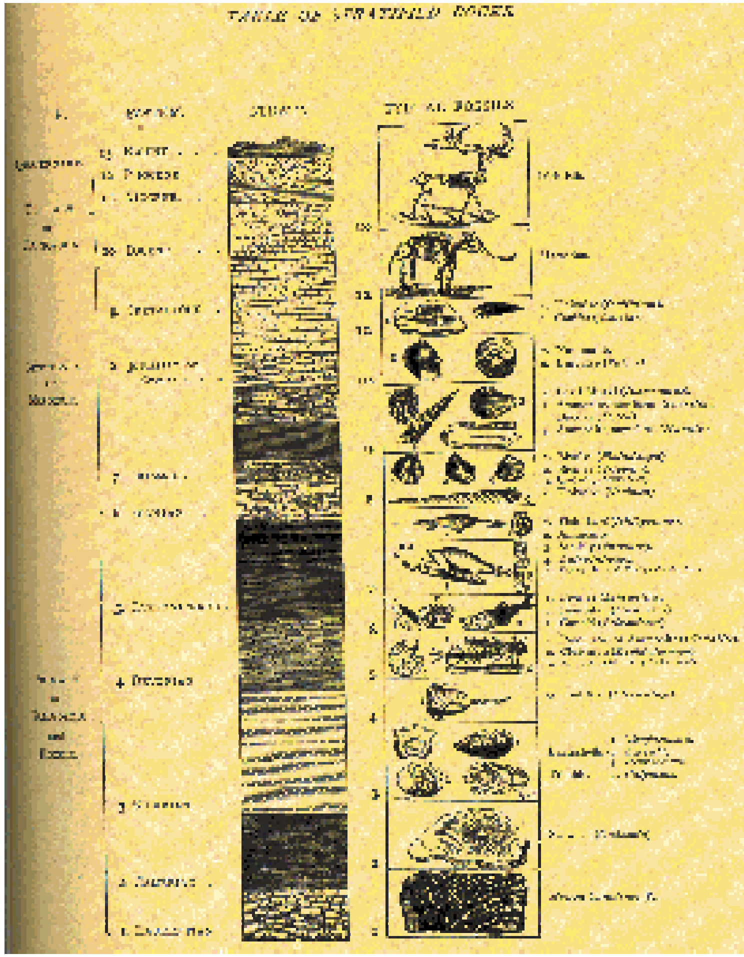
Note the irregular erosional surface. This is an **unconformity**. The clasts (in the bed above the unconformity) are derived from the underlying (older) bed.

The gravel clasts are **older** than the layer which contains them. The layer containing the gravel must be **younger** than the layer from which the clasts originate





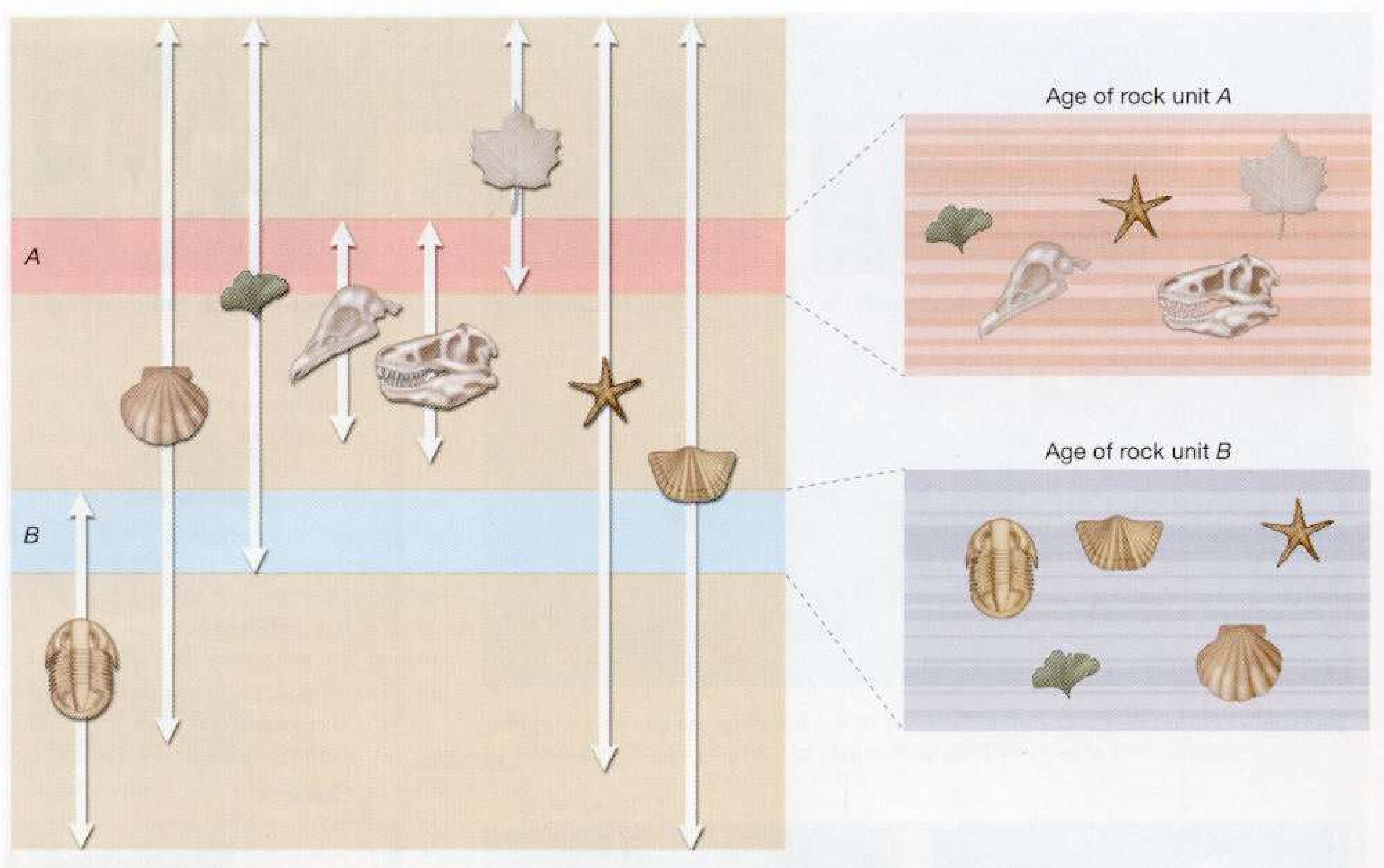
The **Principle of Faunal Succession** was later added by **William Smith** in the late 1700's who observed and studied fossils embedded in rock layers. This principle states that **the oldest fossils in a series of sedimentary rock layers will be found in the lowest layer** (layer A). Progressively younger fossils occur in higher layers (layer B). This is the same concept as superposition, but it helped geologists realize that you can look at the age of these layers and assign relative dates. This parallels evolution. Younger organisms replace older organisms as the older ones become extinct.



The Geological Record

- In Darwin's day the basic concepts of the new science of geology were just beginning to be filled in.
- In the 1790's an enthusiastic amateur, Wm. "Strata" Smith, had realized that the types of fossils found in each rock layer were quite different from those in other strata.

„Princip stejných zkamenělin“



Principle of uniformitarism (actualism)

PRINCIPLE OF UNIFORMITARIANISM based onrealizing that "The Present is the key to the Past.„

a. To understand past, study processes at work today.

b. Origin of rocks understood by how rocks form now.

c. Geologic processes are uniform through Earth history, with only a few minor exceptions.

d. Rates that processes work are NOT uniform.

a more general statement saying: "The laws of nature are constant thru time.„

1. Scientific experiments always give same results.

2. Actualism is a fundamental concept of all science; itwas generalized from geological uniformitarianism.

Differencies in the past

Chemical parameters

1) **Different salinity of the oceans – Precambriam**
2) **Composition of the atmosphere**
3) **Different sediments (some U deposits, banded iron formations)**

Evolution of bilogical systems

1) **Hadaikum – no life**
2) **Absence of floral cover**
3) **Changes in environmental requirements**

Different intensity of geological processes – orogenic cycles, climatic oscillations
Different astronomical parameters – slower the rotation of Earth

LENGTH OF THE DAY

Narrative:
The length of day and number of days per year is slowly changing.

Tidal friction on Earth of lunar and solar tides slows it down. Also, the moon is slowly retreating from the Earth.

Rate: rotation - slows by 1.7 milliseconds/year
moon retreat - 5 cm/year

Geophysical calculations of slowing are validated by evidence from fossils - which record daily bands and lunar cycles.
(primarily the frequency and magnitude of tides)

-Stromatolites
-Corals
-Bivalves

900 million years B.C. -- day: 18 hours; 440 days/year

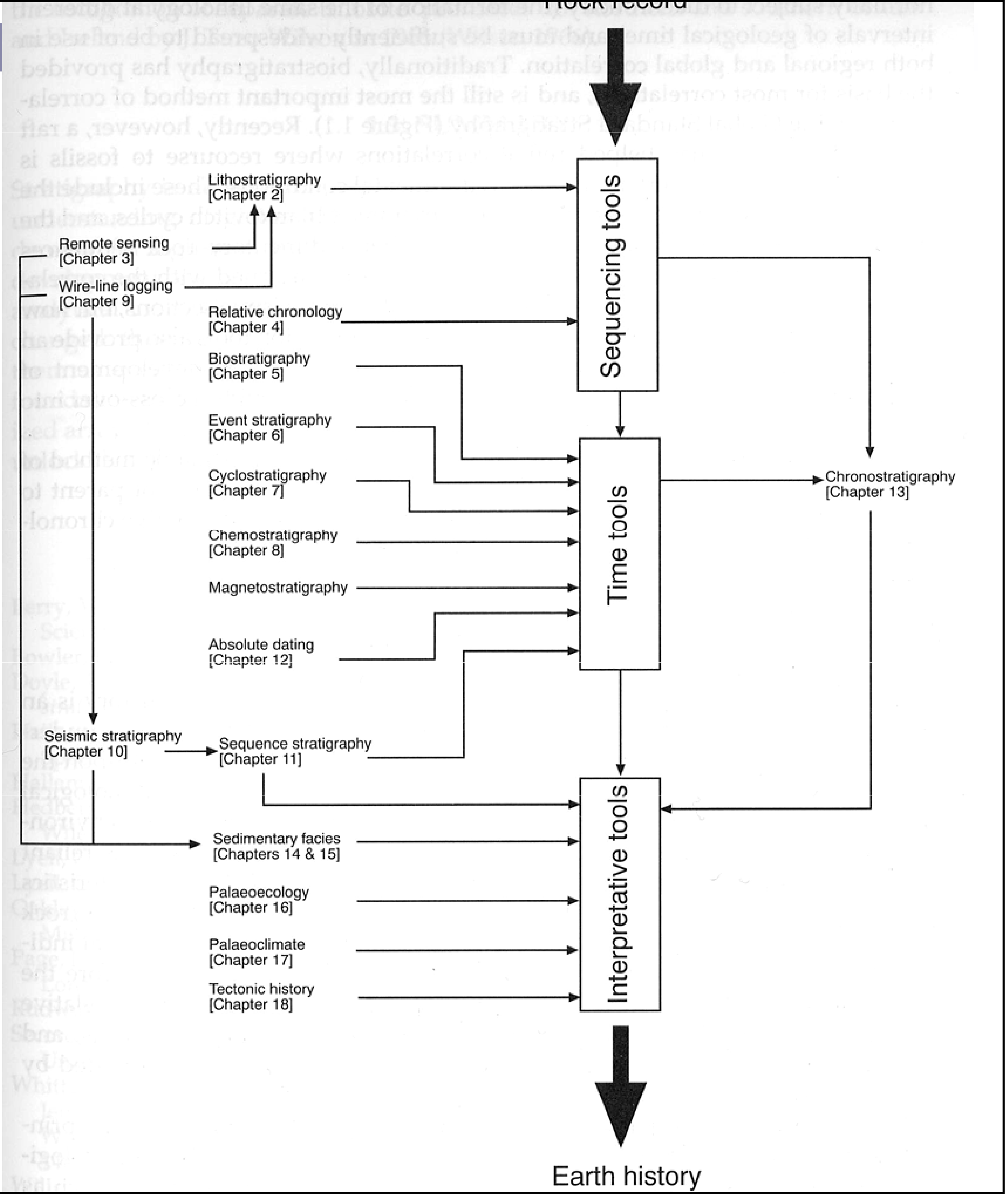
150 million years B.C. -- day: 23.5 hours; 370 days/year (late Jurassic)

Modern -- day: 24 hours; 365.25 days/year

Circadian rhythm in higher animals does not adjust to a period of less than 17-19 hours per day.
Therefore, records the time of emergence of metazoans.

Stratigraphic tool kit

- Vytvoření sekvence
  - Sled „událostí“
  - Časové nástroje
- Interpretace záznamu



Stanovení sekvence,Litostratigrafie

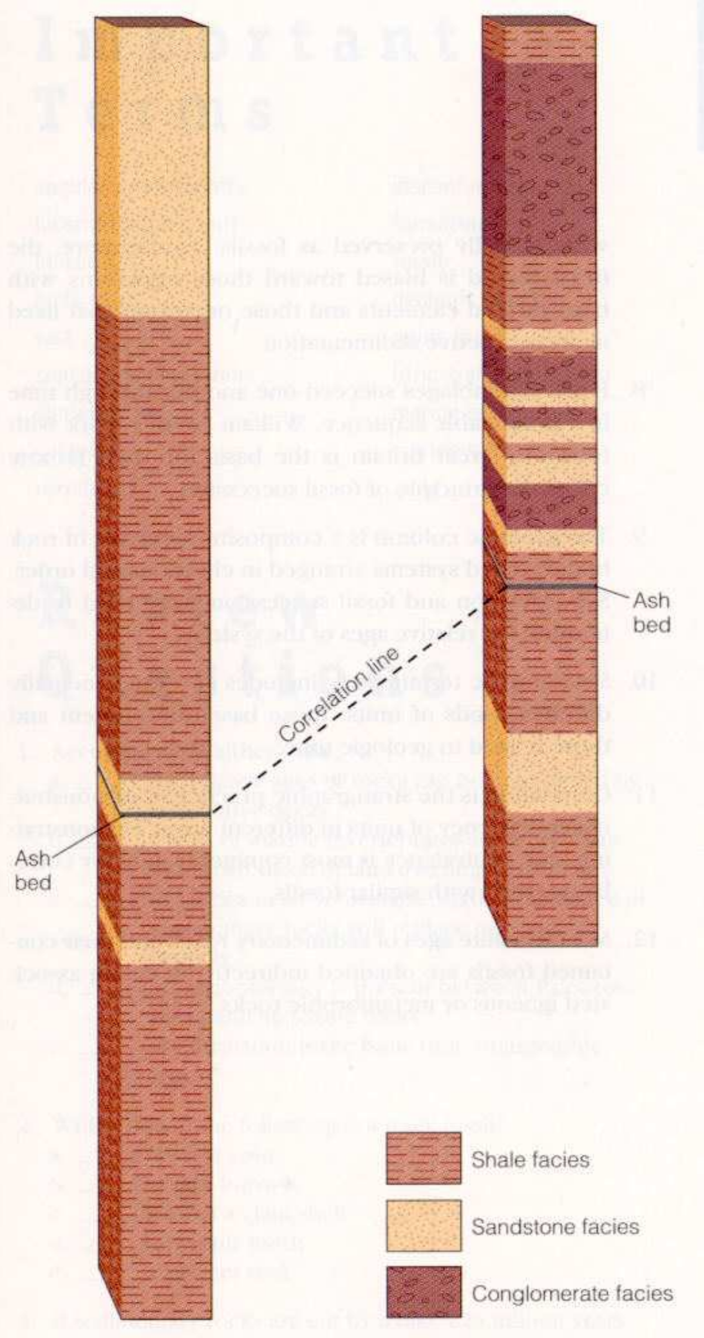
STRATIGRAFIE a STRATIGRAFICKÁ KORELACE

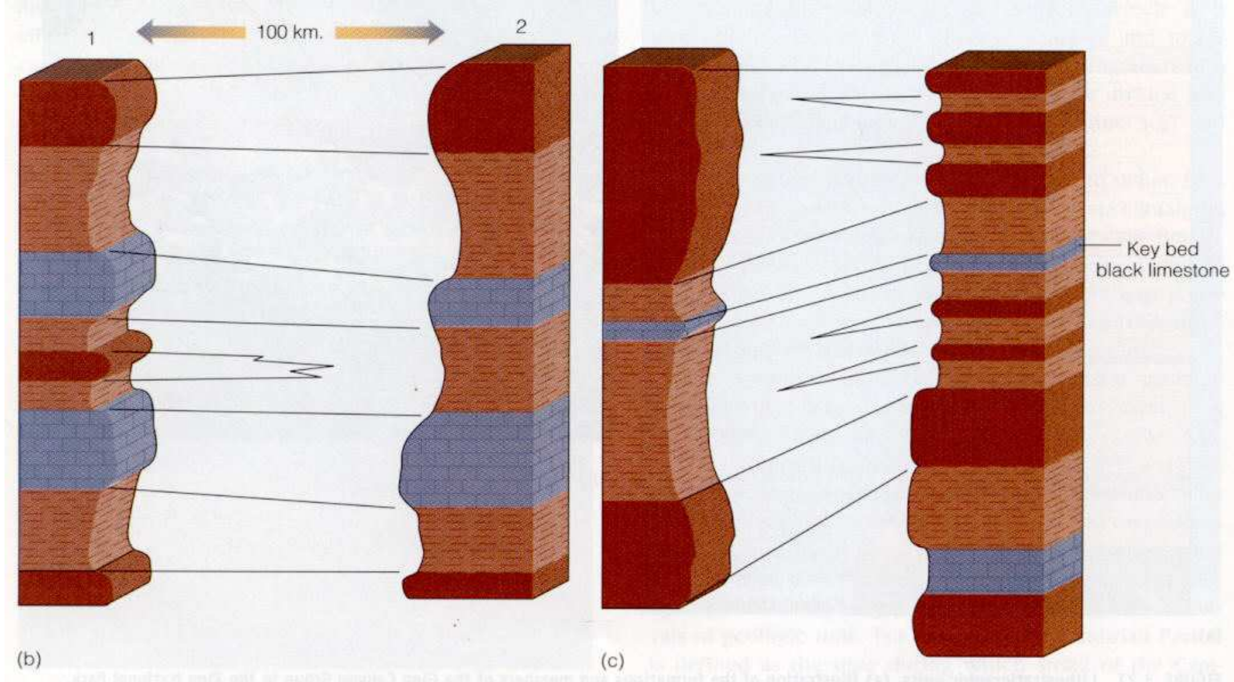
- Stratigrafie:
  nauka o vrstevních sledech (princip superpozice)
  Zabývá se relativním měřením času v geologii

- Stratigrafická korelace:
  (porovnávání stáří prostorově nesouvislých vrstev na základě společných znaků – obsahu fosílií, litologie, chemického složení, fyzikálních vlastností, atd.)

LITOSTRATIGRAFIE (korelace na základě litologických znaků)
BIOSTRATIGRAFIE (korelace na základě fosílií)
CHEMOSTRATIGRAFIE (korelace na základě chemického složení)
MAGNETOSTRATIGRAFIE (korelace na základě magnetické polarity)

LITOSTRATIGRAFIE



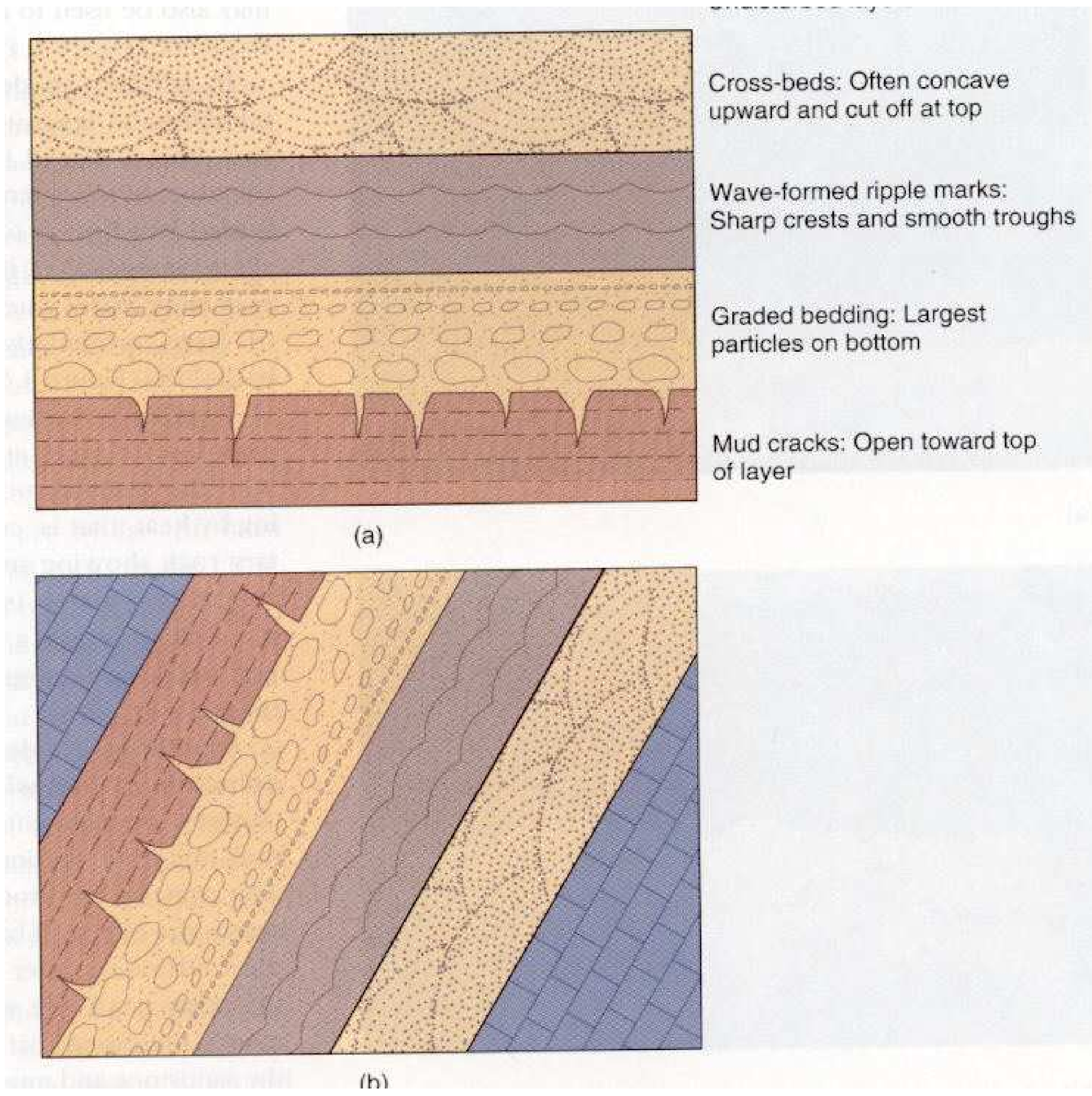


Korelace na základě litologických znaků sedimentu: minerální složení, struktura, textura, mocnosti vrstev, atd.

litostratigrafické jednotky – superskupina > skupina > <u>souvrství</u> > vrstvy (člen) > vrstva

Marker (key bed)

Stratigraphic way-up



Diachonismus horninových těles (litostratigragických jednotek)

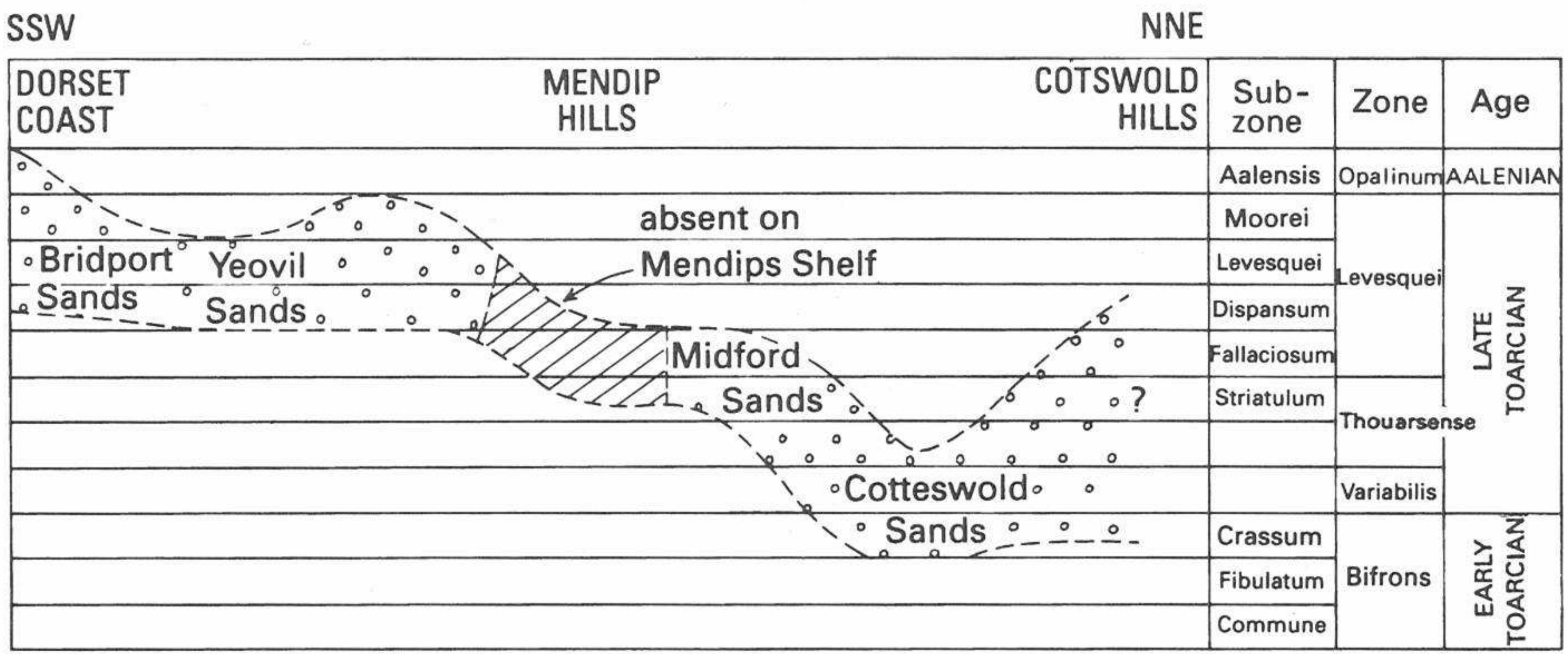


Figure 2.4 Diachronism of the Bridport Sand Formation in south-west England, over a distance of some 150 km. The zones and subzones are based on ammonite faunas. [Modified from: Torrens (1969) and Callomon & Cope (1995)]

Litostratigrafická klasifikace a nomenklatura

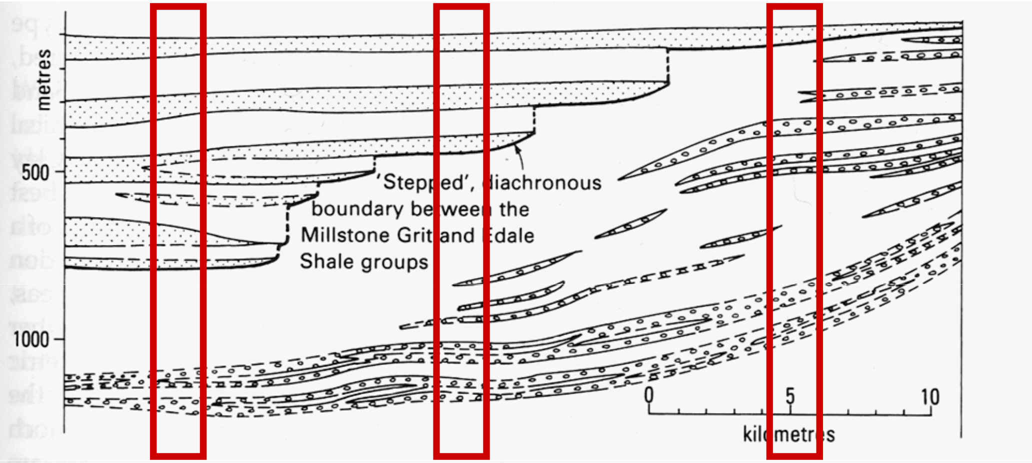


Figure 2.2 *Schematic section showing the lateral boundary between the Millstone Grit and Edale Shale in the Carboniferous of the southern Pennines, UK. These are both traditional names which have been redefined and formalized as groups. Whilst both groups are dominated by mudstone (unshaded), feldspathic sandstones (fine stipple) characterize the Millstone Grit Group, and quartzitic sandstones (coarse stipple) characterize the Edale Shale Group. The boundary between the two groups had to be defined in such a way that it could be drawn objectively and consistently in any one section. In this case, the base of the Millstone Grit Group has been defined at the first appearance of feldspathic sandstone within the mudstone succession.* [*Modified from: Evans* et al. *(1968); new classification by Rees and Wilson (1998)*]

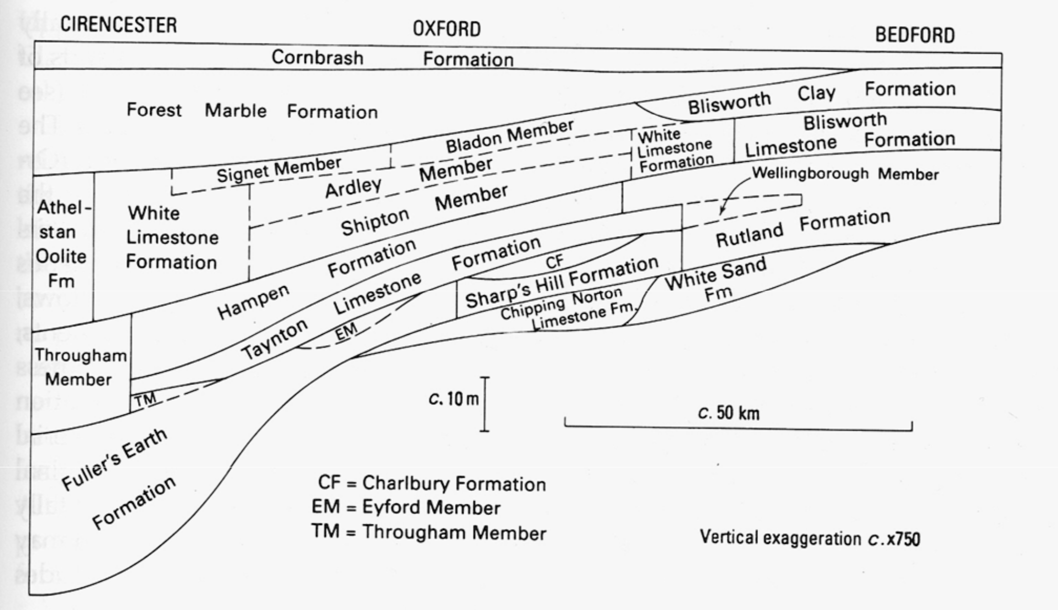


Figure 2.1 *Schematic section illustrating lithostratigraphical relationships within the Great Oolite Group (Middle Jurassic) between Cirencester and Bedford, southern England. The nomenclature used is a mixture of formalized traditional terms (e.g. Cornbrash, Forest Marble, White Limestone) and newer names chosen to accord with modern recommendations (e.g. Rutland Formation)*

- Hranice mezi litologickými jednotkami: diskordance, konkordance, pozvoln= vertikální přechody, laterální prstovité zastupování,
- Hranice mezi litostratigrafickými jednotkami: musí být zvoleny v jednom konkrétním bodě
- Musí splňovat kritérium mapovatelnosti
- Musí platit princip superpozice

Definice a specifikace jednotek

- Název, geografická lokalita, historická priorita, jeden název jen pro jednu jednotku i v odlišném ranku
- Litologie, barva, sedimentární textury, mocnost vrstev, cyklicita, karotážní charakteristika (tam kde chybí výchozy)
- Typový a referenční profil (stratotyp), charakteristické znaky jednotky + její spodní hranice, v případě nouze může být stratotypem jádrovaný vrt, snadná přístupnost
- Hranice (spodní, svrchní), v případě pozvolných přechodů musí být zvolen jeden určitý bod a jednoznačně popsán
- Dělení na dílčí jednotky, uvedení všech dílčích jednotek, nově definovaných i dříve definovaných s patřičnými citacemi
- Mocnost, typický mocnostní rozsah a extrémy
- Rozsah, ve smyslu dnešní geografie a ideálně i ve smyslu původní sedimentační pánve
- Stáří, uvedeno v chronostratigrafických jednotkách

Litodemické jednotky

- Nejsou zvrstvené a neodpovídají pravidlu superpozice,
- Definované na základě litologické charakteristiky
- Litodém (základní)
- Skupina (superskupina) („super/suite“)
- Komplex/terán: skupina dvou a více geneticky odlišných horninových celků

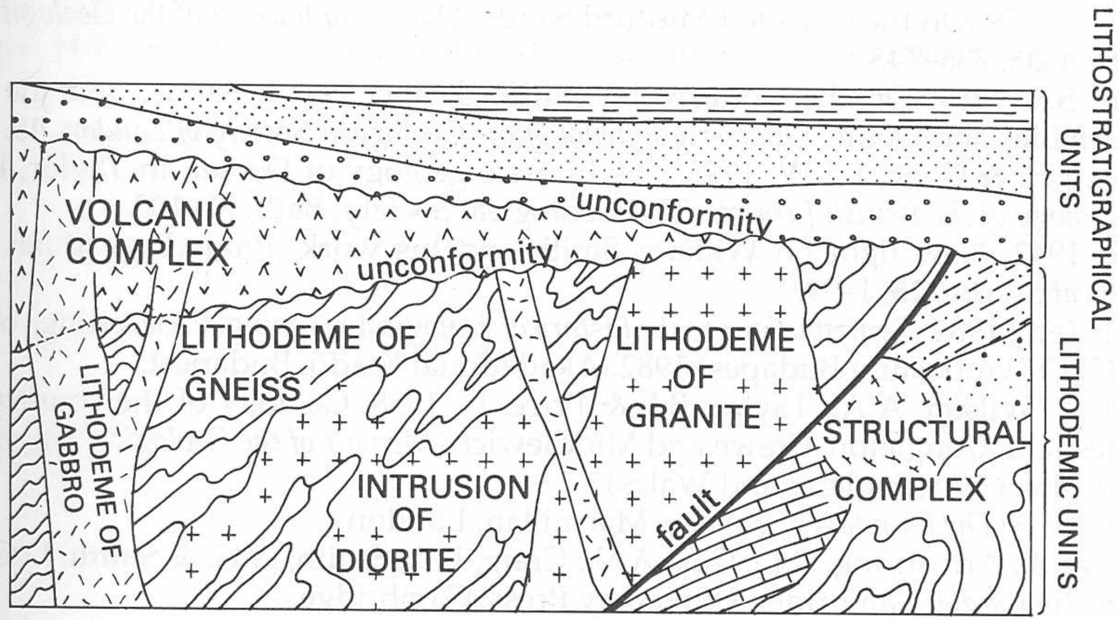


Figure 2.5 *Diagrammatic cross-section showing various lithodemic units. The lithodeme of gneiss and intrusion of diorite were deformed together, and may be regarded as a complex. [Modified from: North American Commission on Stratigraphic Nomenclature (1983)]*

Metody dálkového průzkumu

- Remote sensing: stanovení charakteristiky určitého území bez přímého fyzického kontaktu
- Detekce, zesílení, zobrazení a interpretace odraženého a emitovaného EM záření
- Letecký, satelitní průzkum
- Rozlišení minerálů, vegetačního pokryvu, který odráží geologické podloží

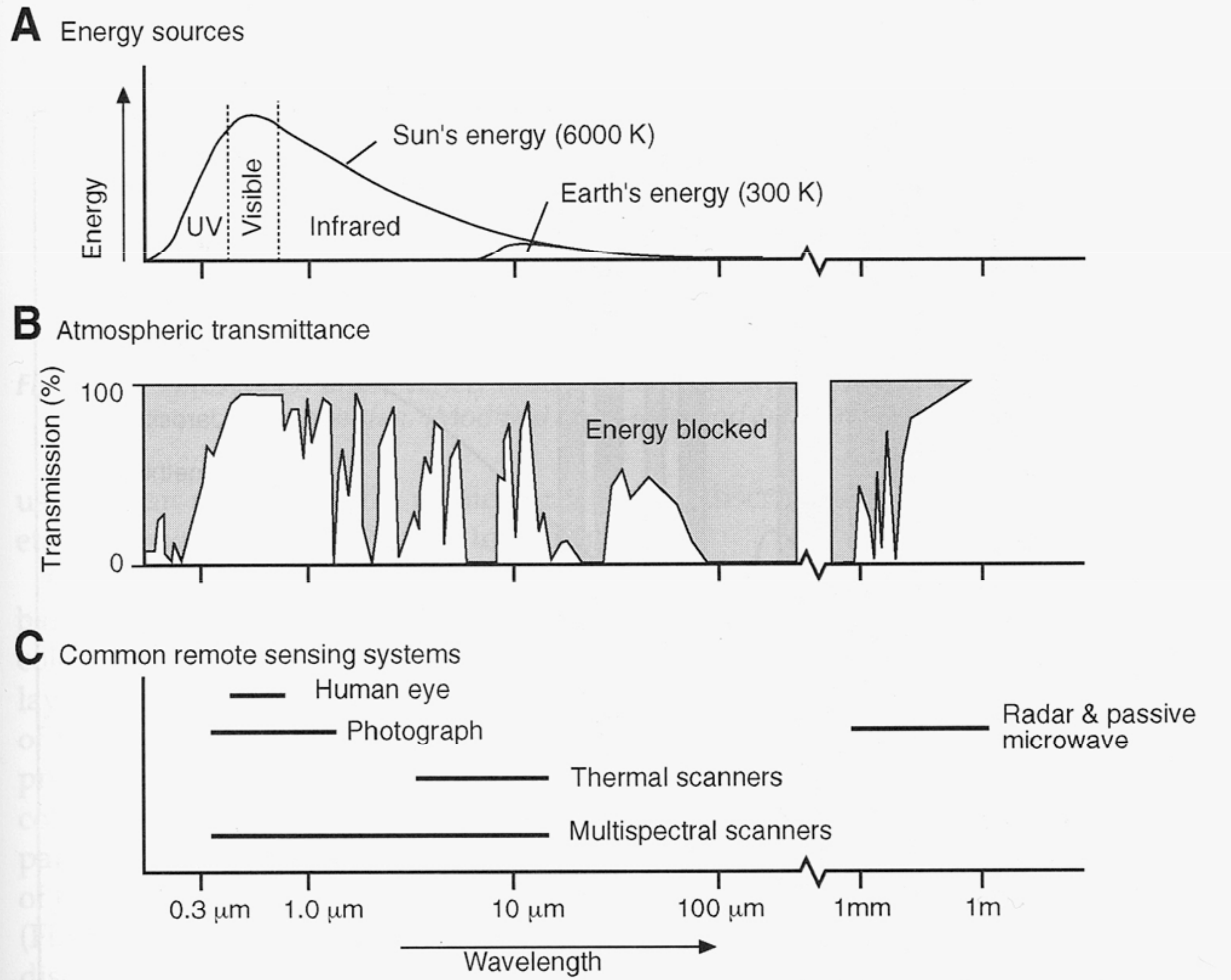
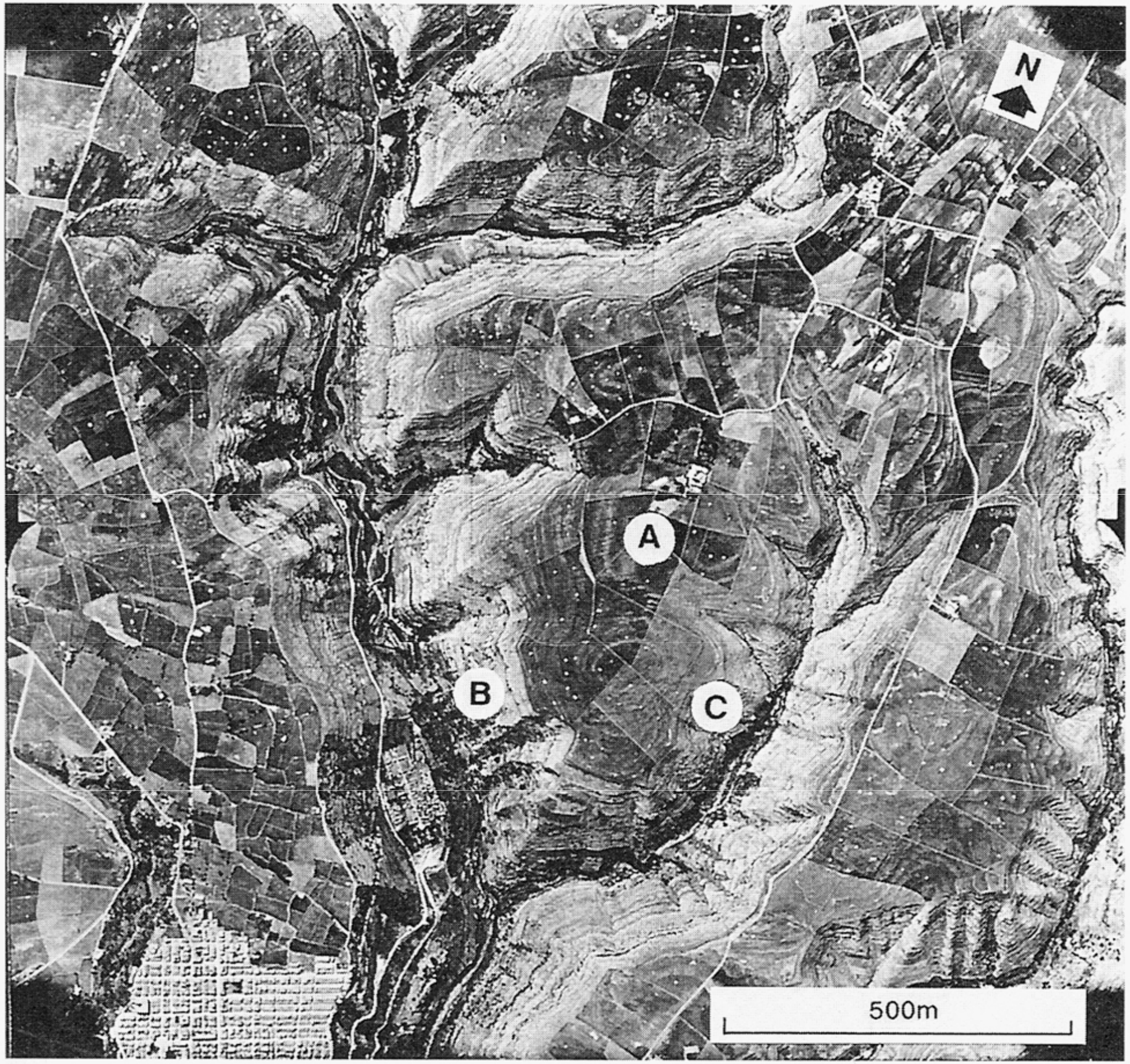
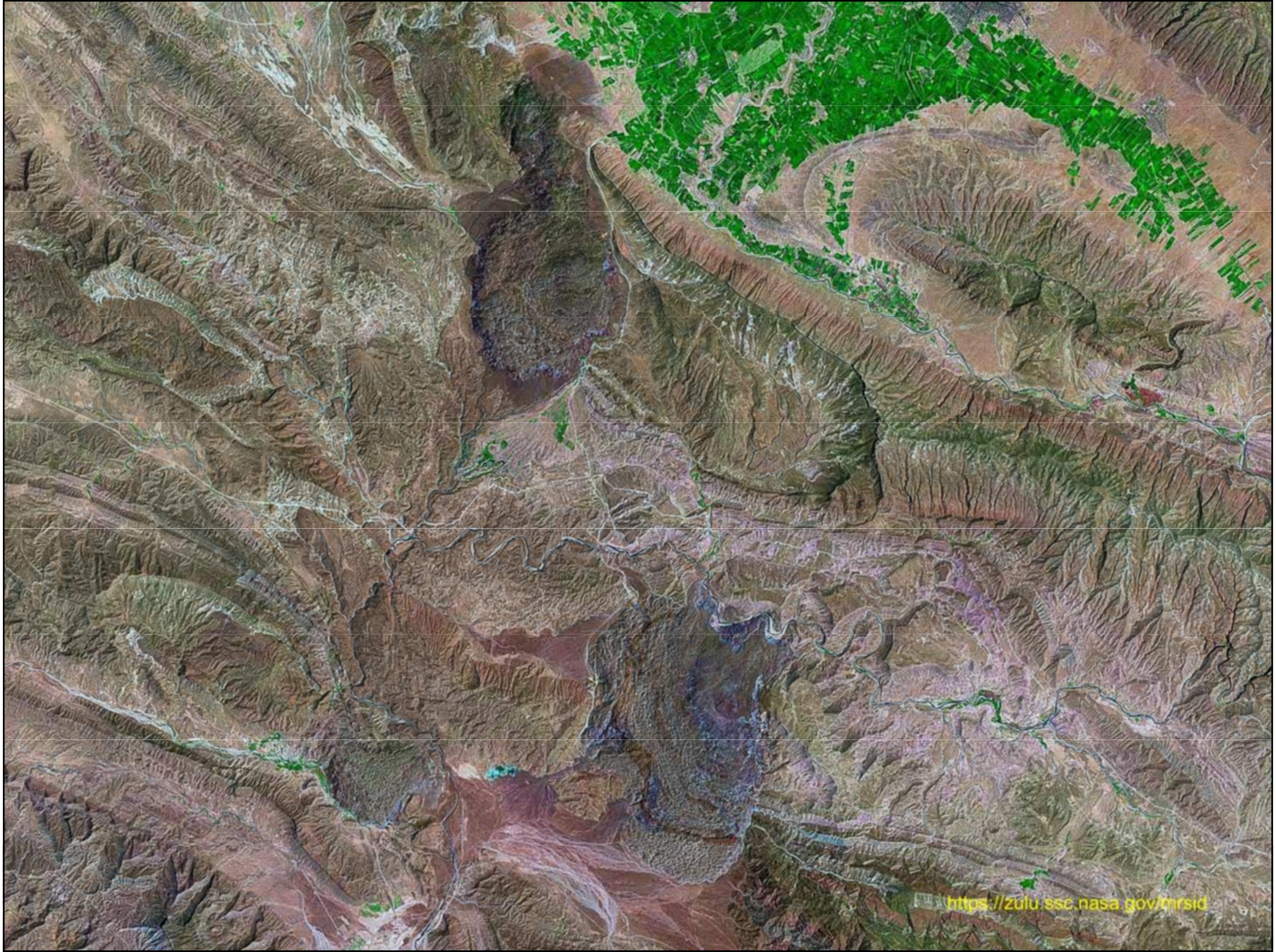


Figure 3.1 The electromagnetic spectrum: sources, atmospheric transmittance and remote sensing systems [Modified from: Lillesand & Kiefer (1994)]

- Jv. Sicílie
- Karbonáty,
- Horizontální vrstevnatost




https://zulu.ssc.nasa.gov/mrsid/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Geophysical methods, wire-line logging

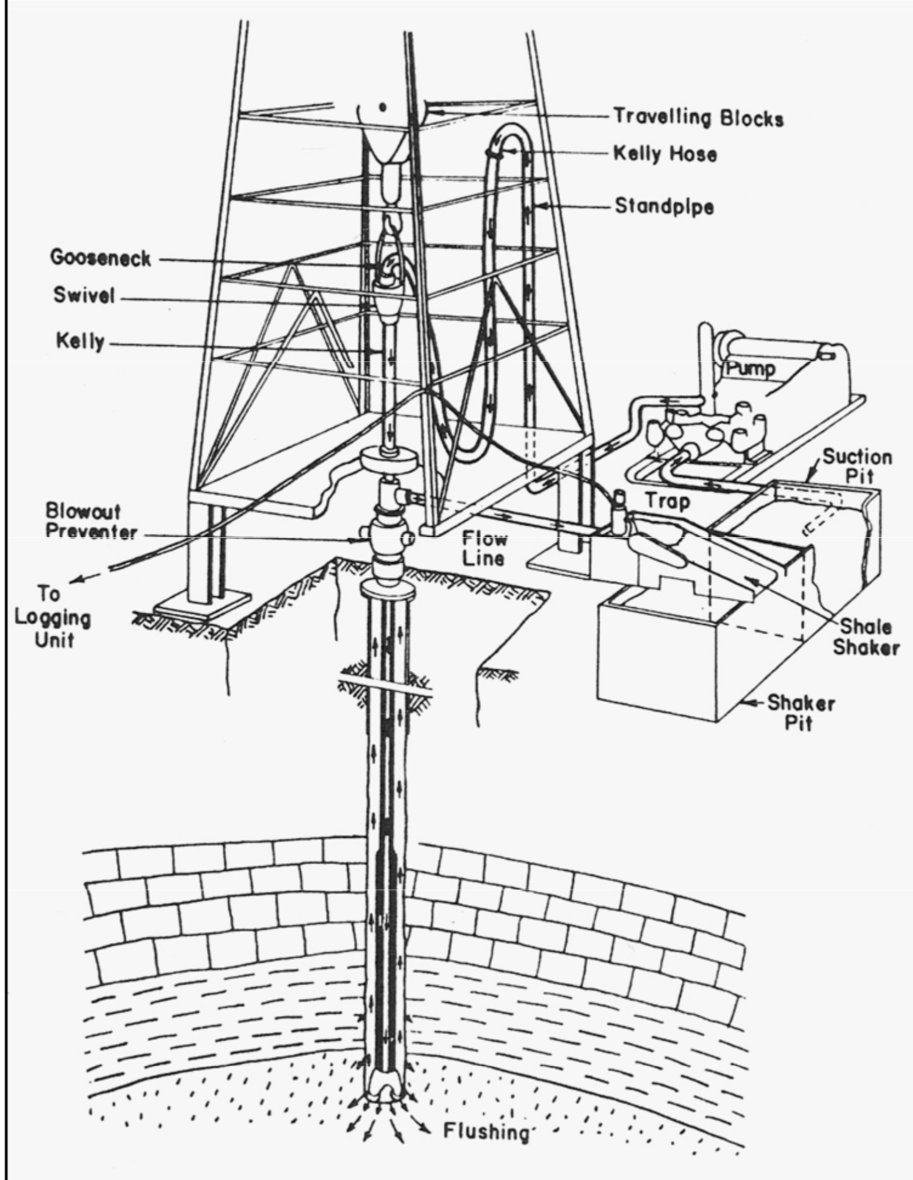
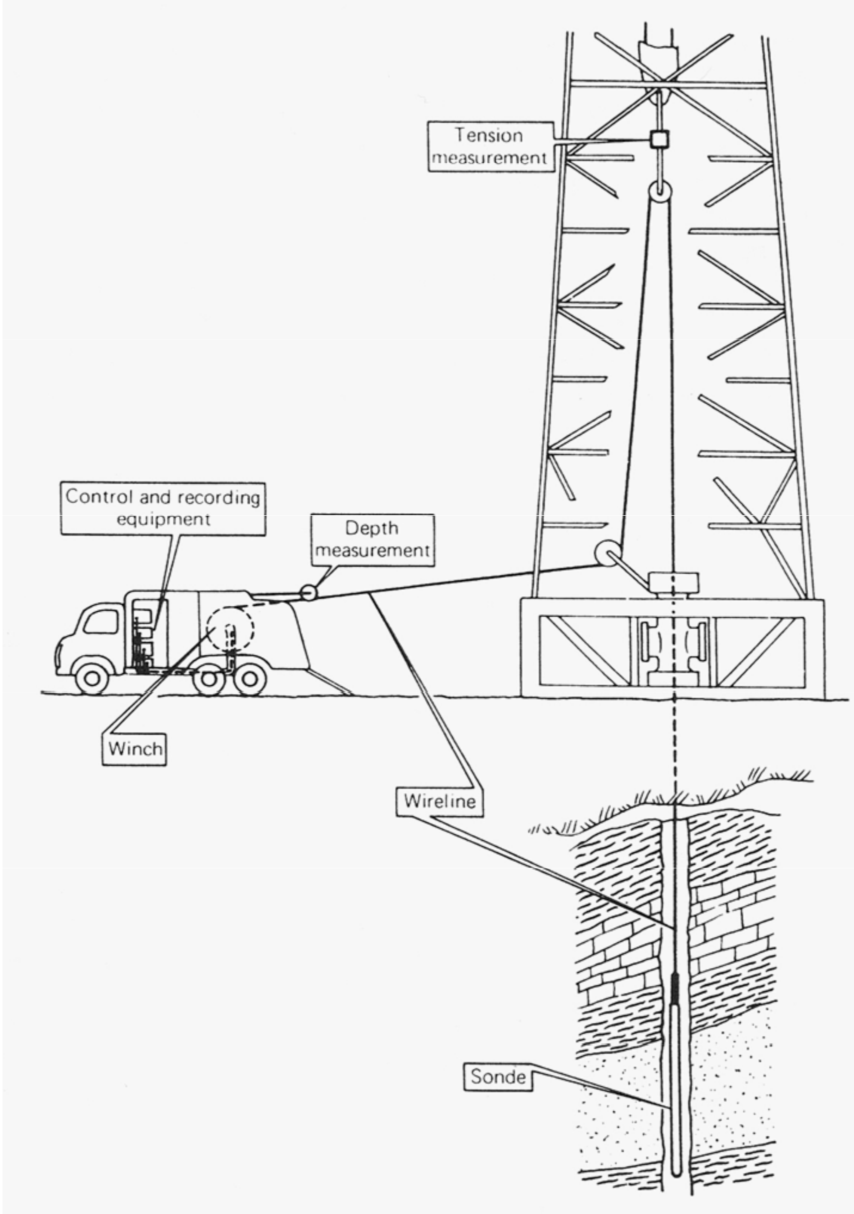


Figure 9.1 Rotary drilling and the associated mud system



Geophysical logging

- **Spontaneous potential logging**: elektrický proud vznikající z rozdílů salinity (potenciálů) vrtných fluid a fluid v hornině, rozlišují permeabilitu
- **Gamma-ray logging**, přirozená radioaktivita hornin a minerálů, struktura a geochemie sedimentu
- **Neutron logging**, neutrony emitované sondou kolidují s částicemi v hornině (H, Cl),které emitují gamazáření o charakteristické energii, indikují obsah vodíku ve vodě obsažené v pórech, definují a kvantitativně odhadují porozitu
- Resistivity logging, odporová karotáž,
  - Křemen, kalcit, dolomit, uhlovodíky, póry naplněné vzuchem: resistivita > 100 miliónů ohmmetrů
  - Póry nasycené vodou a fluidy
    - Sladká voda: 26 ohmm
    - Mořská voda: 0,18 ohmm
    - Podpovrchová horninová solanka: 0,055 ohmm
  - Jílové minerály: schopné iontové výměny: dobrá vodivost = nízká resistivita
- Dipmeter logging: strukturní sklon měřený 4 sondami, které měří mikroresitivitu, tektonický úklon vrstev, šikmé zvrstvení, atd.

Gamma-ray logging

- Spontánně radioaktivní izotopy v horninách (U řada, Th řada, ^{40}K)
- γ záření (EM vlnění)
  - emitované při radioaktivním rozpadu
  - charakteristická energie
    - 1.360 - 1.558 MeV, K,
    - 1.564 - 1.953 MeV, eU (uranium equivalent)
    - 2.414 - 2.804 MeV, eTh (thorium equivalent) (NaI2)
- Scintilační detektor (jodid sodný) detekuje γ - záření,
  - jednotky API (American Petroleum Institute)
  - Obsahy K(%), Th(ppm) a U(ppm) (spektrální gamakarotáž)

Basic G-R log shapes

- K: v krystalové mřížce, draselné živce, muskovit, illit
- Th: vázaný na jílové minerály
- U: organická hmota, fosfáty, vazba na jílové minerály

- K, Th: „indikátory jílů“

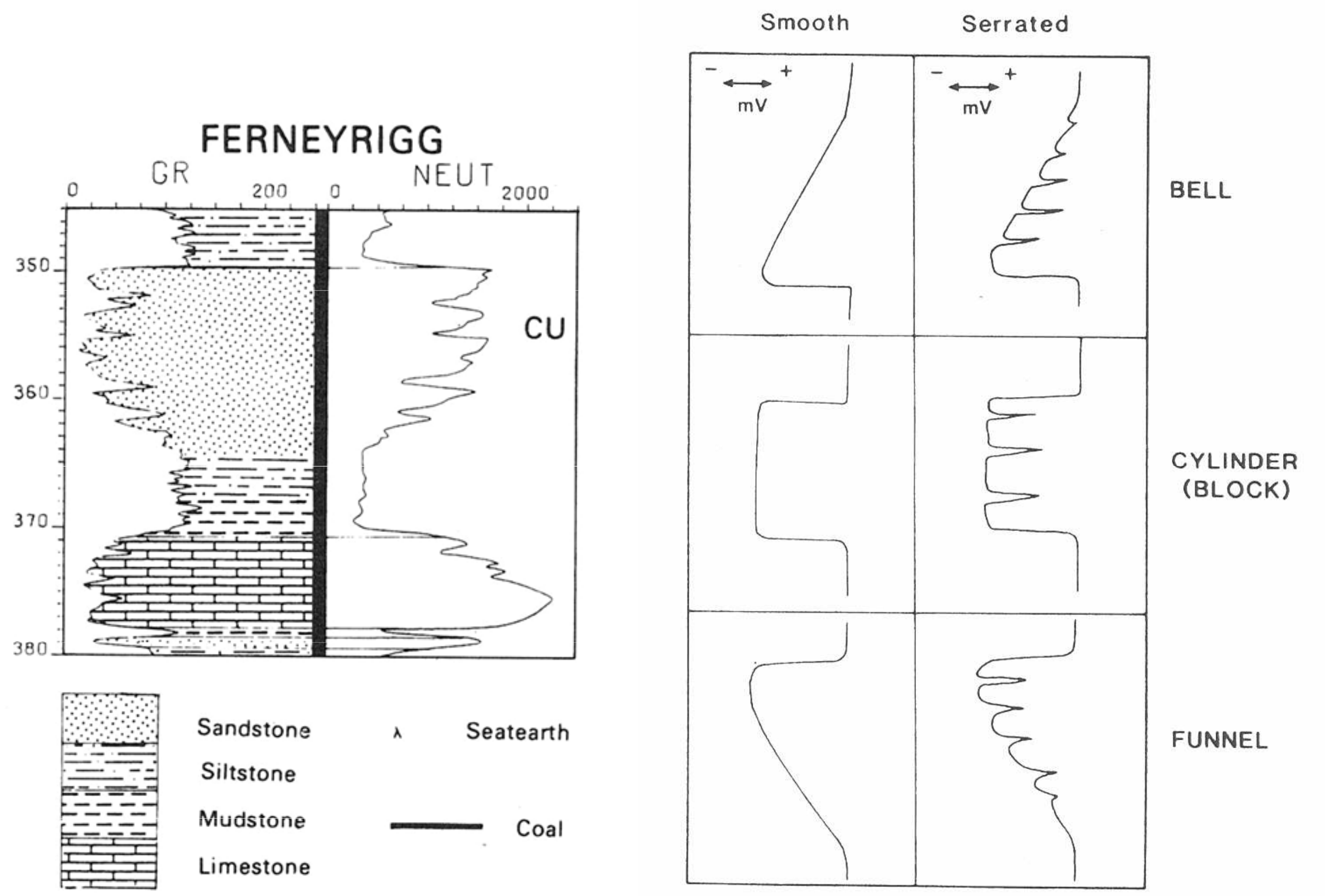


Figure 9.8 *Examples of log shapes from Carboniferous sequences in boreholes from northern England. A coarsening-upwards (funnel-shaped) unit is seen in the Ferneyrigg borehole (confirmed from core data), while fining-upwards (bell-shaped) and uniform (cylinder-shaped) sandstone with a sharp base and top are seen in the Stonehaugh borehole (confirmed from core data). [Reproduced with permission from the Geological Society, from: Whittaker et al. (1985)]*

K/Th poměr

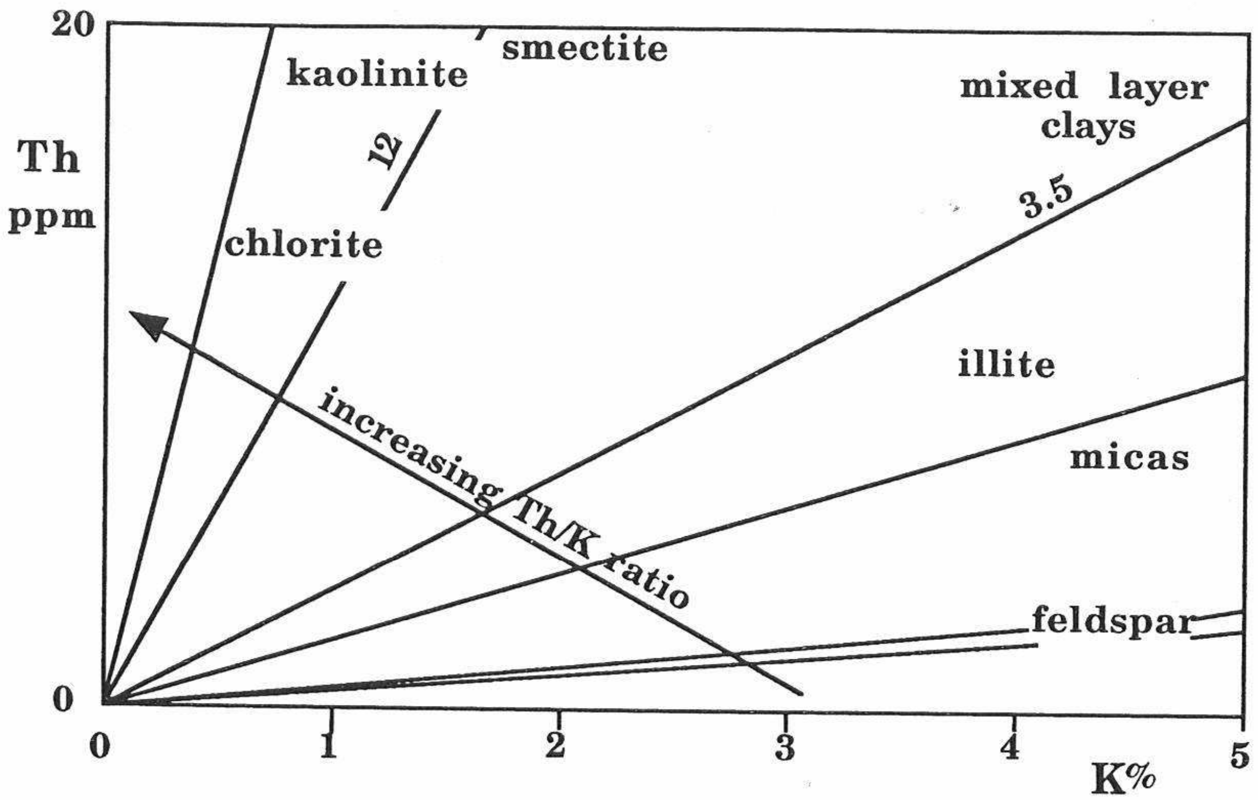
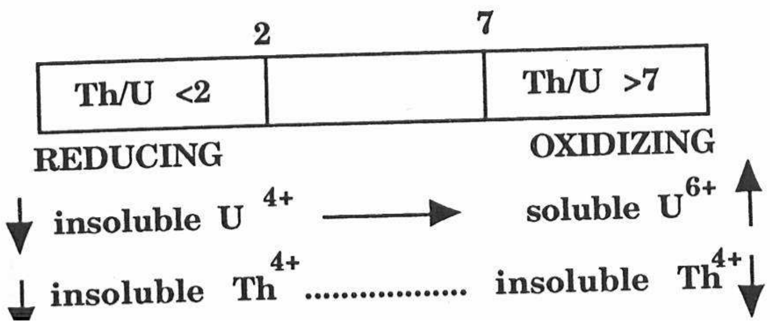


FIG. 17.-- Generalized mineral fields on a potassium-thorium crossplot (modified from Quirein and others, 1982).

Th/U poměr, KUT diagramy



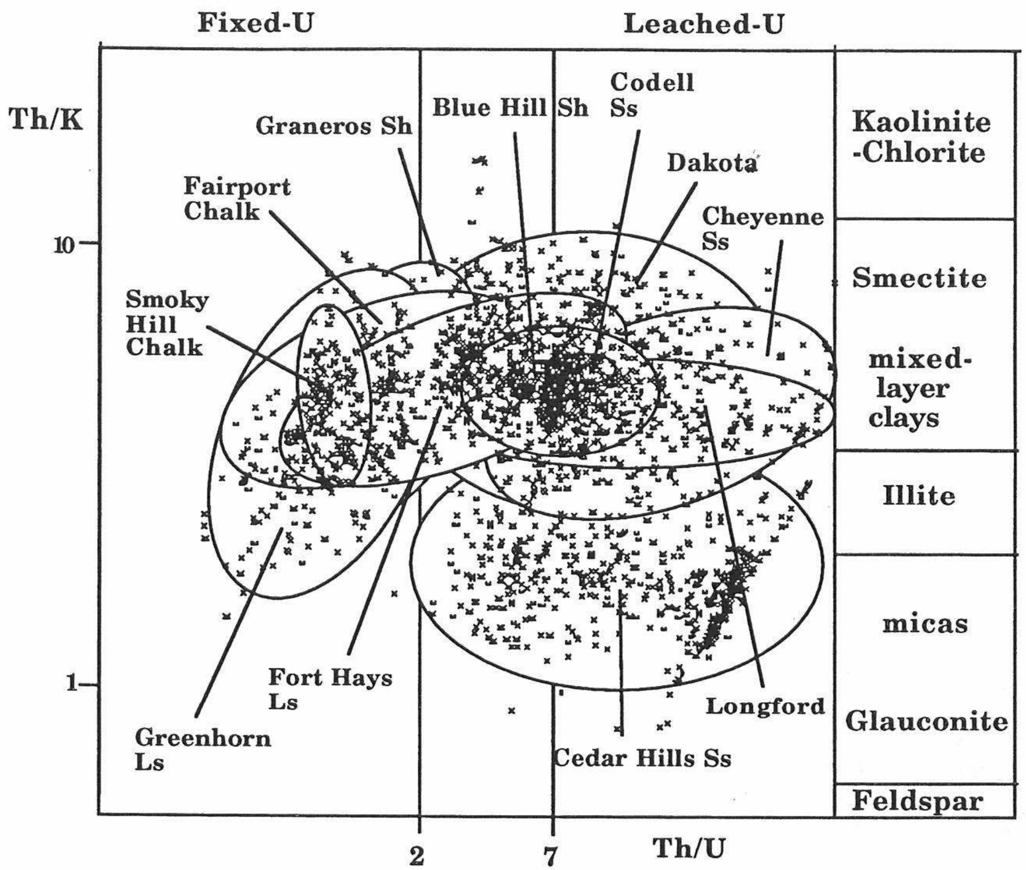


FIG. 22.-- Spectral gamma ray KUT ratio plot of Permian and Cretaceous units from Well #10 in central Kansas.

Gamma-ray logging, correlation

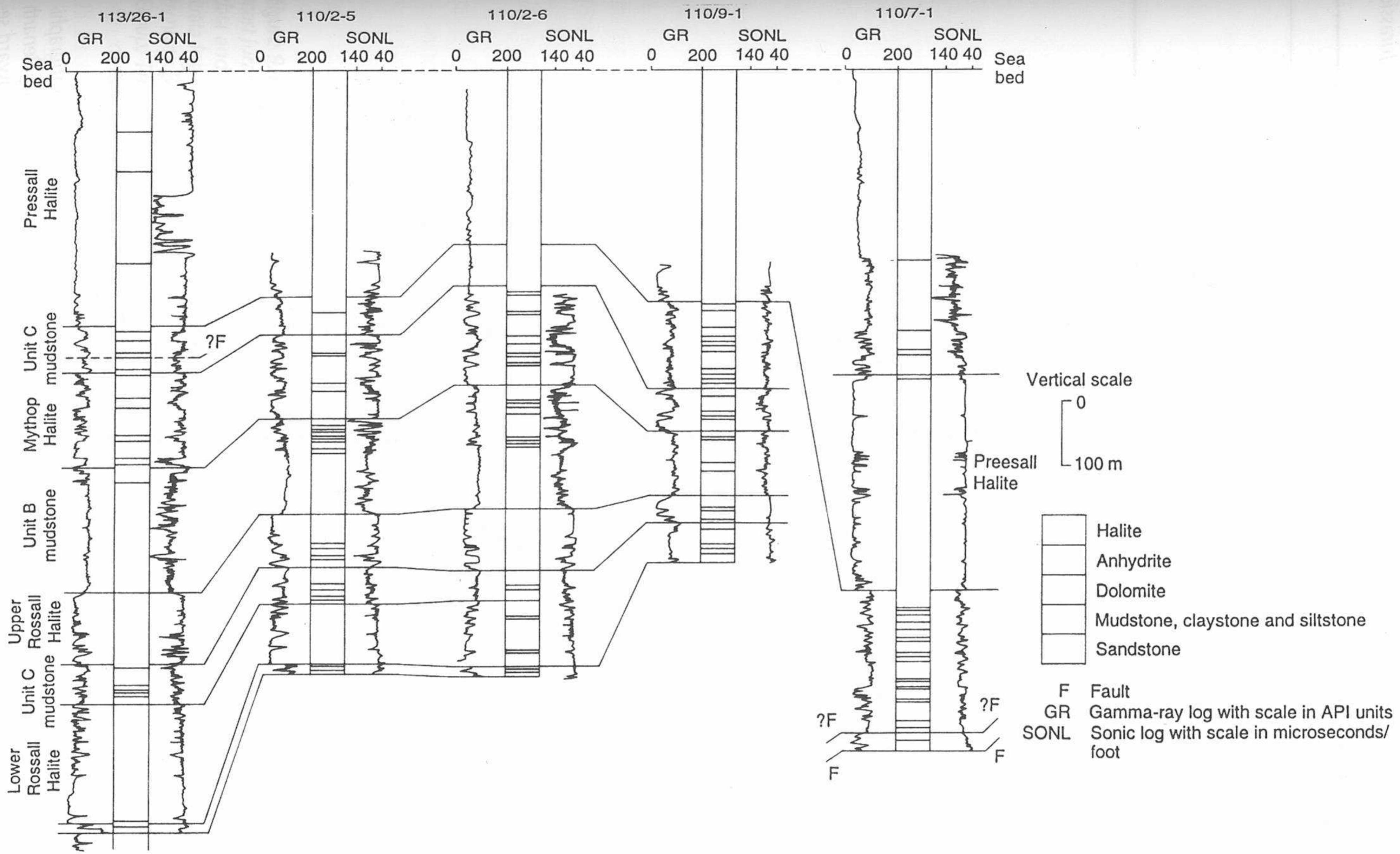
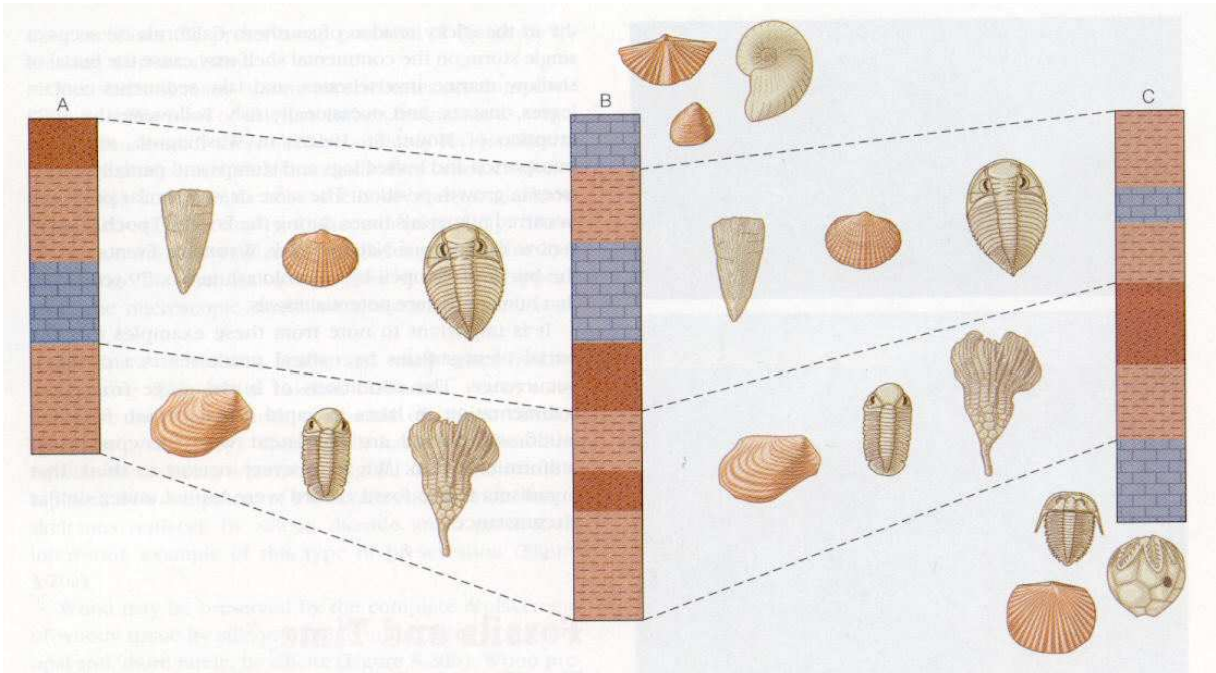
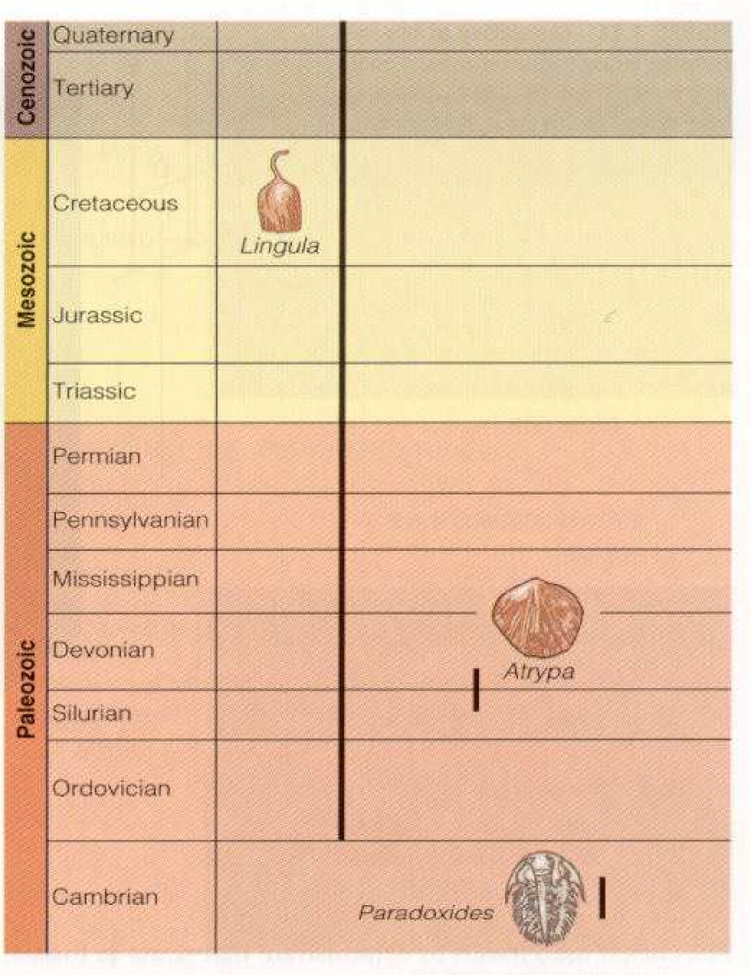


Figure 9.10 *Large-scale regional lithostratigraphical and log correlation of the Mercia Mudstone Group (Triassic) in selected boreholes in the East Irish Sea Basin. [Modified from Jackson* et al. *(1995)]*

BIOSTRATIGRAFIE





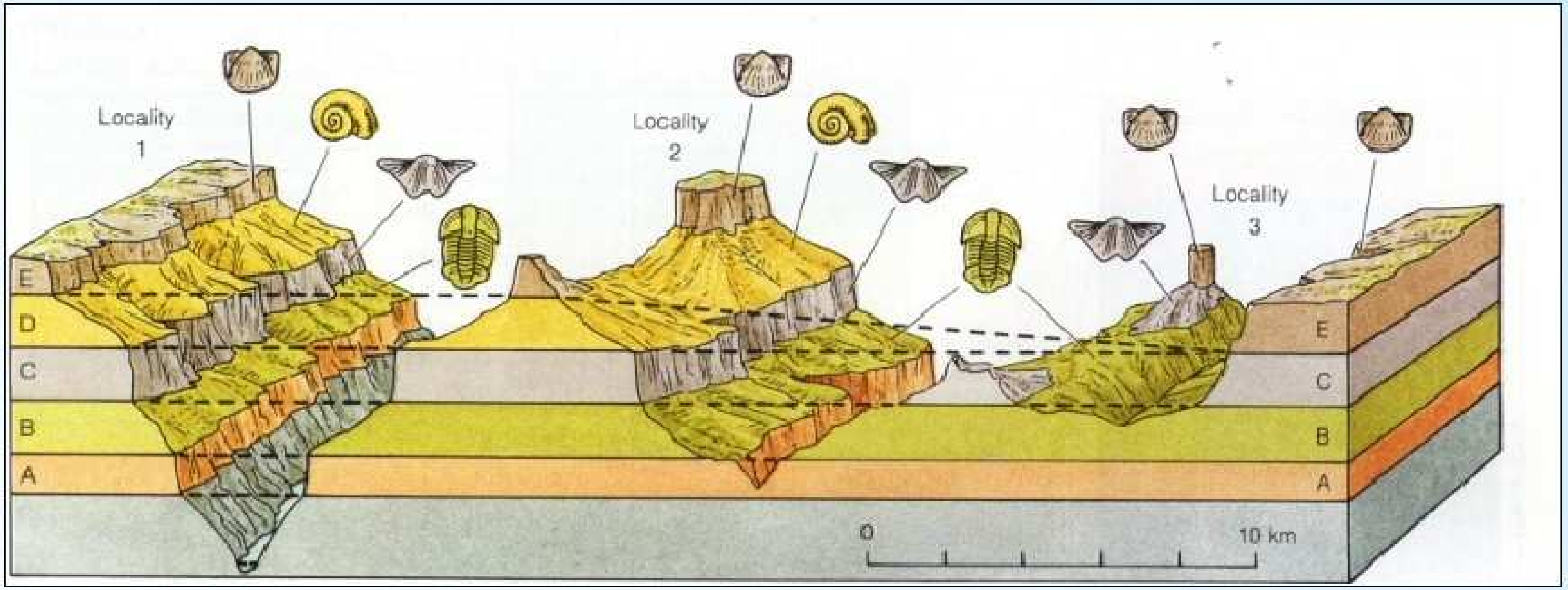
Korelace na základě stejných fosílií (princip stejných zkamenělin)

Indexové fosílie (vůdčí zkameněliny), pravidla: kosmopolitní, dobrá identifikovatelnost, rychlá evoluce, hojný výskyt (Ammonoidea, Radiolaria, Conodonta, Cocclitophorida, Trilobita, atd.)

Biostratigrafická zóna (biozóna), typy zón: intervalová zóna, zóna společenstva, zóna rozsahu

Biostratigrafické zonace

Correlation of strata using fossils



- Identical fossils mean strata are same age

Index Fossils Guide Fossils (other terms used: Zone Fossil, Index Fossil)

A good index fossil must be:

1. Independent of environment
2. Fast to evolve
3. Geographically widespread
4. Abundant
5. Readily preserved
6. Easily recognised

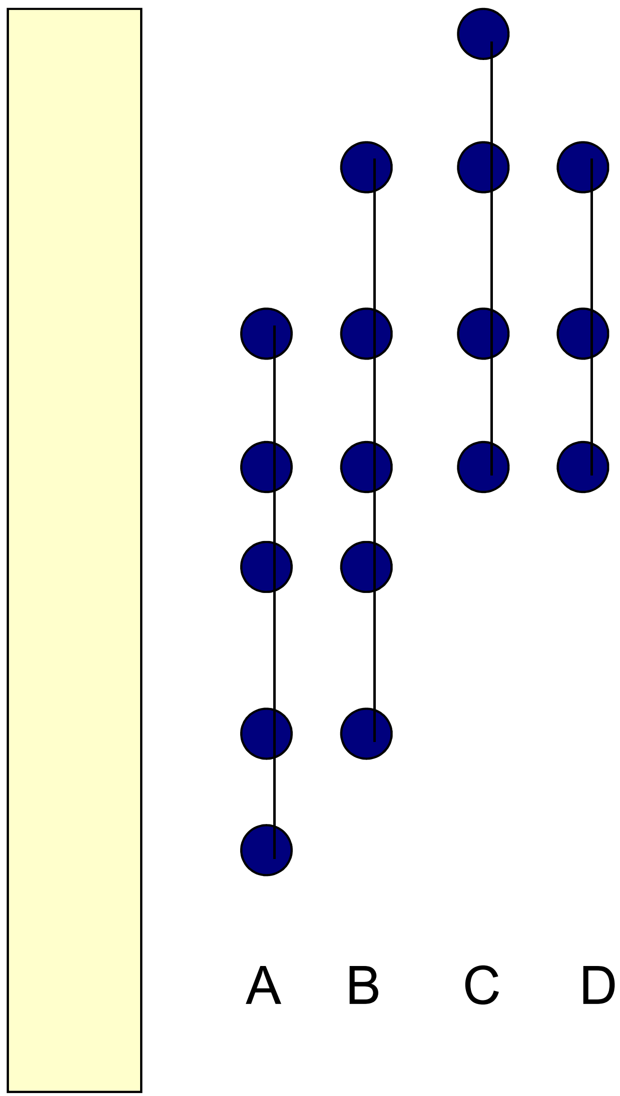
Examples: Graptolites, Ammonites, Foraminiferans, Pollen, Nannoplankton

Biostratigraphic Zones

Biozones - the most fundamental biostratigraphic units.

A zone is a body of rock whose lower and upper boundaries are based on the ranges of one or more taxa (usually species or phena) (see this Figure for graphic examples of the major types of biostratigraphic zones)

Rozsah taxonů na lokalitě



Materiální a časový rozměr biozón

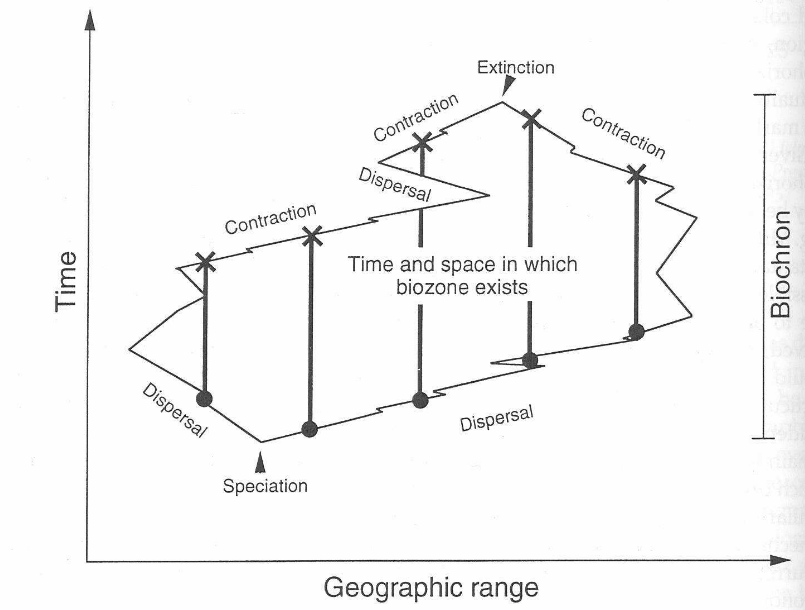
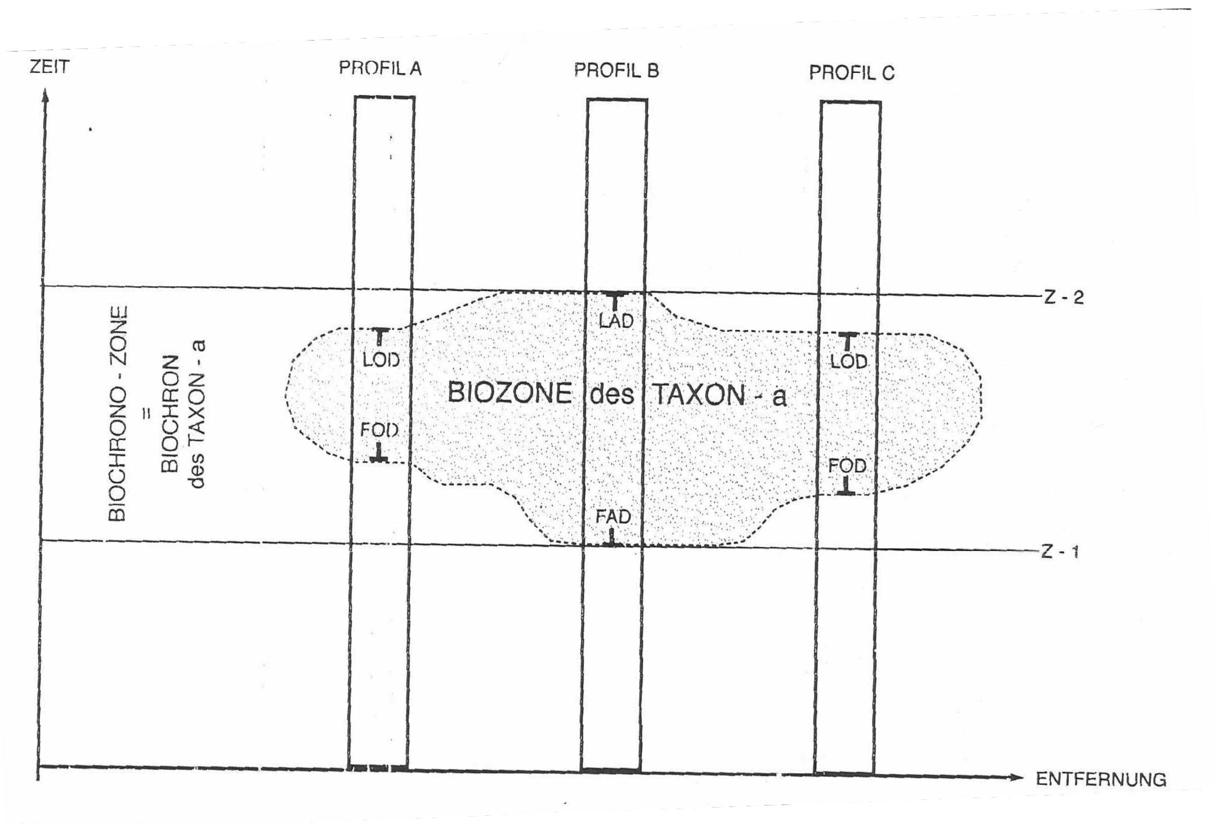
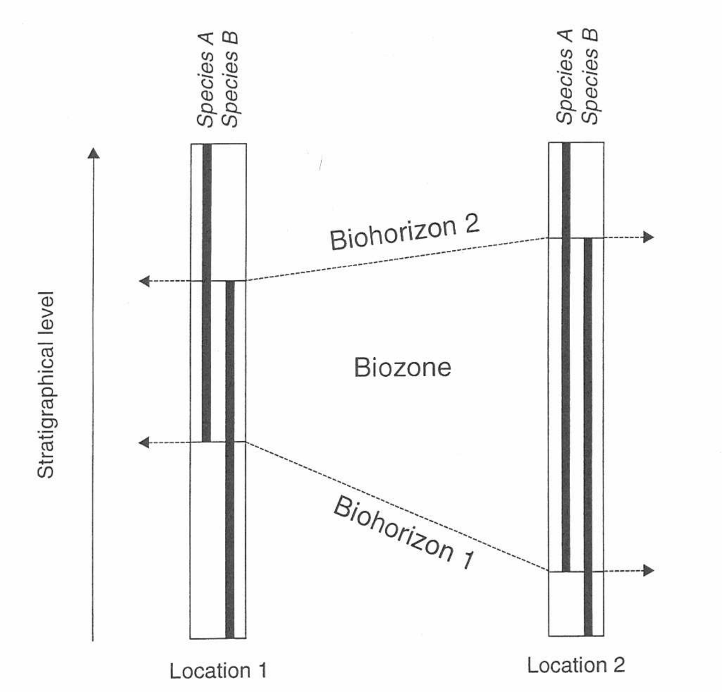
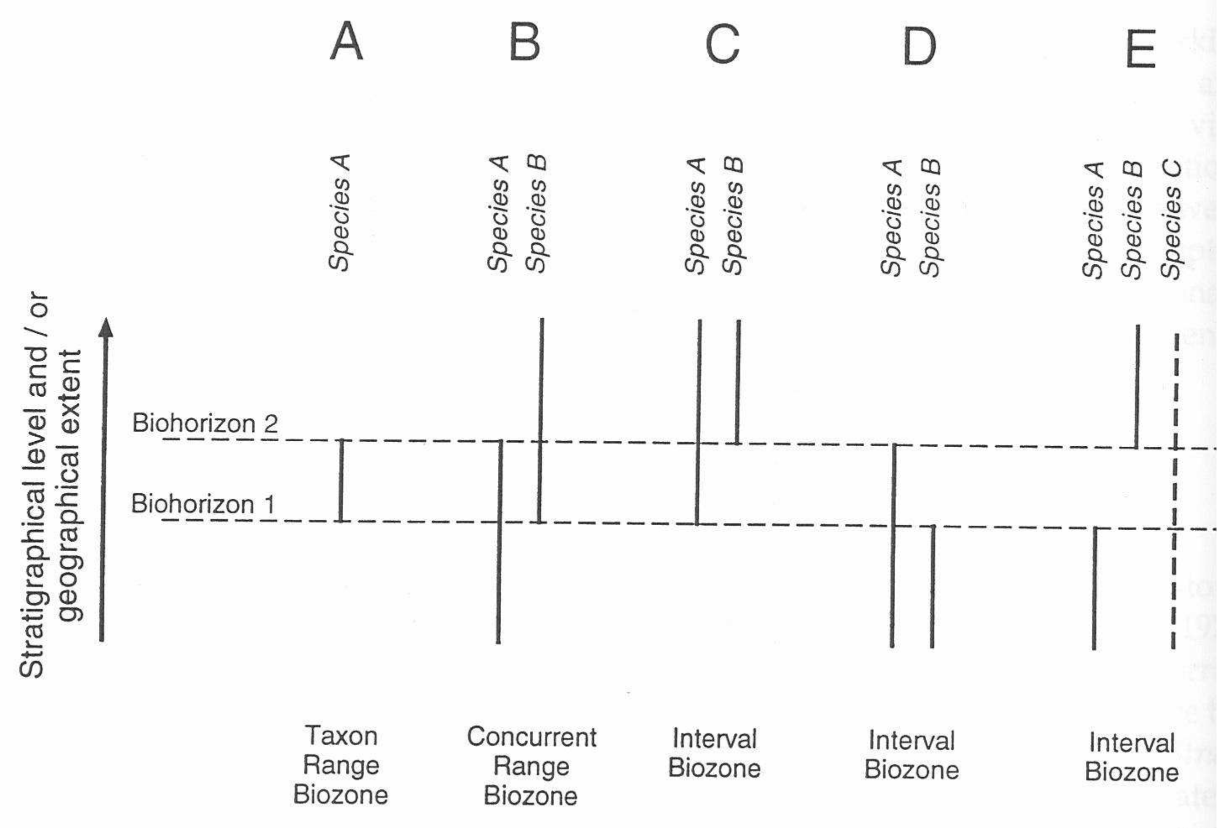


Figure 5.4 Anatomy of a taxon range biozone illustrating the interaction of evolution a... biogeography

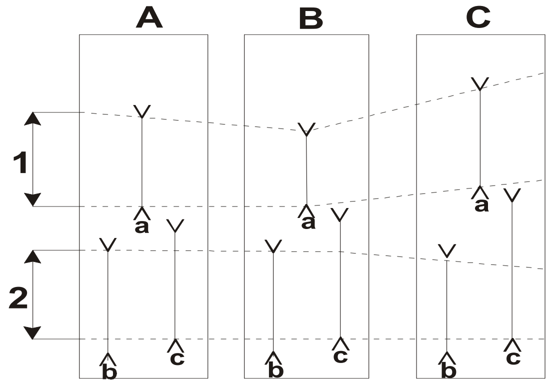


Biozóna a biohorizont, typy biozón

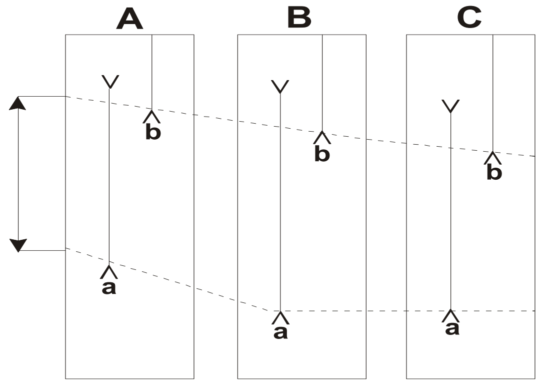




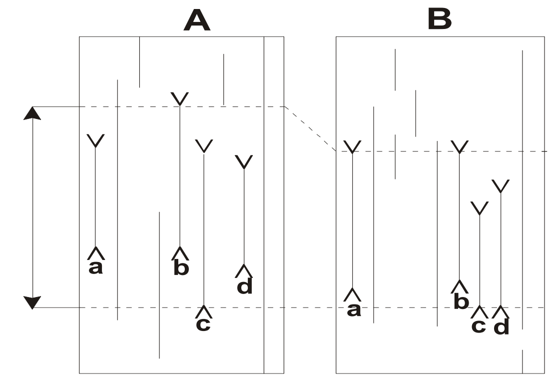
Grafické znázornění příkladů biozón
(upraveno dle Chlupáč & Štorch 1997)



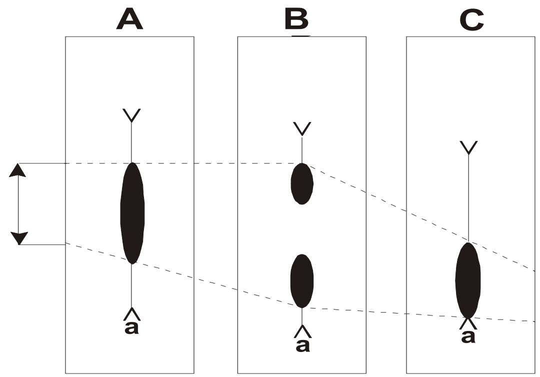
1 - zóna rozsahu taxonu **a**
2 - zóna společného rozsahu taxonů **b**, **c**



intervalová zóna mezi prvním výskytem taxonů **a**, **b**



zóna rozsahu společenstva se čtyřmi vůdčími taxony (**a**, **b**, **c**, **d**)



zóna hojného výskytu taxonu **a**

Vysvětlivky:
A, **B**, **C** - stratigrafické profily
a, **b**, **c**, **d** - vůdčí taxony (znaky)
- nejvyšší výskyt taxonu (znaku)
- nejnižší výskyt taxonu (znaku)
- hojný výskyt taxonu
hranice biozón

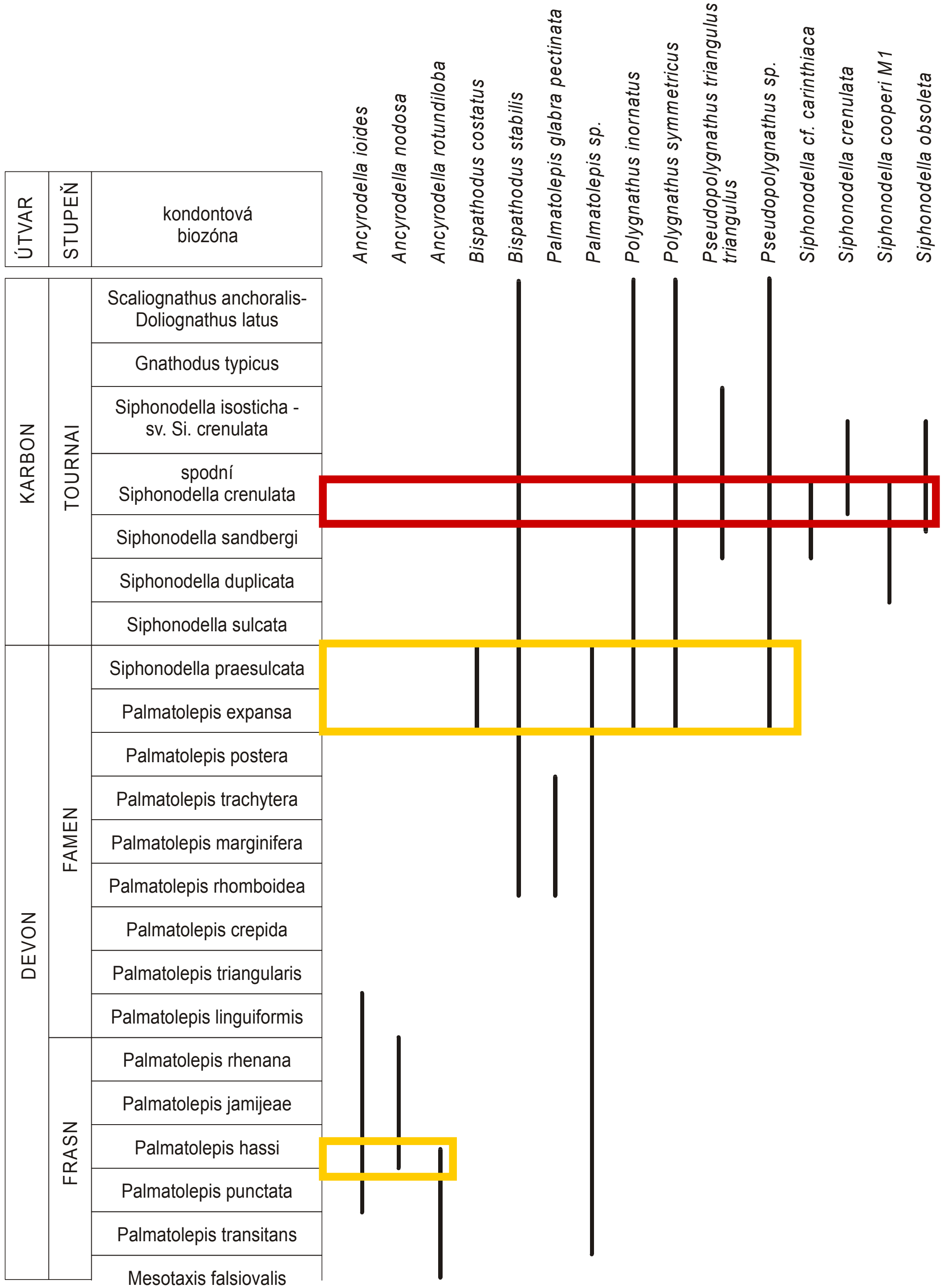
Problémy

- Eroze a přeplavení
- Biozóny definované na základě absence indexového taxonu

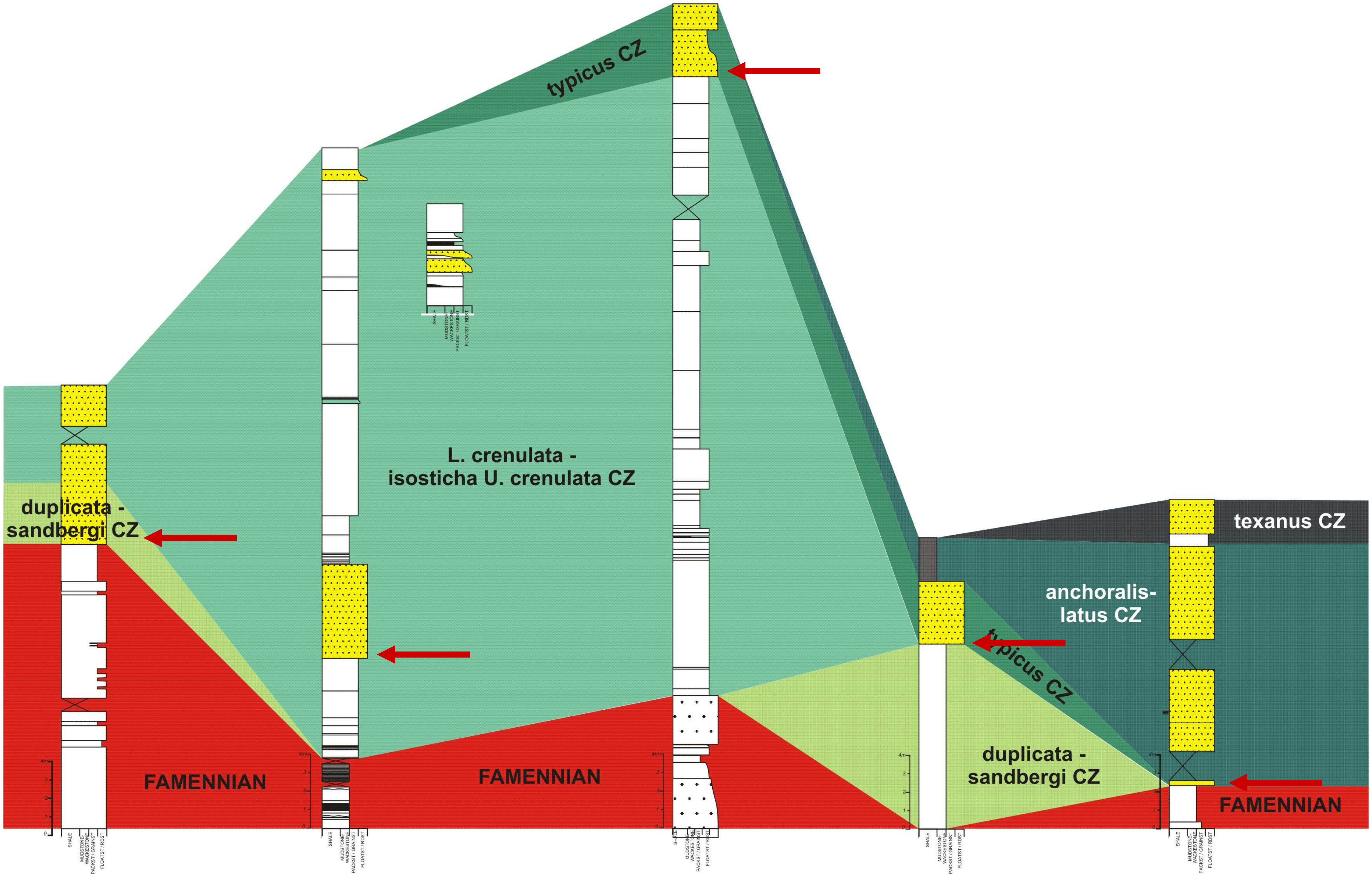
Conodont biostratigraphy

- **Typically, several conodont populations from multiple stratigraphic levels**

- **Stratigraphic inclusion of older conodonts from reworked deeper sediment layers**



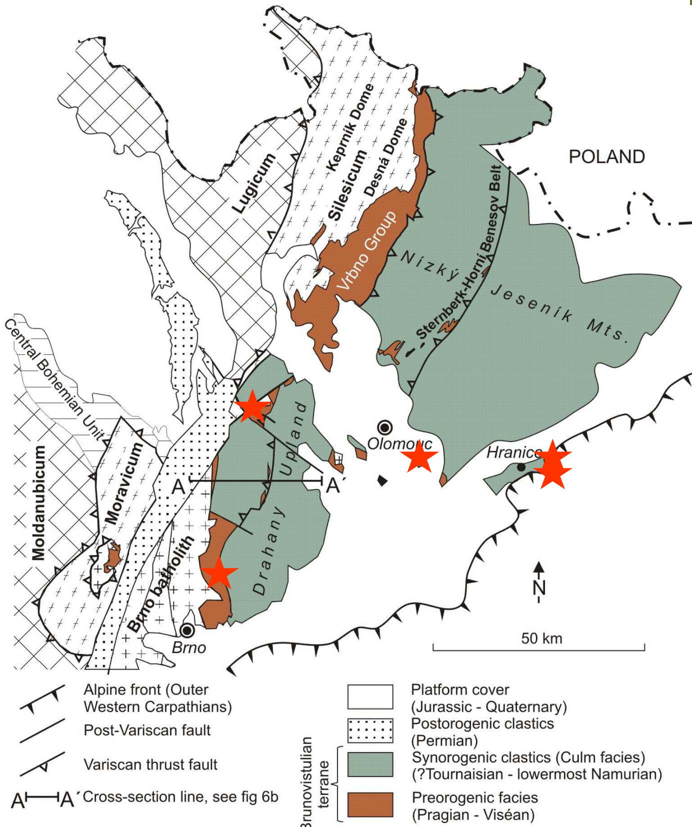
Biostratigraphic correlation

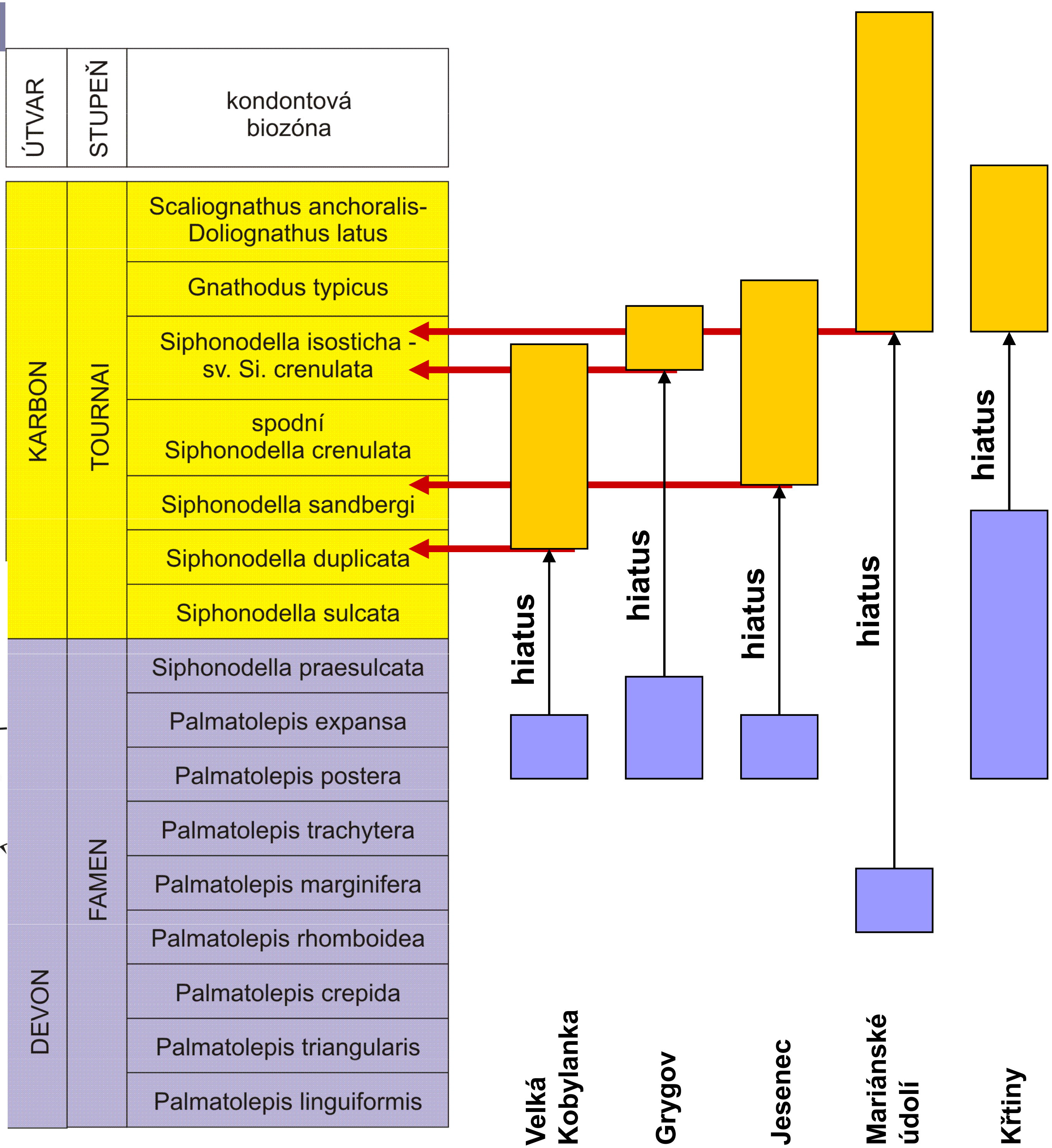


Time correlation

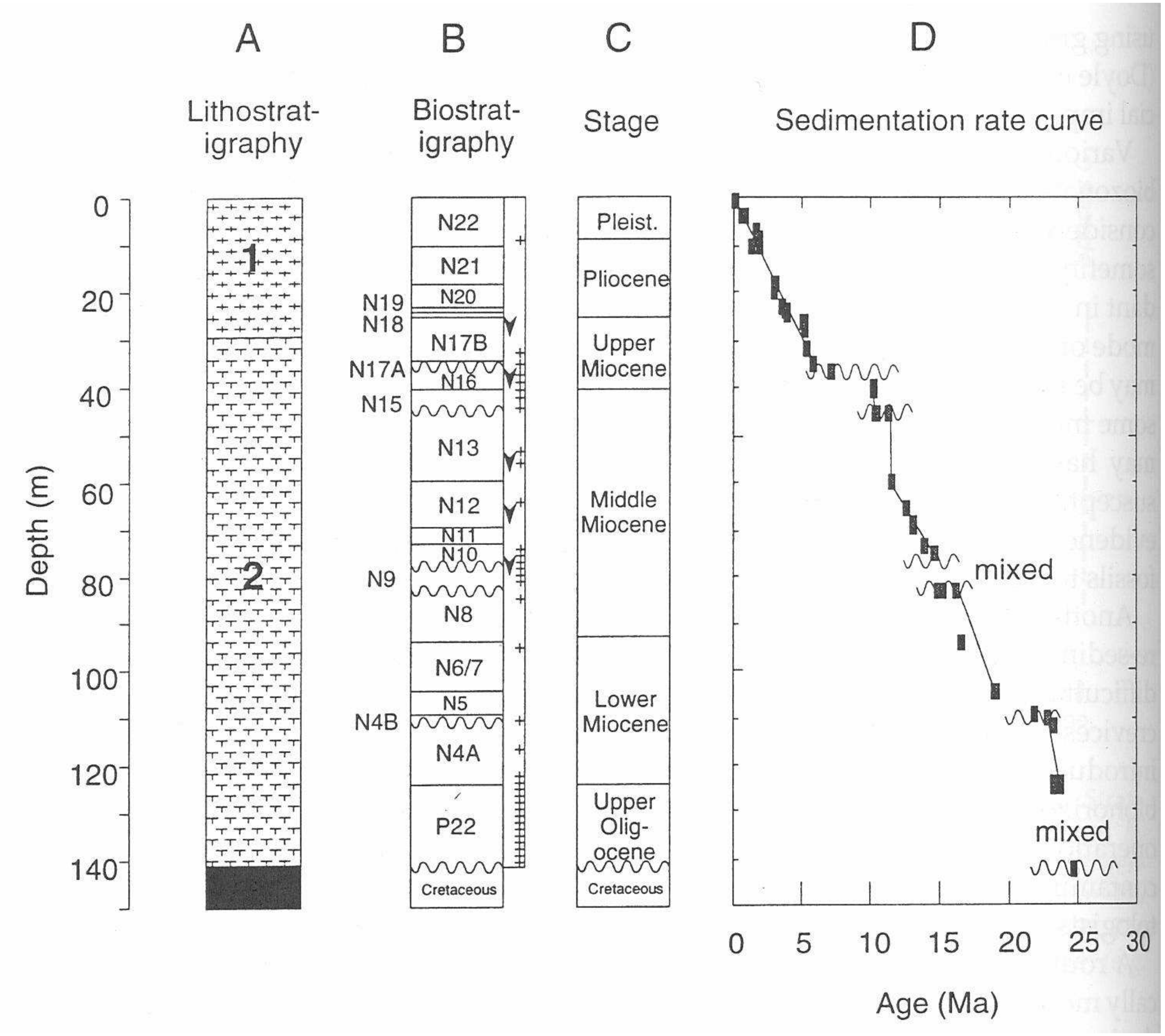
Diachronous onset of breccia deposition =

Local control on deposition: tectonic activity





Bio- vs. litostratigrafie



UDÁLOSTNÍ STRATIGRAFIE EVENTOSTRATIGRAFIE

STRATIGRAFICKÁ UDÁLOST:

- Záznam relativně krátkodobého procesu v horninách
- Depoziční události: téměř okamžité, na sedimentaci „pozadí“
  - Mořské prostředí
  - Terestrické prostředí
- Nedepoziční a erozní události: náhlá eroze, „winnowing“ – třídění vyplavováním, redepozice, kondenzace, „hladovění“,
- Výjimečné fyzikální procesy a události: zemětřesení, impakty
- Antropogenní události
- Biologická (evoluční) událost: (náhlé FOI, hromadná vymření) → biostratigrafie

- Event bed: událostní vrstvy
- Event horizon: událostní horizont

Rekurenční interval vs. velikost události

- Povodně
- Transgrese
- Tsunami
- Tempestity
- Sedimenty gravitačních toků
- Vulkanické erupce
- Zemětřesení
- impakty

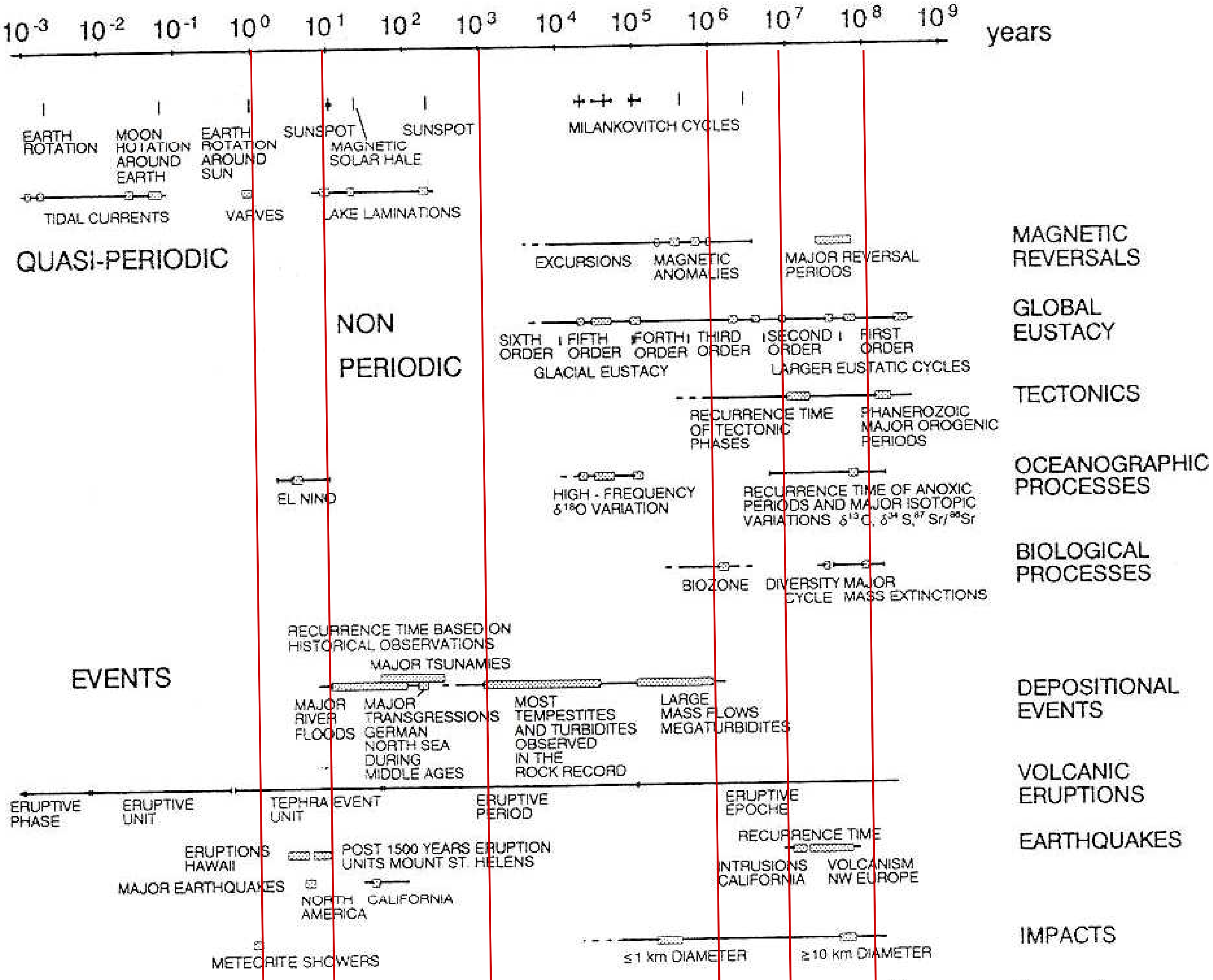


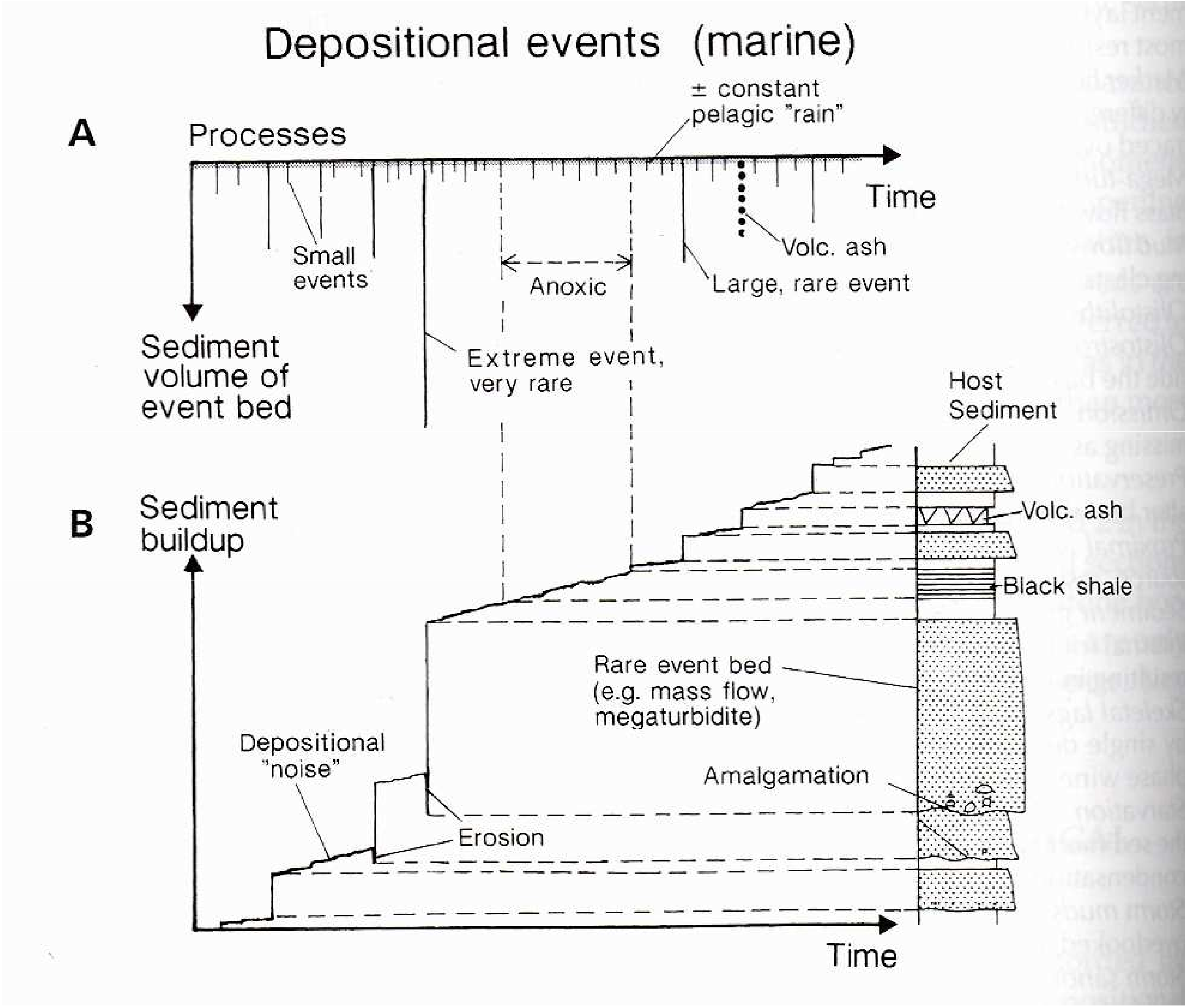
Fig. 6. Major recurrence time of quasi-periodic and nonperiodic processes as well as events. For explanation see text. Data is compiled according to Fischer Chap. 1.2, Glenn and Kelts Chap. 1.9, Schmincke and Boogard Chap. 2.12, as well as Vail et al. Chap. 6.1, (all this Vol.); Bolt (1978); Dott (1988); Fisher and Schmincke (1984); Haq et al. (1987); Holser (1984); Jacobs (1984); Reineck (1978); Sheridan (1987); Shoemaker (1984); van Andel (1985); as well as Ziegler (1982)

DEPOZIČNÍ UDÁLOSTI

Depoziční vrstvy (event)

Přírustek velkého objemu sedimentu za velmi krátký čas

Korelace událostních sedimentů = korelace časového horizontu



Tempestity

- Hummocky cross stratification (hřbítkovité zvrstvení)
- Wave ripples (vlnové čeřiny)
- Current ripples (proudové čeřiny)

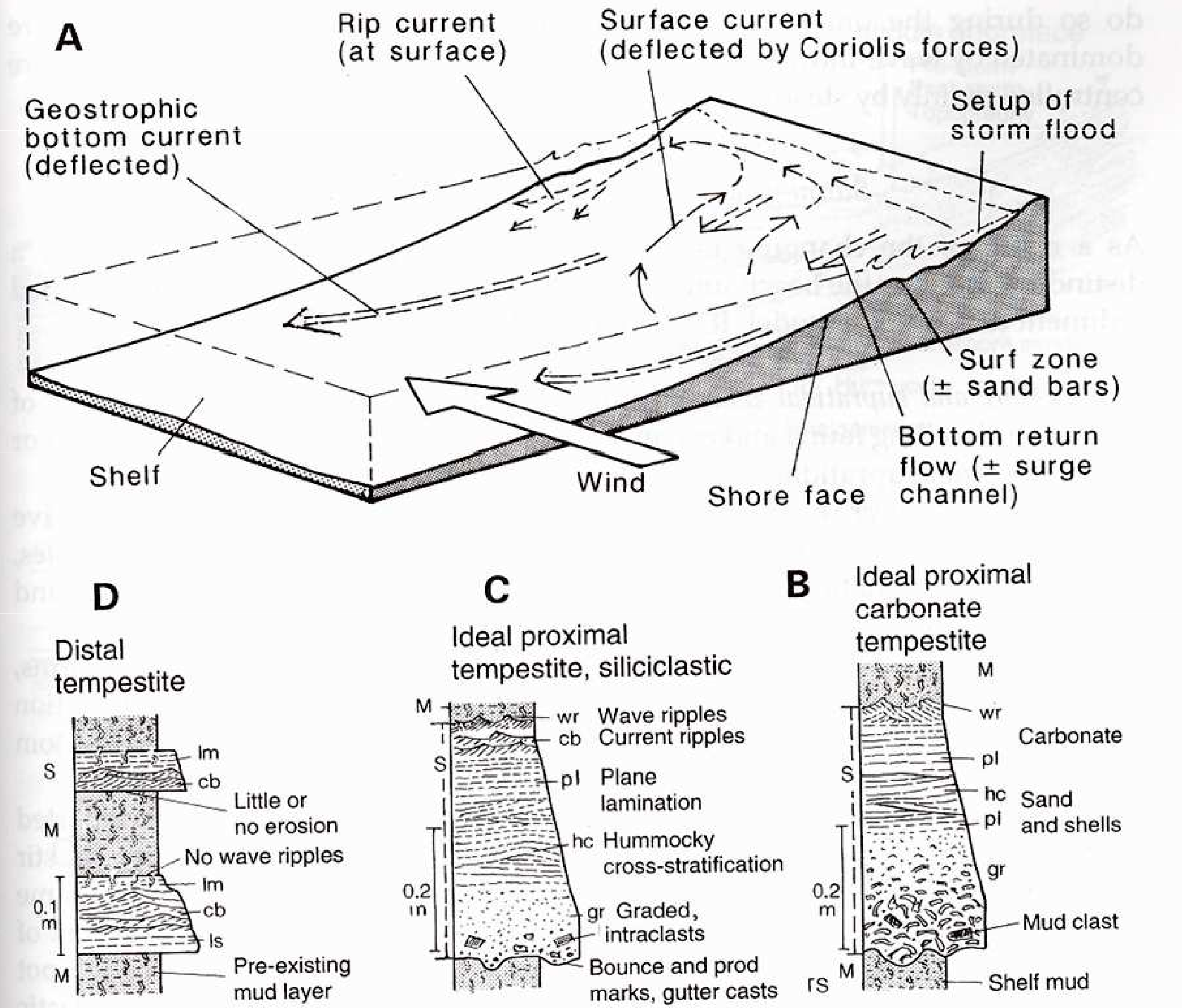
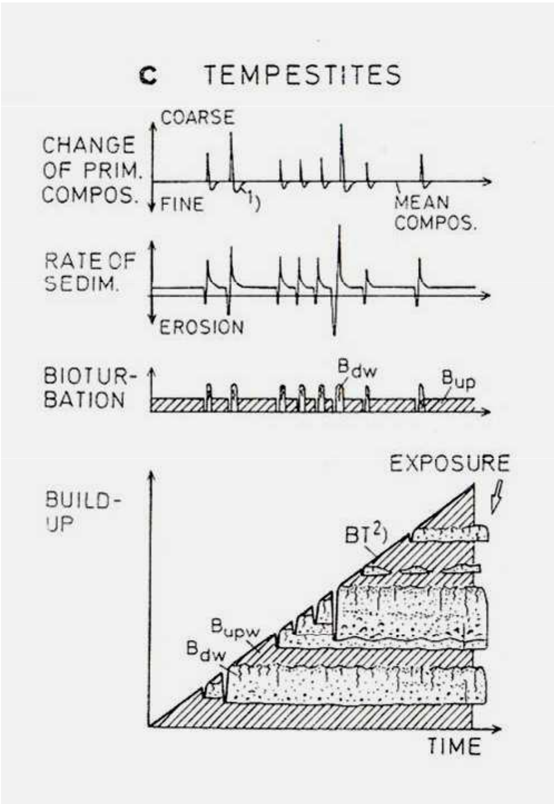


Figure 6.2 *A. Wind-driven storms producing coastal set up of storm flood, foreshore bottom return flow, and geostrophic bottom currents affecting the inner and outer shelf. As a result of Coriolis forces, all currents are deflected to the right in the Northern Hemisphere.* ***B*** *and* ***C.*** *Sedimentary structures of individual proximal carbonate and siliciclastic storm deposits (tempestites).* ***D.*** *Distal tempestite. S, sand; M, mud; gr, graded and massive; lm, laminated mud. [Modified from: Einsele (1992)]*

Tempestity

- Amalgamace (slévání vrstev)
- Scours (výmoly)
- Tool marks (otisky po dopadu)
- Combined flow (vícesměrný)
- Unidirectional (jednosměrný)
- Proximální vs. distální
- Fining and thinning upward (transgrese)
- Coarsening and thickening upward (regrese)



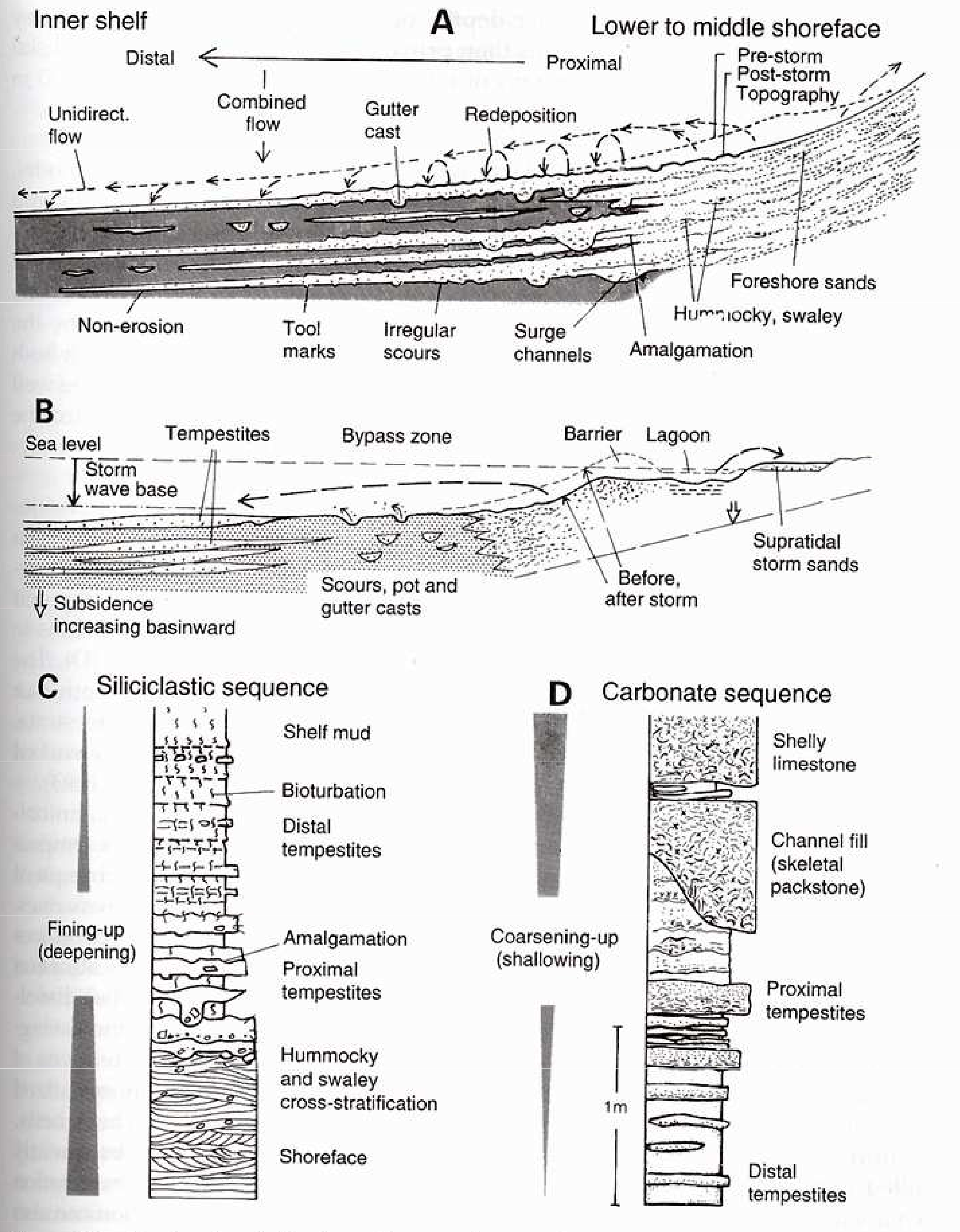


Figure 6.3 Proximal and distal trends (**A**) without and (**B**) with sediment bypass zone. **C.** Siliciclastic sequence with deepening (fining and thinning) upward trend. **D.** Shallowing (coarsening and thickening) upward calcareous tempestite sequence. Note the amalgamation of proximal sandy to gravelly tempestites. [Modified from: Einsele (1992)]

Sedimenty gravitačních toků: bahnotoky

- Cohesive flow, plastický tok soudržného materiálu (bahno)
- Turbidity
- Intraclasts (útržky dna)
- Slump fold (gravitační vrásy)
- Extraclasts (klasty „odjinud“)

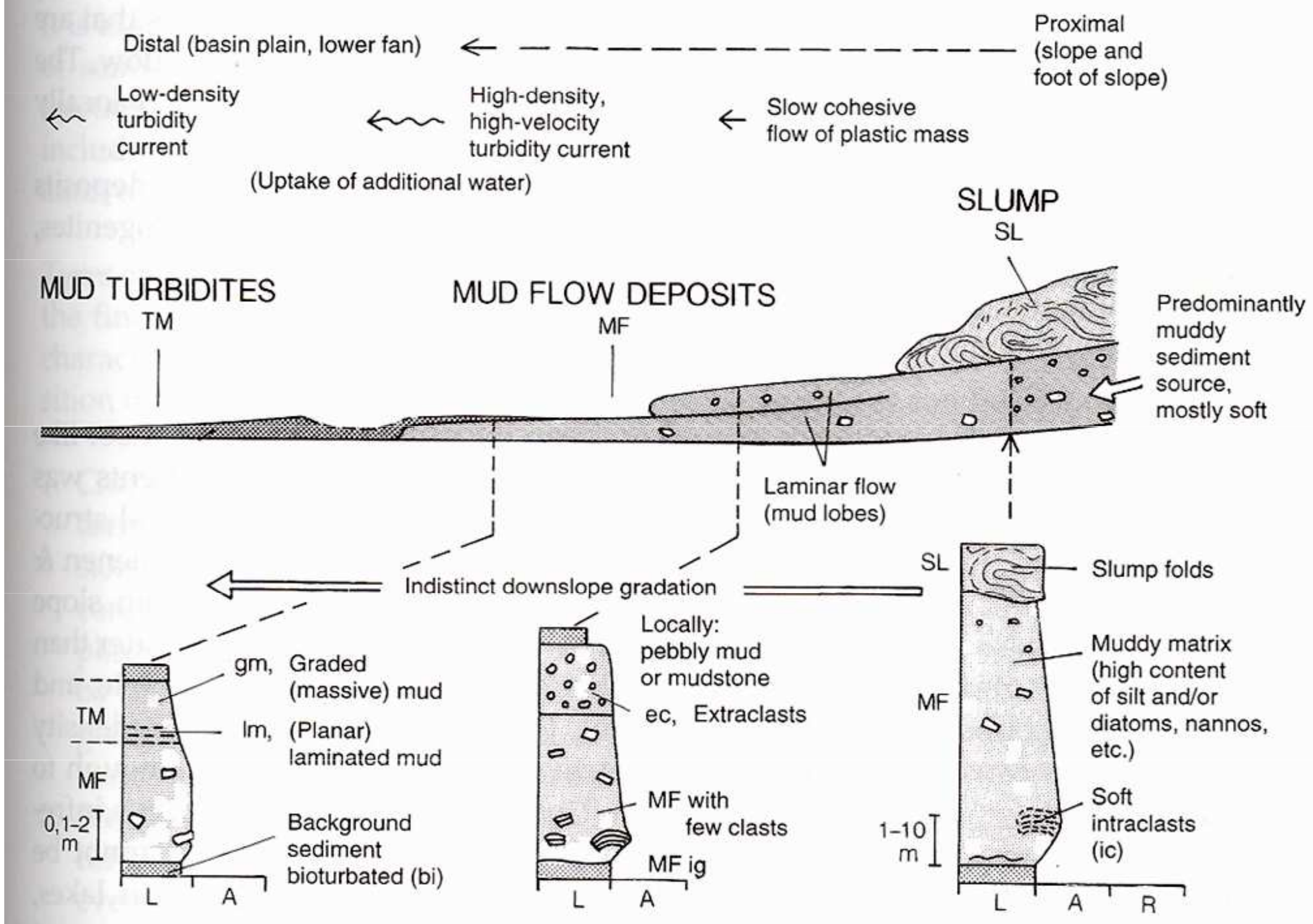
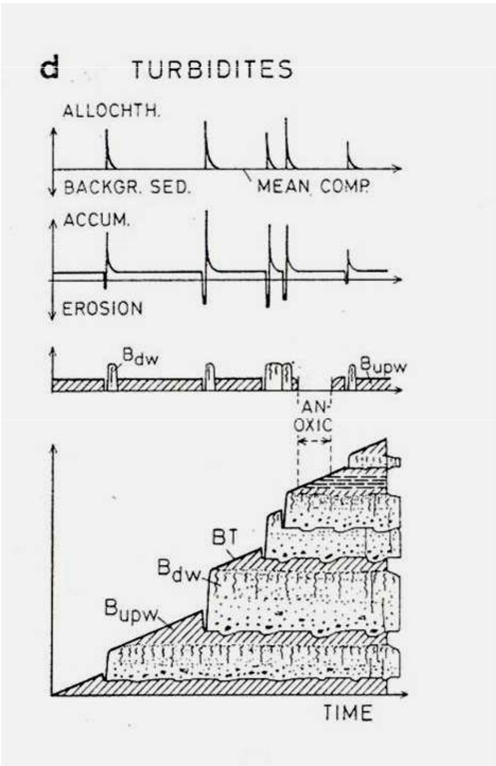
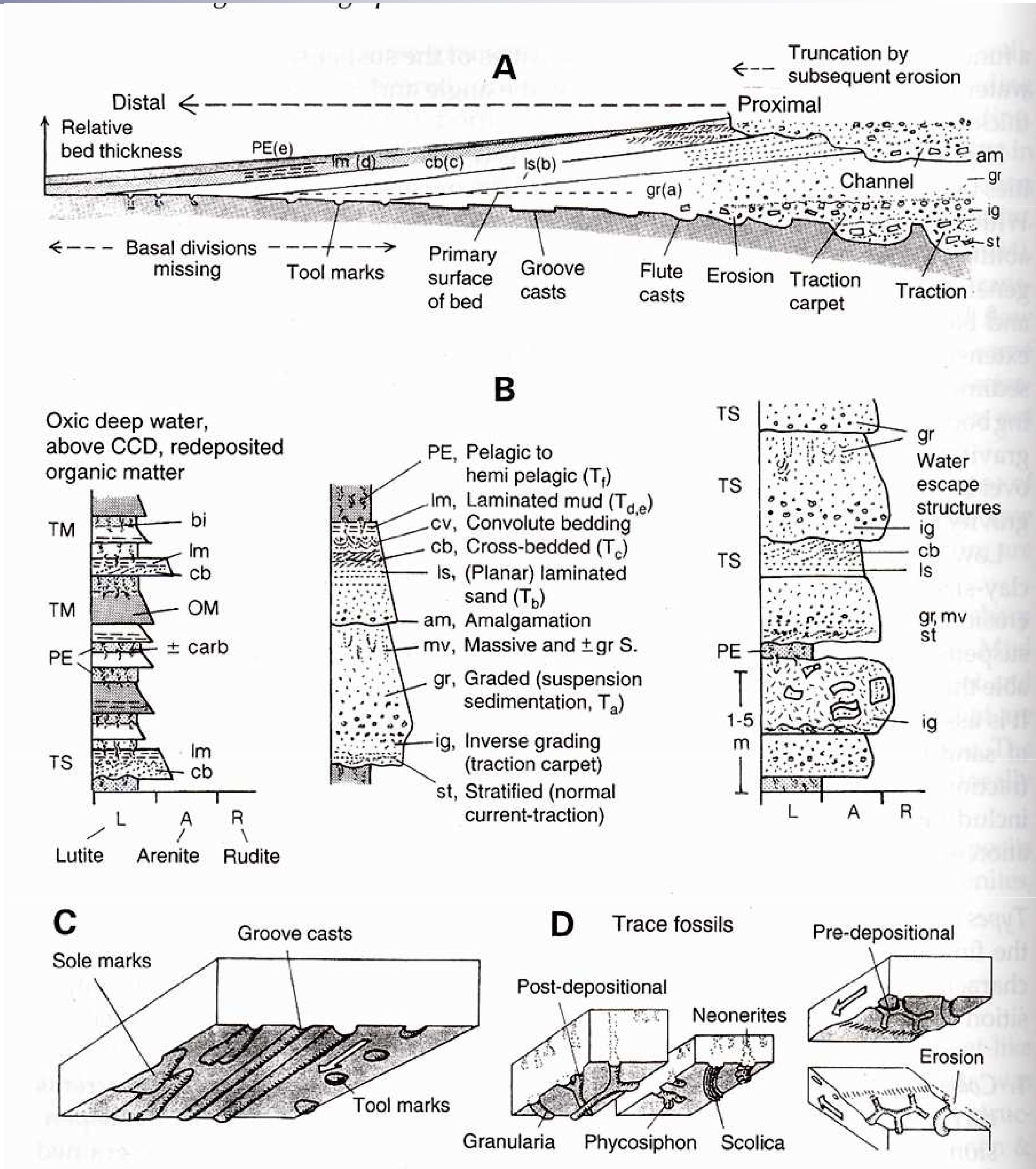


Figure 6.5 Conceptual model for mud flow deposits (with transition to debris flow deposits) ultimately evolving into mud turbidites. L, lutite (clay and silt); A, arenite (sand); R, rudite (gravel); MF, mud flow deposits; TM, turbidite mud; ig, inverse grading. [Modified from: Einsele (1992)]

Turbidity:

- Groove, flute casts, tool marks (erozní výmoly)
- Traction (klouzání zrn po povrchu)
- Amalgamace
- Grading (gradační zvrstvení) : normální, inverzní (převrácené)
- Trace fossils (fosilní stopy)
- Proximální vs. distální





Kalové turbidity

- Biogenní gradace

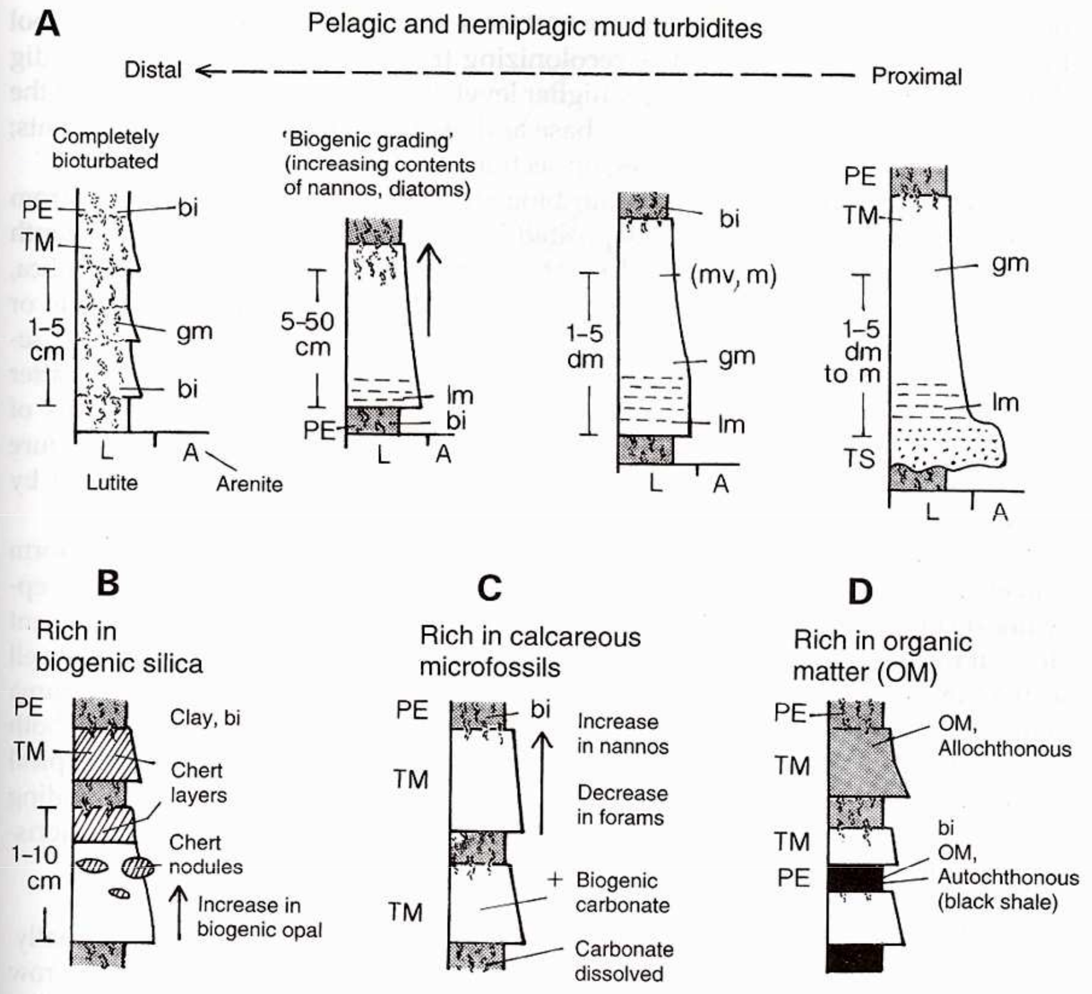
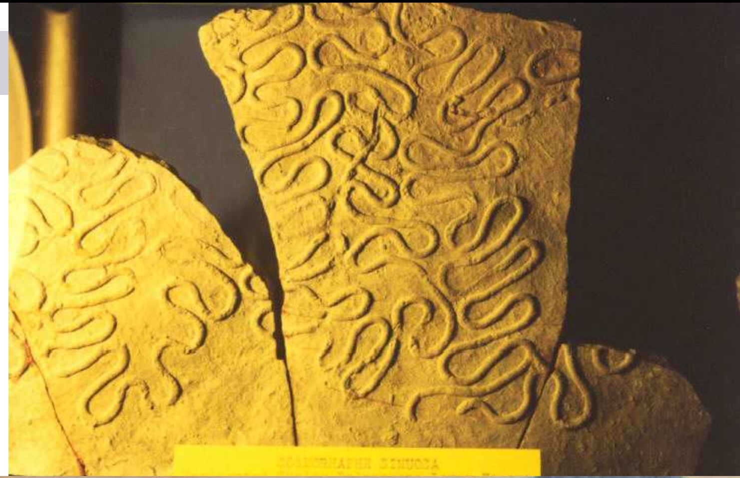
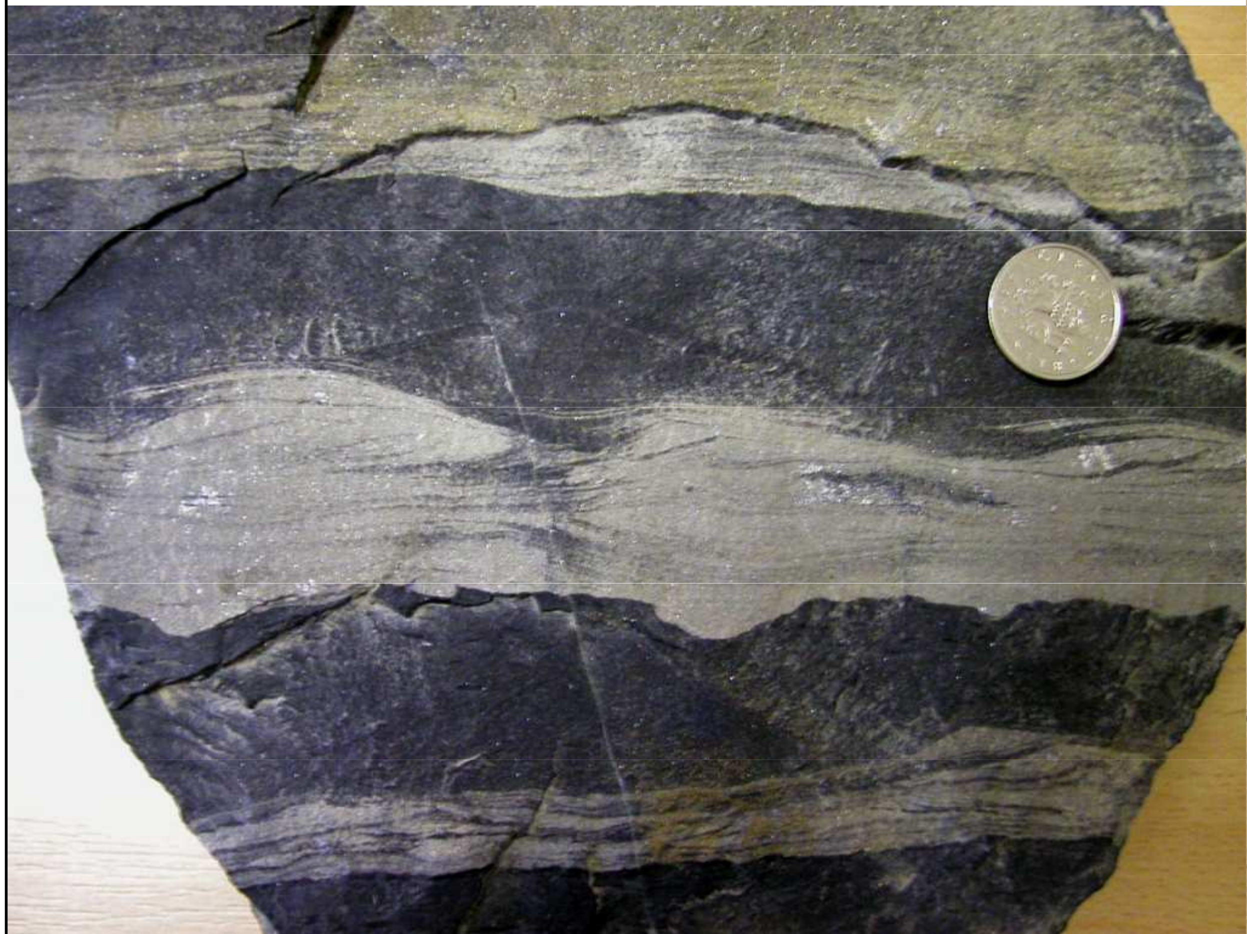


Figure 6.8 *Various types of mud turbidites.* ***A.*** *Proximal–distal trend of hemipelagic types, predominantly siliciclastic.* ***B*** *and* ***C.*** *Pelagic mud turbidites rich in opaline silica (transformed into chert) or calcareous microfossils; these beds may alternate with pelagic clay devoid of carbonate.* ***D.*** *Mud turbidites either rich or poor in organic carbon alternating with black shale or oxygenated and bioturbated pelagic deposits. Symbols are explained in Figure 6.6 [Modified from: Einsele (1992)]*


Depoziční události v kontinentálním prostředí: Tefrostratigrafie

400 Chapter 2 Event Stratification

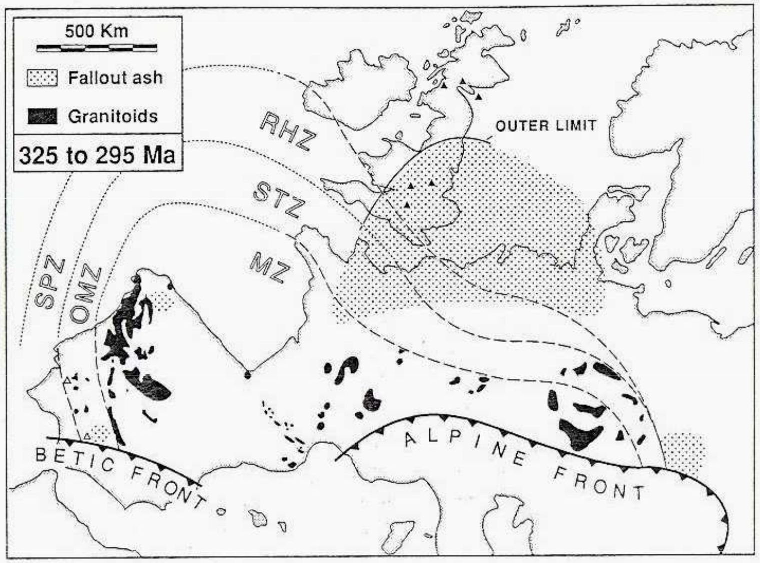


Fig. 6. Areal distribution of Lower Carboniferous fallout ash layers (bentonite or "tonstein" layers) in front of the main areas of granite intrusions in Europe. *Open triangles* (felsic) and *closed triangles* (mafic) indicate occurrences of volcanic rocks. *SPZ* South Portugese zone; *OMZ* Ossa Morena zone; *RHZ* Rhenohercynian zone; *STZ* Saxothuringian zone; *MZ* Moldanubian zone. (After Francis 1988)

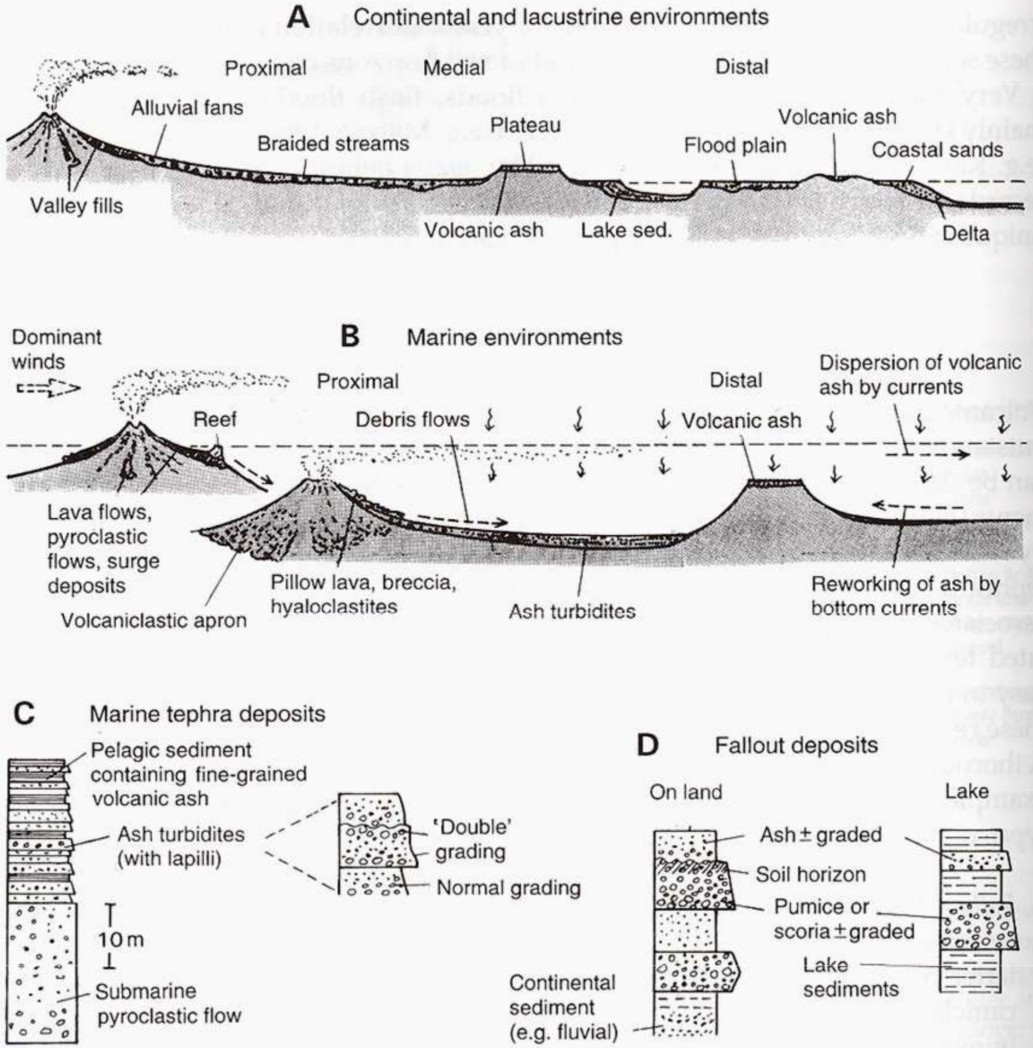


Figure 6.11 *Various tephra events in (**A**) continental and (**B**) marine environments. **C.** Compound section of marine tephra deposits reflecting the transition from maximum to waning stages of submarine eruption. **D.** Repeated fallout deposits on land surface and in lake. [Modified from: Einsele (1992)]*

Tefrostratigrafie

Schmincke and van den Bogaard: Tephra Layers and Tephra Events 403

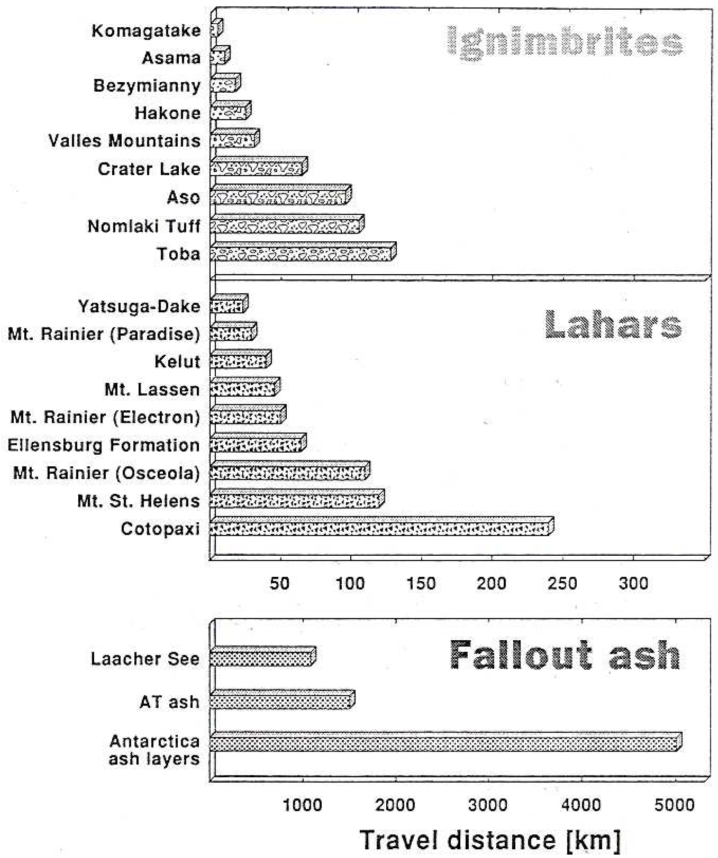
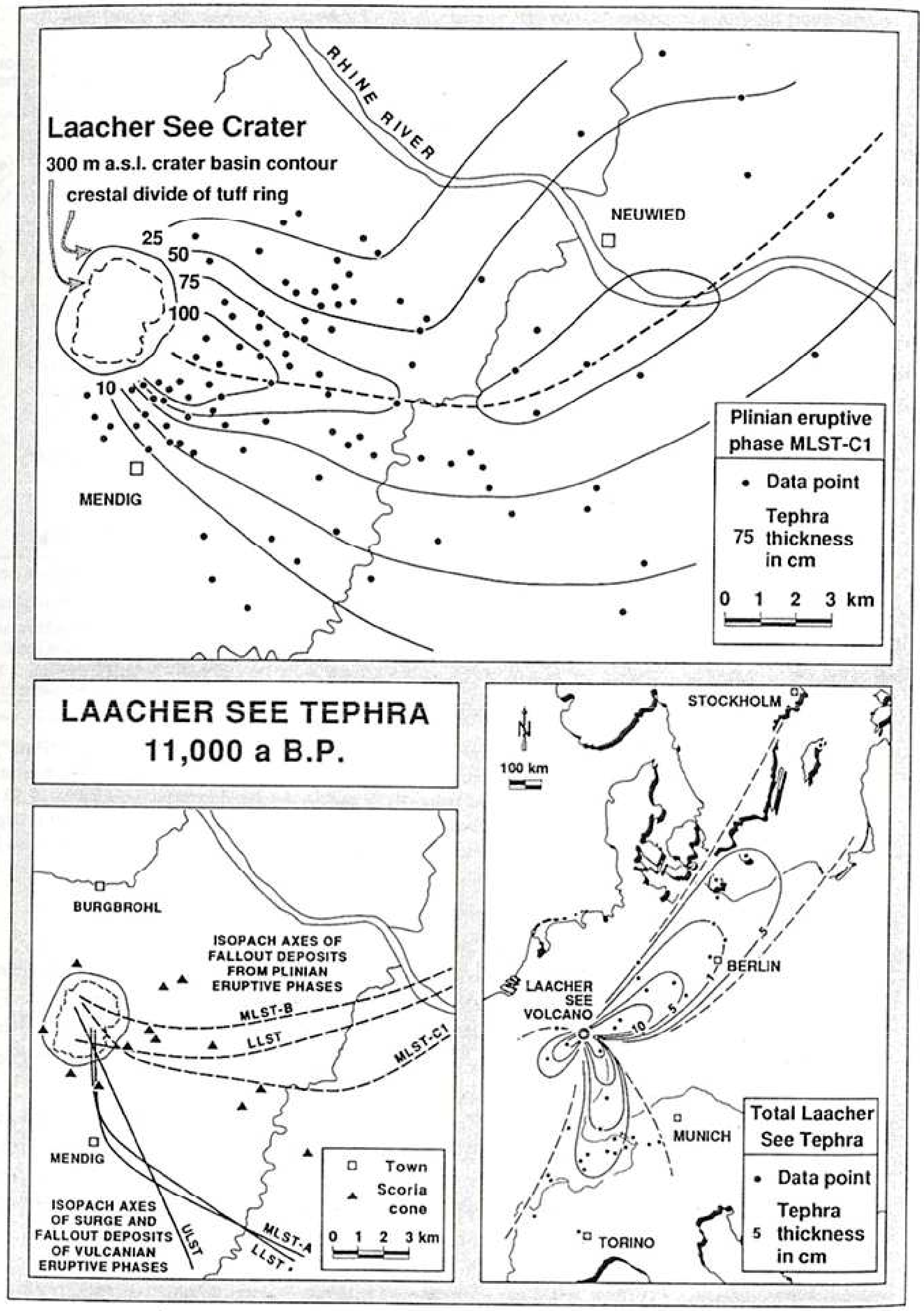
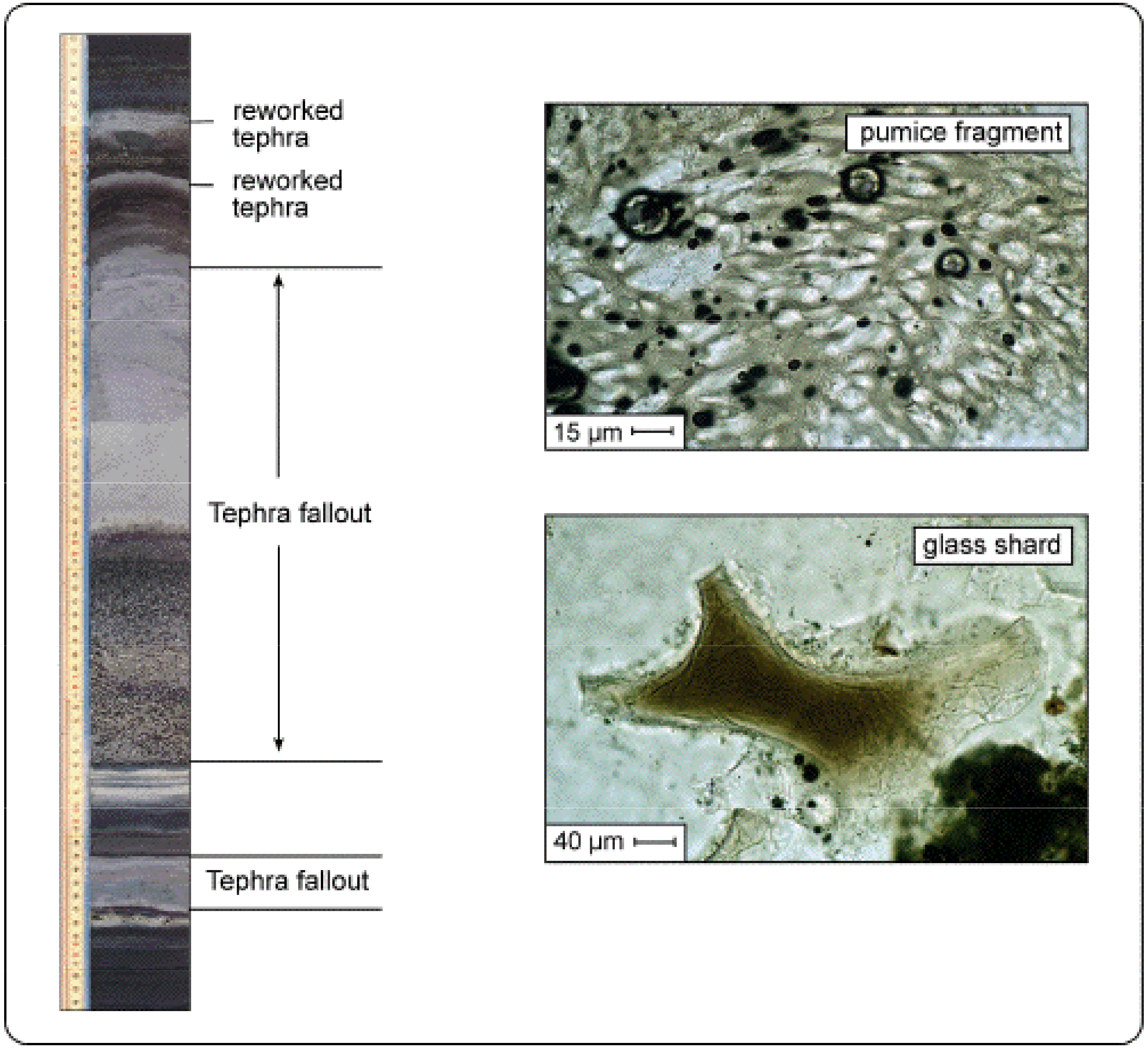


Fig. 8. Typical transport distances of ignimbrites and lahars, and traceable extent of Plinian fallout ash layers. Various sources compiled in Schmincke (1988) and Fisher and Schmincke (1984, 1990). Cotopaxi and St. Helens lahar data may include lahar run-out hyper-concentrated stream deposits as well. (Fallout data from Machida 1981, Kyle and Seward 1984, and van den Bogaard and Schmincke 1985)



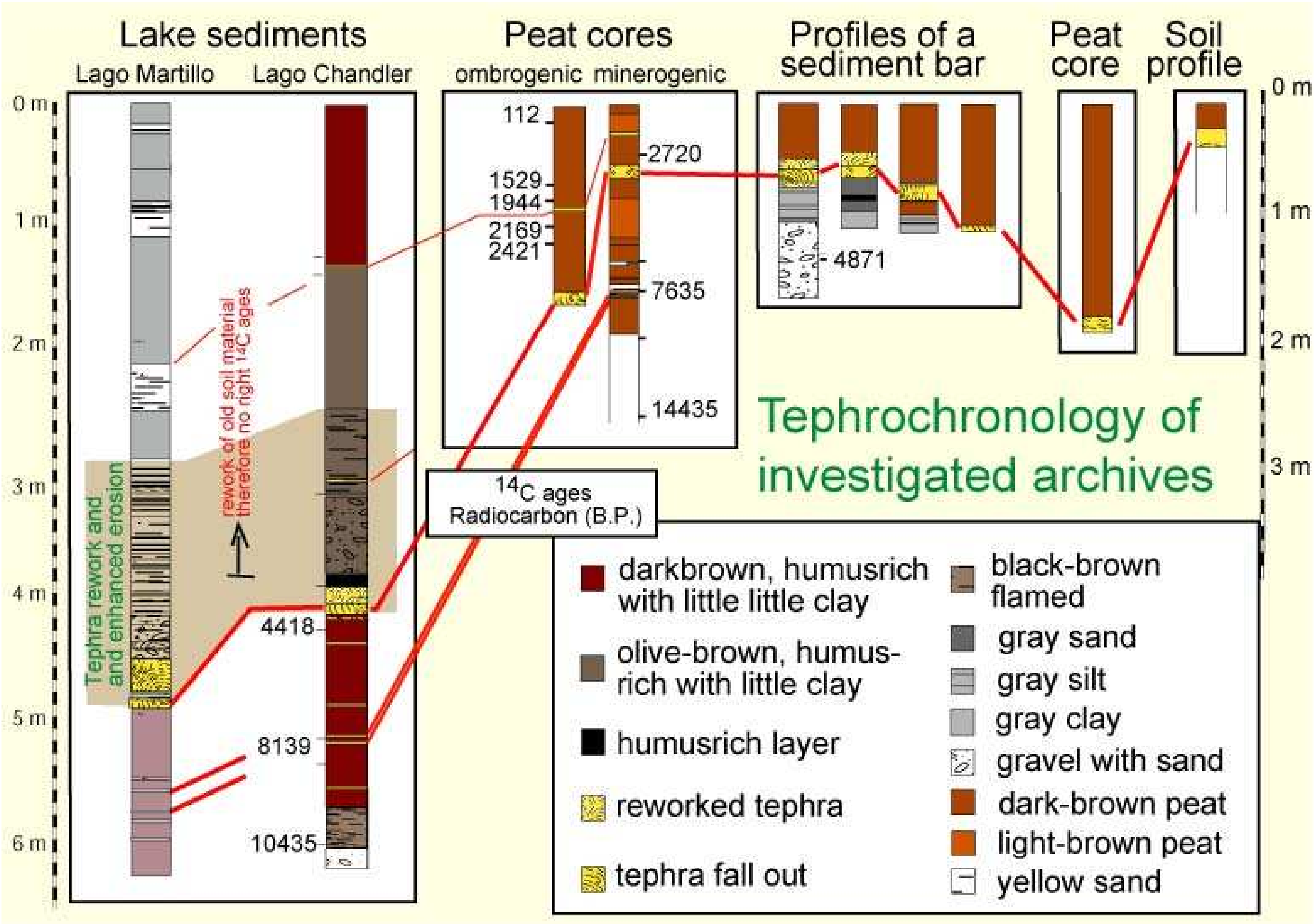
Událostní stratigrafie: tefrochronologie

- Petrographic and chemical studies can identify unique tephra signatures which can then be used in a tephrochronology



http://www.gfz-potsdam.de/pb3/pb33/projects/monticchio_tephrochronology/content_en.html

Tefrochronologie



http://www.grancampo.de/english/tephra/tephra3.htm

VÝJIMEČNÉ UDÁLOSTI: Zemětřesení
Sediment: „seismit“

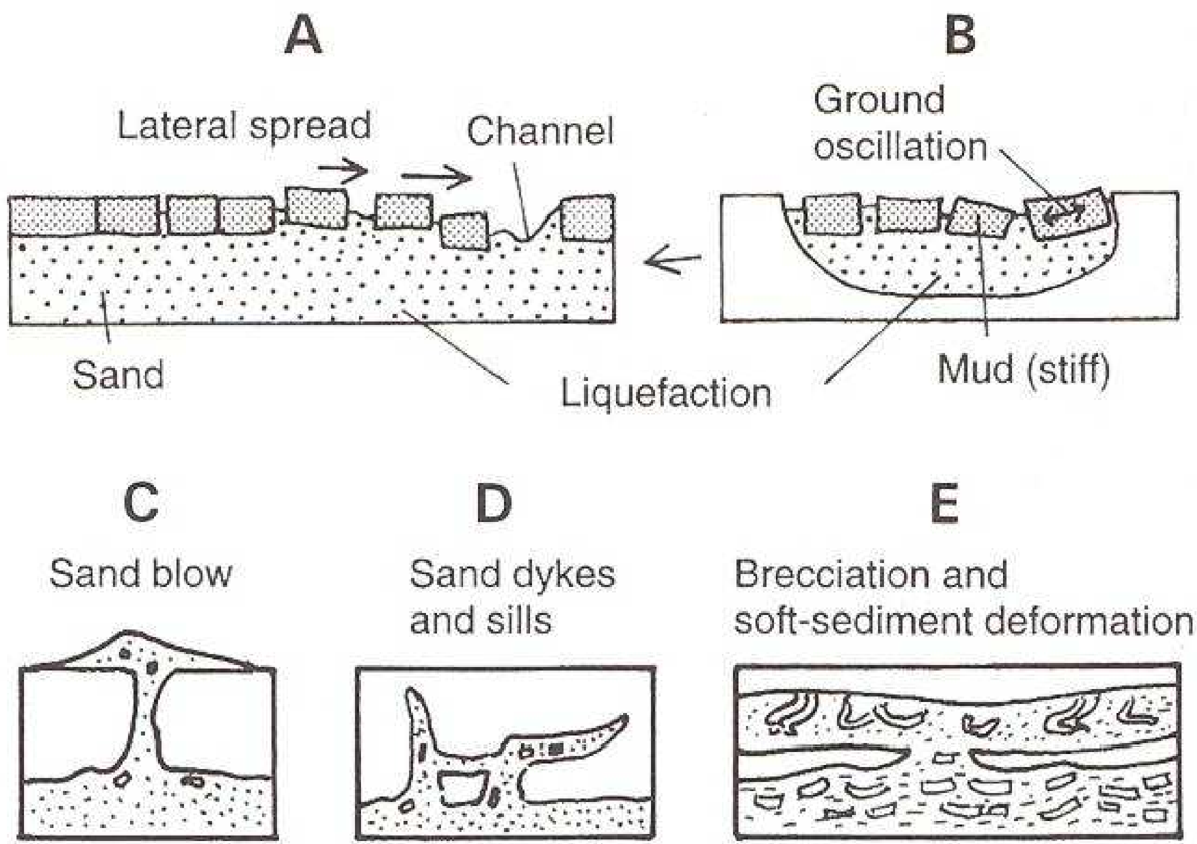
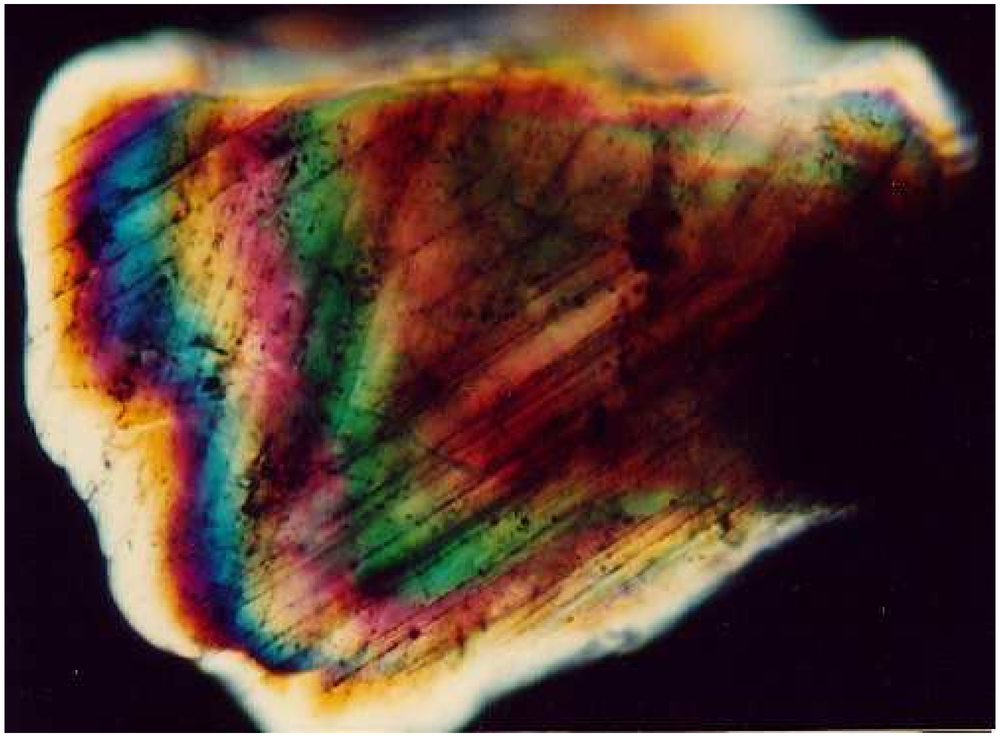


Figure 6.19 *Earthquake-induced seismites displaying* in situ *disturbances of flat-lying sediments. [Based on information in Guiraud & Plaziat (1993) and Greene* et al. *(1994)]*

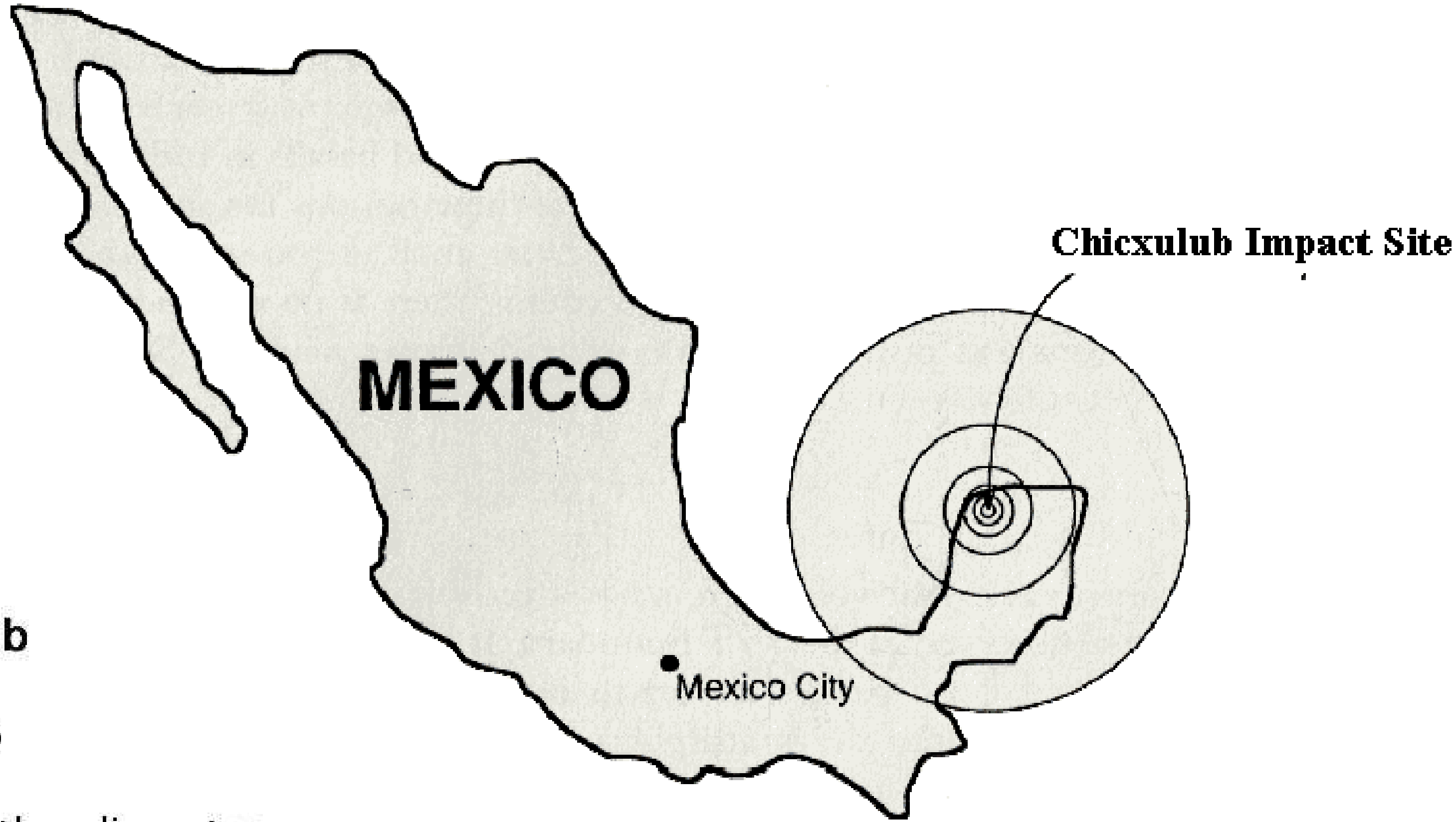
The asteroid impact theory was first proposed by Louis and Walter Alvarez in 1980.

They discovered high concentrations of **iridium** - an element rarely found on Earth but found in abundance in **extraterrestrial bodies** such as asteroids and meteorites - in a thin layer of clay from Italy. The iridium was found at the Cretaceous-Tertiary (K/T) boundary, the layer of geological deposits dated at 65 million years when the dinosaurs became extinct.

This theory is that an asteroid 4-9miles in diameter hit the Earth.
Since the asteroid scattered awful amount of dust and debris in the atmosphere, the dust and debris blocked the most of the sunlight, and the temperature lowed down globally. The low temperature caused the mass extinction.



- Šokový křemen
- Tektity
- Iridiová anomálie



Chicxulub Impact Site

Chicxulub

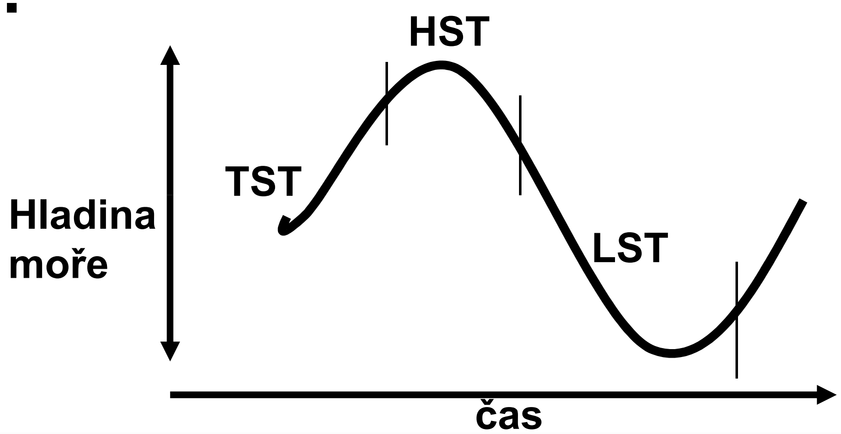
Yucatan Penisula, Mexico
180 km diameter
More than 100 times the diameter of Berringer

65,000,000 million years ago
Cretaceous mass extinction
Disappearance of the dinosaurs

Worldwide debris
Iridium anomaly
in clay at K/T boundary

Non-depoziční a erozní události: Záznam transgrese – regrese

- Transgresní rezidua
- Skeletální (fosilní) koncentrace
- Erozní diskordance
- Kondenzované vrstvy



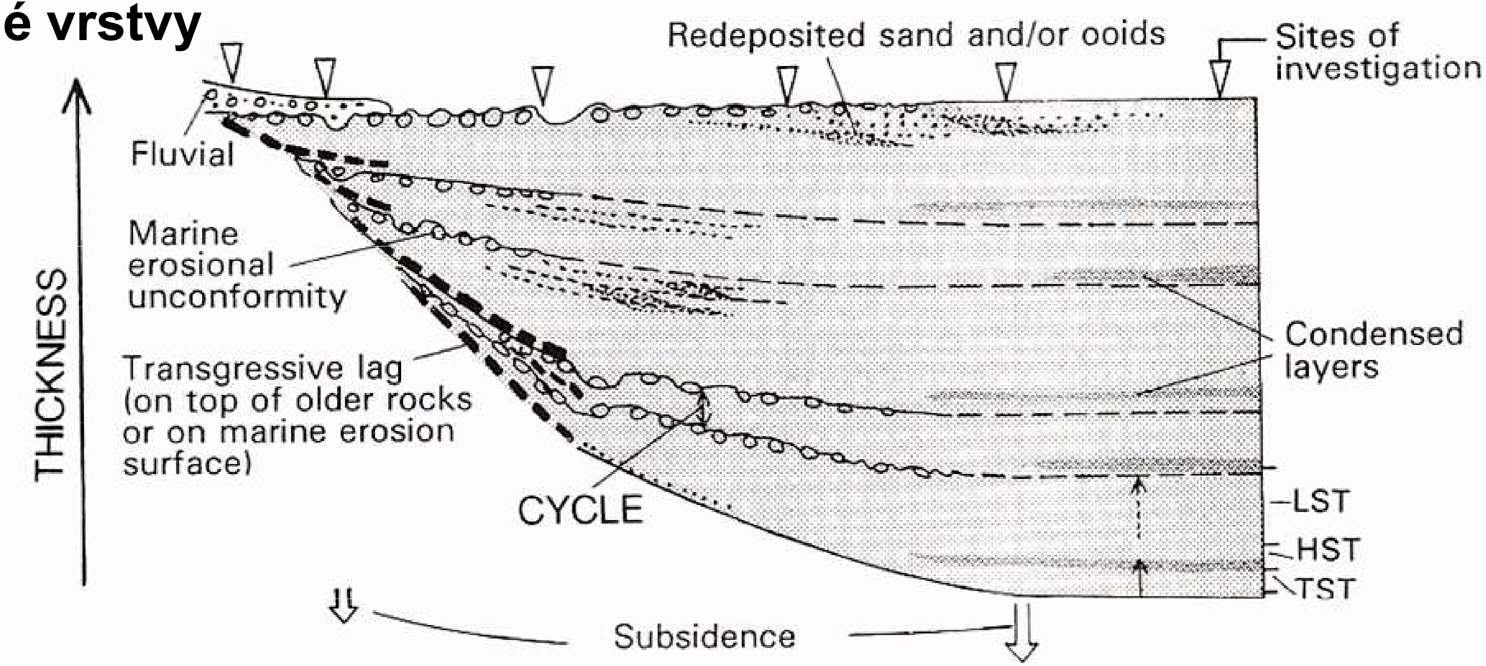


Figure 6.18 *Transect of shallow, differentially subsiding basin which has experienced several cycles of relative sea-level change with differing periods and amplitudes. Regressive and transgressive lags merge and mix landward; the stratigraphic section in the basin centre tends to be complete, but may contain thin condensed sections (e.g. black shales). [Modified from: Einsele (1992)]*

Transgrese - regrese

- Redepozice (reworking)
- „Pevné dno“ (hardground)
- Fosfatizace

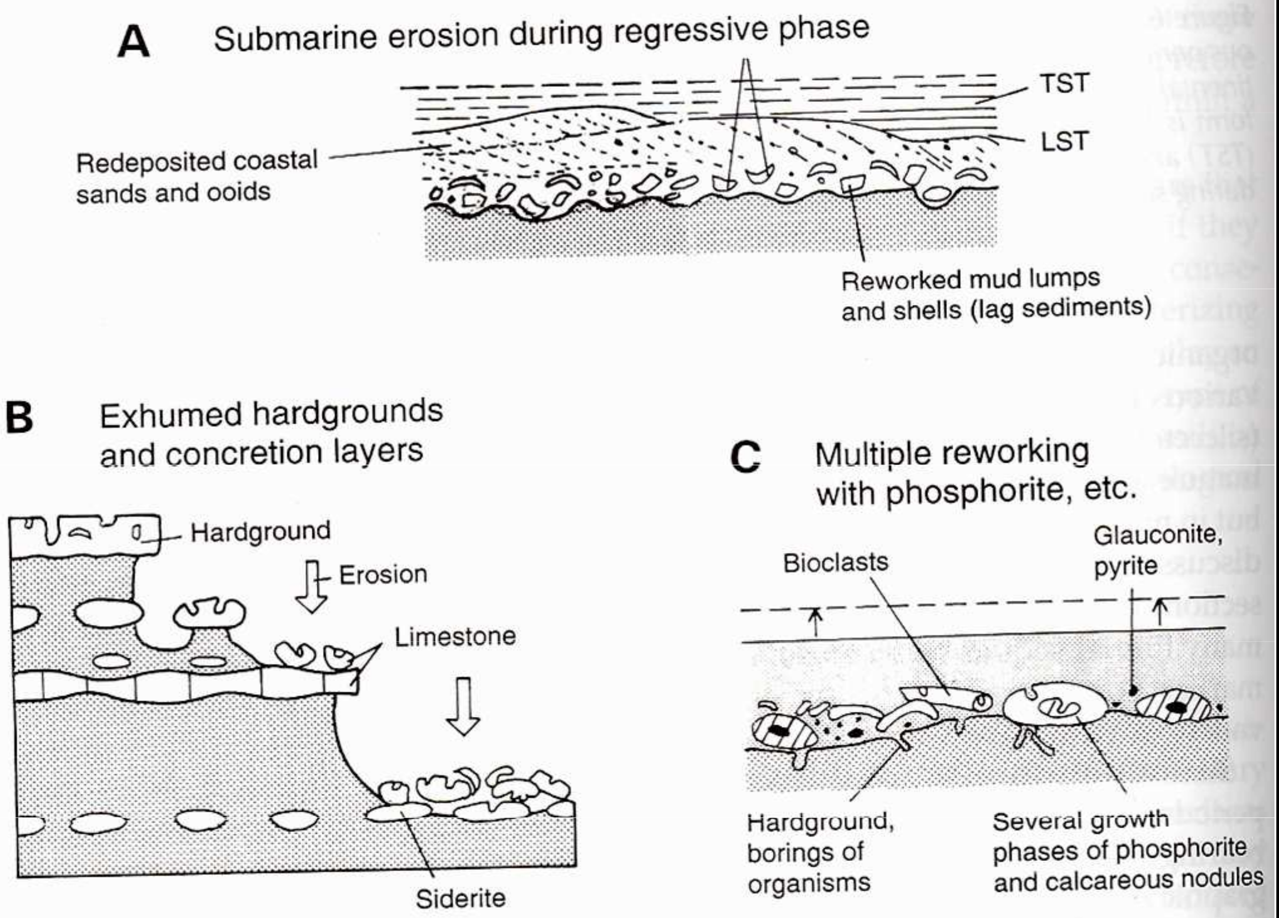


Figure 6.14 *Various types of submarine, mostly non-skeletal, stratal discontinuities.* ***A.*** *Erosional lag and seaward transported coastal sand and ooids (carbonate or iron ooids; lowstand deposits, LST) overlain by transgressive deposits (TST).* ***B.*** *Hardgrounds or concretion horizons exhumed by wave and current action.* ***C.*** *Close-up of B, containing phosphorite nodules and accentuated by multiple reworking. See text for explanation. [Modified from: Einsele (1992)]*

Skeletální akumulace (coquiny, lumachely)

- Vyplavování (winnowing)
- (vlnová báze, hloubka vody = ½ vlnové délky)
  - FWB
  - SWB
- Transgresní rezidua (lags)
- Koncentrace proudem (current)
- Tempestity
- kondenzace

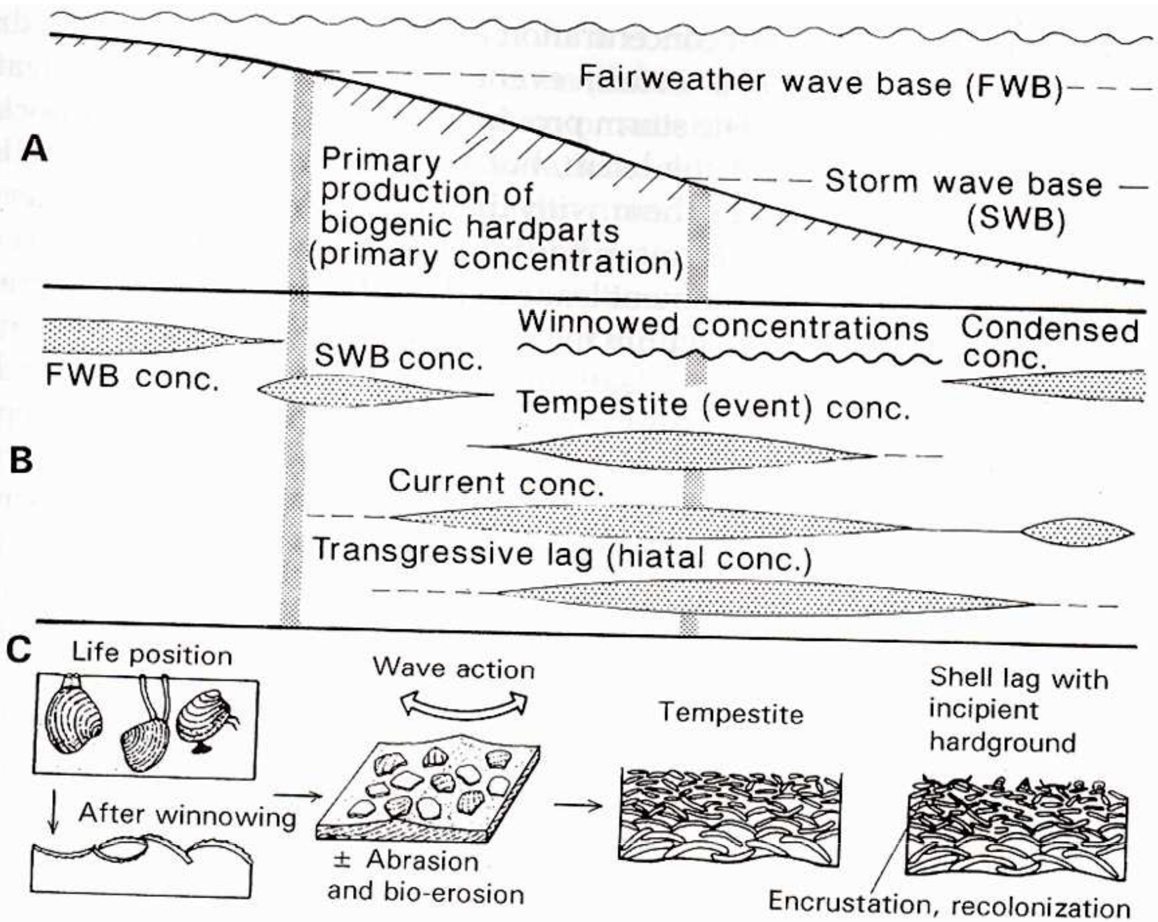


Figure 6.15 *Various modes of skeletal concentrations.* ***A.*** *Cross-section of shallow-marine basin; primary production of biogenic hardparts changes along onshore–offshore gradient.* ***B.*** *Processes generating skeletal concentrations along A.* ***C.*** *Examples of shell (bivalves) concentrations resulting from winnowing, wave action, storms and geostrophic currents, and overprint by life–death interaction (see Figure 6.16). [Modified from: Fürsich & Oschmann (1993)]*

Non-depoziční a erozní události: kontinentální prostředí

Sedimenty:

- půdní horizonty (paleosoly)
- Krasovění
- „incised valleys“

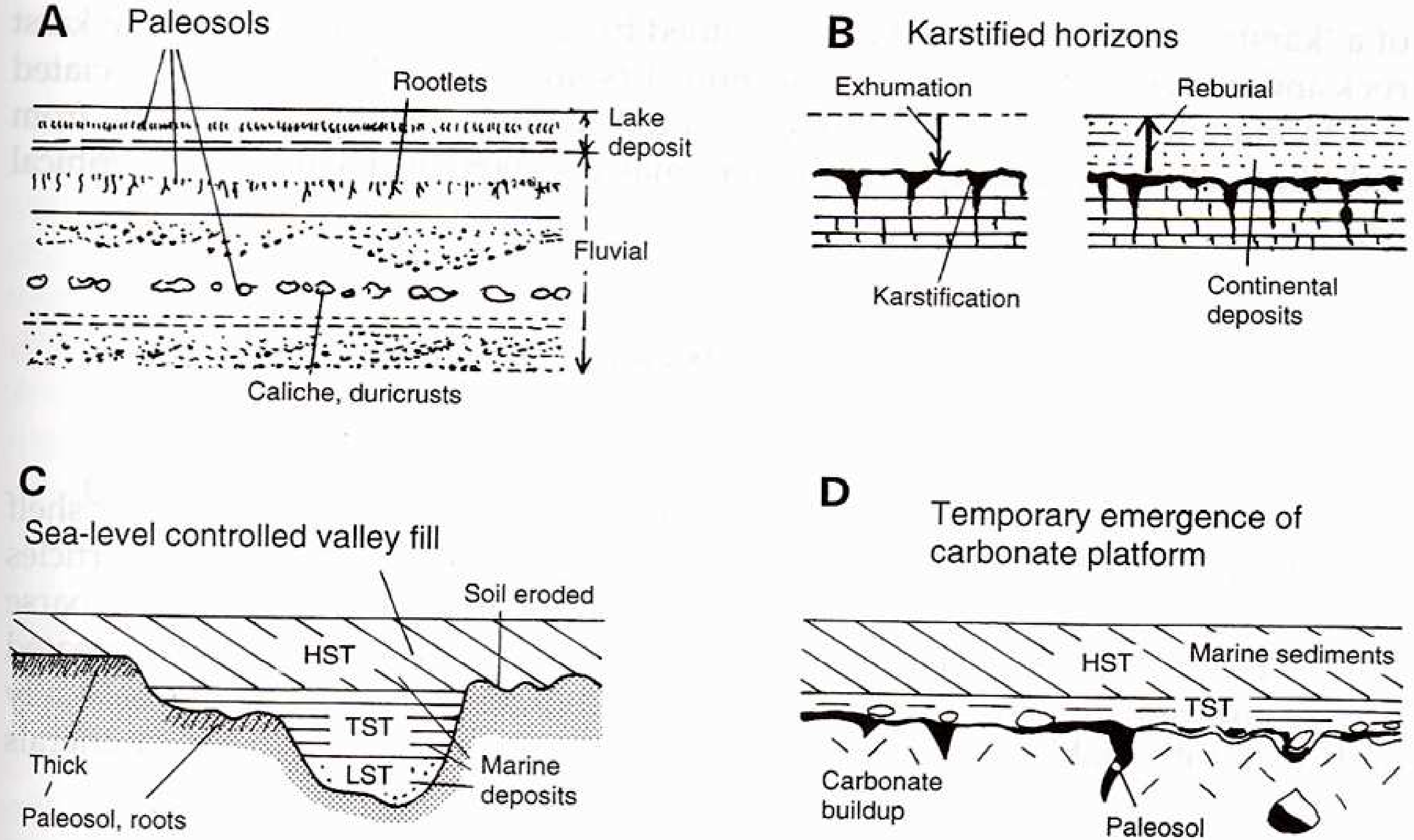


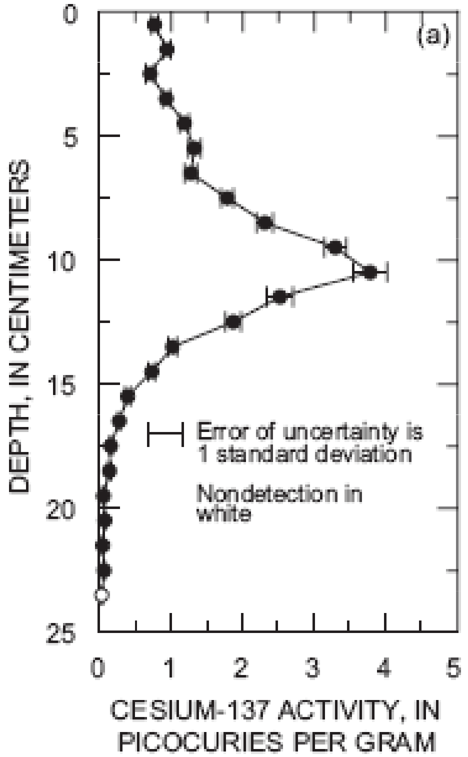
Figure 6.13 **A.** Various paleosols in fluvial deposits. **B.** Stratal discontinuity caused by previous period of karstification on land, later exhumed by erosion or reburied under younger continental sediments. **C.** Valley incision and soil formation during sea-level lowstand; the landform is later successively filled and overlain by late lowstand deposits (LST), transgressive (TST) and highstand deposits (HST). **D.** A carbonate platform, which emerged and karstified during sea-level lowstand, is overlain by the sediments of the transgressive and highstand systems tracts (TST and HST)

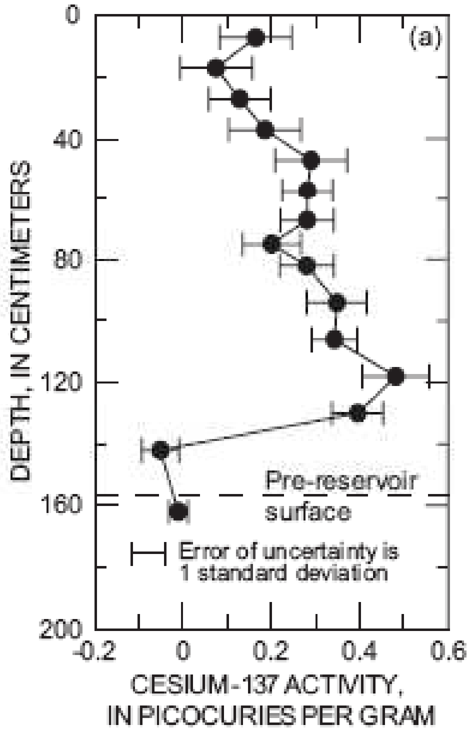
Antropogenní události: Datování ^{137}Cs

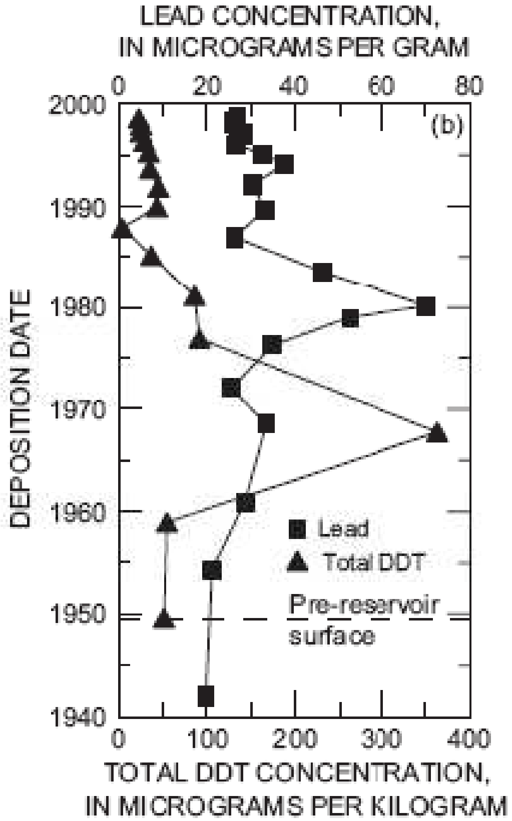
- ^{137}Cs: antropogenní izotop, vzniká jako produkt umělých radioaktivních rozpadů (jaderné elektrárny, jaderné výbuchy)

- Černobyl 1986
- Pacific nuclear weapon tests 1960-61

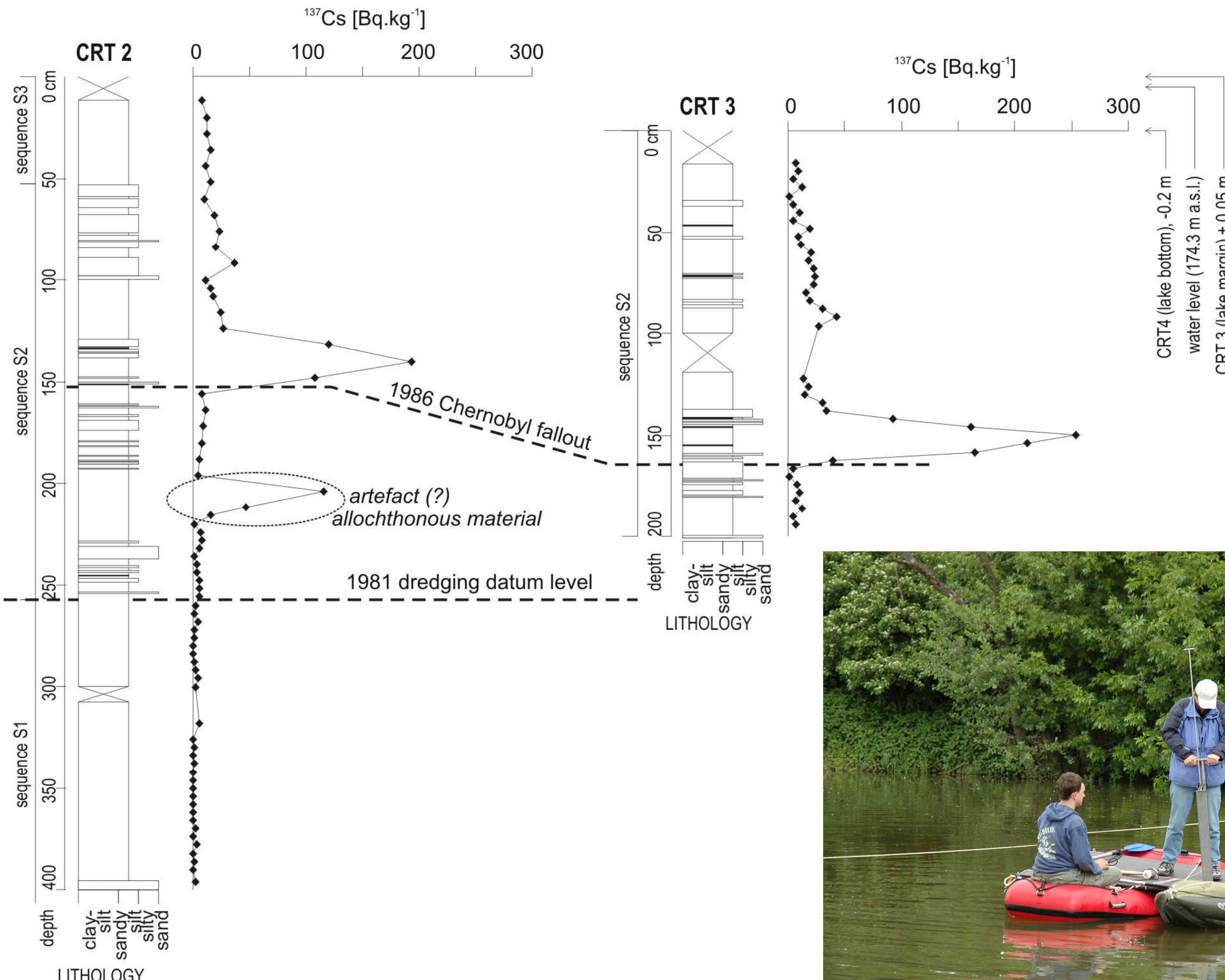
Datování ^{137}Cs







Mrtvé rameno Moravy Čerťák, Uh Hradiště

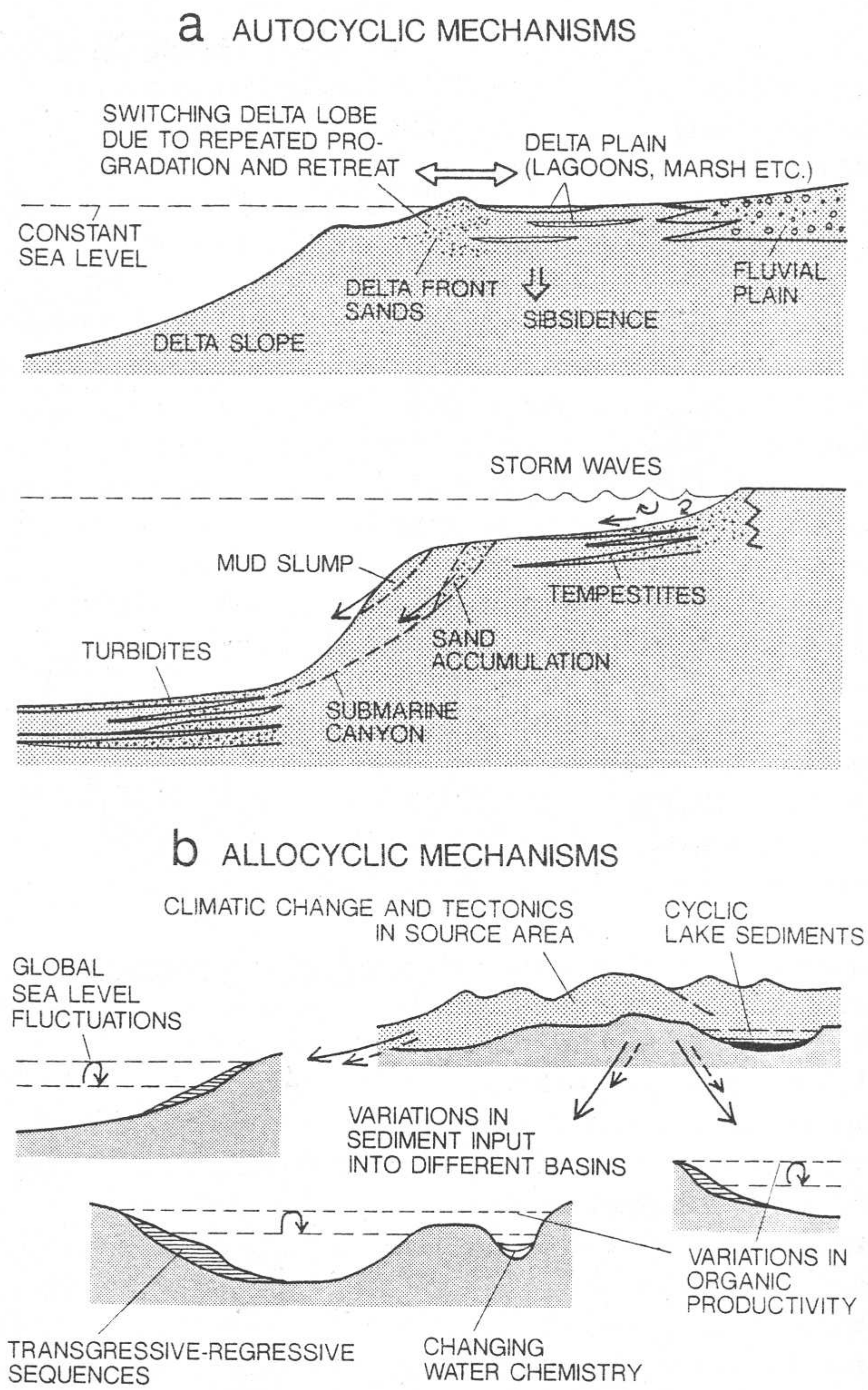


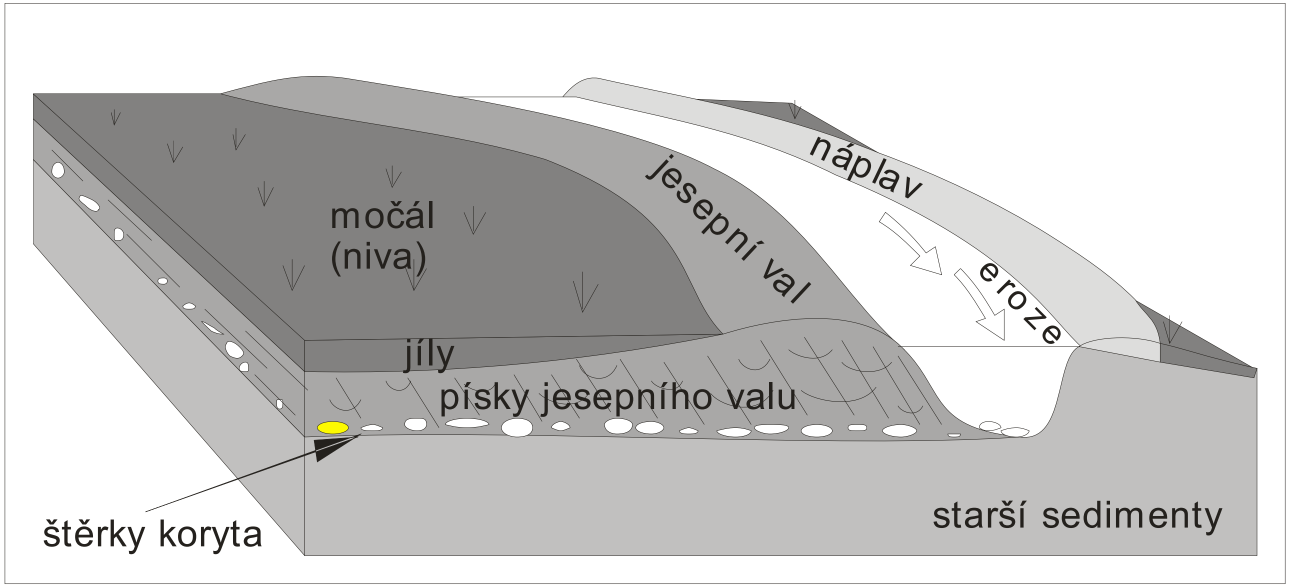
Cyklostratigrafie

- Korelace na základě sedimentačních cyklů o stálé periodě

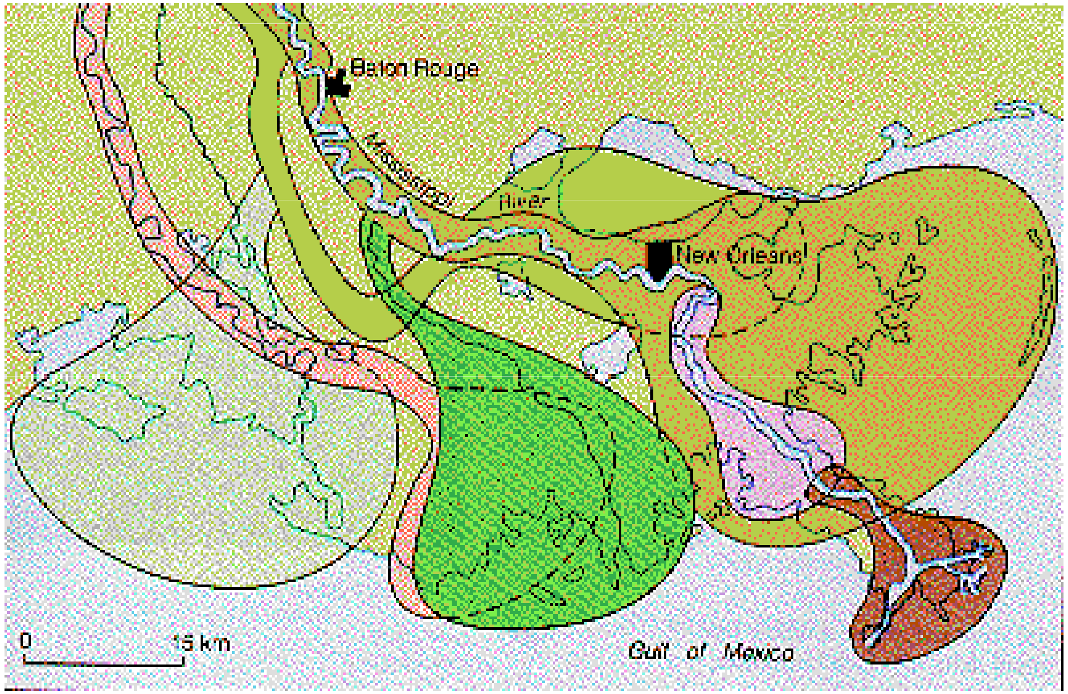
Cyklicita sedimentace

- Autocyklické mechanismy (zpravidla nestálá perioda)
  - Delta switching
  - Turbidite compensation cycles
  - Meandering river
  - …
- Alocyklické mechanismy (stálá nebo variabilní perioda)
  - Sea-level fluctuations
  - Transgression-regression
  - Sediment supply changes
  - Climate changes
  - Organic productivity changes
  - Ocean and atmosphere chemistry changes



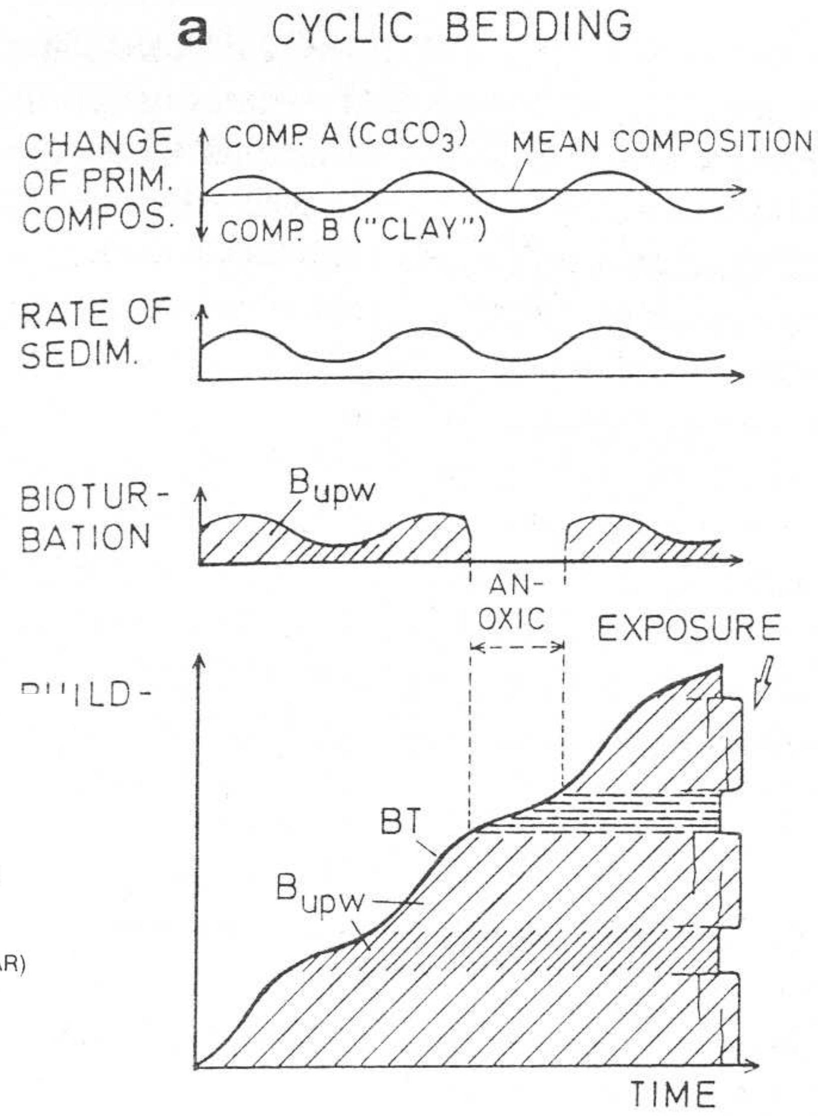


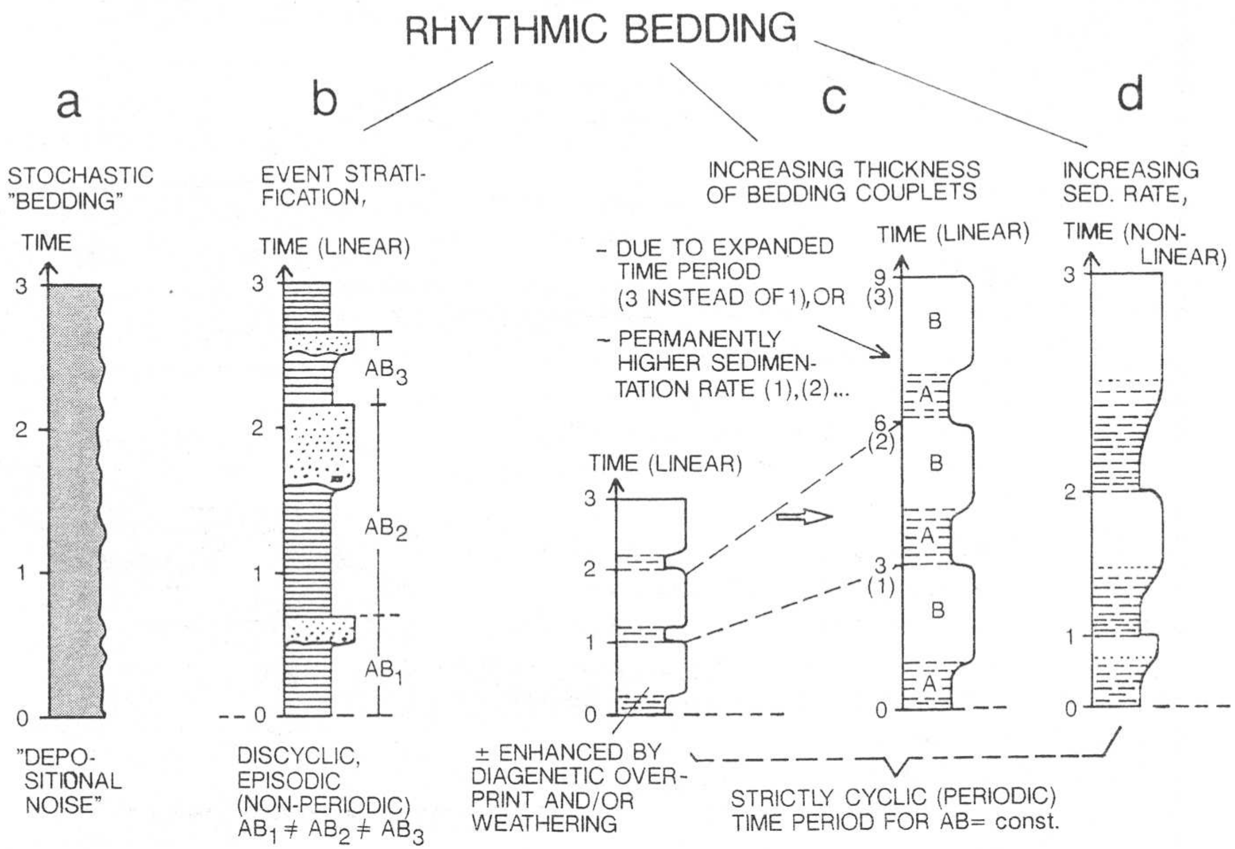
náplav
jesepní val
močál
(niva)
eroze
jíly
písky jesepního valu
štěrky koryta
starší sedimenty



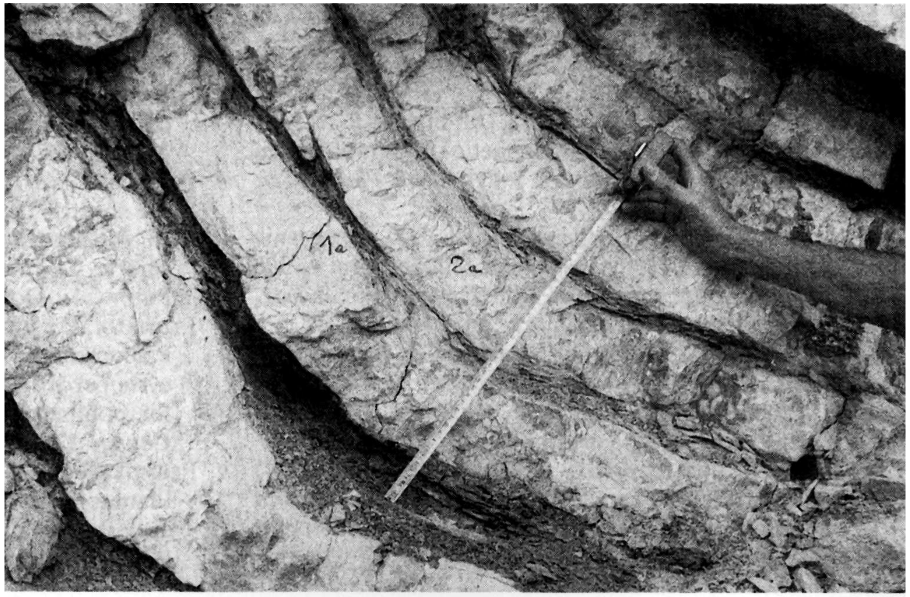
Baton Rouge
Mississippi
River
New Orleans
0
15 km
Gulf of Mexico

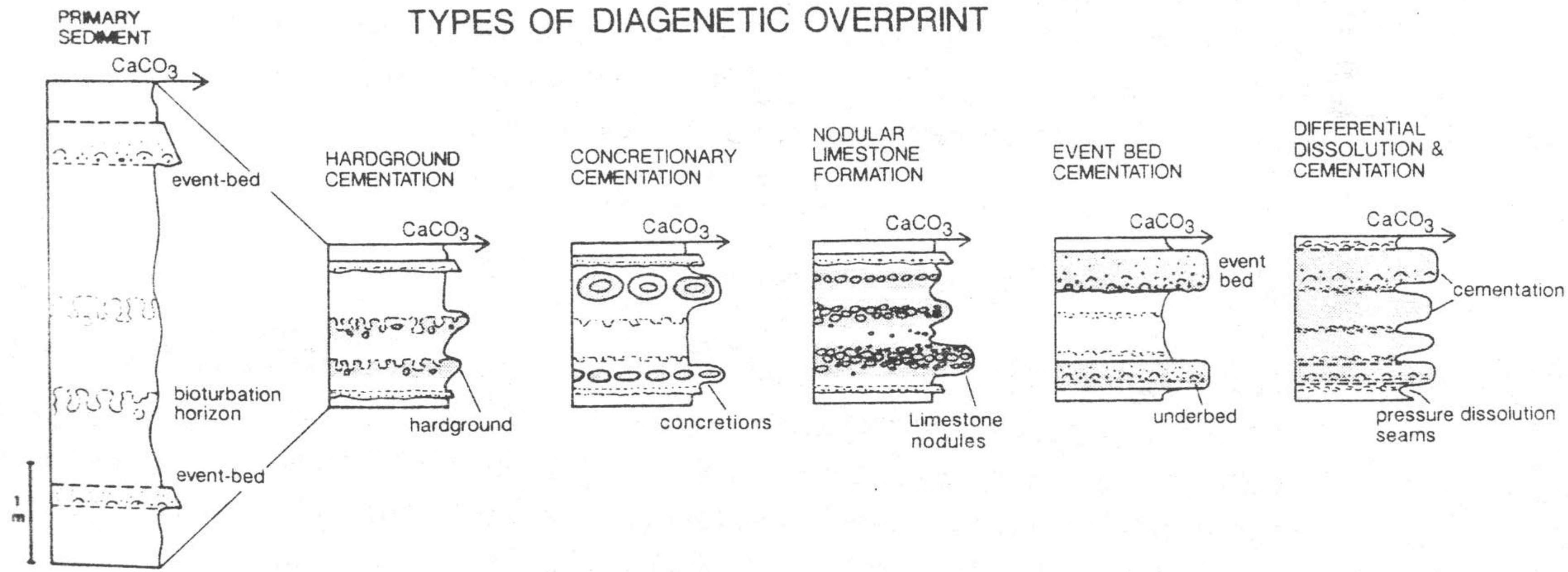
Vrstvy a cykly



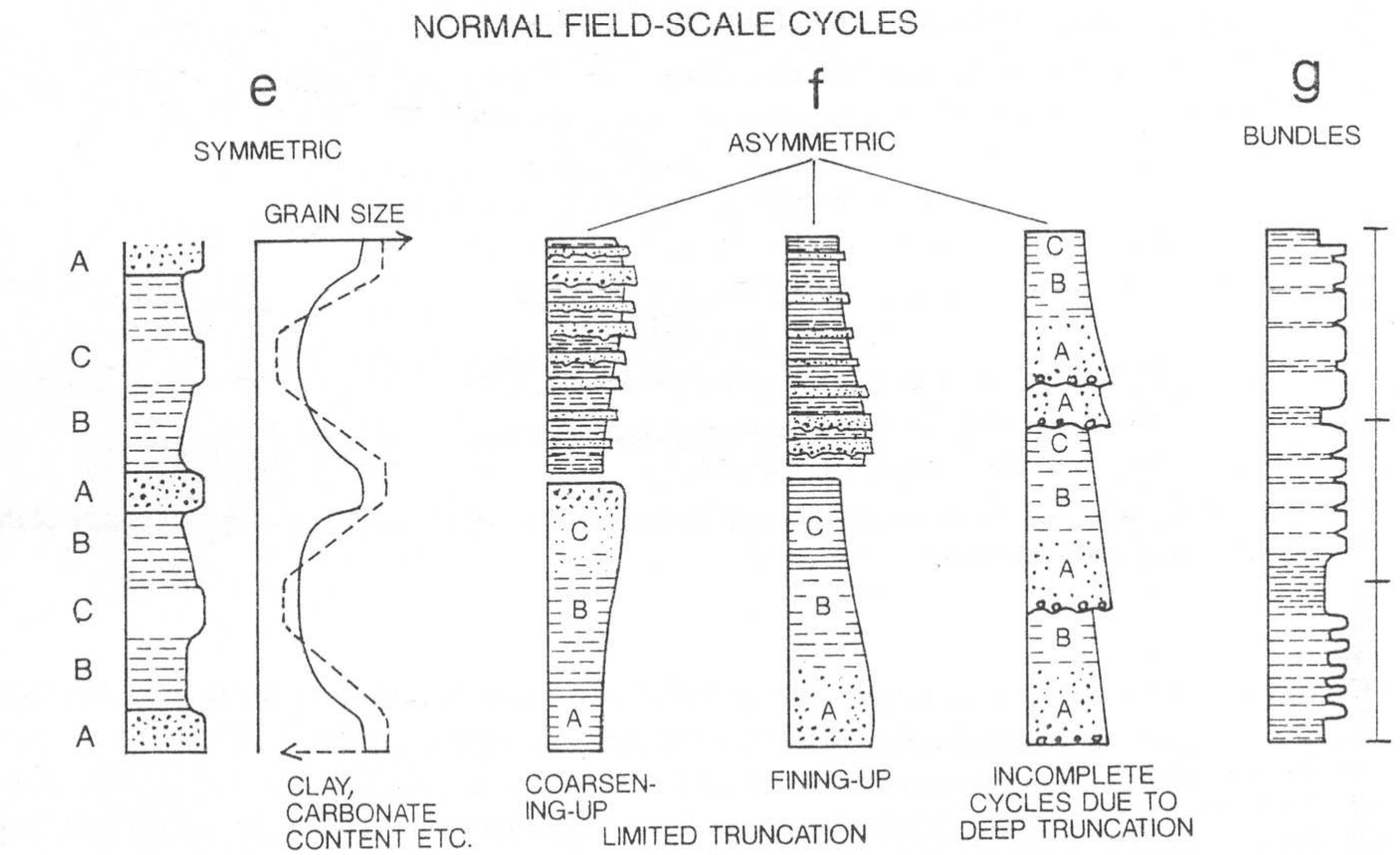


Diagenetický přetisk cyklicity



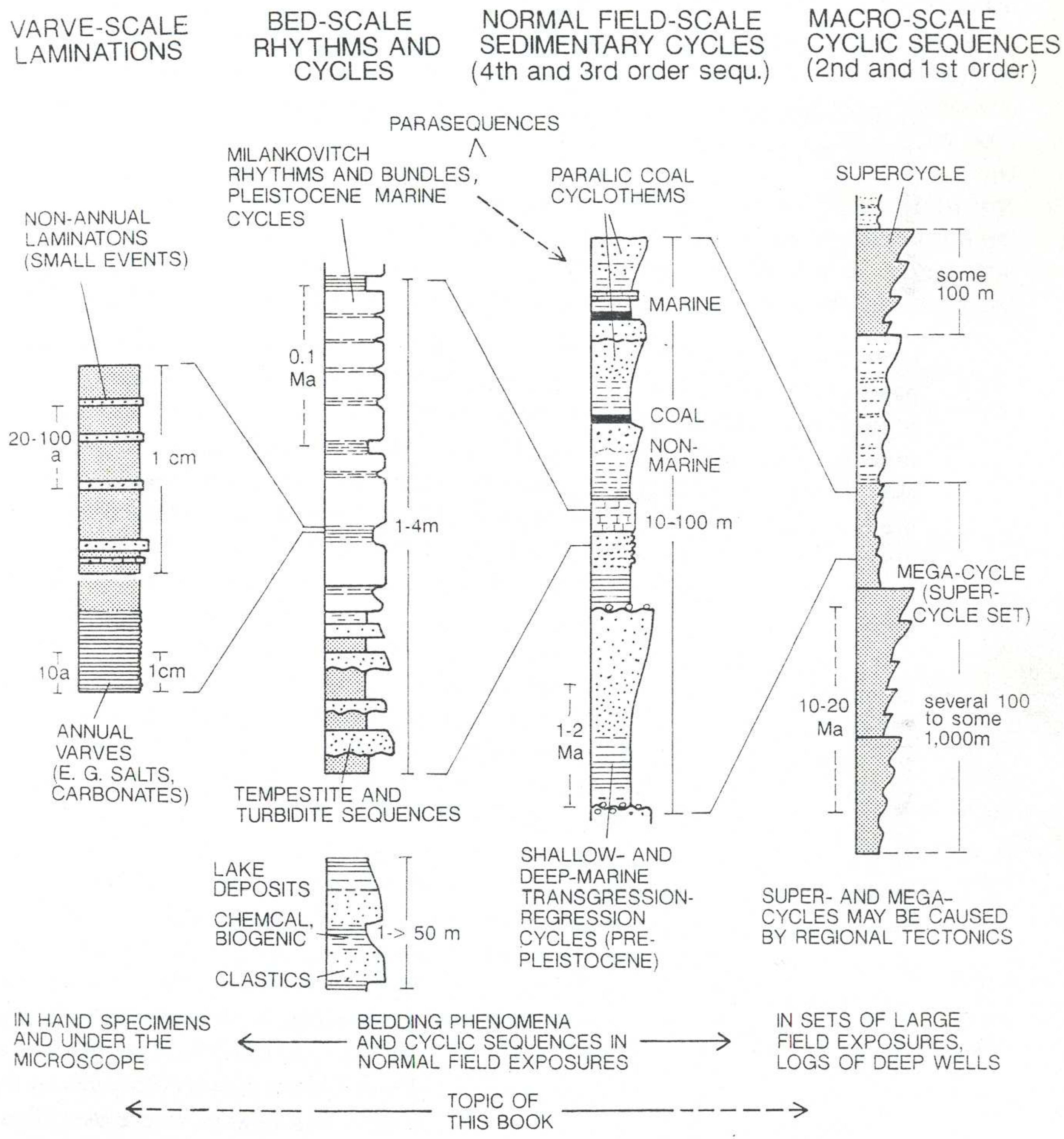


Symetrické / asymetrické cykly

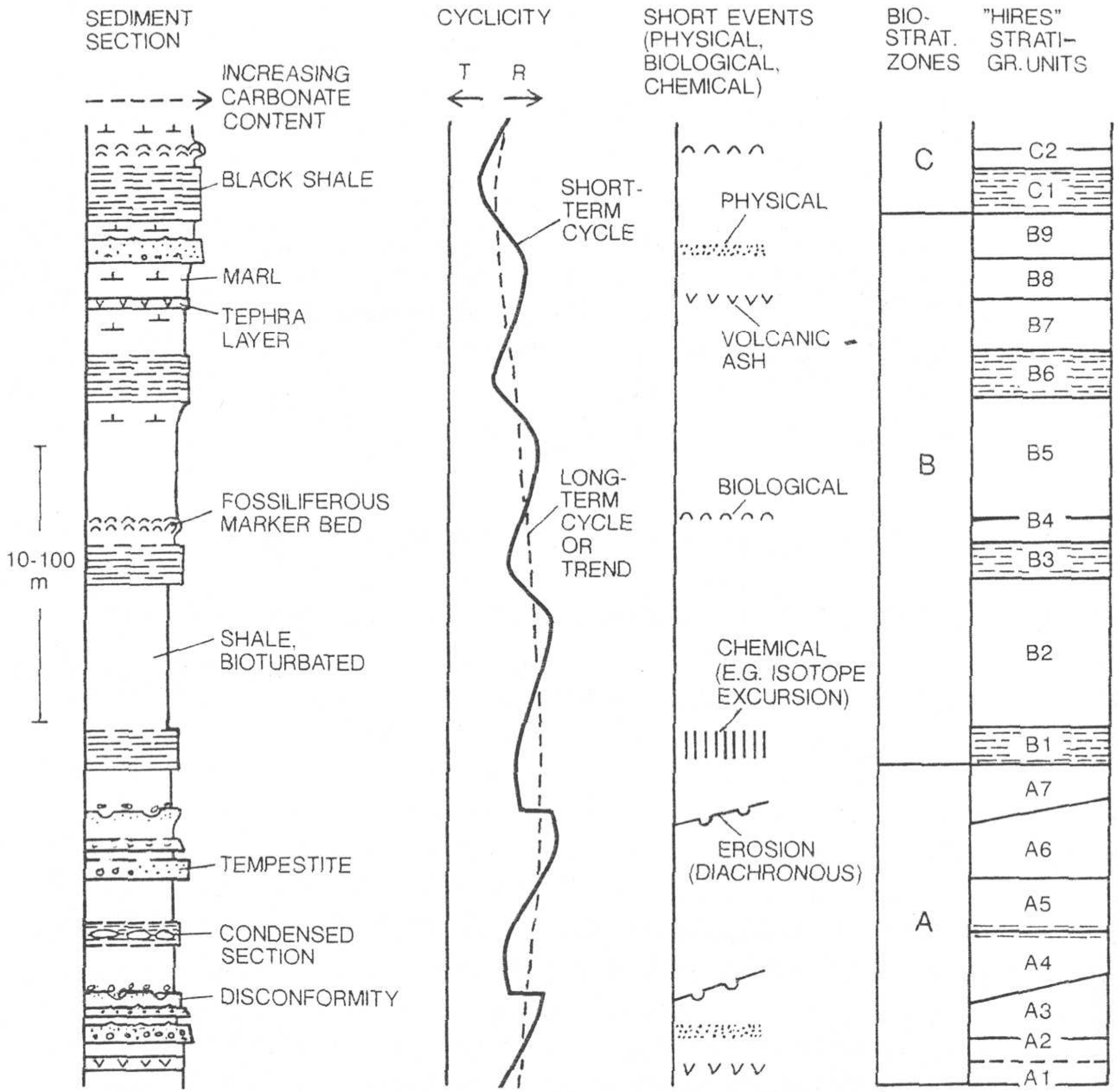


Různé řády cyklické sedimentace

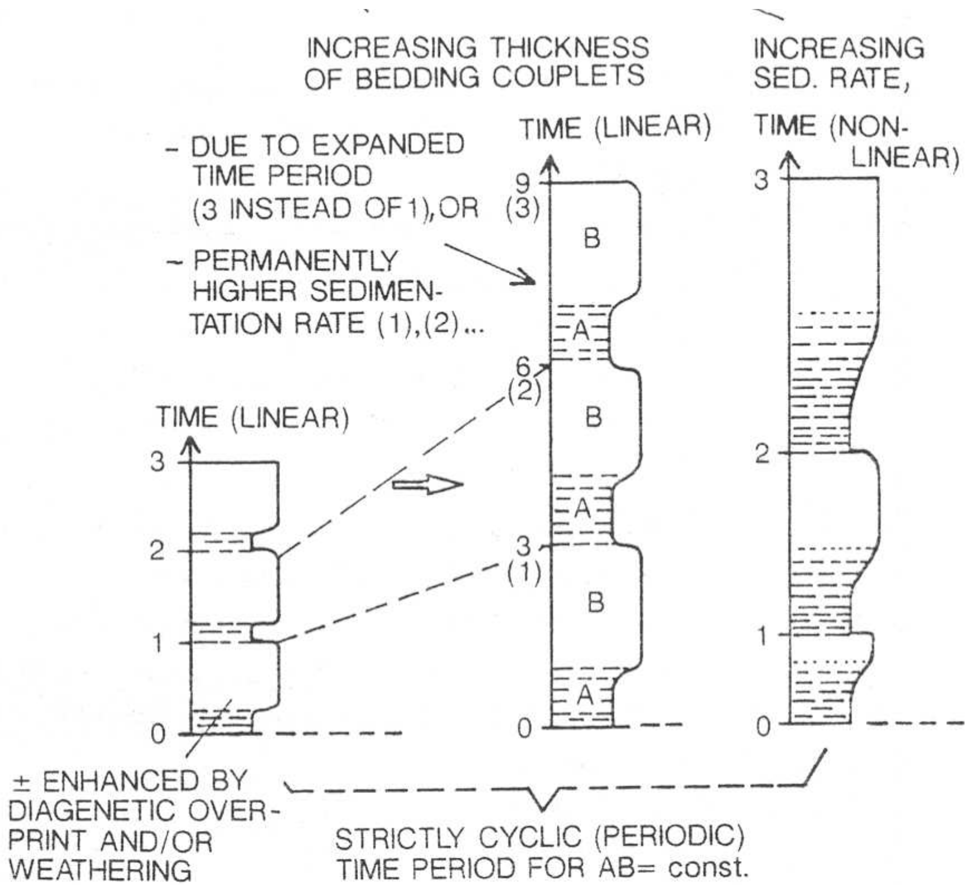
Měřítko mocnosti ~ měřítko času

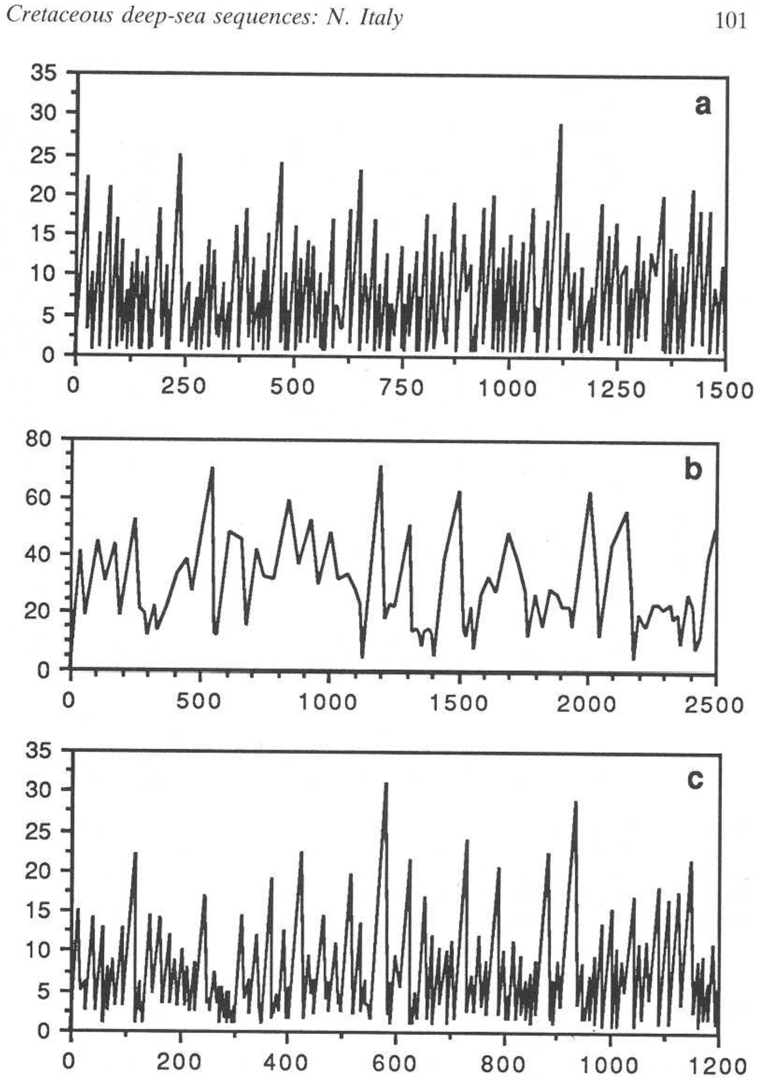


HIRES, High Resolution Stratigraphy



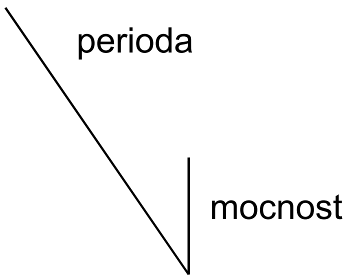
Cyklicita v mocnosti vrstev (rychlosti sedimentace)

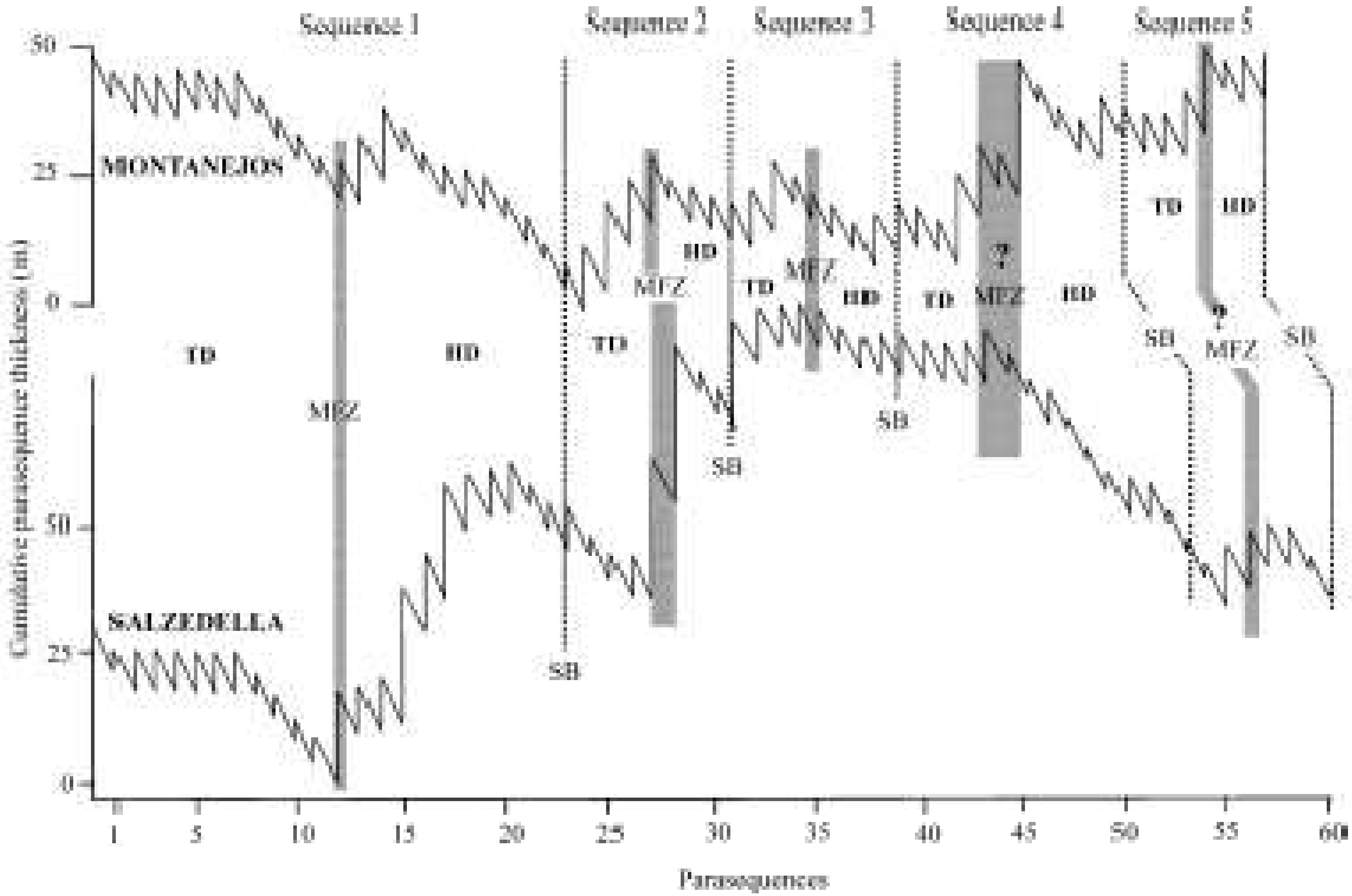




Fisher plot correlation

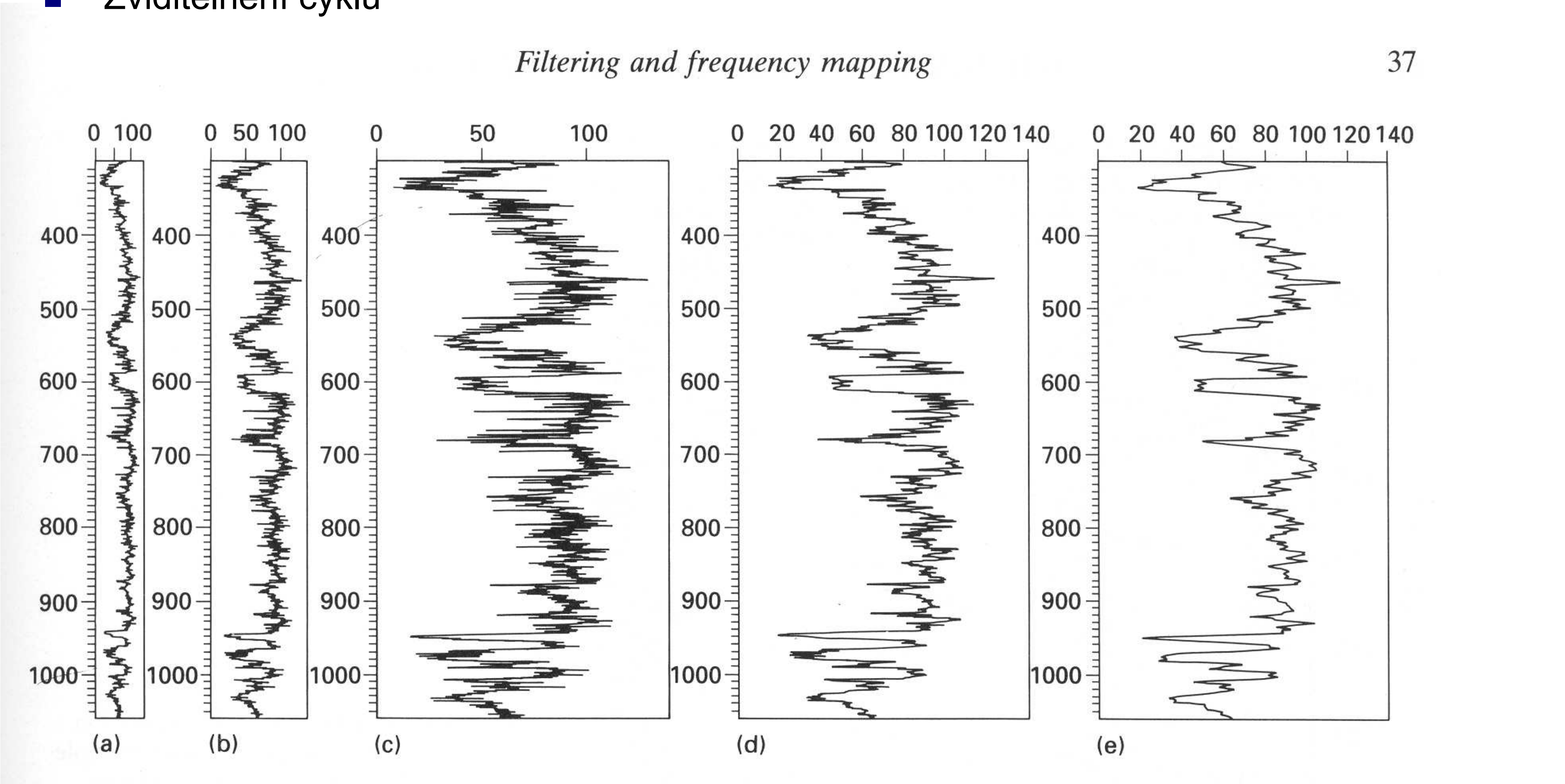
Fig. 13 Correlation of the Fischer plots of Montanejos and Salzedella (Lower 2nd-order Sequence) based in the equal durati on of parasequences. *Dashed lines* and *grey intervals* indicate the correlation of sequence boundaries and maximum flooding zones (or surfaces) of the 3rd-order sequences defined in Montanejos



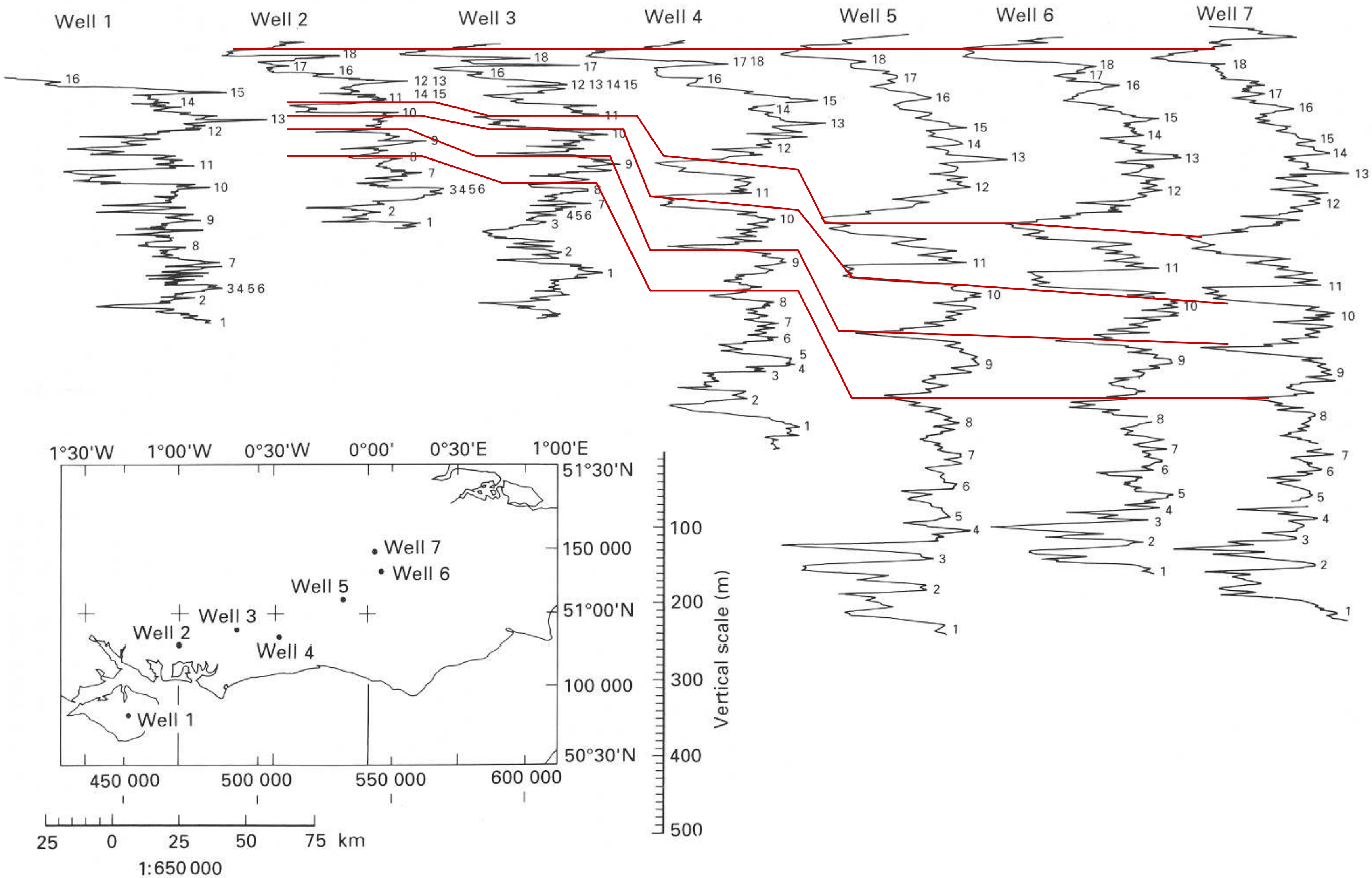


Cycles in gamma-ray logs

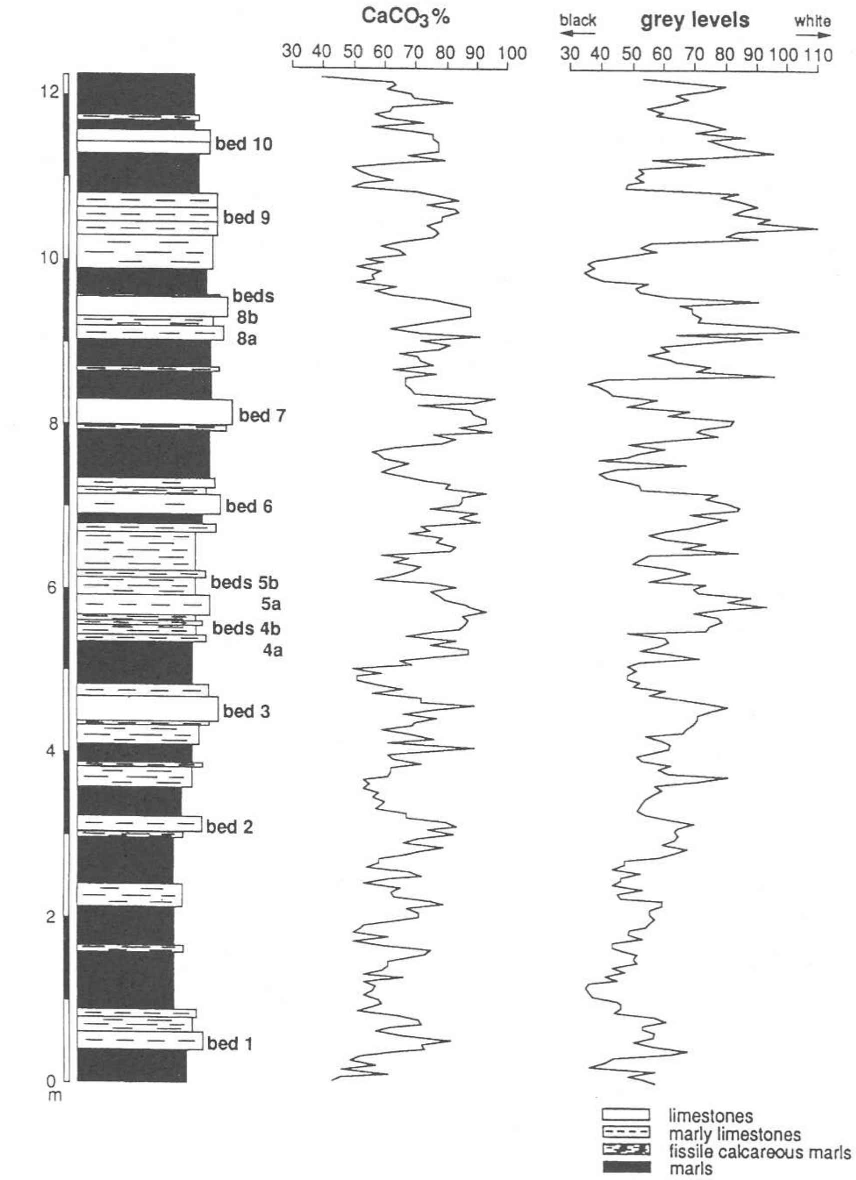
- Filtrace záznamu: roztažení amplitudy
- „moving average“, 3-point, 5-point, or more
- Zviditelnění cyklů



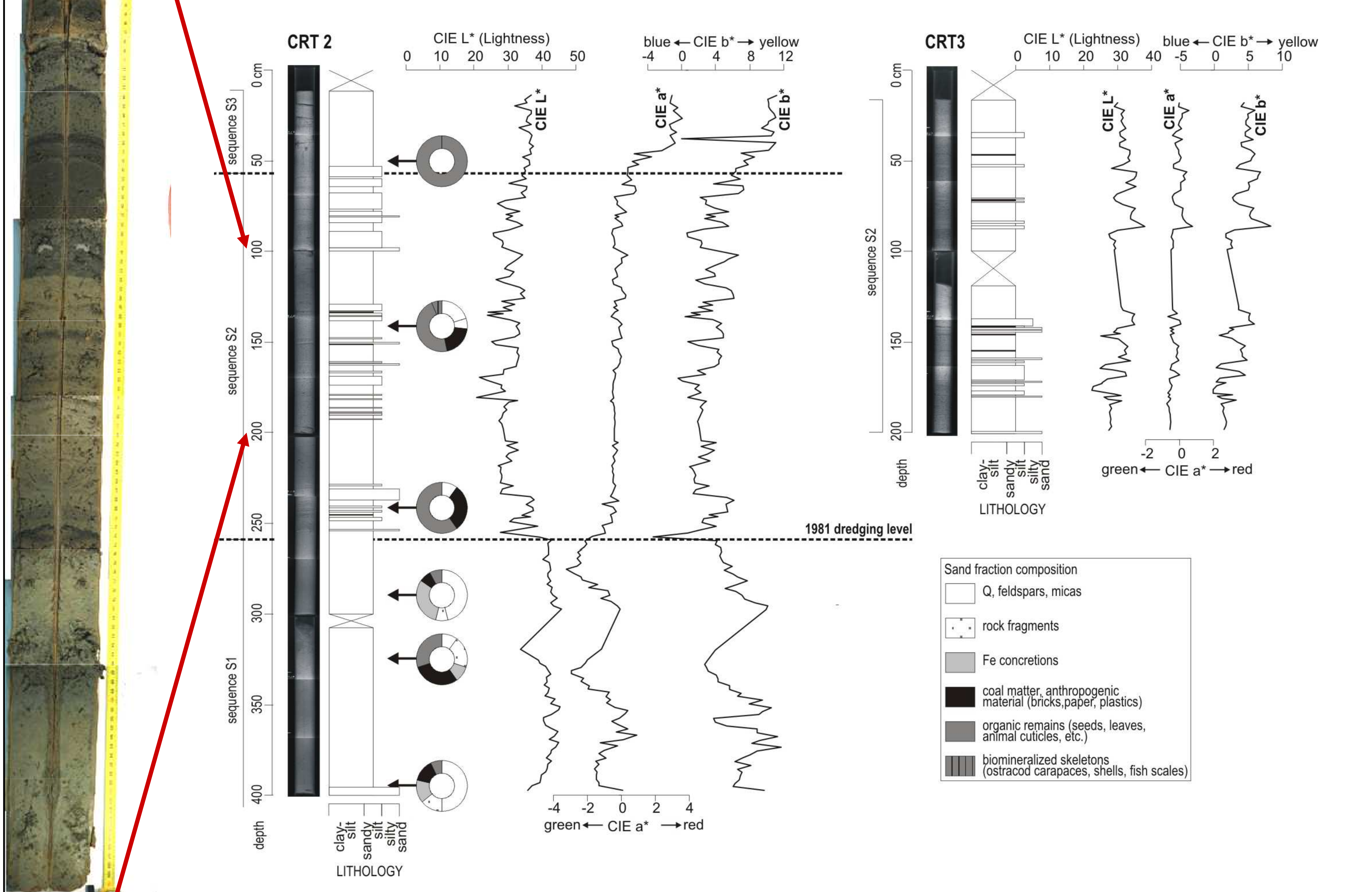
Gamma-ray cycle correlation



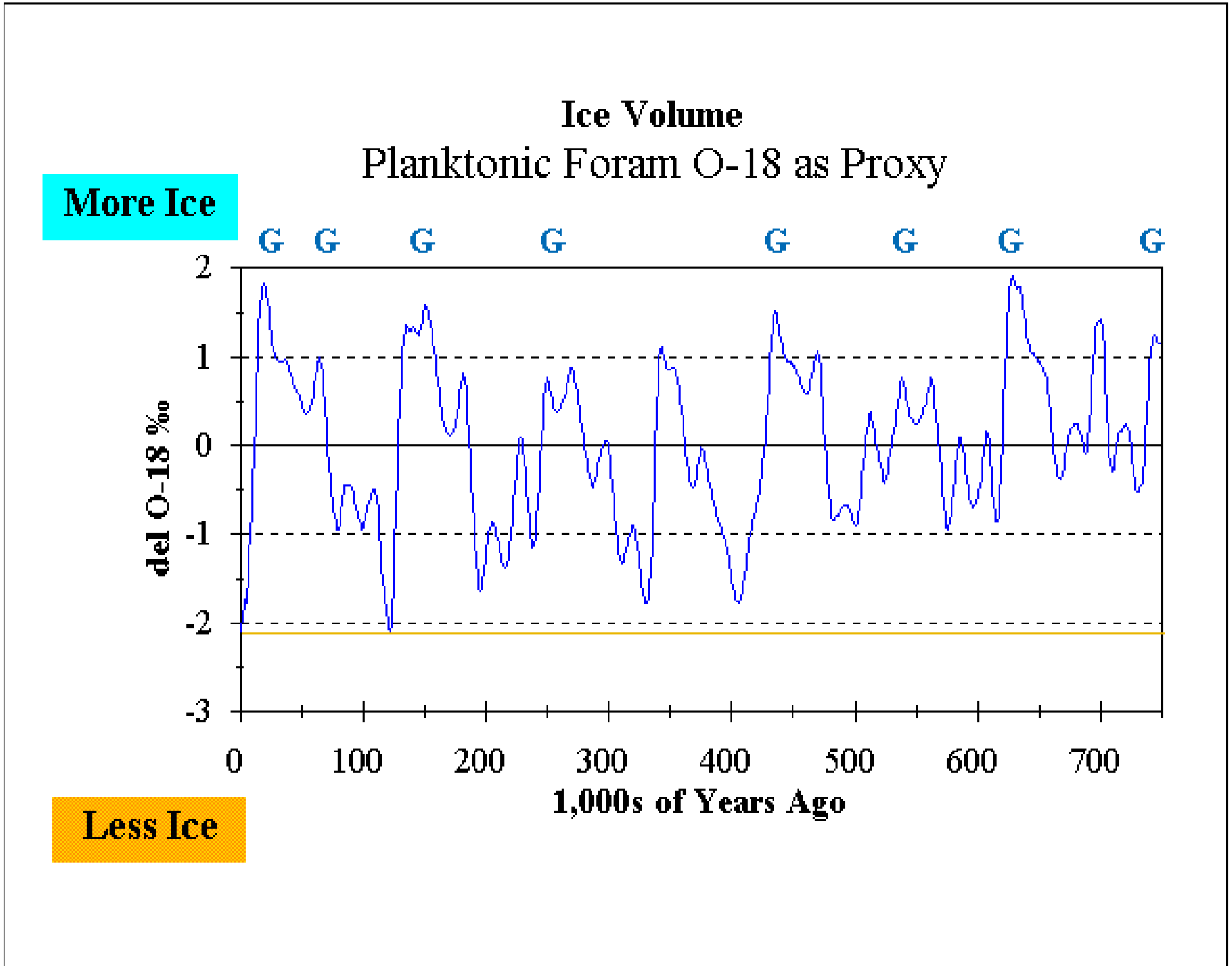
Geochemická cyklicita



Cyklicita v obsahu TOC



Záznam izotopů kyslíku v mořských sedimentech za posledních 700 tisíc let



Vrtné projekty DSDP a ODP

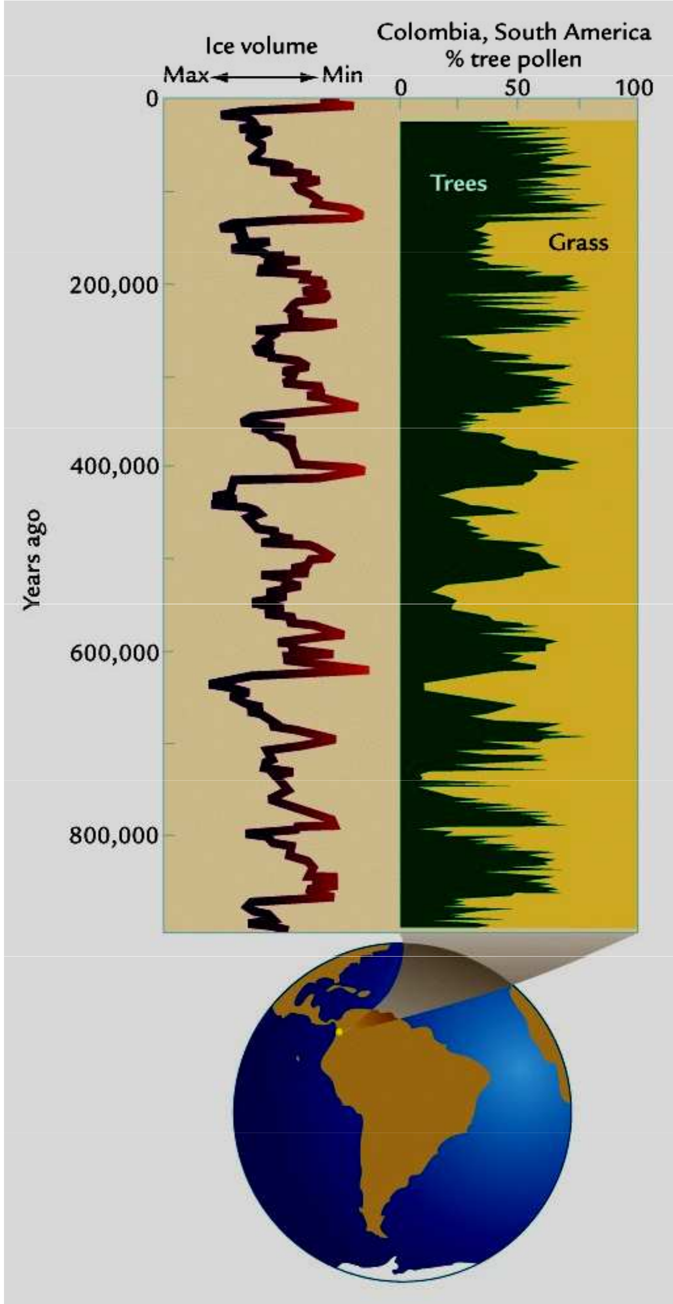
Pelagické sedimenty, cca konstantní rychlost sedimentace, datování

^{18}O v schránkách plaktonních foraminifer ($CaCO_3$)

Časové řady

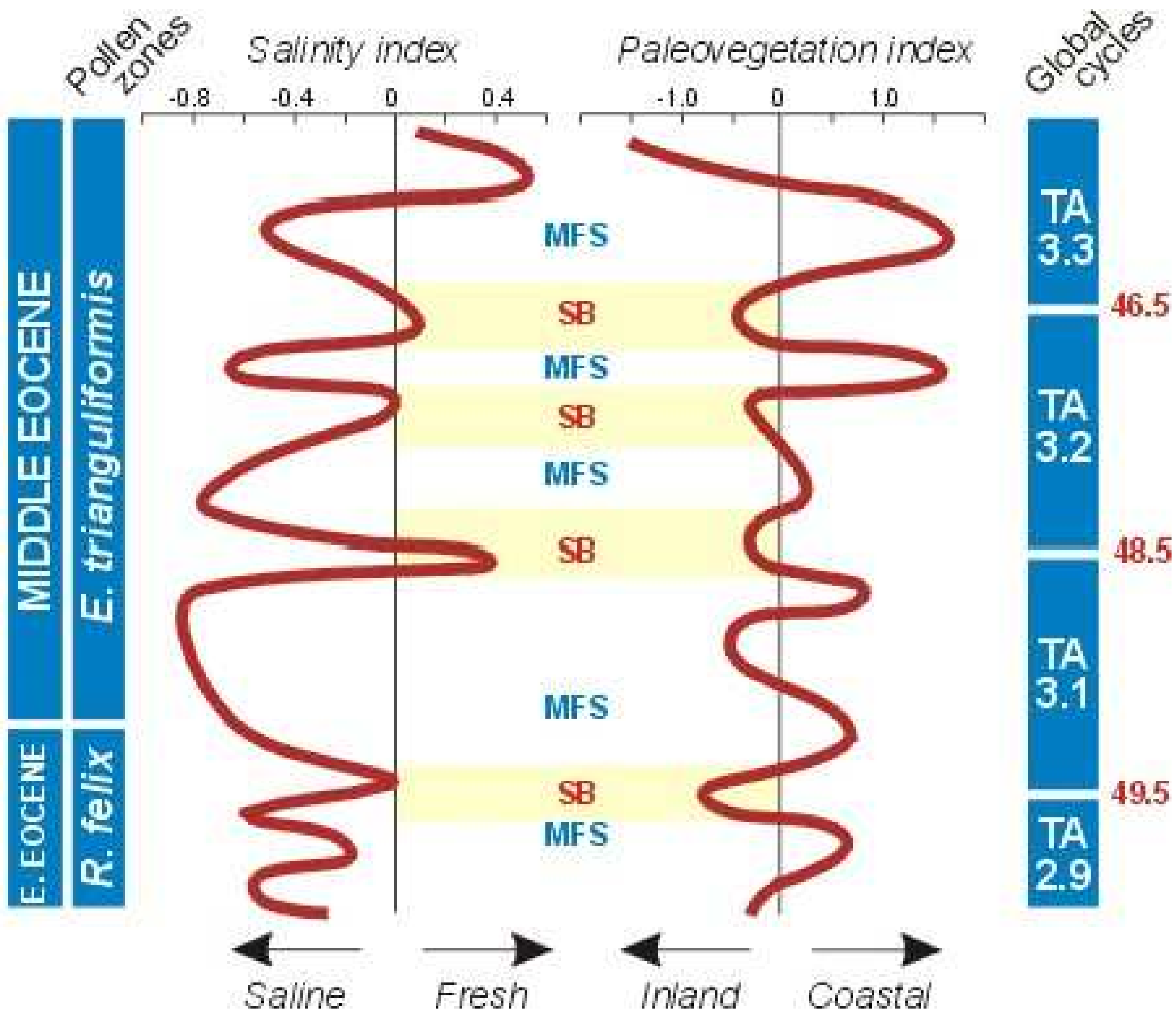
Pylové analýzy

- Long cores from eastern Columbian lakes
  - Pollen records that alternate between grass and trees
  - 100,000 year cycles
    - **Trees** grew **during rapid warming**
    - **Grassland** dominated **during slow cooling** intervals



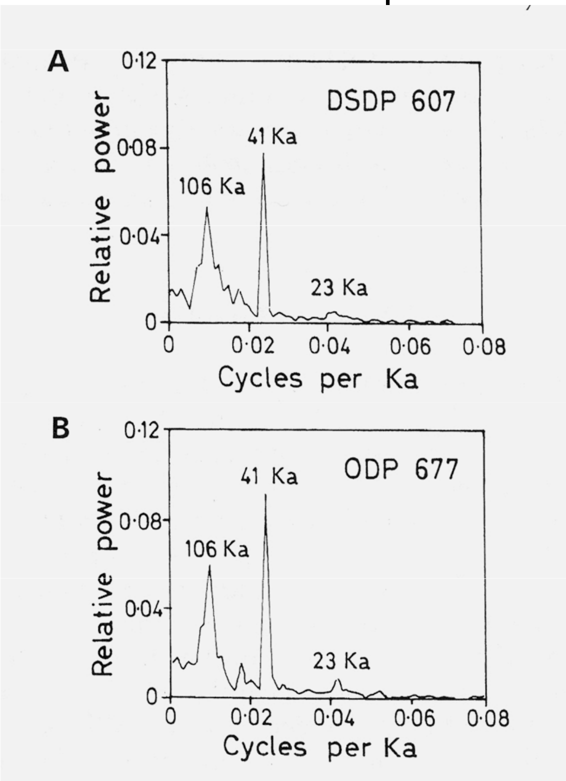
Ecostratigraphy

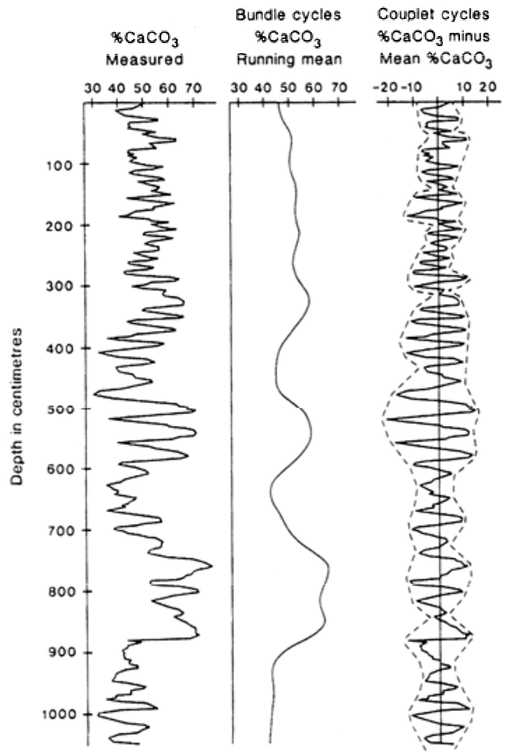
is the stratigraphy of ecosystems, a powerful tool for high-resolution cyclic and sequential stratigraphy, based on biostratigraphy. It is founded on the application of ecological knowledge to the reconstruction of past ecosystems and their succession, in relation to global external forcing agents such as sea level oscillations, climate changes, etc. The ecostratigraphic techniques used in this study (mainly palynocycles and ecologs) have provided regional chronostratigraphic correlation frames from 2nd order cycles (3 to 50 million years duration) to periodic cycles within the Milankovitch band (around 100,000-year period), for Paleocene, Eocene, Oligocene, and Miocene stratigraphic sequences.

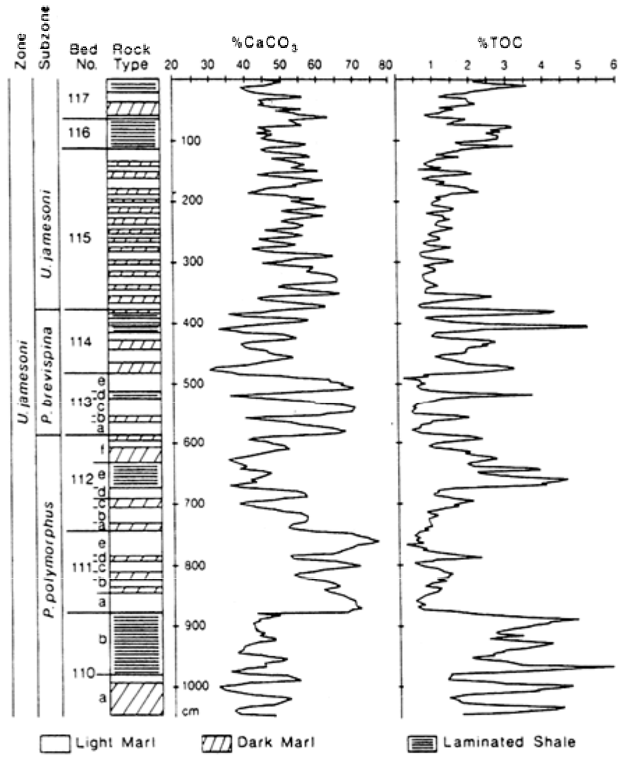


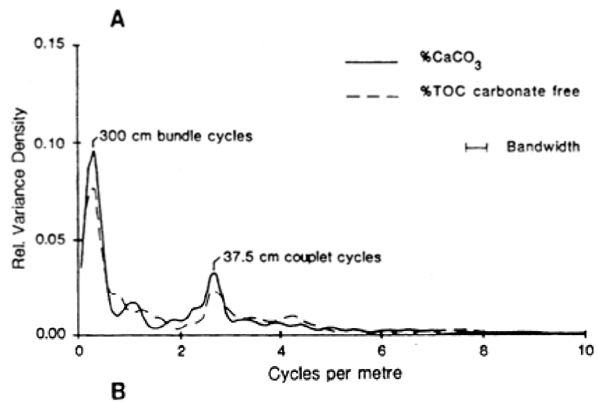
Mapování frekvence cyklů

- Normalizace na aritm. průměr nebo pohyblivý aritm. průměr
- Frekvence
- Frekvenční spektrum







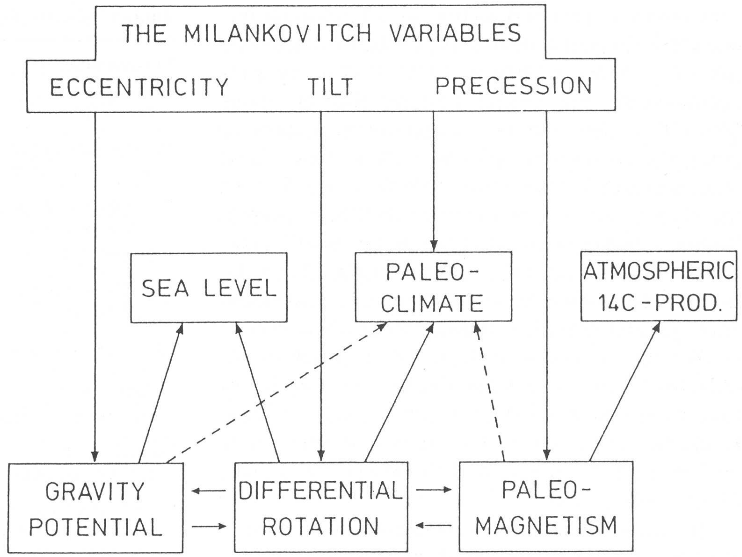


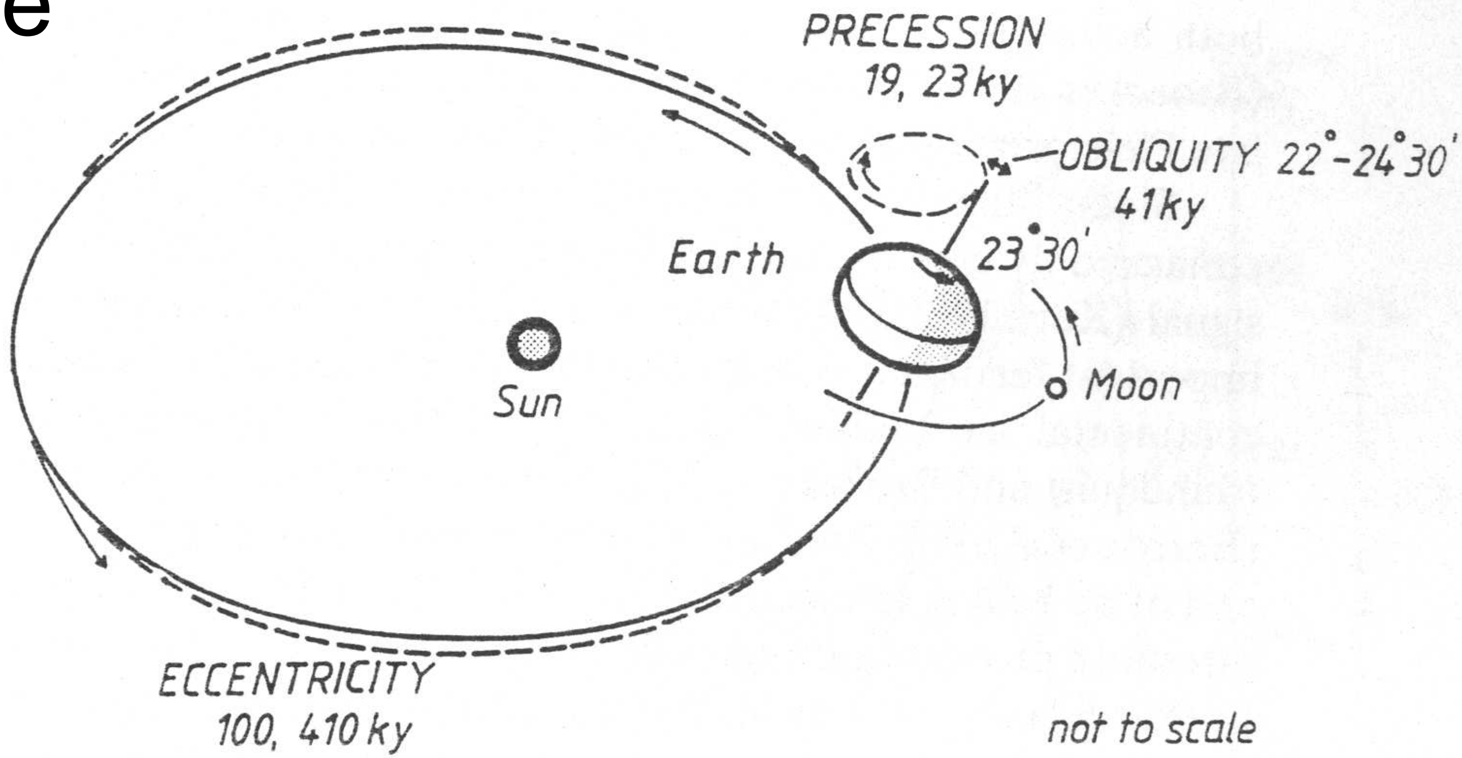
Globální cykly a jejich řády

FREQUENCY	YEARS	ORBITAL CYCLES
Galactic Band	1.0Ga	galactic year
	100Ma	(extinction)
	10Ma	
	1.0Ma	
Milankovitch Band	100Ka	3, 2, 1 eccentricity; obliquity
	10Ka	precession; perihelion
Solar Band	1.0Ka	
	100a	Hale; lunar nodal; pole elliptic; solar year
	10a	
Calendar Band	1.0a	Chandler; annual; equinox
	0.1a	lunar month
	0.01a	spring tides
	0.001a	daily; tidal

Orbitální cykly

- Excentricita
- Náklon (šikmost)
- Precese

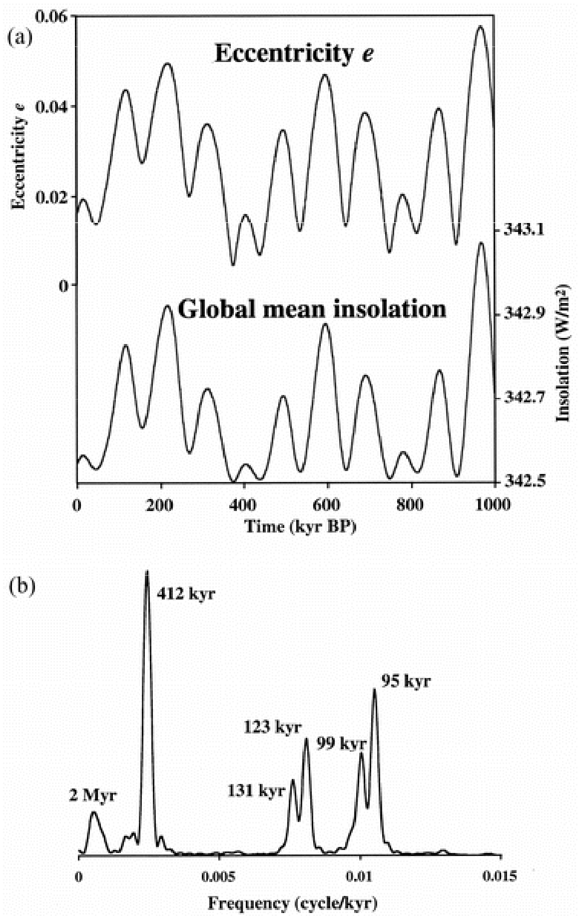




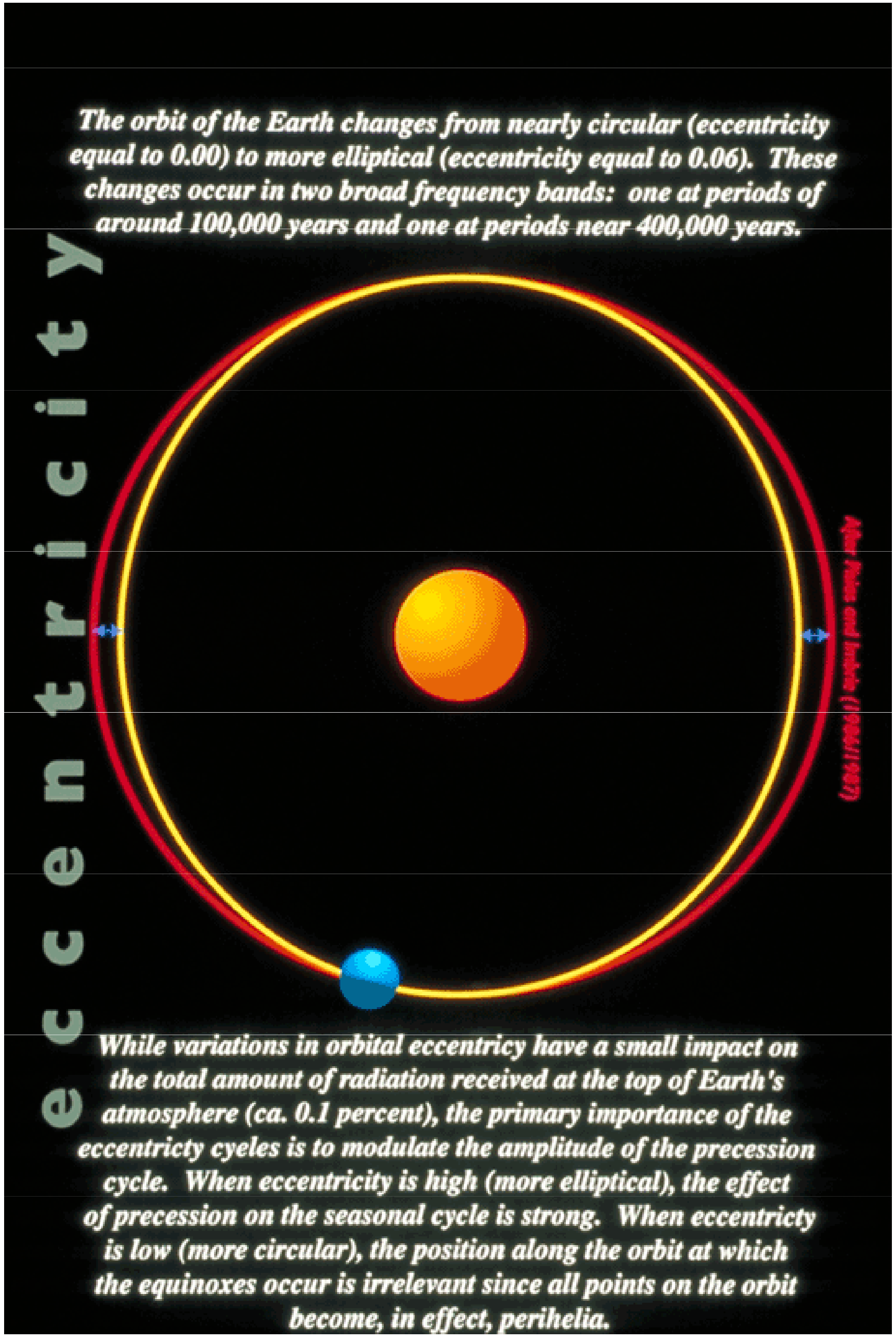
Excentricita

Excentricita =
(vzdálenost mezi ohniskem a středem elipsy) / (délka vedlejší osy)

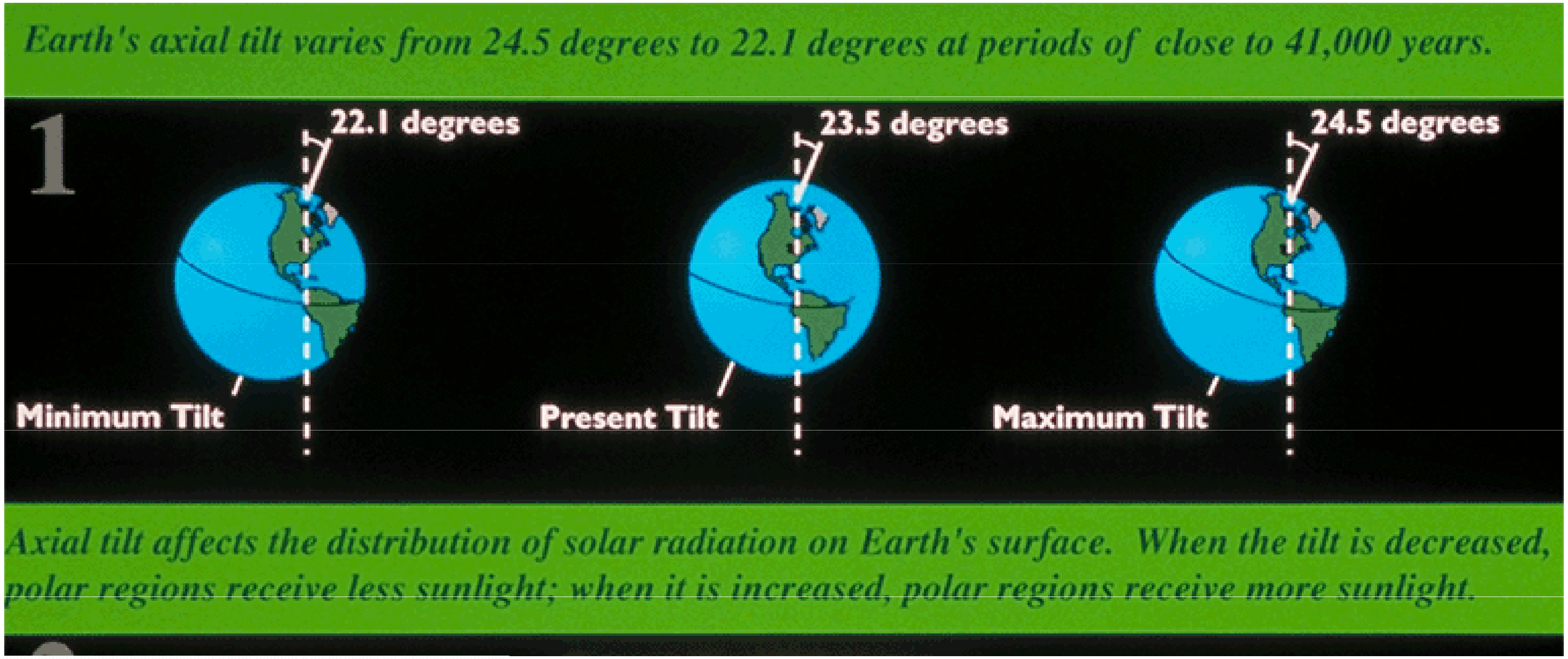
Excentricita dráhy Země kolem slunce kolísá od 0 do 0.05, s periodou 100 tis. Let, 400 tis. let a 2 mil let.



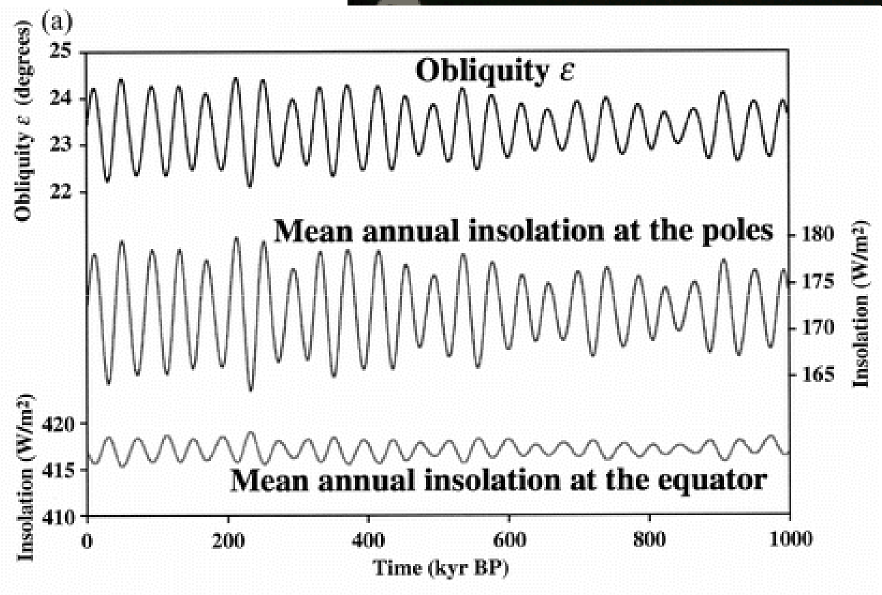
- Časová řada Excentricita Oslunění (W/m^2)
- Frekvenční spektrum

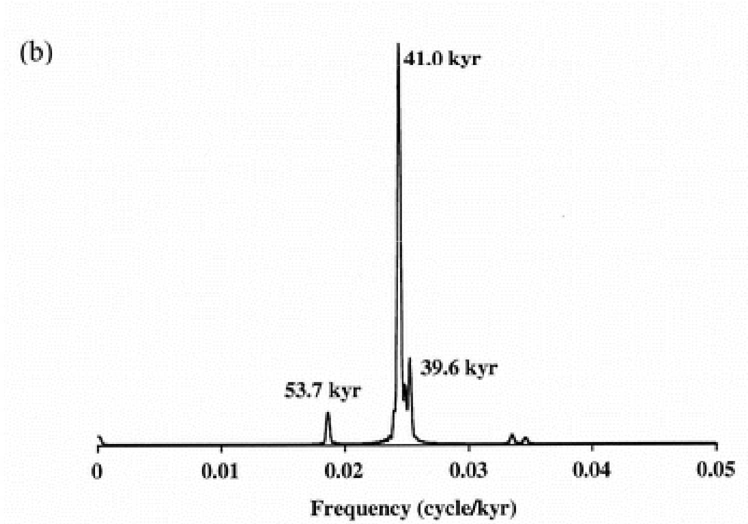


Náklon (šikmost) zemské osy

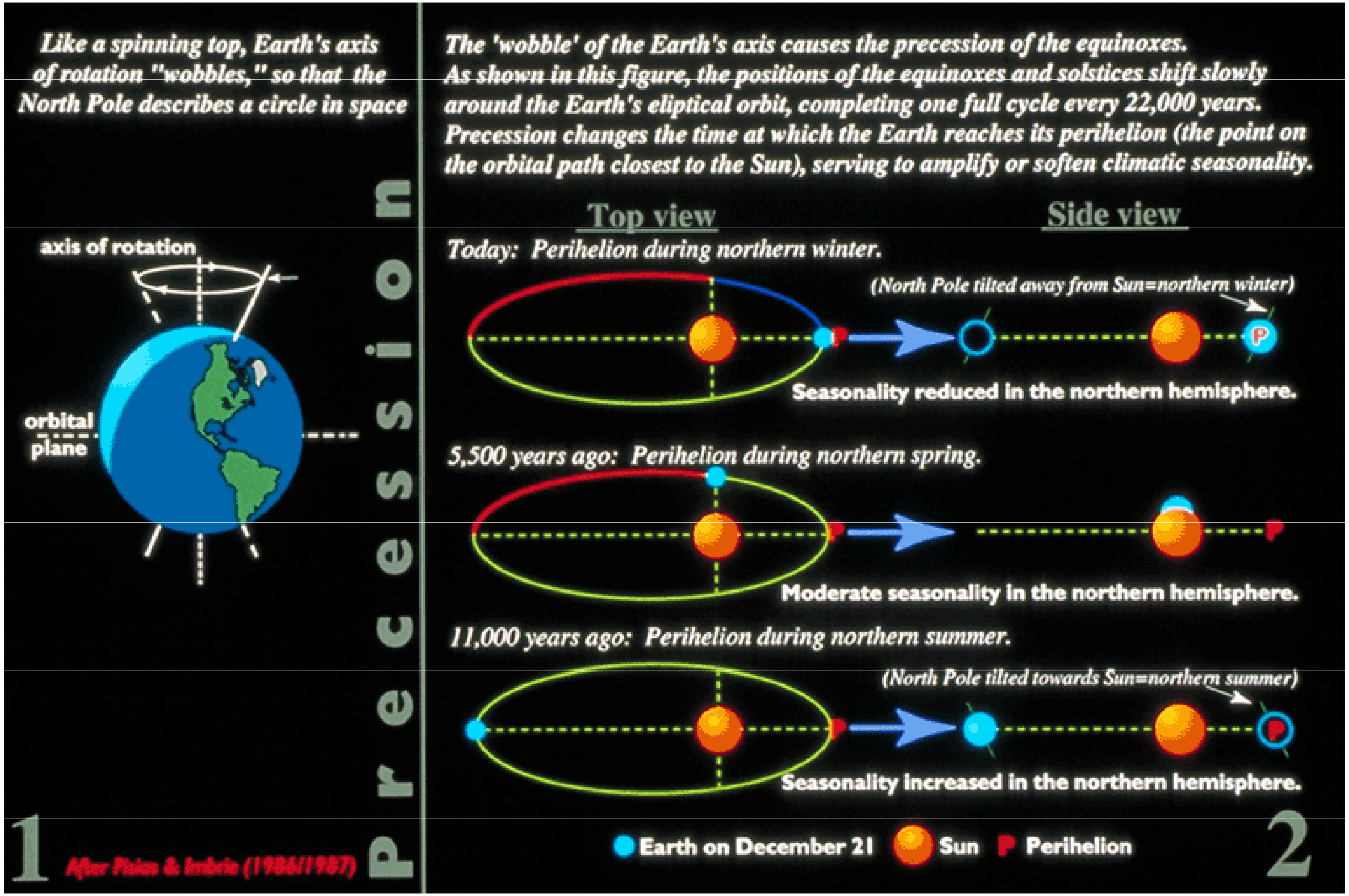


Náklon zemské osy kolísá od 22° do 24,5°, perioda 41 tis. let.





Precese



Modulace záznamu precese excentricitou:

Zima na S. polokouli v perihéliu, léto v aféliu: **zmírněné sezónní výkyvy** (DNEŠEK)

Zima na S. polokouli v aféliu, léto v perhéliu: **zesílené sezónní výkyvy** (KONEC POSLEDNÍHO GLACIÁLU)

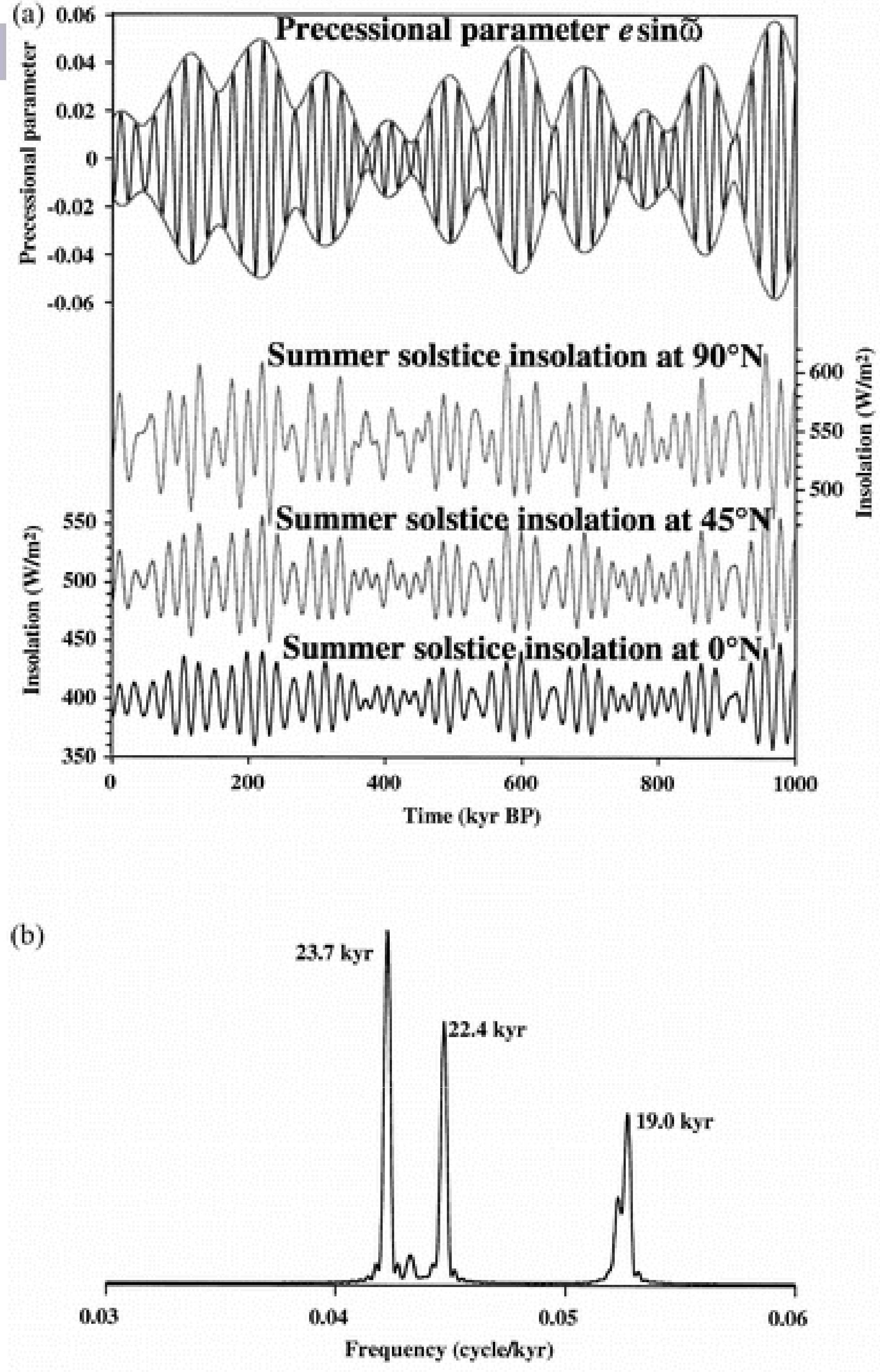
Kolísání zemské osy s periodou 19 tis. let a 23 tis. let.

Precese

- Časová řada
  - Precese
  - Oslunění (W/m²)

- Frekvenční spektrum

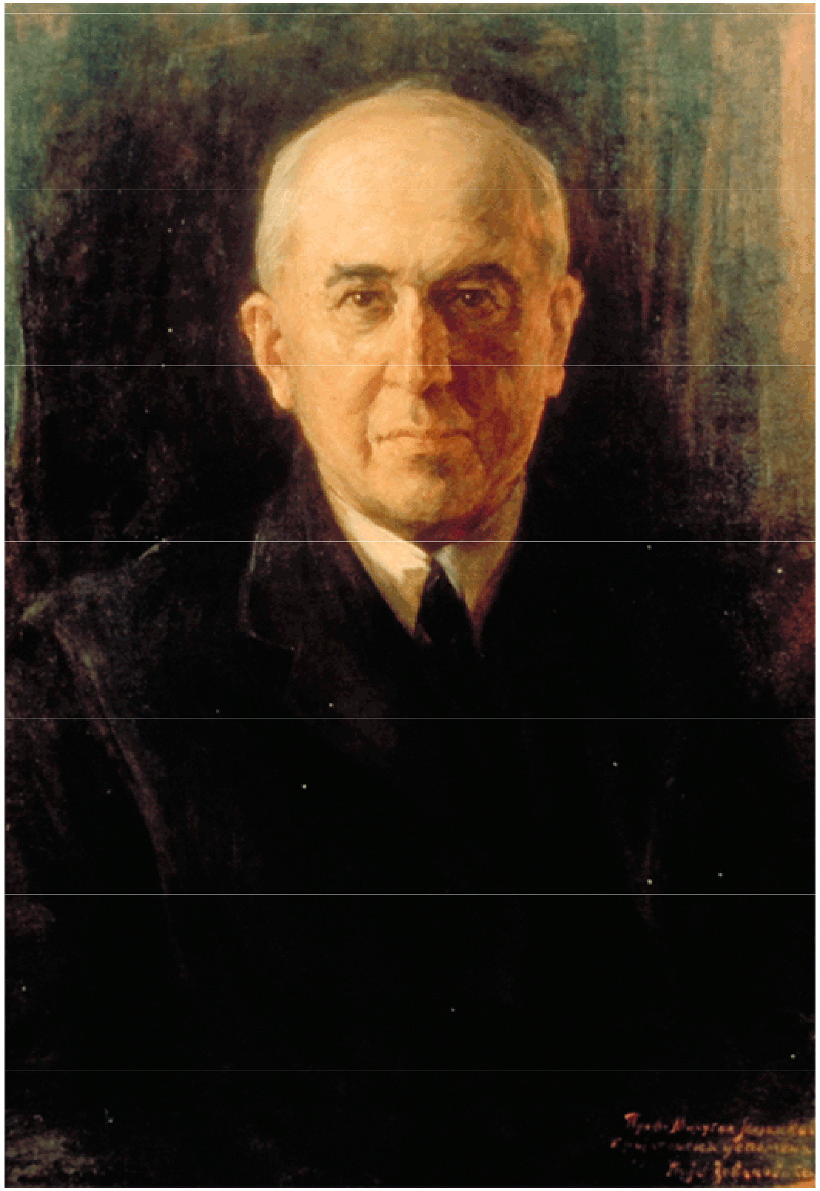
- Modulace excentricitou



M. Milankovič

- Renewed interest in orbital forcing of glacial cycles occurred when M. Milankovitch (1941) computed long-term variations in insolation.

- Milankovitch believed that cold summers led to glaciation by allowing snow to survive into the next year.



Oslunění na 65°N

- High latitude summer insolation (June, 65°N) has been regarded as an index of orbital forcing of glaciation. (This is the original Milankovitch hypothesis: Cool summers are beneficial to ice growth.)

- Note that the effects of precession are modulated by eccentricity.

- For low summer insolation: Aphelion in summer (esp. with high eccentricity), low obliquity.

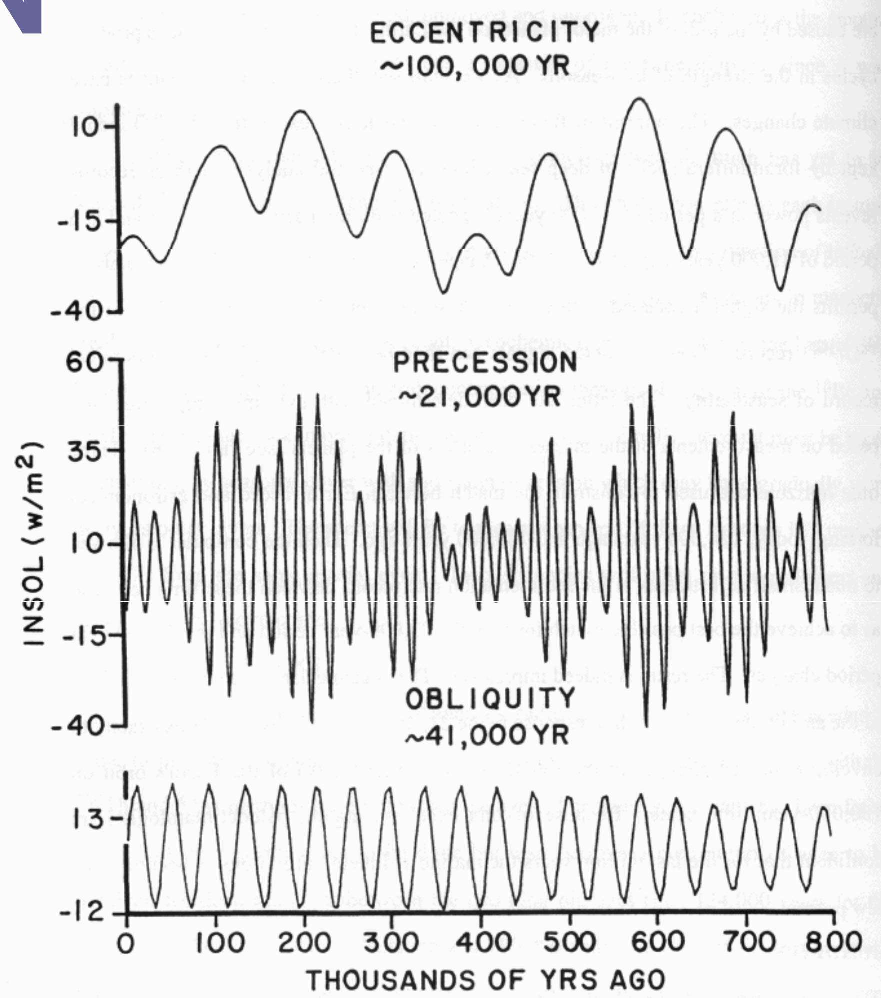
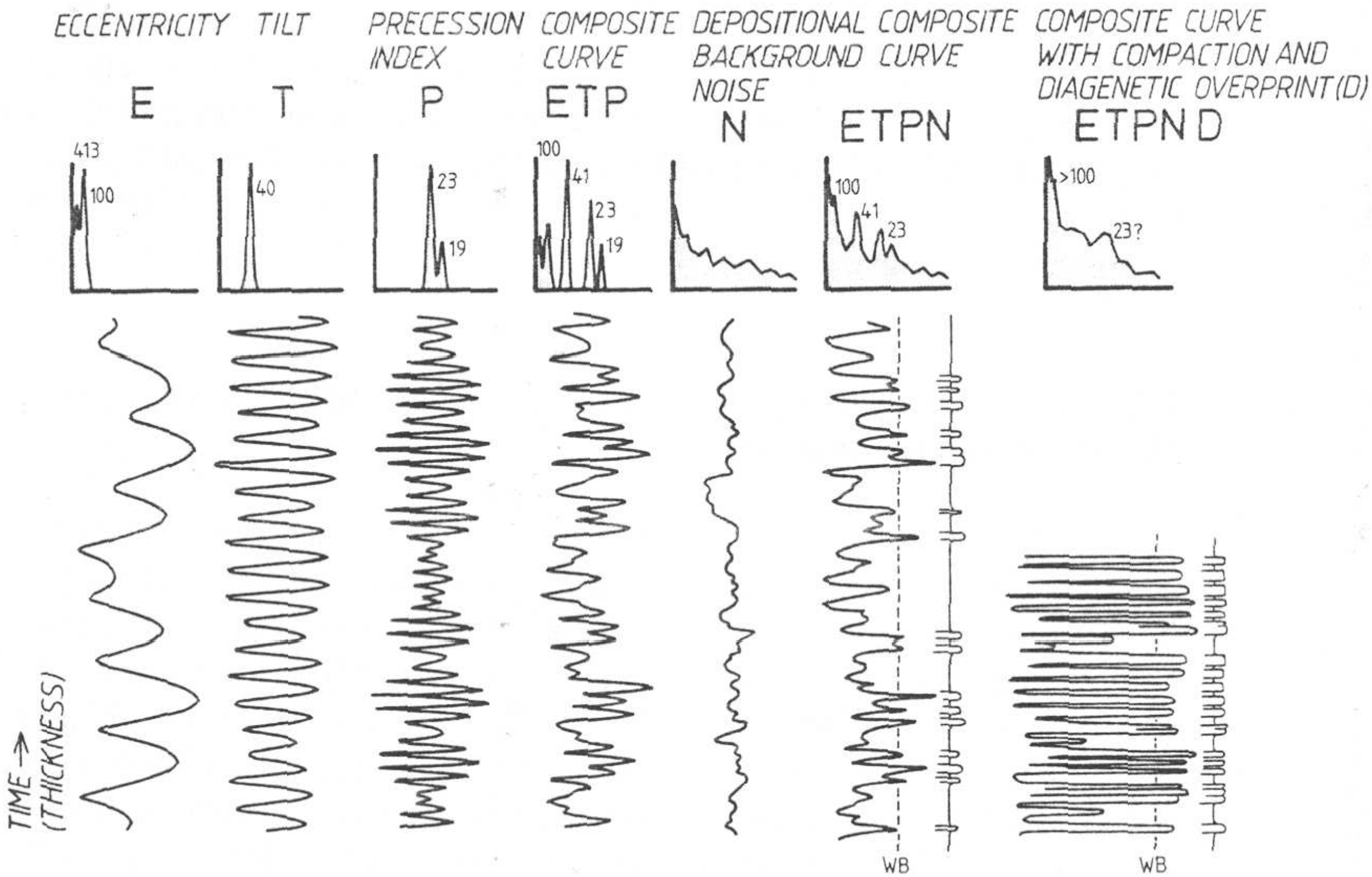
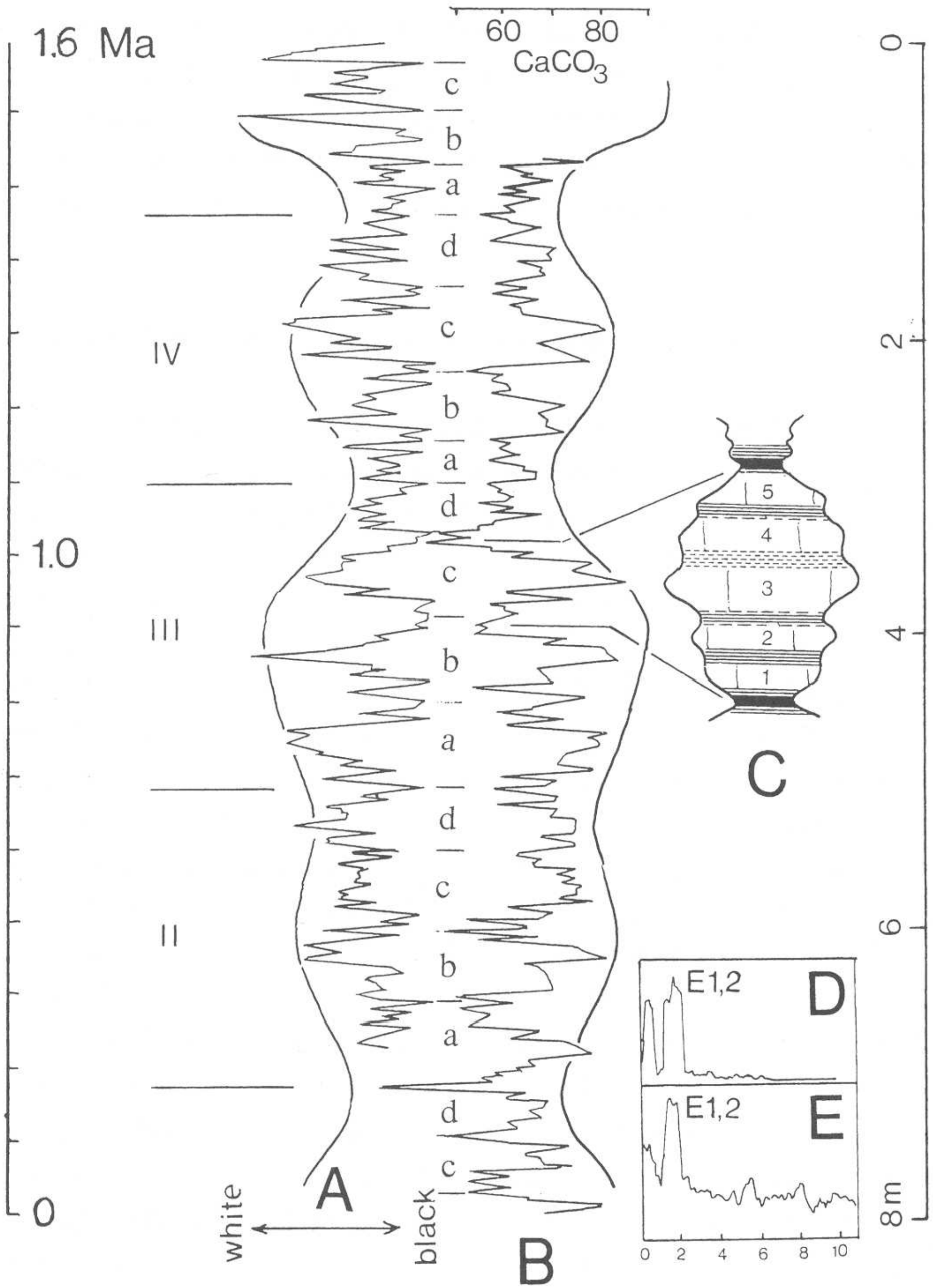


Figure 16. June insolation changes at 65°N caused by changes in the eccentricity of the Earth's orbit (100,000 and 450,000 year cycles), by changes in the phasing between the Earth's distance and tilt seasonality (19,000 and 23,000 year cycles) and by changes in the tilt of the Earth's axis (41,000 year cycle).

Přetisk orbitálního záznamu do vrstevního sledu: faktory



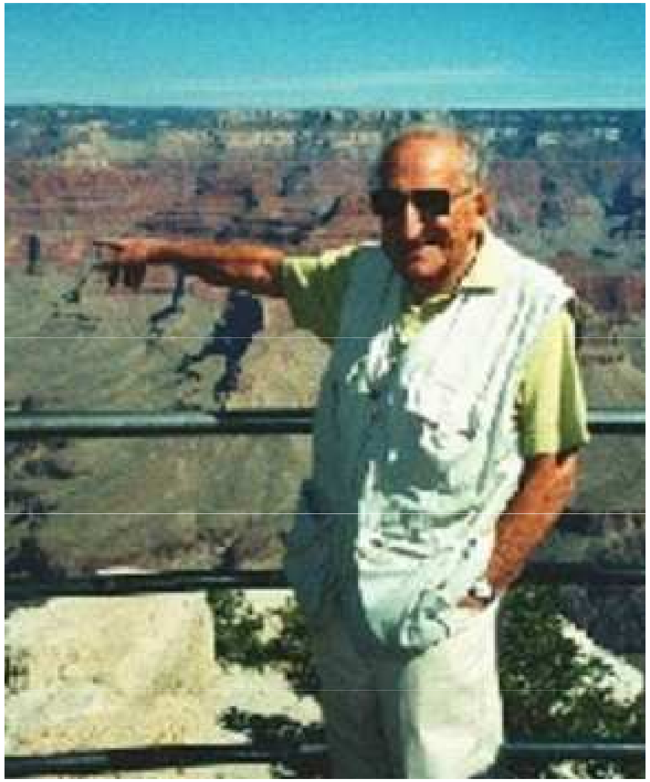


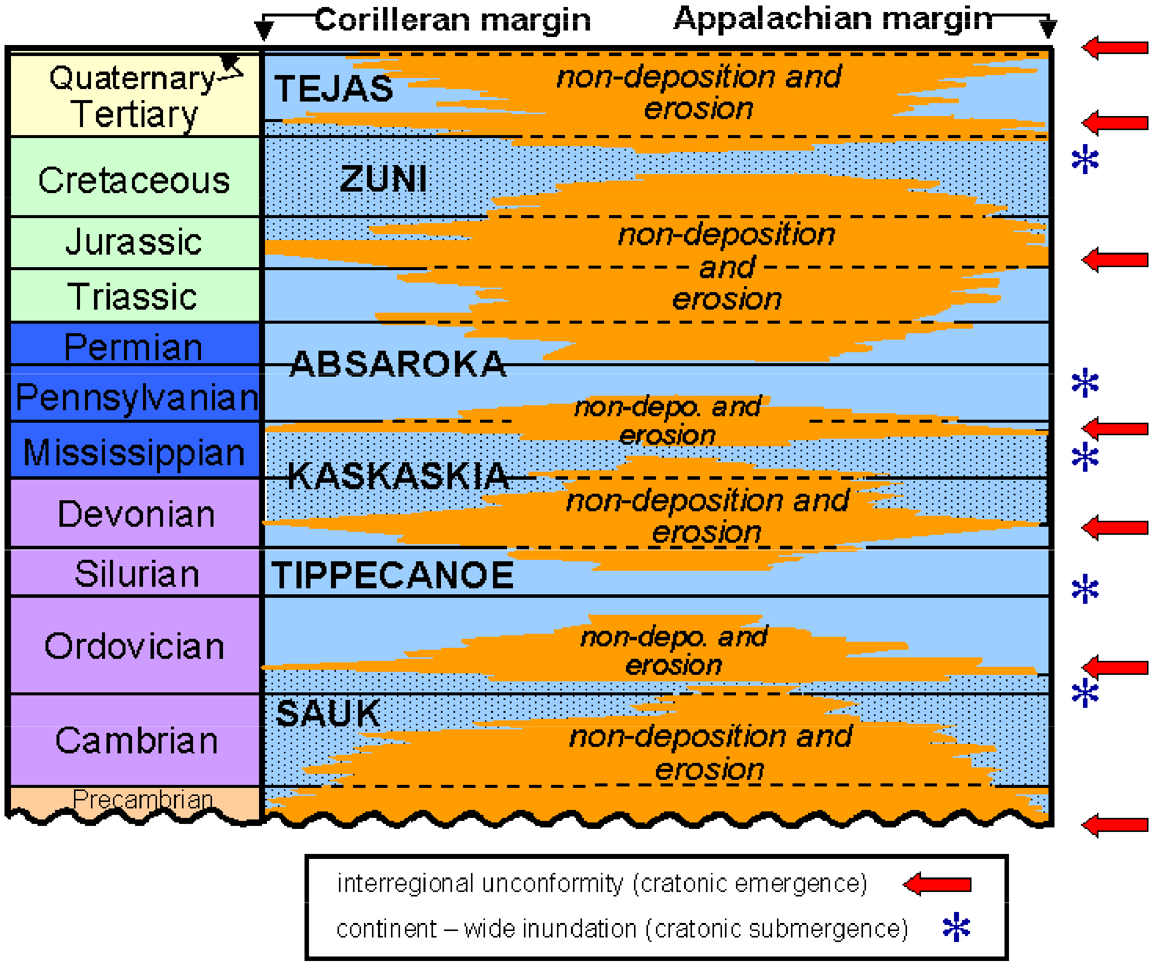
1.6 Ma
1.0
0
IV
III
II
60
80
CaCO3
c
b
a
d
0
2
4
6
8 m
5
4
3
2
1
C
E1,2
D
E
0
2
4
6
8
10
white
black
A
B

Sekvenční stratigrafie

- Sequence stratigraphy is a relatively new branch of geology that attempts to link prehistoric sea-level changes to sedimentary deposits.
- The 'sequence' part of the name refers to cyclic sedimentary deposits. The term 'stratigraphy' refers to the geologic knowledge about the processes by which sedimentary deposits form and how those deposits change through time and space on the Earth's surface.
- Sequence stratigraphy constitutes a ‘minor revolution’ in the Earth sciences, and has certainly revitalized stratigraphy

Slossovy sekvence



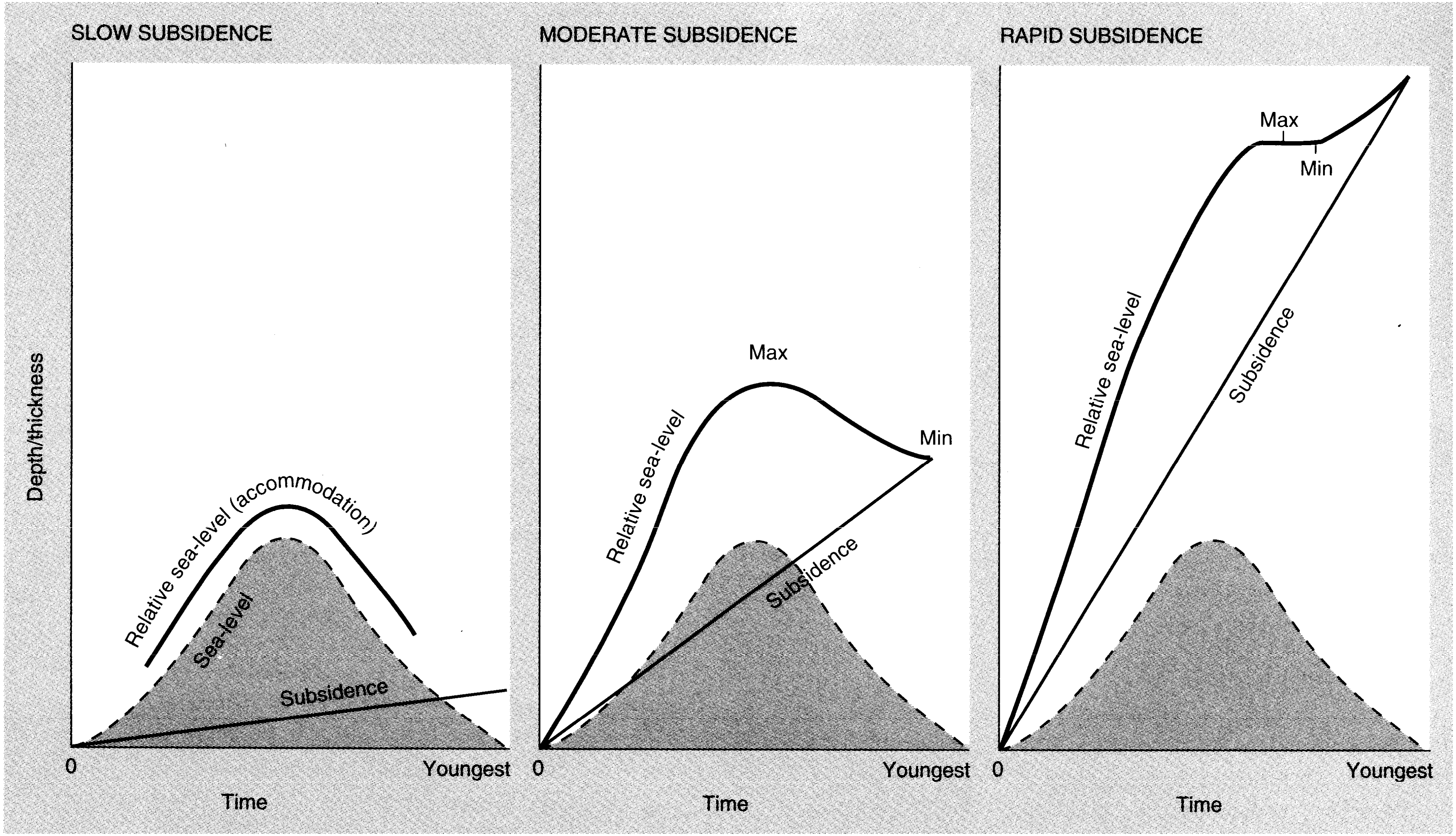


1963 Lawrence Sloss recognized 6 major sequences in North America controlled by eustatic sea level changes

Sekvenční stratigrafie

- Sequence stratigraphy highlights the role of ‘**allogenic**’ (or external) controls on patterns of deposition, as opposed to ‘**autogenic’** controls that operate **within** depositional environments

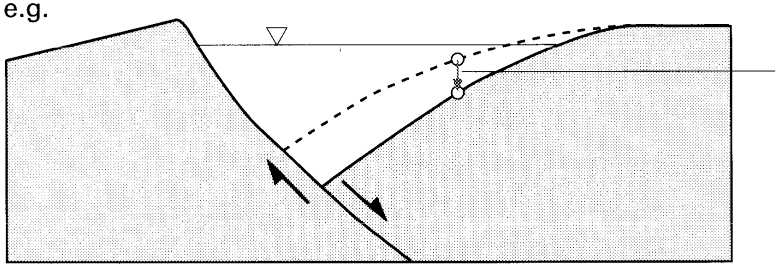
  - **Eustasy** (changes in sea level)
  - **Subsidence** (changes in basin tectonics)
  - **Sediment supply** (changes in climate and hinterland tectonics)



SLOW SUBSIDENCE
MODERATE SUBSIDENCE
RAPID SUBSIDENCE
Depth/thickness
Relative sea-level (accommodation)
Sea-level
Subsidence
Relative sea-level
Max
Min
0
Youngest
Time

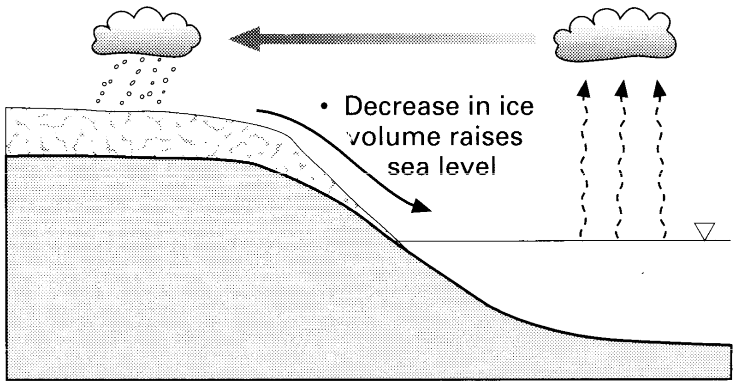
CAUSES OF SEA LEVEL CHANGE

Local tectonics
e.g.



Very variable rates and magnitudes of relative sea level changes

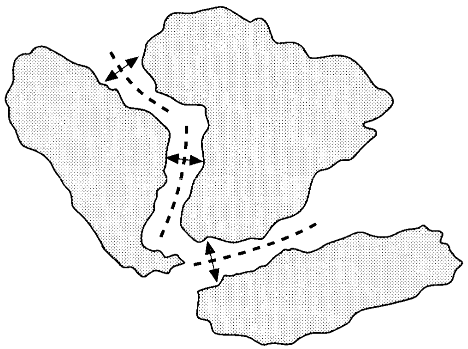
Continental ice caps



- Increase in ice volume lowers sea level

Around 100 m sea level change over 100 ka

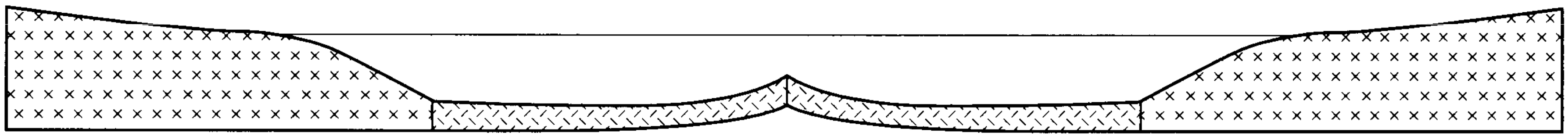
Global scale thermo-tectonic



- Formation and breakup of supercontinents
- Changes in rates of formation of ocean crust

10–100 m sea level change over 10–100 Ma

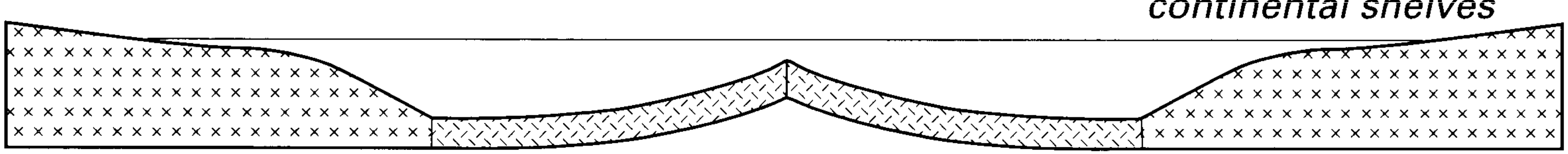
Slow mid-ocean ridge spreading



Oceanic crust cools and contracts

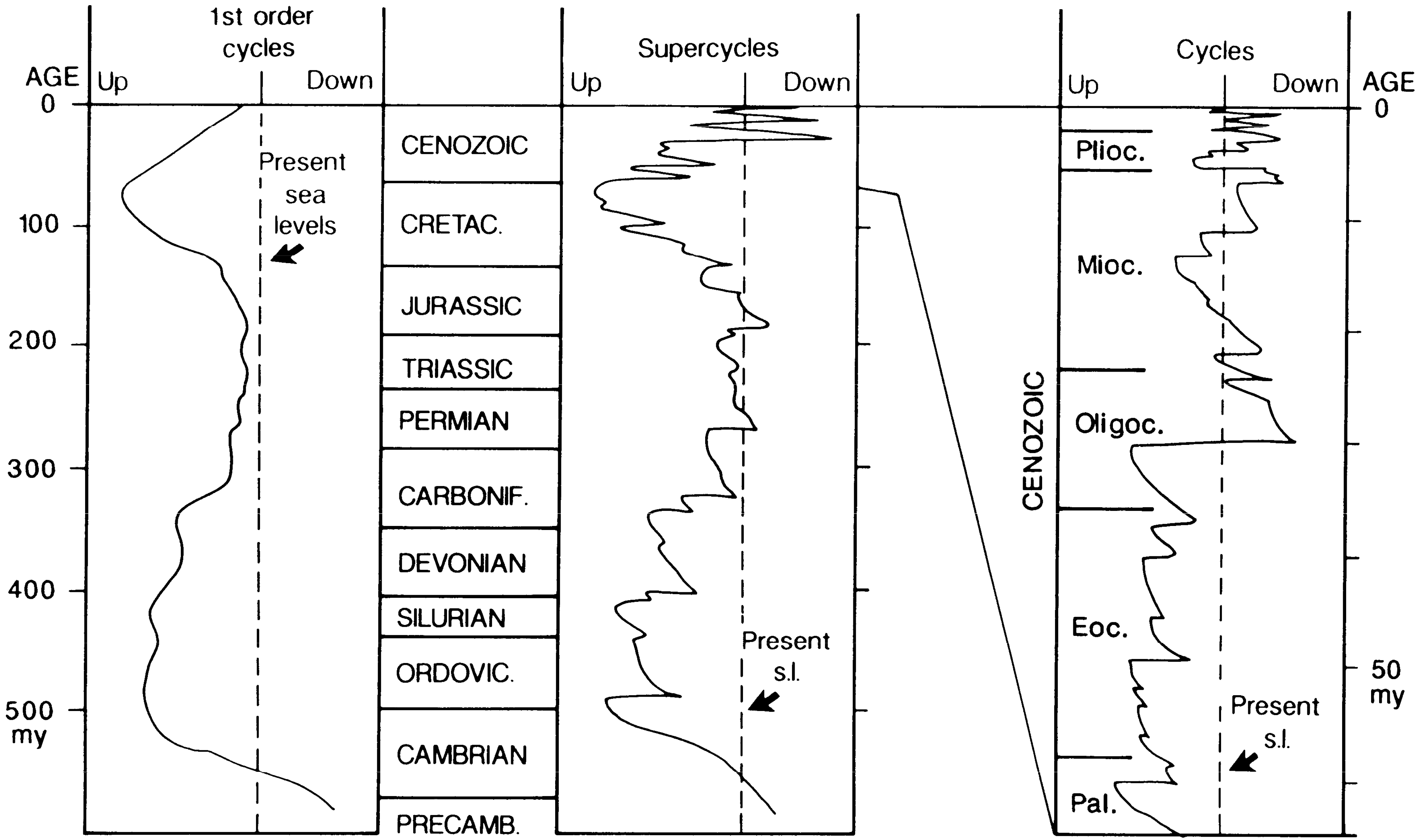
Fast mid-ocean ridge spreading

Sea water displaced onto continental shelves



More hot, buoyant oceanic crust occupies more space in the ocean basin

VAIL SEA LEVEL CHANGE CURVE



Sequence stratigraphy

Sea-level change

- Causes of relative sea-level change (amplitudes ~10^1-10^2 m)
  - Tectono-eustasy (time scales of 10-100 Myr)
  - Glacio-eustasy (time scales of 10-100 kyr)
  - Local tectonics
- The time scales of these controls have given rise to the distinction of eustatic cycles of different periods
  - First-order (10^8 yr) and second-order (10^7 yr) cycles (primarily tectono-eustatic)
  - Third-order (10^6 yr) cycles (mechanism not well understood)
  - Fourth-order (10^5 yr) and fifth-order (10^4 yr) cycles (primarily glacio-eustatic)

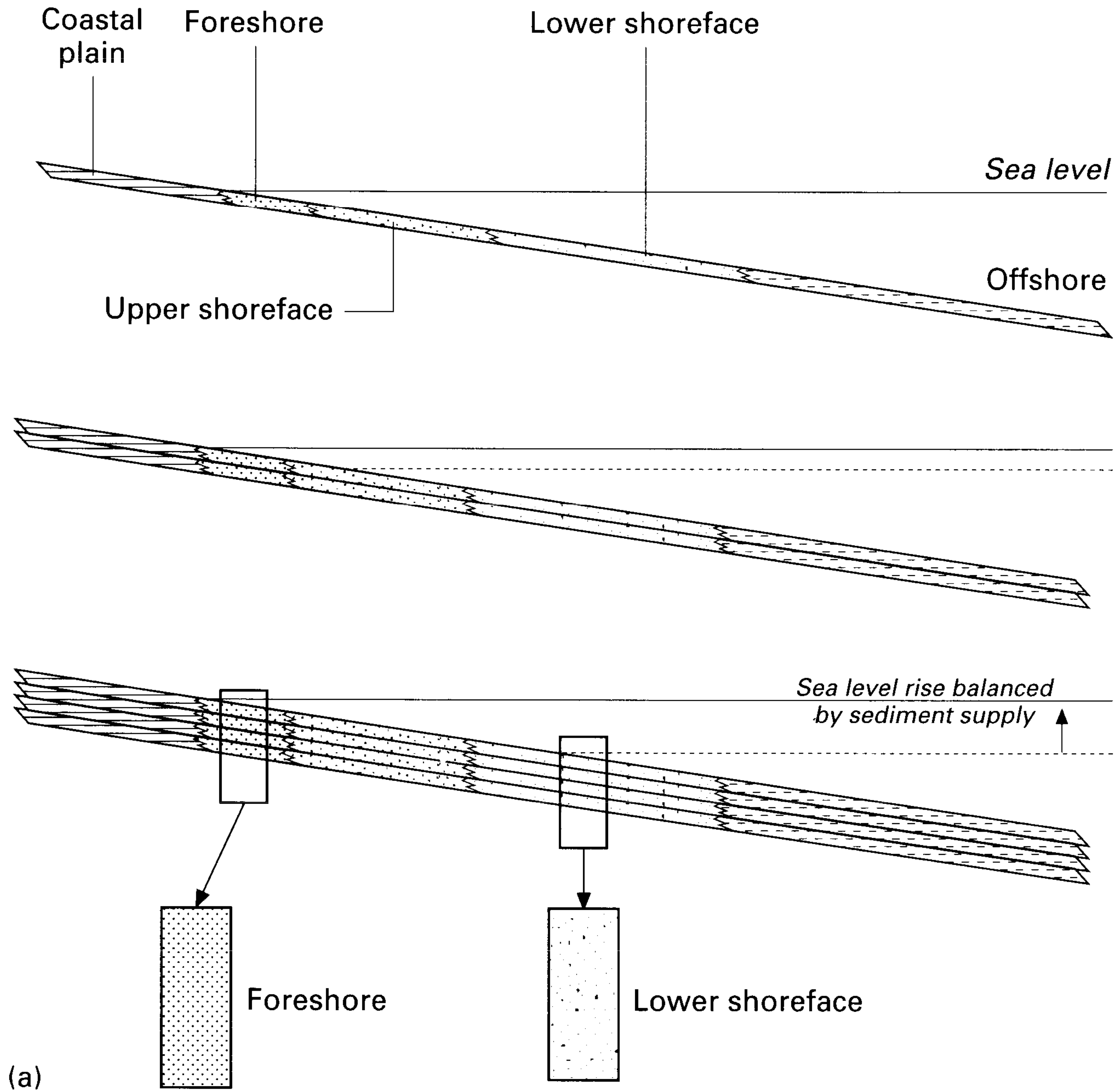
Akomodační prostor: agradace, progradace, retrogradace

- **Accommodation** refers to the space available for deposition (closely connected to relative sea level in shallow marine environments); however, application of this concept to subaerial and deep-sea environments is problematic

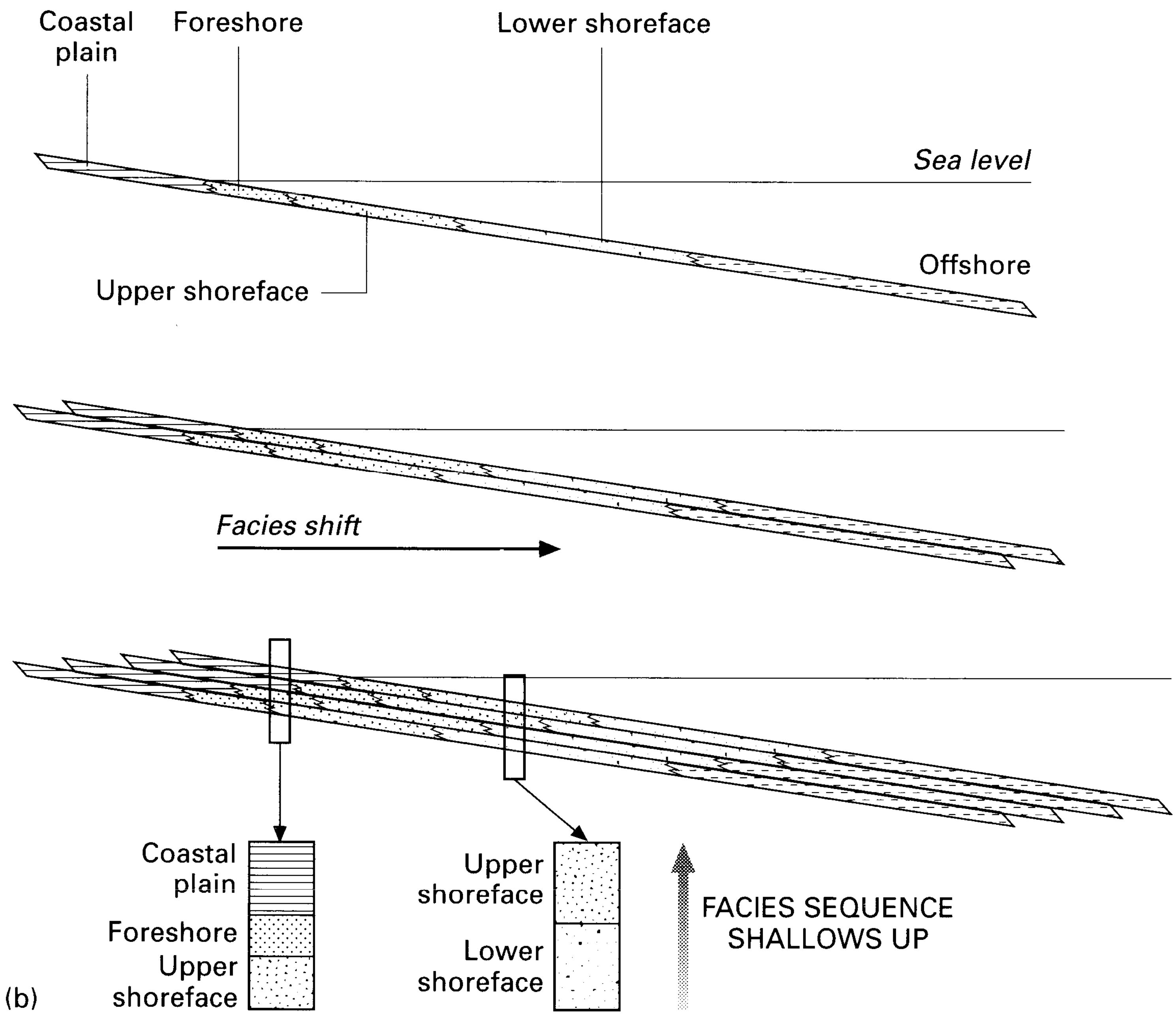
- An increase of accommodation is necessary to build and preserve a thick stratigraphic succession; this requires eustatic sea-level rise and/or basin subsidence (i.e., relative sea-level rise), as well as sufficient sediment supply

- The subtle balance between relative sea-level change and sediment supply controls whether **aggradation**, **regression** (progradation), **forced regression**, or **transgression** (retrogradation) will occur

Aggradation

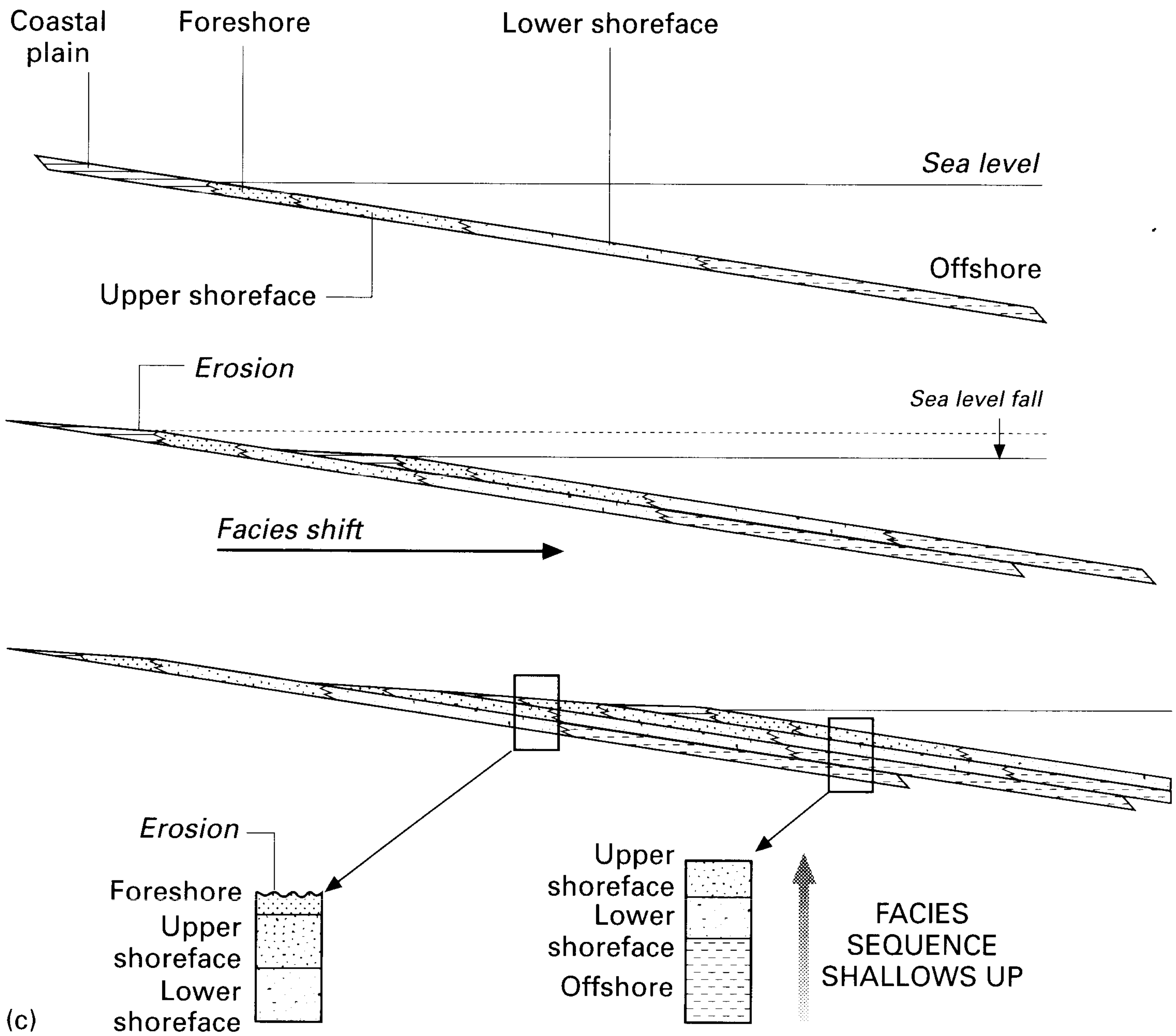


Regression

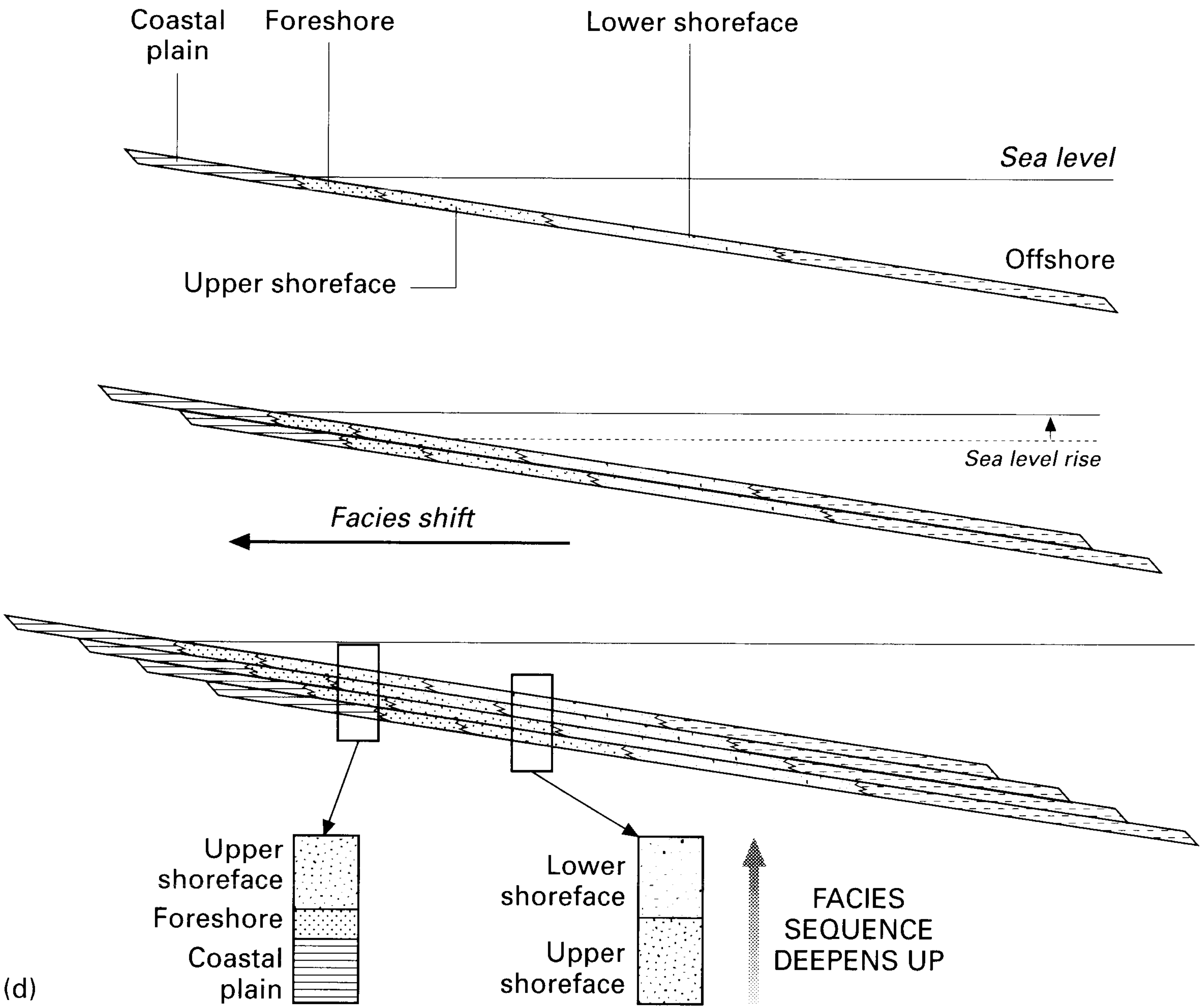


Coastal plain
Foreshore
Lower shoreface
Sea level
Offshore
Upper shoreface
Facies shift
Coastal plain
Foreshore
Upper shoreface
(b)
Upper shoreface
Lower shoreface
FACIES SEQUENCE SHALLOWS UP

Forced regression

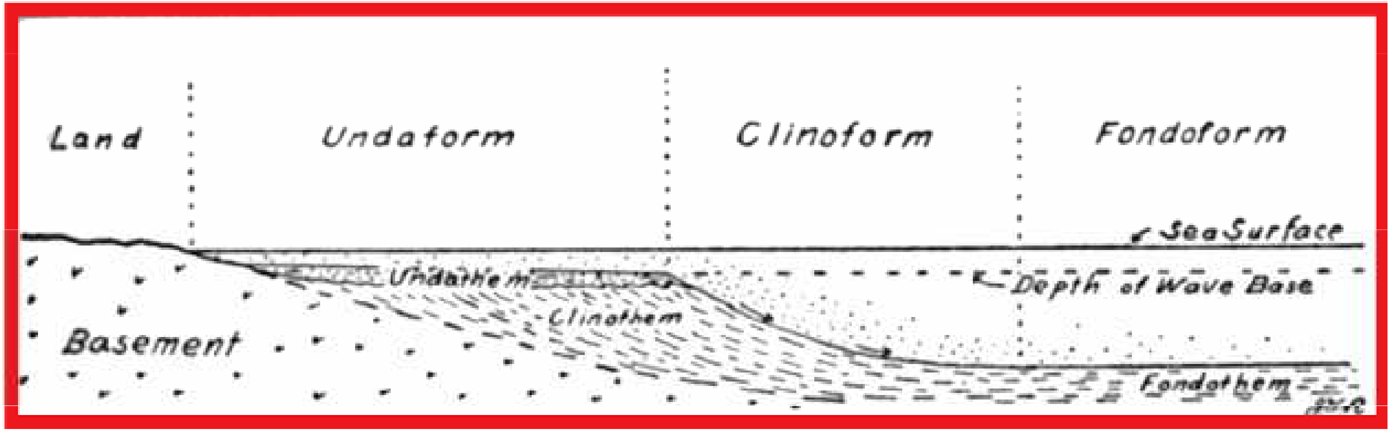


Transgression

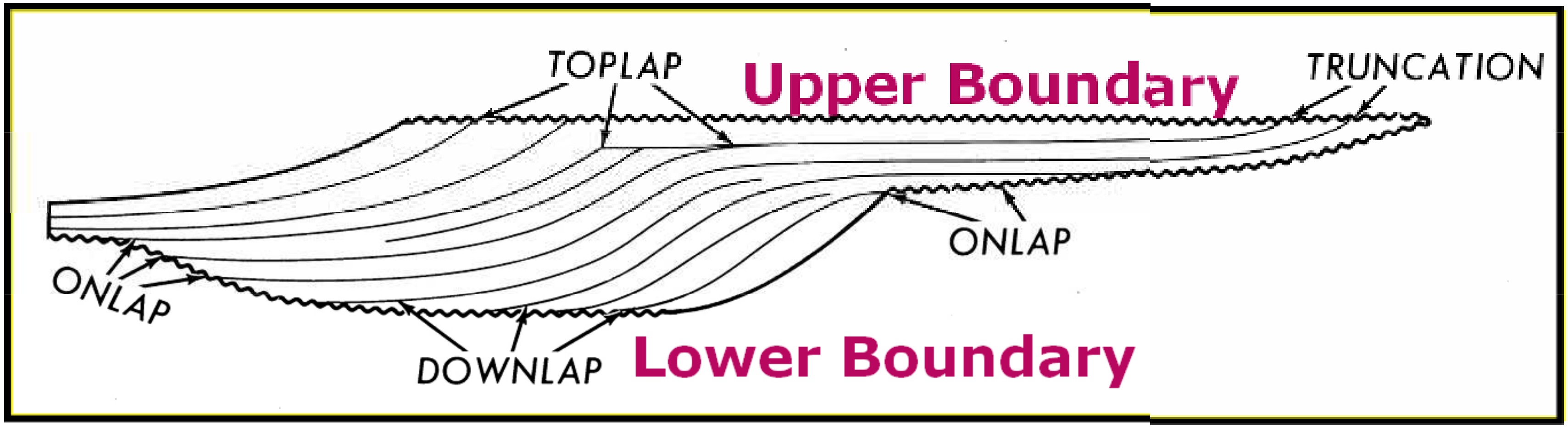


Seismická a sekvenční stratigrafie koncept klinoforem

1951 John L. Rich proposes the concept of clinoforms…



…recognition of seismic reflection geometries



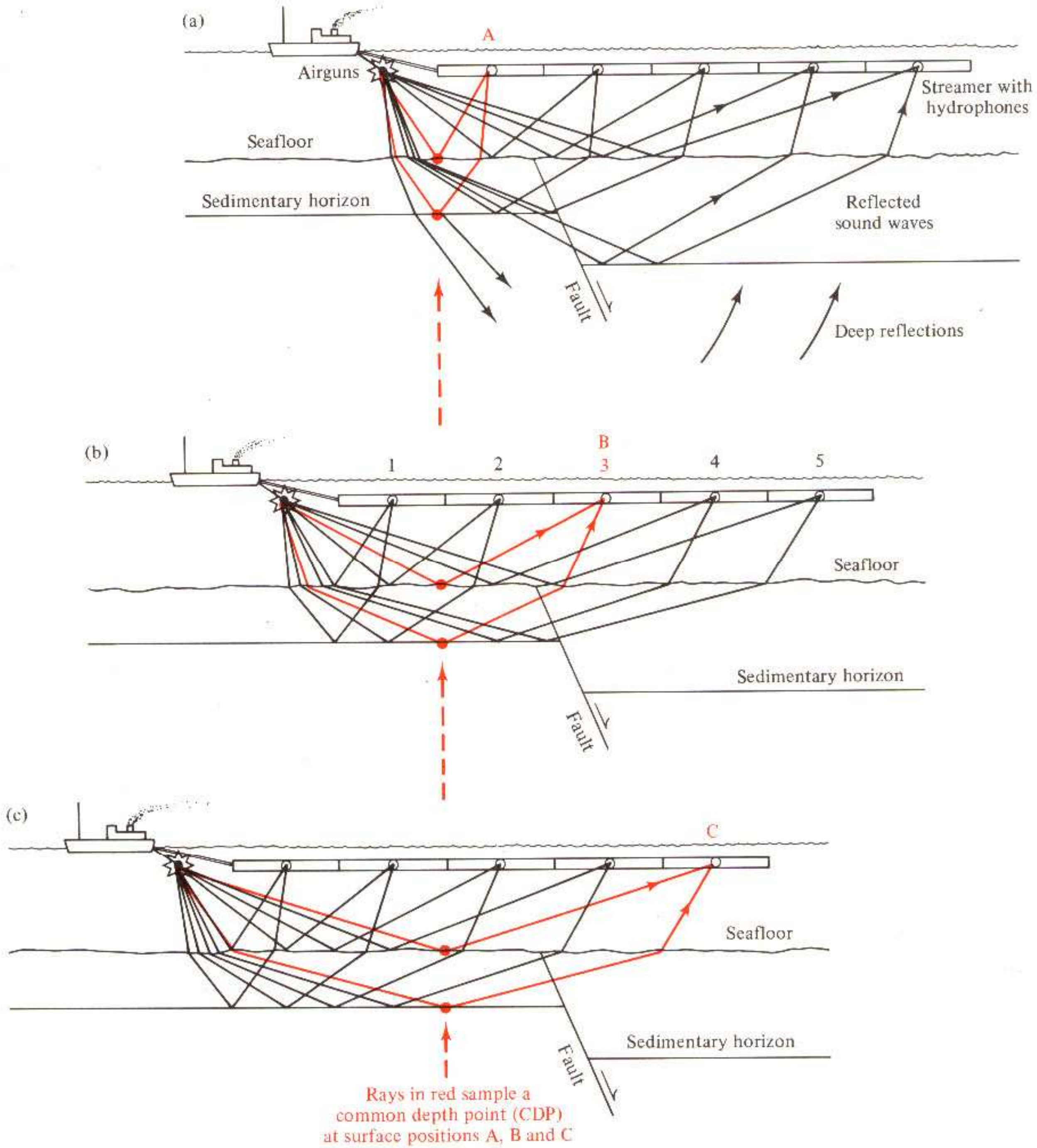
Seismická stratigrafie

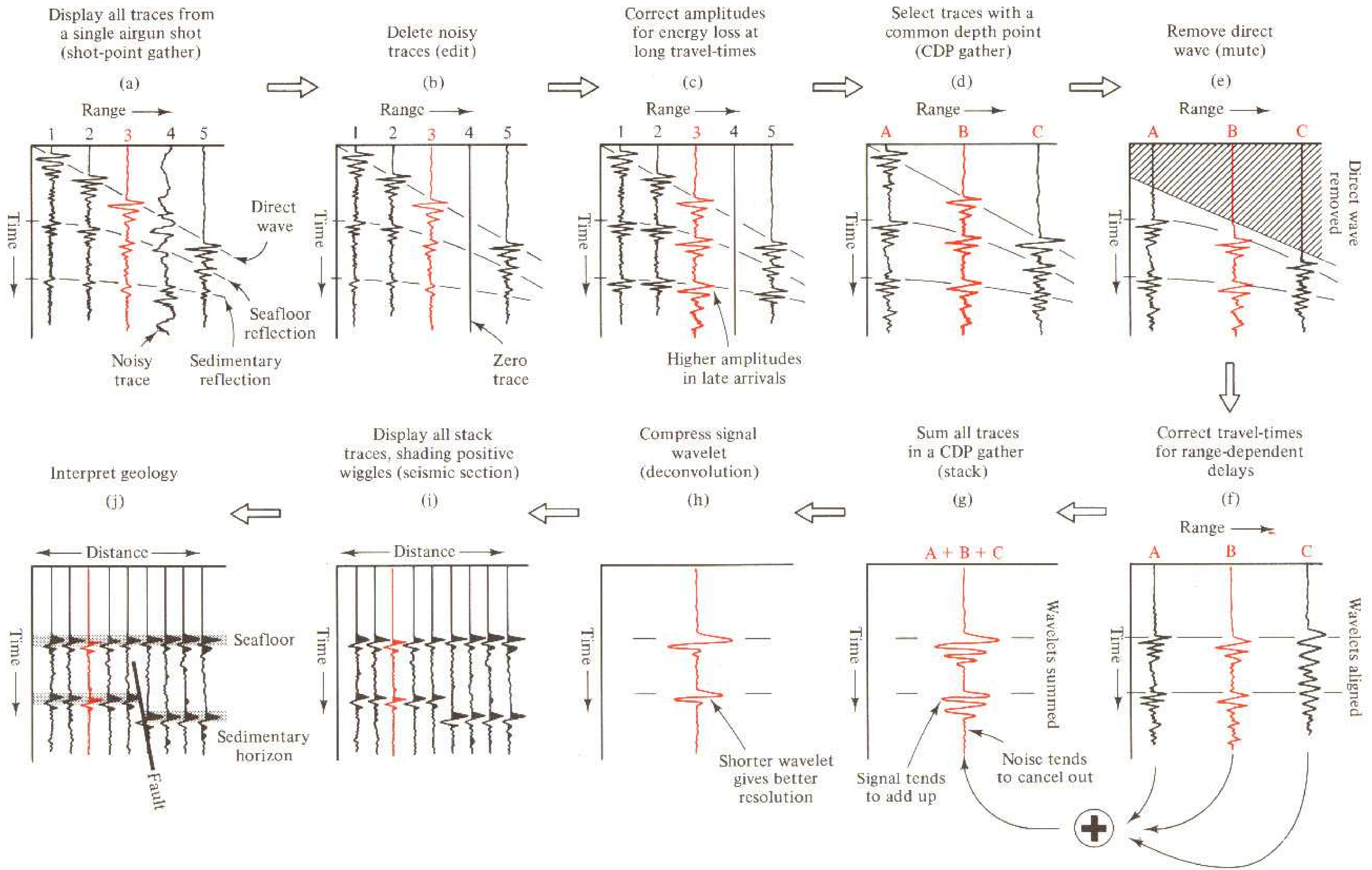
Reflekční seismické profilování

- **Seismic reflection profiling** forms the basis of seismic stratigraphy, which in turn has been the foundation for the development of sequence stratigraphy
- The technique is based on contrasts in **acoustic impedance** between different materials; reflections of sound or shock waves occur at transitions between different types of sediment or rock

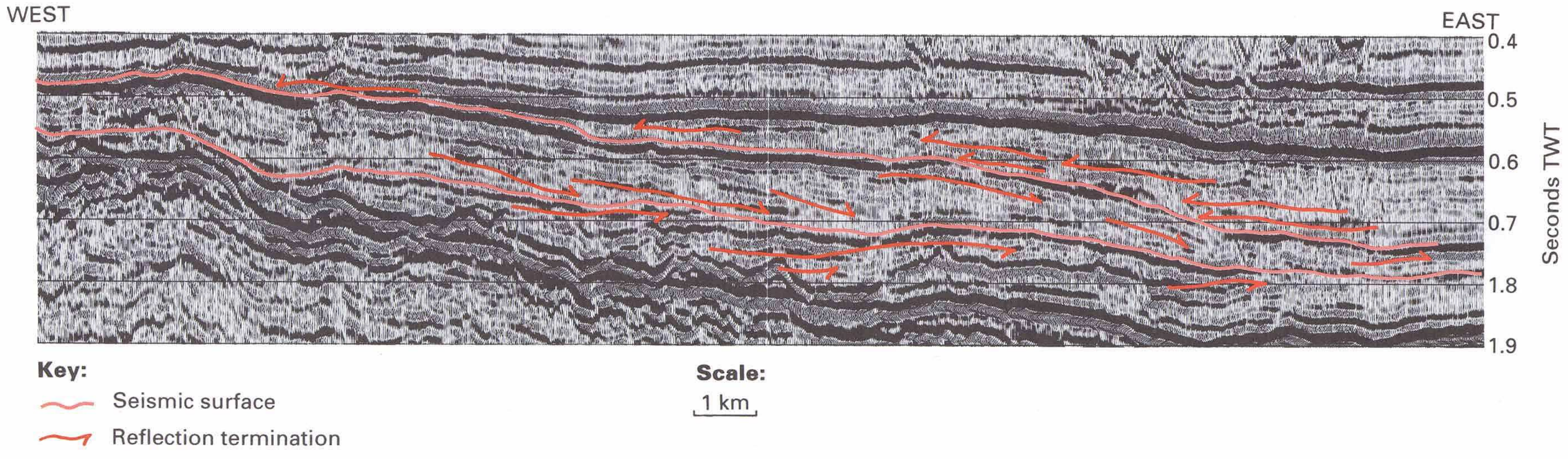
$$AI = v\rho$$

v=sonic velocity; ρ=sediment or rock density


(a)
A
Airguns
Streamer with hydrophones
Seafloor
Sedimentary horizon
Reflected sound waves
Fault
Deep reflections
(b)
B
1
2
3
4
5
Seafloor
Sedimentary horizon
Fault
(c)
C
Seafloor
Sedimentary horizon
Fault
Rays in red sample a common depth point (CDP) at surface positions A, B and C



Display all traces from a single airgun shot (shot-point gather)
(a)
Range
Time
1 2 3 4 5
Direct wave
Seafloor reflection
Noisy trace
Sedimentary reflection
Delete noisy traces (edit)
(b)
Zero trace
Correct amplitudes for energy loss at long travel-times
(c)
Higher amplitudes in late arrivals
Select traces with a common depth point (CDP gather)
(d)
A B C
Remove direct wave (mute)
(e)
Direct wave removed
Correct travel-times for range-dependent delays
(f)
Wavelets aligned
Sum all traces in a CDP gather (stack)
(g)
A + B + C
Wavelets summed
Signal tends to add up
Noise tends to cancel out
Compress signal wavelet (deconvolution)
(h)
Shorter wavelet gives better resolution
Display all stack traces, shading positive wiggles (seismic section)
(i)
Distance
Interpret geology
(j)
Seafloor
Sedimentary horizon
Fault

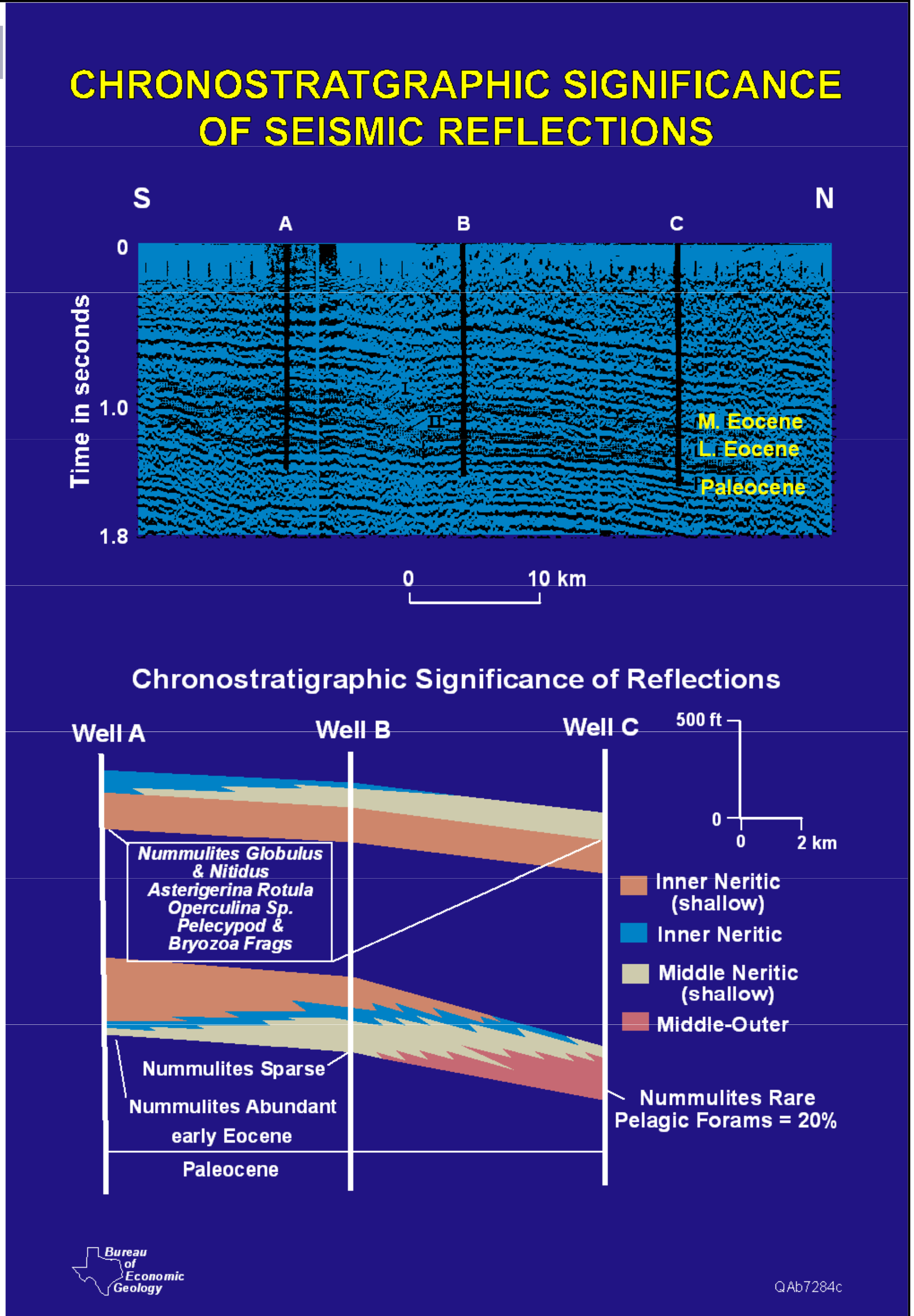


WEST
EAST
0.4
0.5
0.6
0.7
1.8
1.9
Seconds TWT
Key:
Seismic surface
Reflection termination
Scale:
1 km

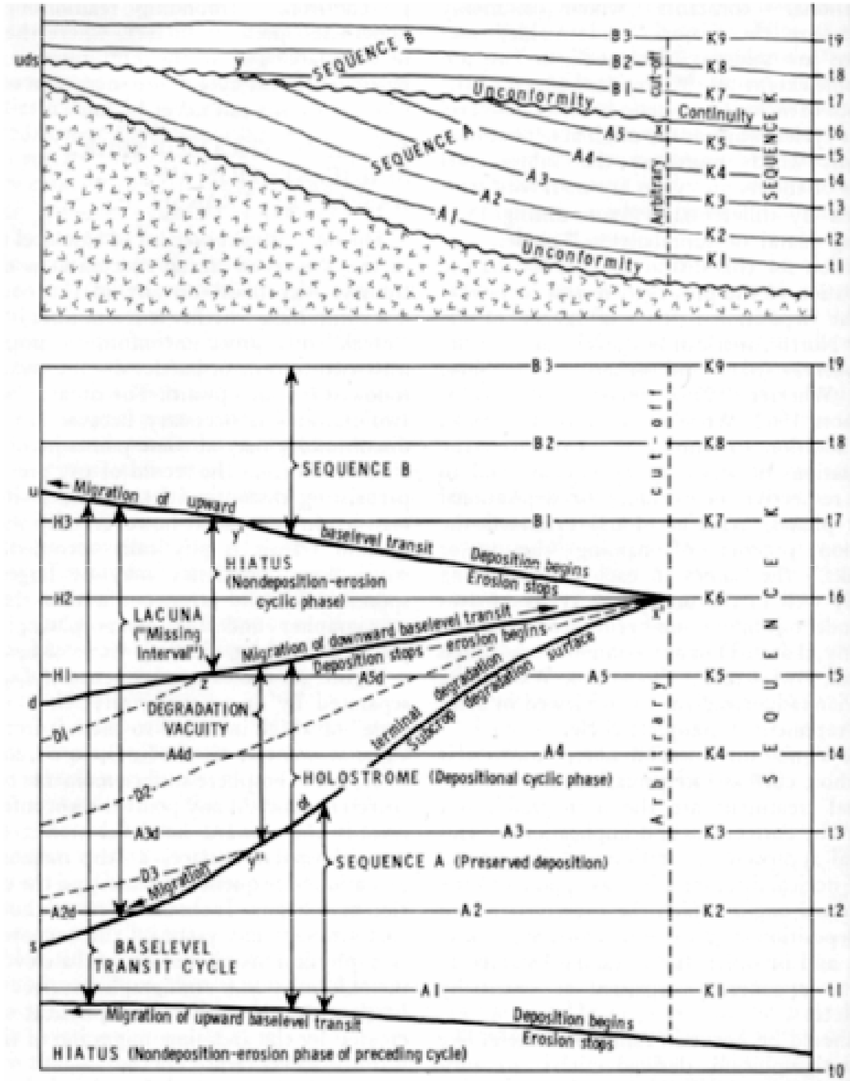
Seismické reflektory představují časově ekvivalentní (synchronní) linie

A critical assumption of the seismic stratigraphic approach, illustrated in this diagram from Vail et al (1977), is that seismic reflectors follow time surfaces rather than facies impedance boundaries.

Note the regional scale of this illustration.



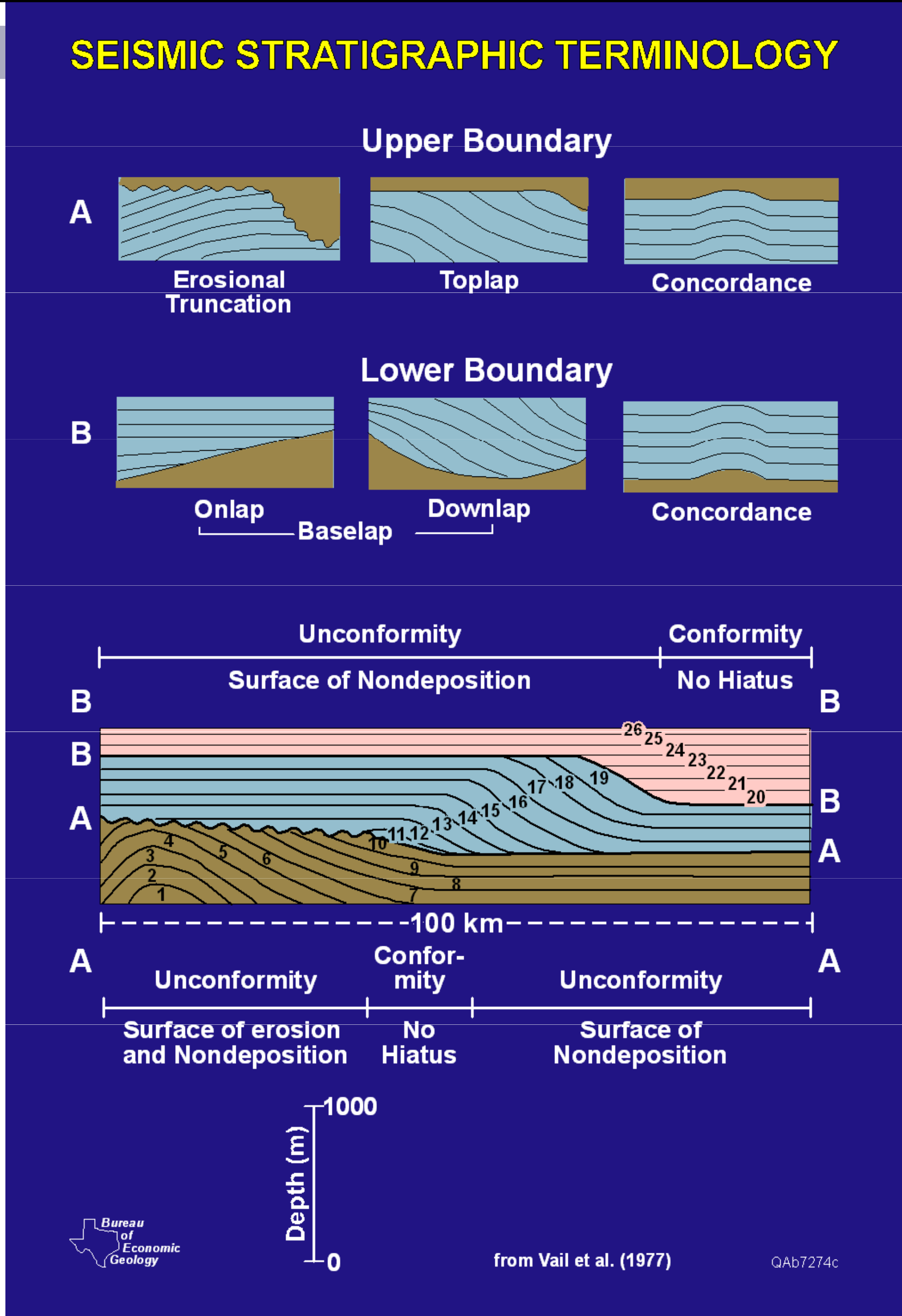
Wheelerovy diagramy



1958 Harry Wheeler produced first chronostratigraphic chart

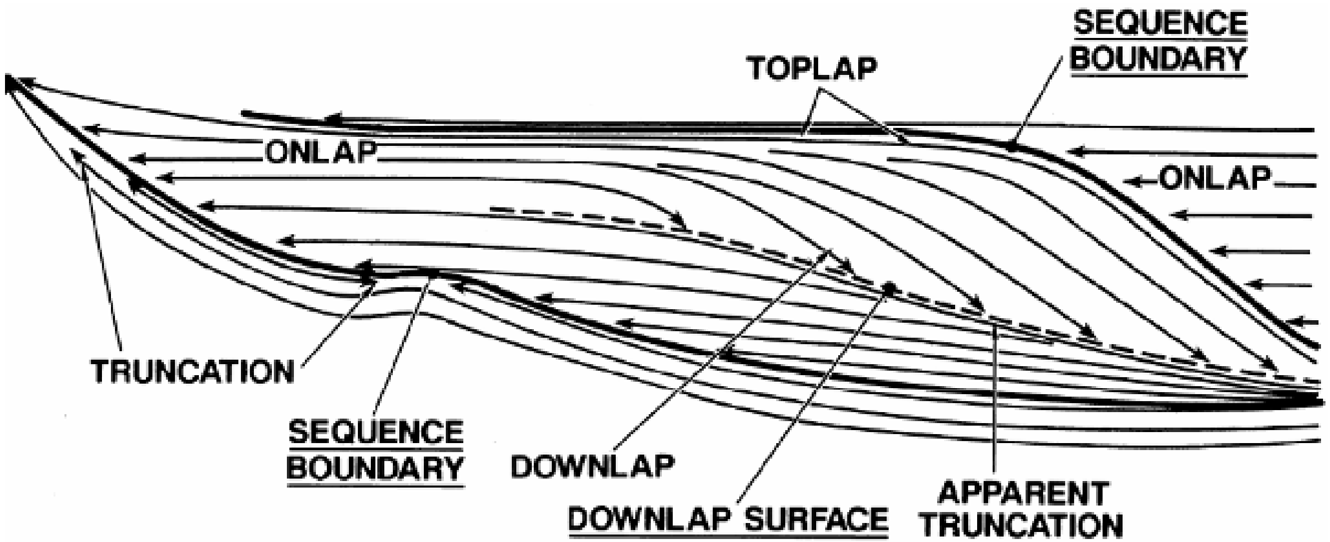
Sekvence omezené diskordancemi

Original Sequence Stratigraphic Approach (seismic stratigraphy) was based on recognition of unconformity-bound sequences using geometry and termination patterns of seismic reflectors.

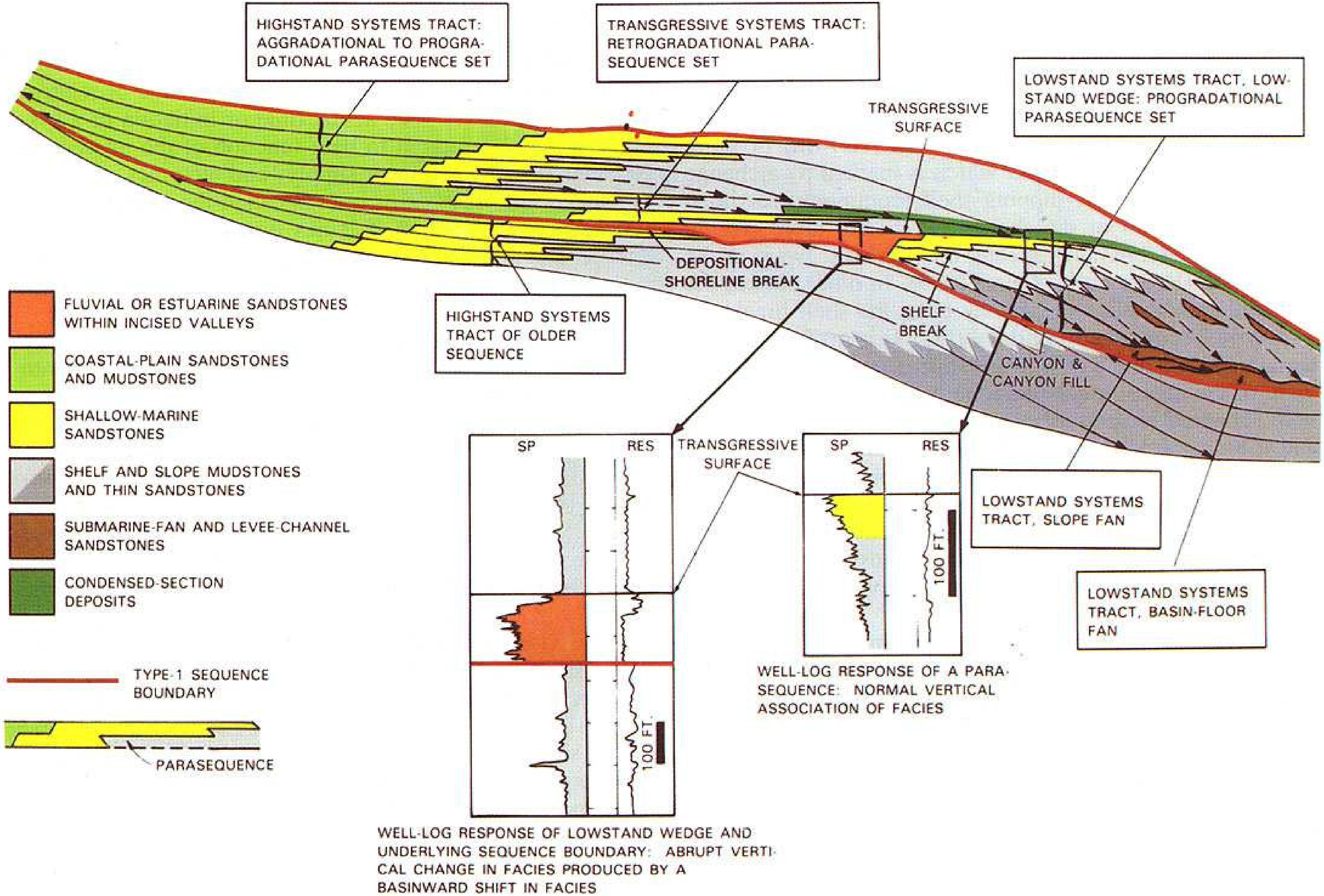


Exxonská škola

1977 Peter Vail and Robert Mitchum co-ordinated the publishing of AAPG Memoir #26 based on the assumption that a seismic relection surface represents a time line



Základní sekvenční model: Exxonská škola, pasivní kontinentální okraj



Depoziční sekvence a sekvenční hranice

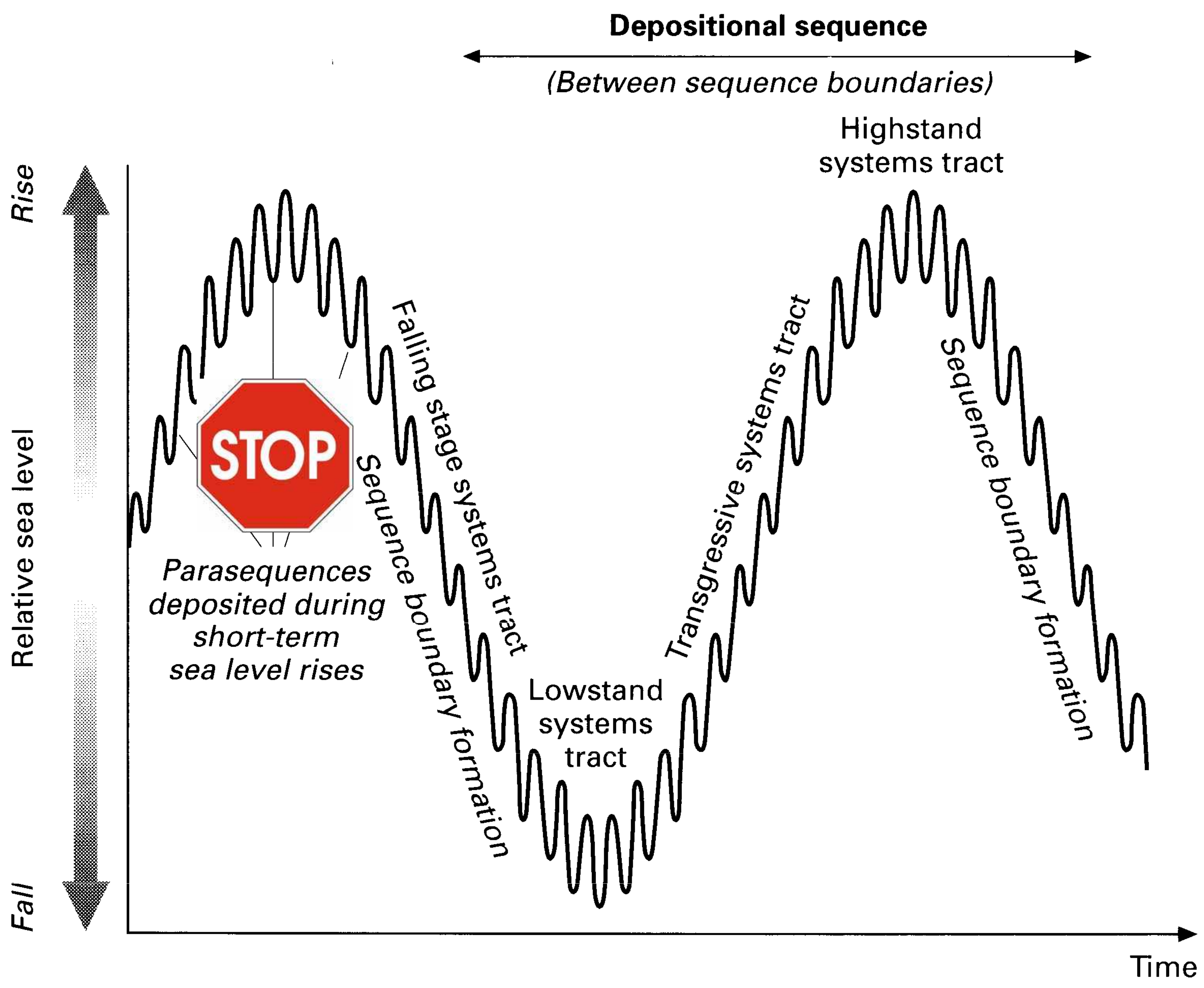
- A **depositional sequence** is a stratigraphic unit bounded at its top and base by **unconformities** or their **correlative conformities**, and typically embodies a continuum of depositional environments, from updip (continental) to downdip (deep marine)

- A **relative sea-level fall** will lead to a basinward shift of the shoreline and an associated **basinward shift of depositional environments**; commonly (but not always) this will be accompanied by **subaerial exposure**, erosion, and formation of a widespread unconformity known as a **sequence boundary**

- **Sequence boundaries** are the key stratigraphic surfaces that separate successive sequences

Parasekvence a systémové trakty

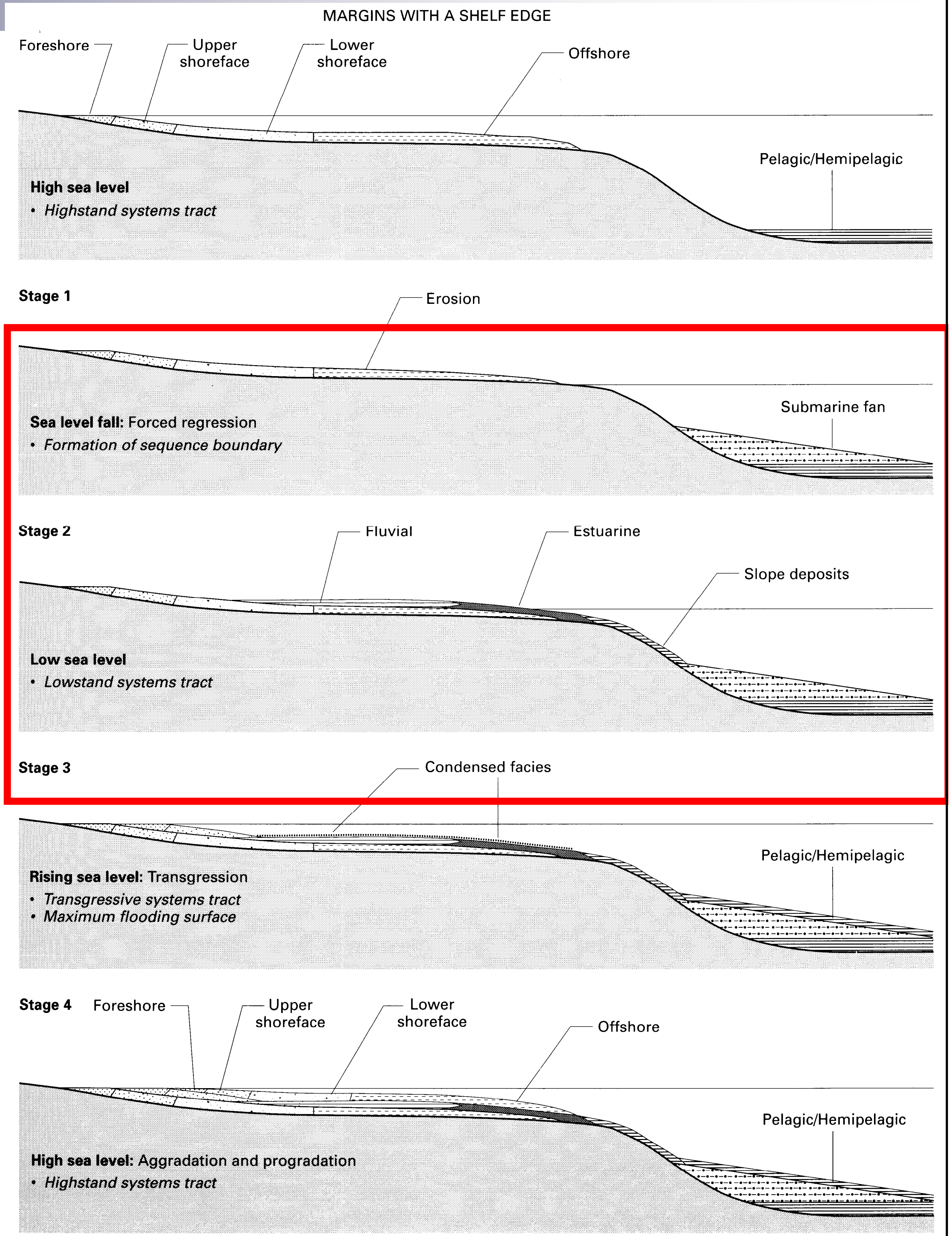
- **Parasequences** are lower order stratal units separated by (marine) flooding surfaces; they are commonly autogenic and not necessarily the result of smaller-scale relative sea-level fluctuations
- **Systems tracts** are the building blocks of sequences, and different types of systems tracts represent different limbs of a relative sea-level curve
  - **Falling-stage (forced regressive) systems tract**
  - **Lowstand systems tract**
  - **Transgressive systems tract**
  - **Highstand systems tract**
- The various systems tracts are characterized by their position within a sequence, by shallowing or deepening upward facies successions, or by parasequence stacking patterns



Depositional sequence
(Between sequence boundaries)
Highstand systems tract
Rise
Relative sea level
Fall
Time
STOP
Parasequences deposited during short-term sea level rises
Falling stage systems tract
Sequence boundary formation
Lowstand systems tract
Transgressive systems tract
Sequence boundary formation

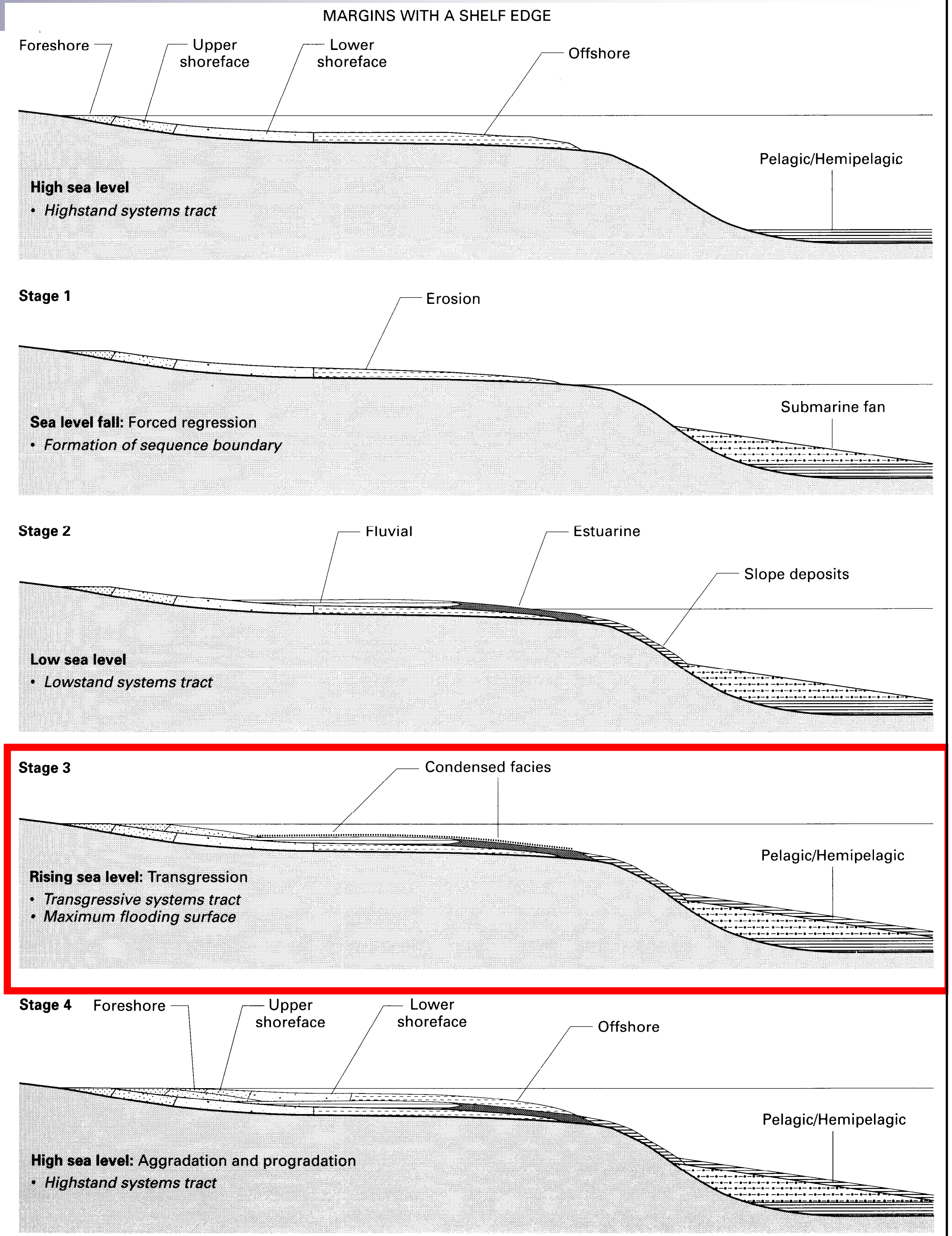
Sekvenční hranice a systémový trakt nízkého stavu hladiny (LST)

- The unconformity or correlative conformity that bounds a sequence
- Commonly (but not always) represents a significant change in stratal arrangements and therefore reservoir properites
- In a very general sense, relative sea-level fall leads to reduced deposition and formation of sequence boundaries in updip areas, and increased deposition in downdip settings (e.g., submarine fans)



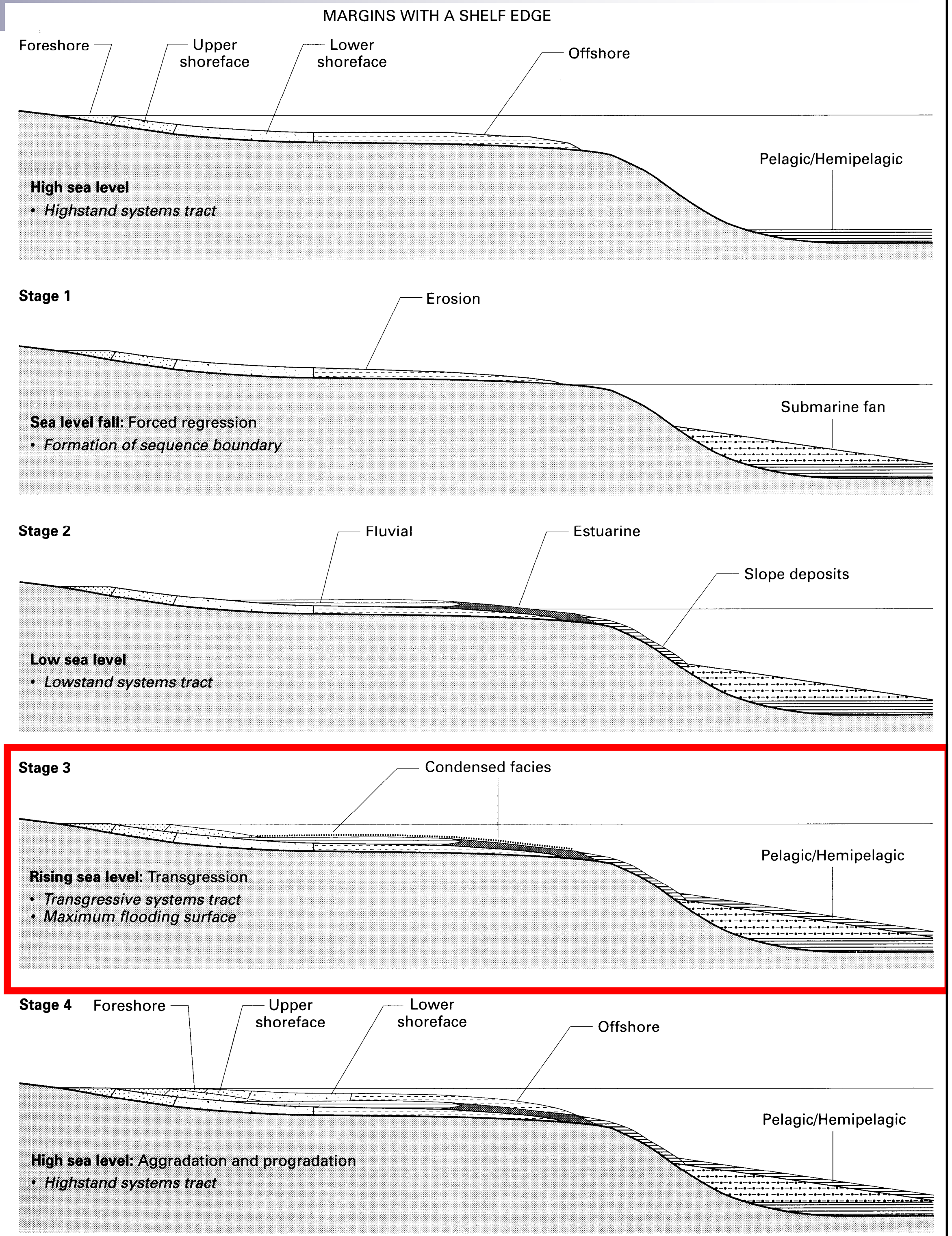
Transgresivní systémový trakt (TST)

- Bounded below by underlying sequence boundary and above by maximum flooding surface
- Generally more mounded in geometry
- Sets of high-frequency cycles show upward thickening and upward deepening trends



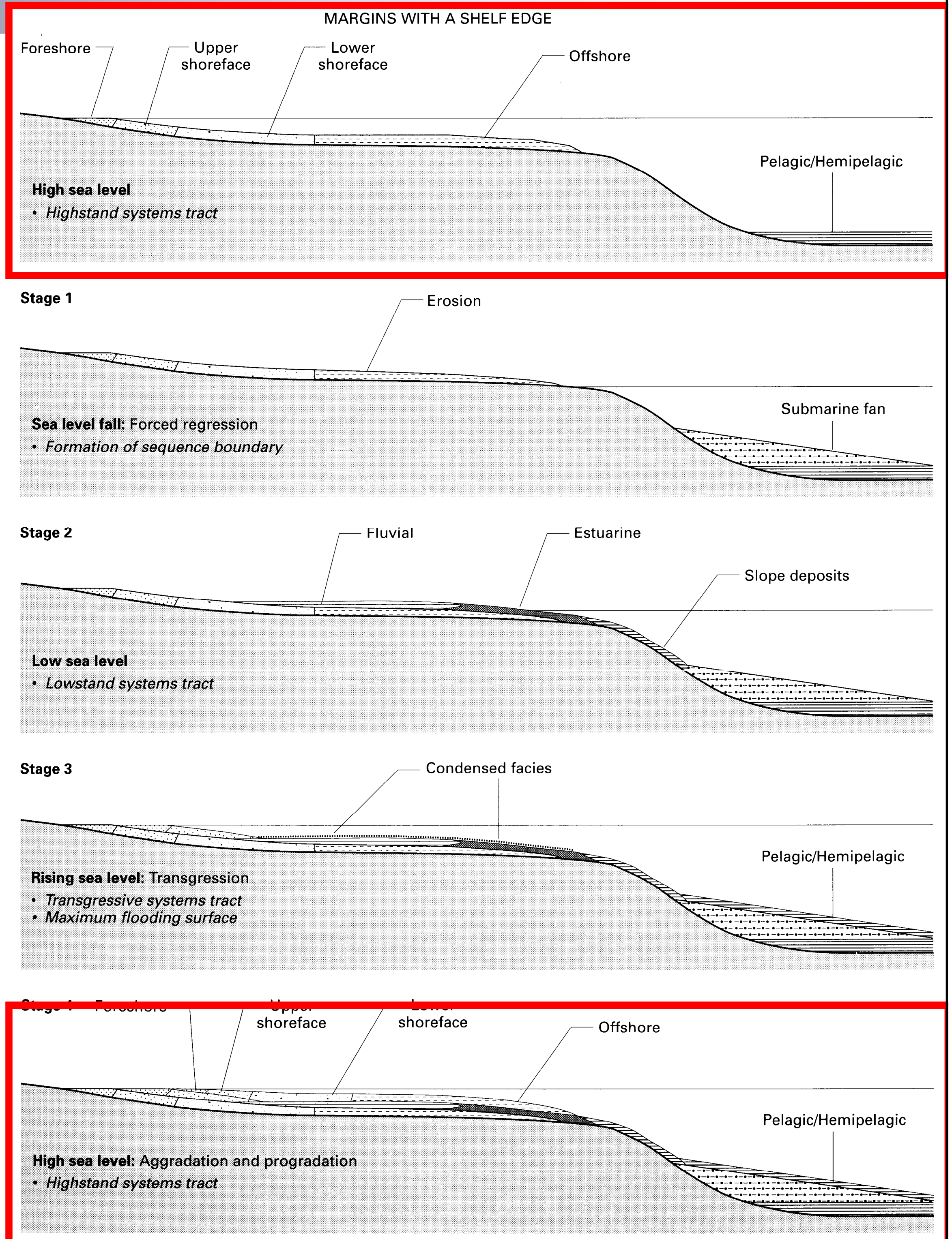
Povrch maximální záplavy (MFS)

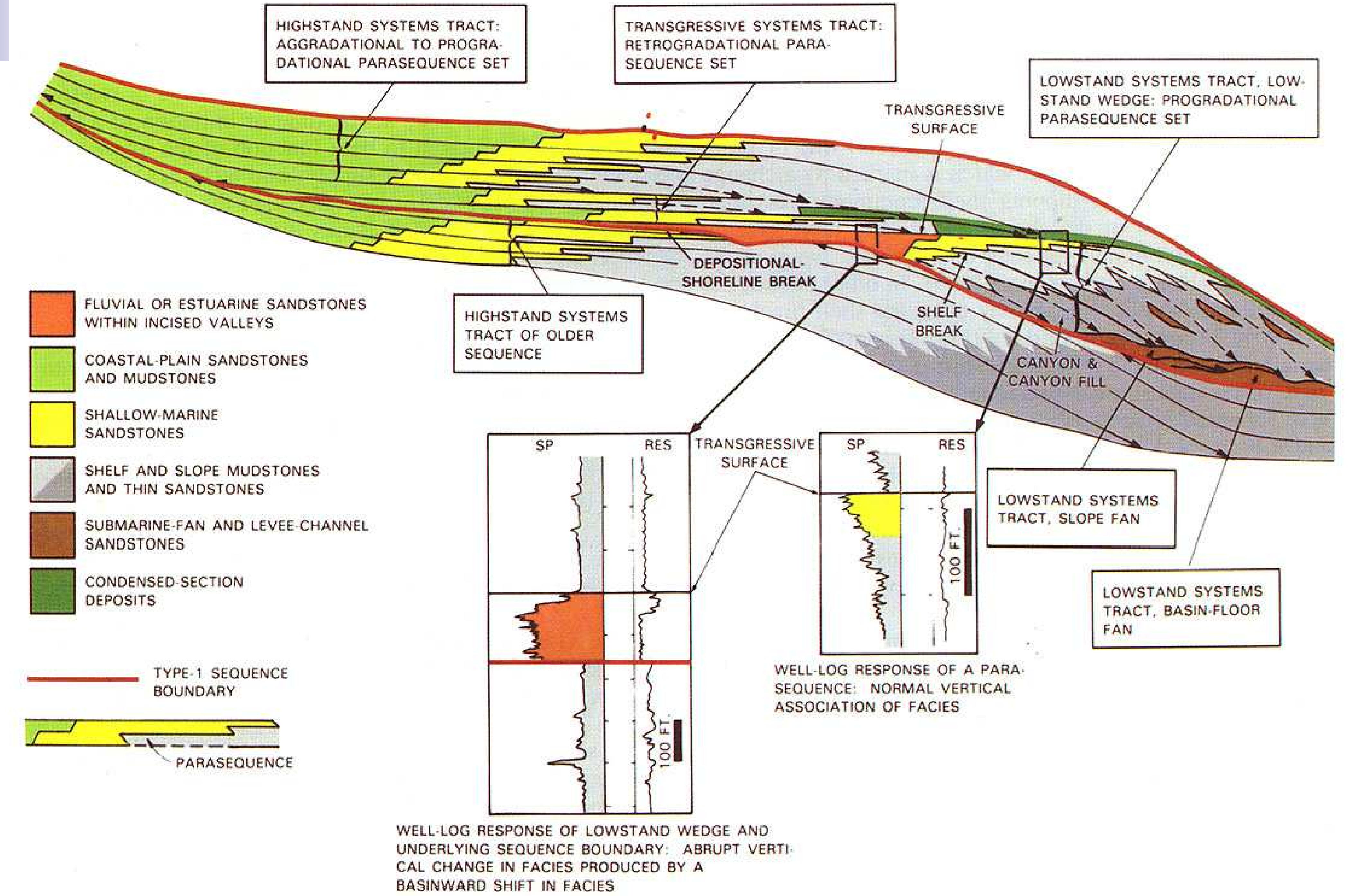
- **Maximum flooding surfaces (MFS)** form during the culmination of sea-level rise
- Surface that marks the turn-around from landward-stepping to seaward stepping strata
- Farther out on platform coincides with the downlap surface (depending on the degree of condensation of clinoform toes)
- Recognition of the MFS is important for separating TST and HST
- Relative sea-level rise will lead to trapping of sediment in the updip areas (e.g., coastal plains) and reduced transfer of sediment to the deep sea (pelagic and hemipelagic deposition; condensed sections)



Systémový trakt vysokého stavu hladiny

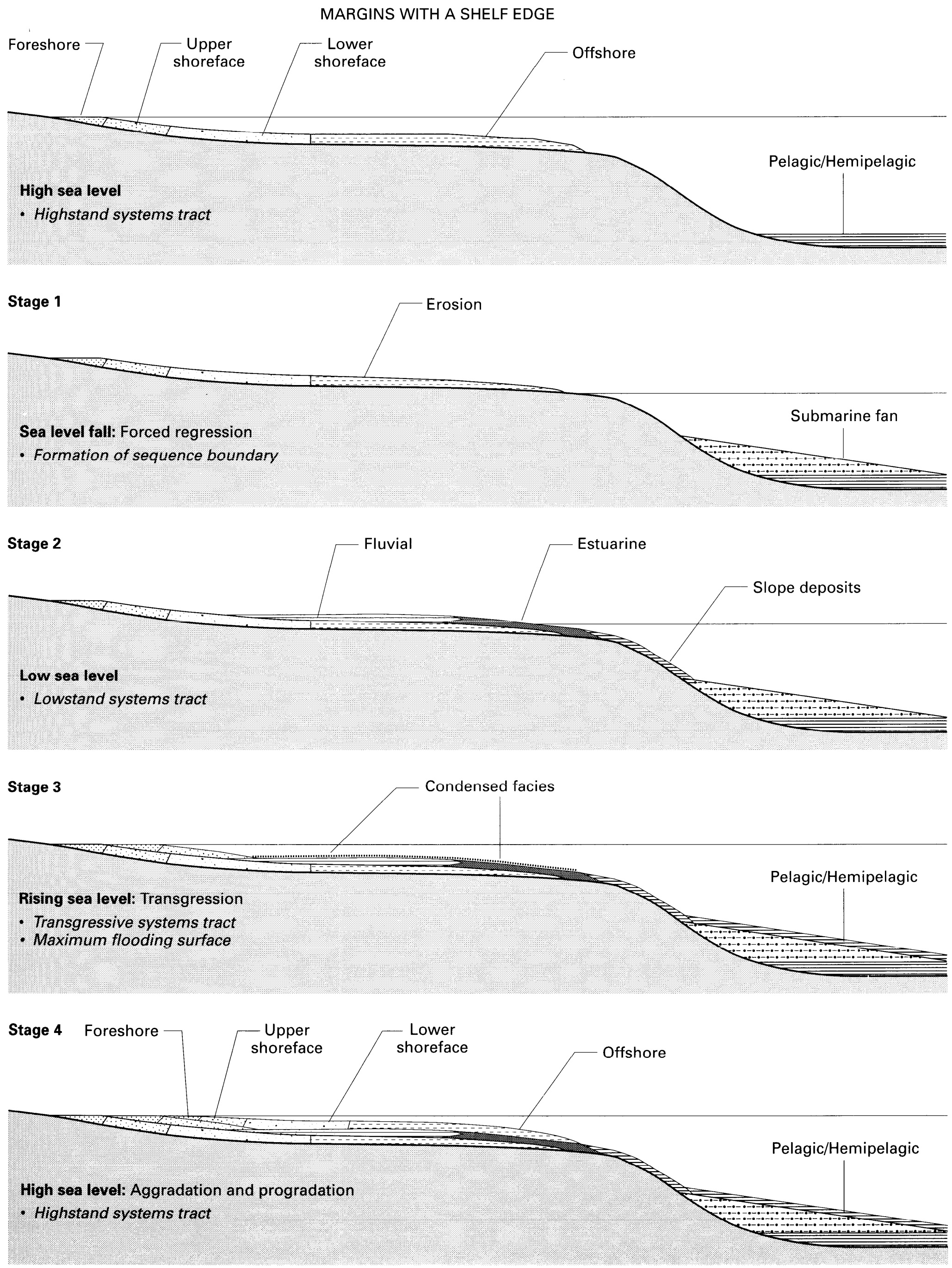
- Bounded below by maximum flooding surface and above by overlying sequence boundary
- Generally shingled or offlapping (clinoformal) stratal geometry
- Sets of high-frequency cycles show upward thinning and upward shallowing trends




HIGHSTAND SYSTEMS TRACT: AGGRADATIONAL TO PROGRADATIONAL PARASEQUENCE SET
TRANSGRESSIVE SYSTEMS TRACT: RETROGRADATIONAL PARASEQUENCE SET
TRANSGRESSIVE SURFACE
LOWSTAND SYSTEMS TRACT, LOWSTAND WEDGE: PROGRADATIONAL PARASEQUENCE SET
DEPOSITIONAL SHORELINE BREAK
SHELF BREAK
CANYON & CANYON FILL
HIGHSTAND SYSTEMS TRACT OF OLDER SEQUENCE
FLUVIAL OR ESTUARINE SANDSTONES WITHIN INCISED VALLEYS
COASTAL-PLAIN SANDSTONES AND MUDSTONES
SHALLOW-MARINE SANDSTONES
SHELF AND SLOPE MUDSTONES AND THIN SANDSTONES
SUBMARINE-FAN AND LEVEE-CHANNEL SANDSTONES
CONDENSED-SECTION DEPOSITS
TYPE-1 SEQUENCE BOUNDARY
PARASEQUENCE
SP
RES
100 FT.
TRANSGRESSIVE SURFACE
SP
RES
100 FT.
LOWSTAND SYSTEMS TRACT, SLOPE FAN
LOWSTAND SYSTEMS TRACT, BASIN-FLOOR FAN
WELL-LOG RESPONSE OF A PARASEQUENCE: NORMAL VERTICAL ASSOCIATION OF FACIES
WELL-LOG RESPONSE OF LOWSTAND WEDGE AND UNDERLYING SEQUENCE BOUNDARY: ABRUPT VERTICAL CHANGE IN FACIES PRODUCED BY A BASINWARD SHIFT IN FACIES

Siliciklastické systémy

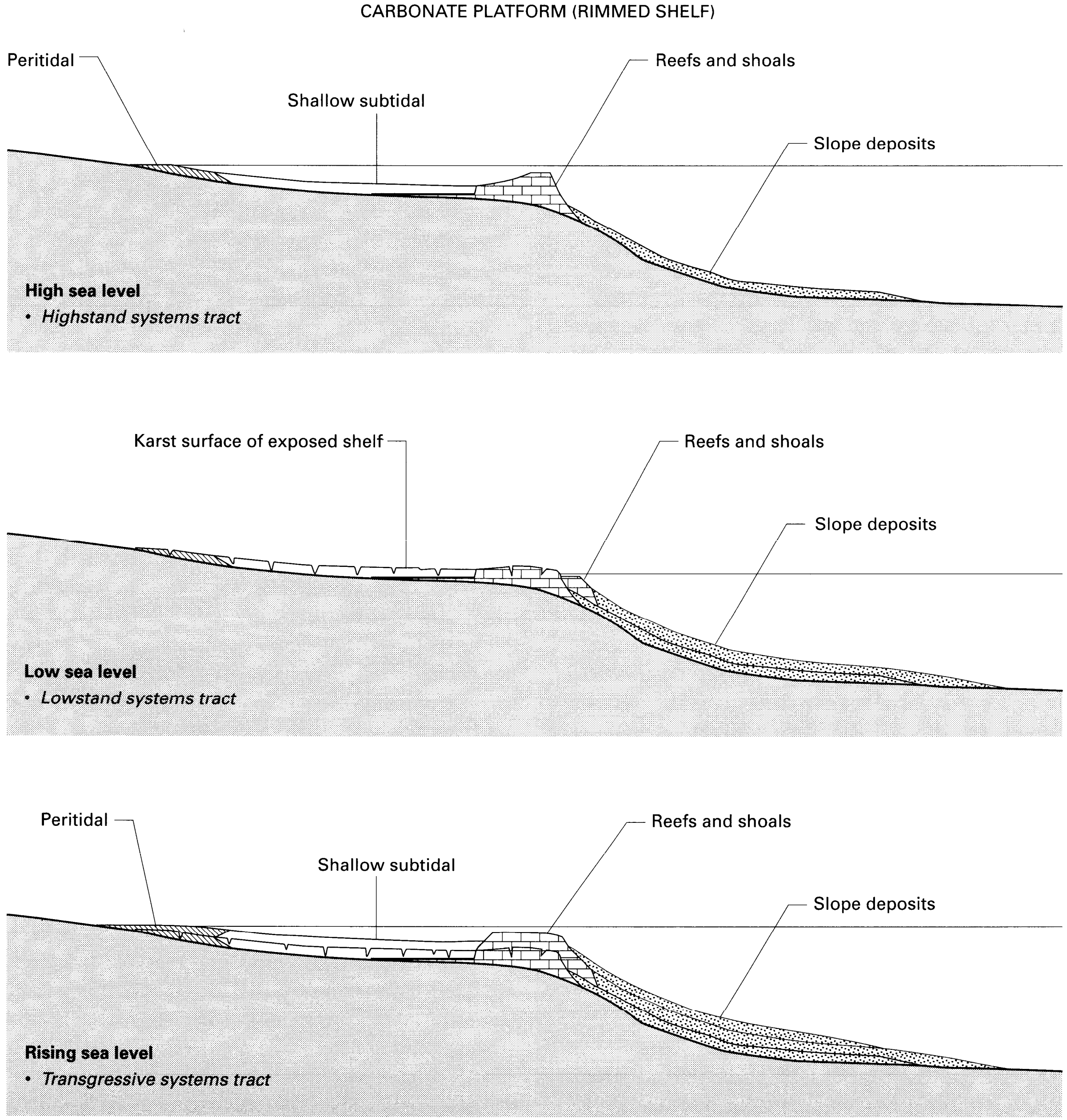
- Relative sea-level fall:
  - fluvial incision into offshore (shelf) deposits
  - usually associated with soil formation (paleovalleys with interfluves)
- Relative sea-level rise
  - filling of paleovalleys, commonly with estuarine or even shallow marine deposits
- Submarine fans in the deep sea:
  - during late highstand and lowstand, when sediments are less easily trapped updip of the shelf break

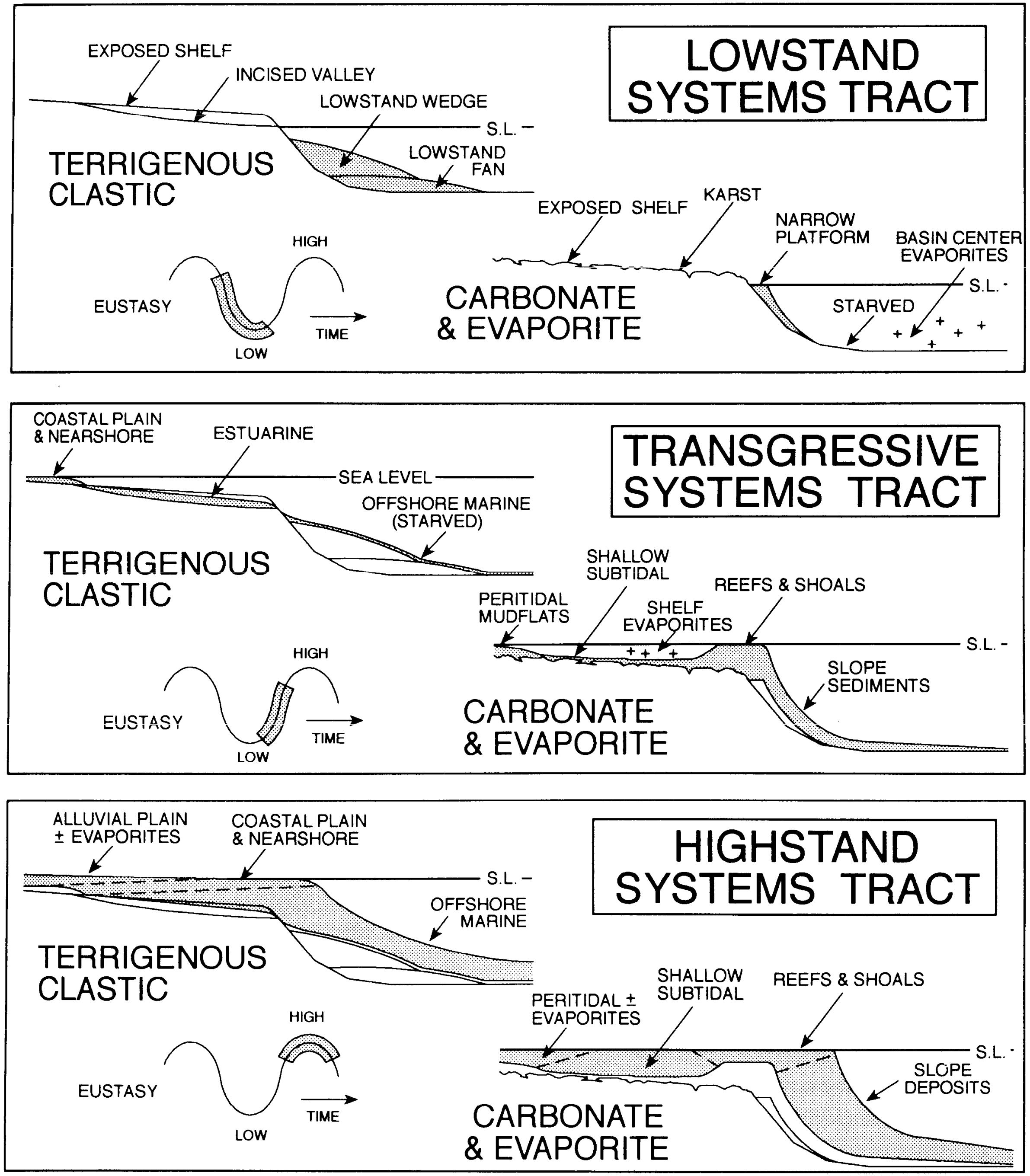


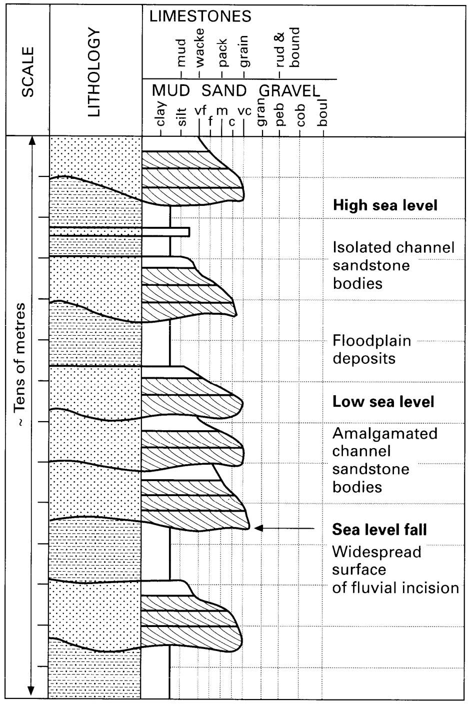
Karbonátové systémy

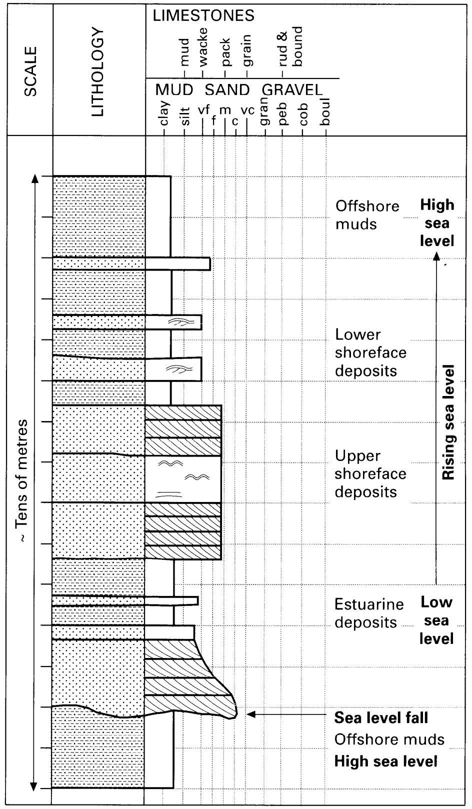
Carbonate environments

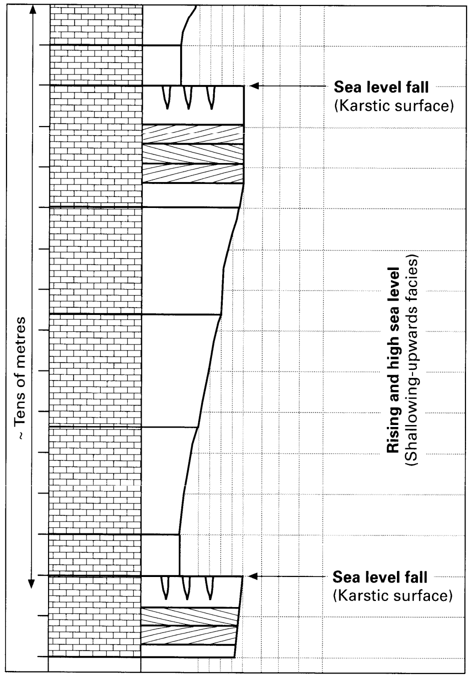
- Relative sea-level fall:
  - development of karstic surfaces (dissolution of limestones) or evaporites (e.g., sabkhas), depending on the climate
- Highstands:
  - expand the area of the carbonate factory (drowning of shelves) and vertical construction of reefs
  - accumulation of other carbonates is enhanced
- Extreme rates of relative sea-level rise:
  - drowning of carbonate platforms

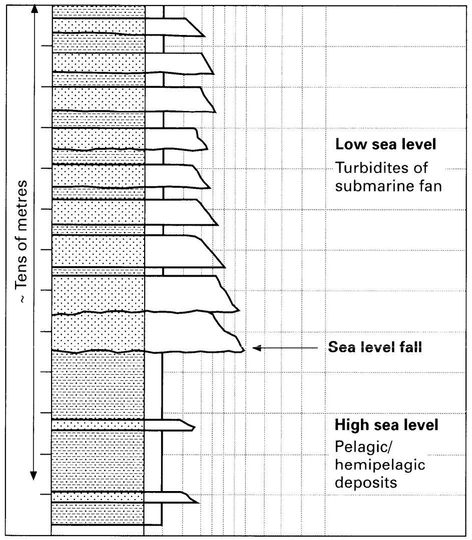



LOWSTAND SYSTEMS TRACT
EXPOSED SHELF
INCISED VALLEY
LOWSTAND WEDGE
S.L.
LOWSTAND FAN
TERRIGENOUS CLASTIC
HIGH
EUSTASY
TIME
LOW
EXPOSED SHELF
KARST
NARROW PLATFORM
BASIN CENTER EVAPORITES
S.L.
STARVED
CARBONATE & EVAPORITE
TRANSGRESSIVE SYSTEMS TRACT
COASTAL PLAIN & NEARSHORE
ESTUARINE
SEA LEVEL
OFFSHORE MARINE (STARVED)
TERRIGENOUS CLASTIC
SHALLOW SUBTIDAL
PERITIDAL MUDFLATS
SHELF EVAPORITES
REEFS & SHOALS
S.L.
SLOPE SEDIMENTS
HIGH
EUSTASY
TIME
LOW
CARBONATE & EVAPORITE
HIGHSTAND SYSTEMS TRACT
ALLUVIAL PLAIN ± EVAPORITES
COASTAL PLAIN & NEARSHORE
S.L.
OFFSHORE MARINE
TERRIGENOUS CLASTIC
SHALLOW SUBTIDAL
PERITIDAL ± EVAPORITES
REEFS & SHOALS
S.L.
SLOPE DEPOSITS
HIGH
EUSTASY
TIME
LOW
CARBONATE & EVAPORITE


SCALE
LITHOLOGY
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
peb
cob
boul
~ Tens of metres
High sea level
Isolated channel sandstone bodies
Floodplain deposits
Low sea level
Amalgamated channel sandstone bodies
Sea level fall
Widespread surface of fluvial incision


SCALE
LITHOLOGY
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
peb
cob
boul
~ Tens of metres
Offshore muds
High sea level
Lower shoreface deposits
Rising sea level
Upper shoreface deposits
Estuarine deposits
Low sea level
Sea level fall
Offshore muds
High sea level


~ Tens of metres
Sea level fall
(Karstic surface)
Rising and high sea level
(Shallowing-upwards facies)
Sea level fall
(Karstic surface)


~ Tens of metres
Low sea level
Turbidites of submarine fan
Sea level fall
High sea level
Pelagic/ hemipelagic deposits

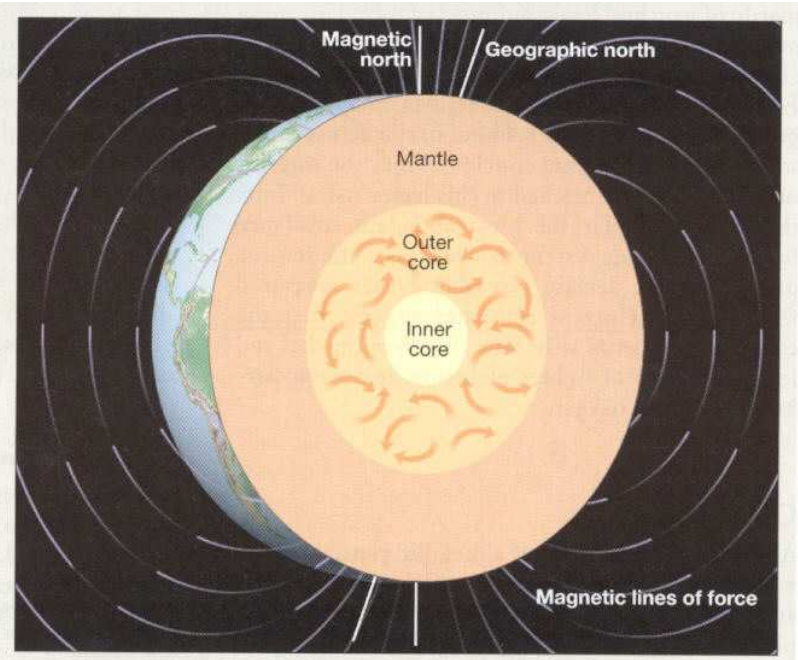
Problémy sekvenční stratigrafie

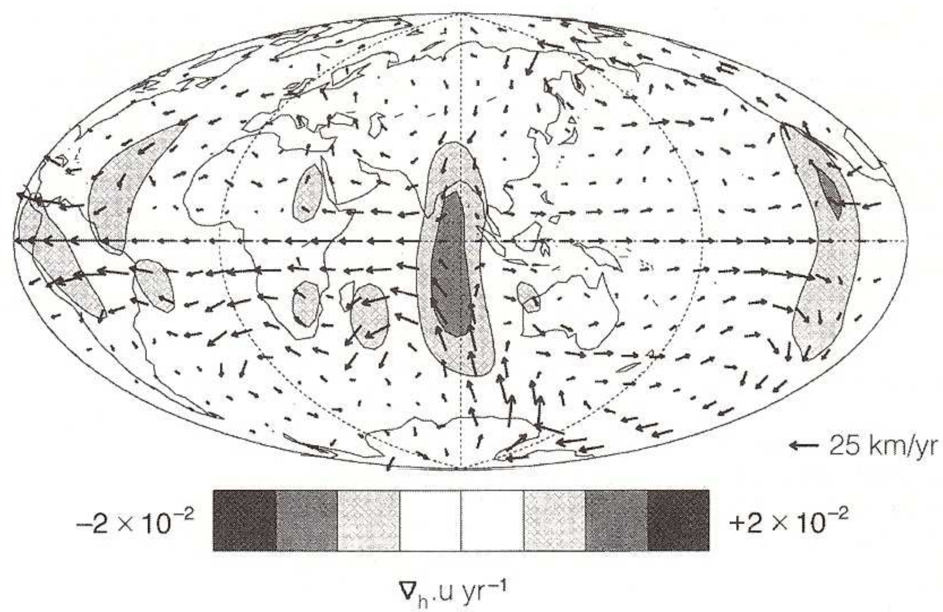
- **Sequence-stratigraphic concepts contain numerous pitfalls!**

- Variations in sediment supply can produce stratigraphic products that are very similar to those formed by sea-level change
- Sea-level fall does not necessarily always lead to the formation of well-developed sequence boundaries (e.g., fluvial systems do not always respond to sea-level fall by means of incision); sequence boundaries may therefore be very indistinct and difficult to detect
- Allogenic incision is easily confused with autogenic scour

MAGNETOSTRATIGRAFIE
Původ zemského magnetismu

- Původ zemského magnetismu: vnější jádro Země.
- Feromagnetické látky ztrácejí své magnetické schopnosti již při teplotě okolo 500 st. C (Curieův bod) a teplota v zemském jádře přesahuje 4000 st. C, nemůže být jádro permanentním magnetem.
- Vysvětlení : Teorie hydromagnetického dynama (první polovina 20. století)
- Seismologická měření: vnější jádro Země je kapalné, je tvořeno proudícími elektricky vodivými látkami
- Faradayův zákon magnetické indukce: pohyb vodiče v elektrickém poli indukuje magnetické pole a naopak -- v našem případě proudění vodivých látek ve vnějším jádře indukuje magnetické pole Země.





Magnetická inklinace a deklinace

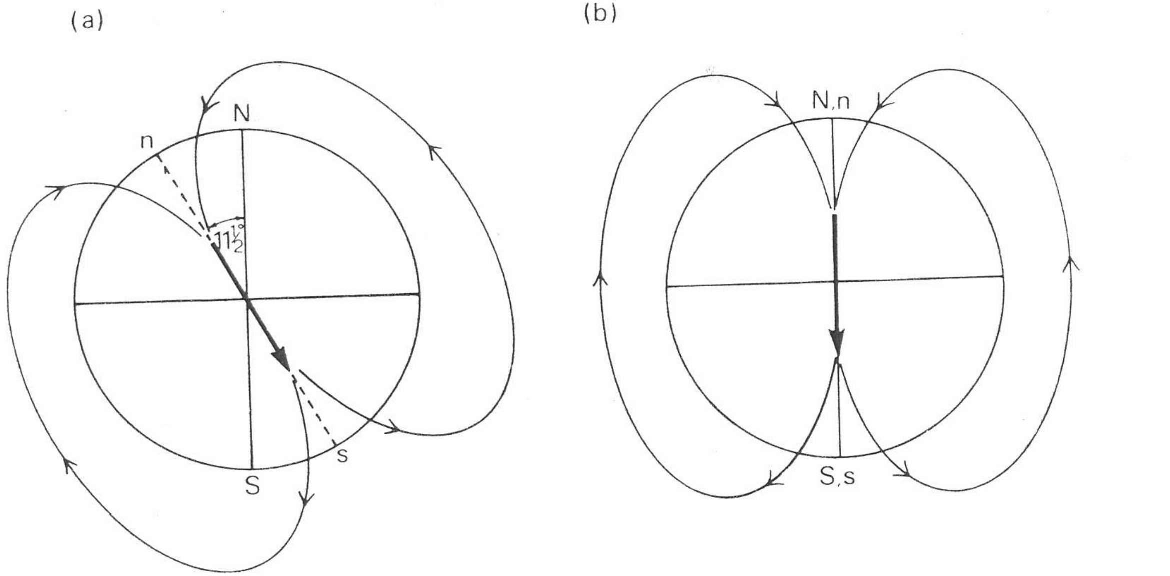


FIG. 1. (a) Model for present day geomagnetic field. Best fitting magnetic dipole axis is inclined at about 11.5° to the geographical axis. (b) Model for time averaged geomagnetic field (over $c.10^4$ years). Best fitting magnetic dipole axis coincides with the geographical axis. N and S are the geographical poles; n and s are the magnetic poles.

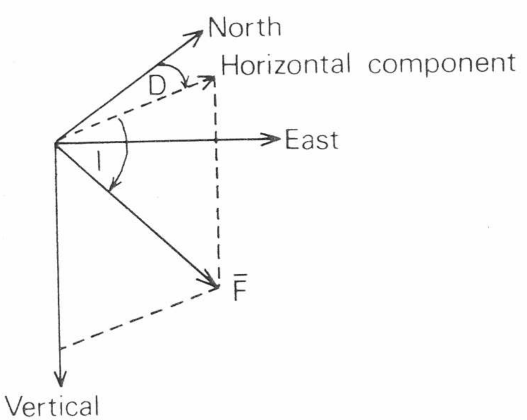


FIG. 2. Specification of direction of geomagnetic field vector, F̄, in terms of angles of declination (D) and inclination (I).

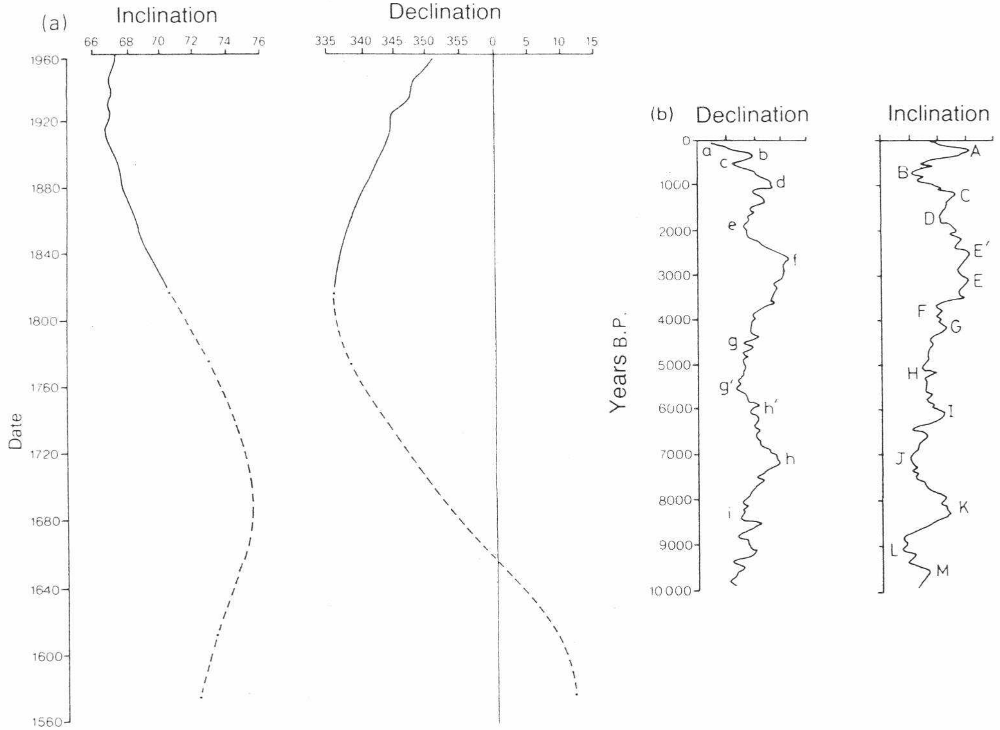


FIG. 4. (a) Variation of geomagnetic inclination and declination at the Greenwich magnetic observatory since 1580. (b) Variations of geomagnetic declination and inclination for the past 10 000 years recorded in the remanent magnetism of UK lake sediments (from Turner & Thompson 1981). Scale divisions are at 5° intervals on both plots. Features of these records that have proved useful for stratigraphical correlations between cores are lettered.

Magnetometrie, magnetometrické veličiny a jednotky

PROPERTY	SI UNIT	SI COMMONLY USED SUB-UNIT	COMMONLY USED cgs UNITS	CONVERSION FACTOR
Intensity of remanent magnetization of rock	Amperes per metre (Am^{-1})	Milliamperes per metre ($mA\ m^{-1}$)	Gauss (G)	$1\ mA\ m^{-1} = 10^{-6} G$
Magnetic moment of rock	Ampere metre^2 (Am^2)	Milliampere metre^2 ($mA\ m^2$)	Gauss cm^3 ($G\ cm^3$)	$1\ mA\ m^2 = 1 G\ cm^3$
Magnetic field	Tesla (T)	Millitesla (mT) Nanotesla (nT)	Oersted (Oe) Gamma (γ)	$1\ mT = 10\ Oe$ $1\ nT = 1\gamma = 10^{-5}\ Oe$
Magnetic susceptibility (per unit volume)	Dimensionless		Gauss/ oersted ($G.Oe^{-1}$)	1 SI unit $= 4\pi$ $G.Oe^{-1}$

FIG. 6. Magnetic units.

Remanentní magnetizace

- Remanentní magnetismus – zbytkový magnetismus
- Nositelé magnetismu v horninách: minerály Fe:
  - Oxidy, hydroxidy, sulfidy Fe: (titanomagnetit, ilmenohematatit, maghemit – γFe_2O_3, hematit αFe_2O_3), goethit, spontánní magnetizace magnetitu cca 200x vyšší než u hematitu
  - Fylosilikáty Fe, amfiboly a pyroxeny – indukovaný magnetismus v aktuálním magnetickém poli, nejsou nositeli remanentního magnetismu
- Blocking temperature

Magnetizace hornin

- Termoremanentní magnetizace (TRM)
  - Currie Point – Below which the igneous rock's magnetic record is fixed
  - Effective on lava flows and baked clays at archaeological sites
- Detritická remanentní magnetizace (DRM)
  - Magnetic particles become aligned with the ambient magnetic field as they settle through the water column
- Postdepoziční magnetizace
  - Based on the water content for some sediments, they may take on their magnetic characteristic after deposition
- Chemická remanentní magnetizace (CRM)
  - Post-Depositional magnetization due to chemical changes in magnetic minerals
- Viskózní remanentní magnetizace (VRM)

Primární a sekundární magnetizace: testy

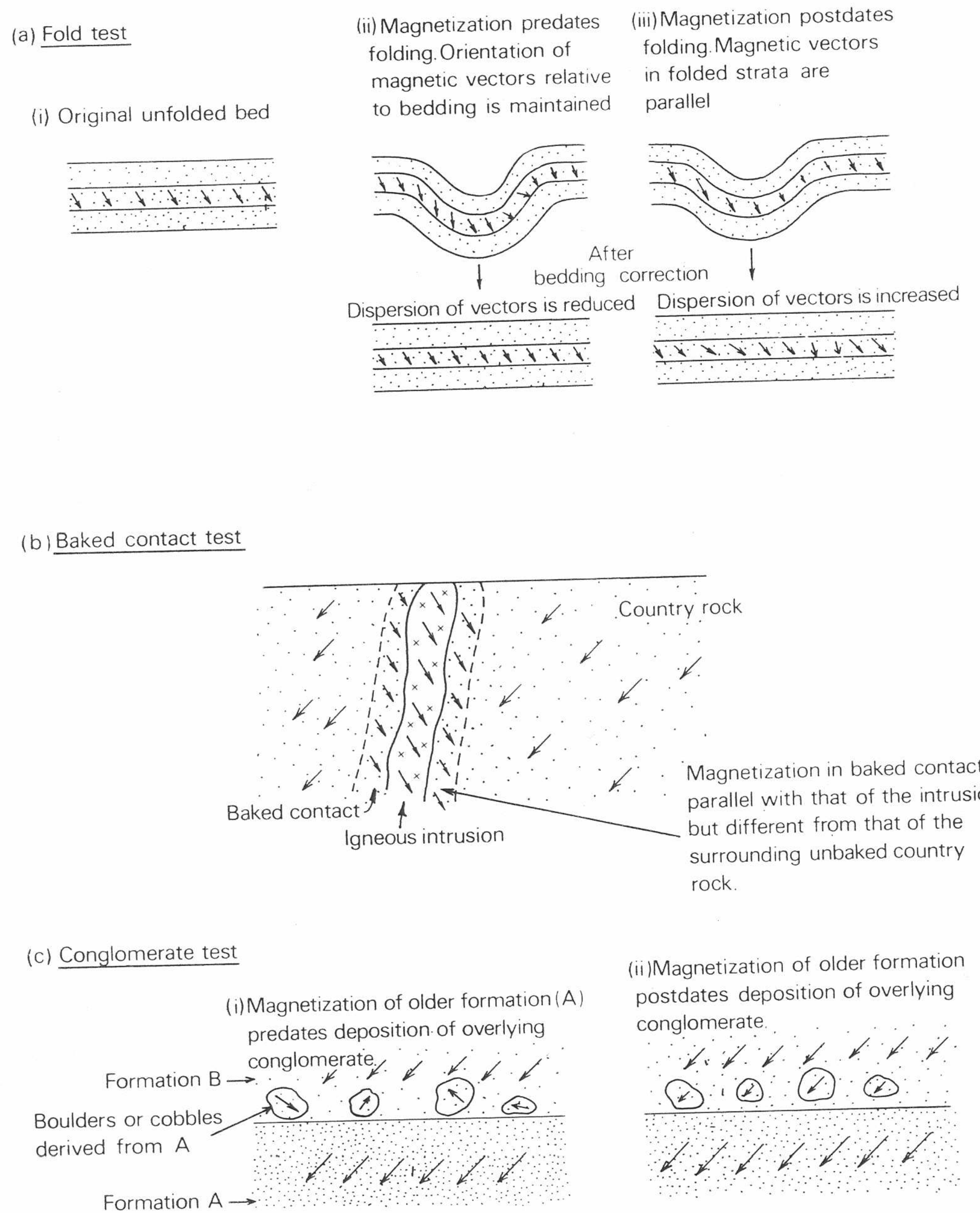


FIG. 8. Field stability tests. Small arrows represent magnetization vectors.

Přirozená remanentní magnetizace

- Primární magnetizace
- Sekundární magnetizace
- Běžně více fází magnetizace: posloupnost magnetizací

Demagnetizace

- Separace různých komponent remanentního magnetismu s různými blokovacími teplotami
- Magnetometry

Magnetická polarita

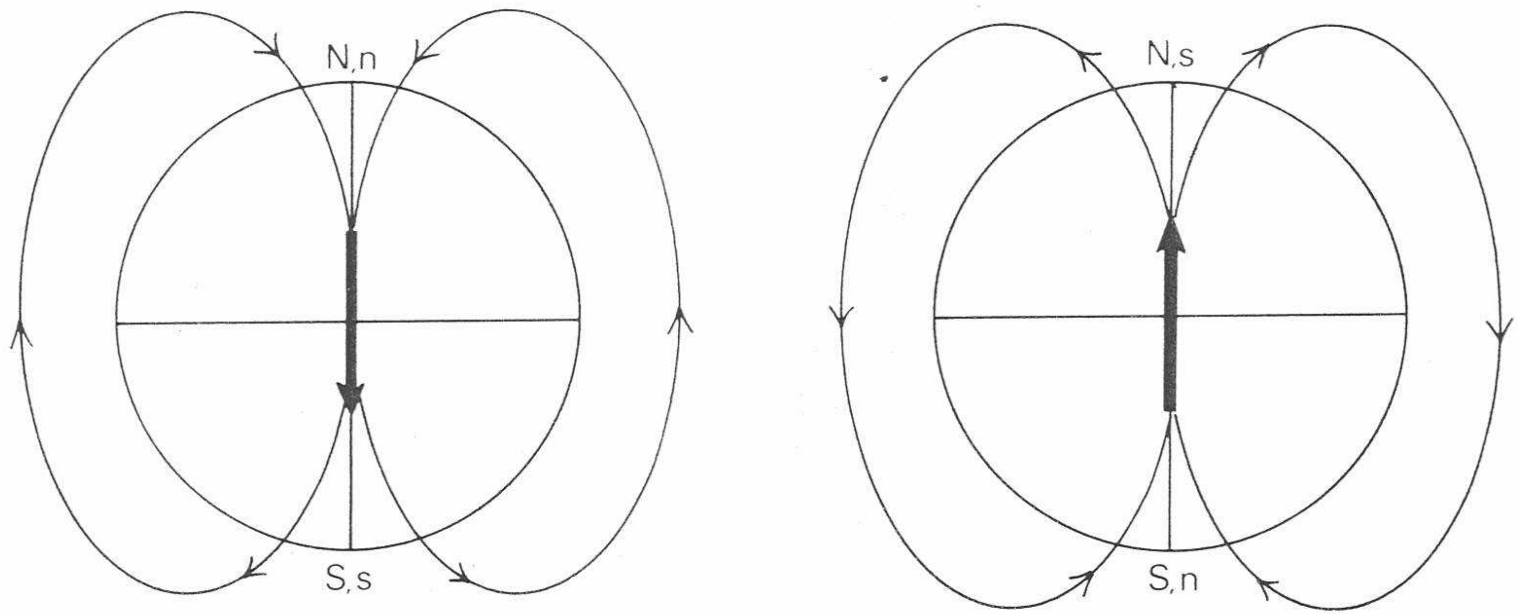


FIG. 5. Configuration of the axial dipole geomagnetic field during (a) a normal polarity interval: and (b) a reverse polarity interval. During a normal polarity interval the magnetic north pole (n) lies close to the geographical north pole (N). Consequently, during a normal polarity interval the lines of force are directed towards the geographical north pole. The magnetic declination is northerly, and the inclination is positive (downward-directed) in the northern hemisphere and negative (upward-directed) in the southern hemisphere. Conversely, during a reverse polarity interval the magnetic declination is southerly, and the inclination is negative in the northern and positive in the southern hemisphere.

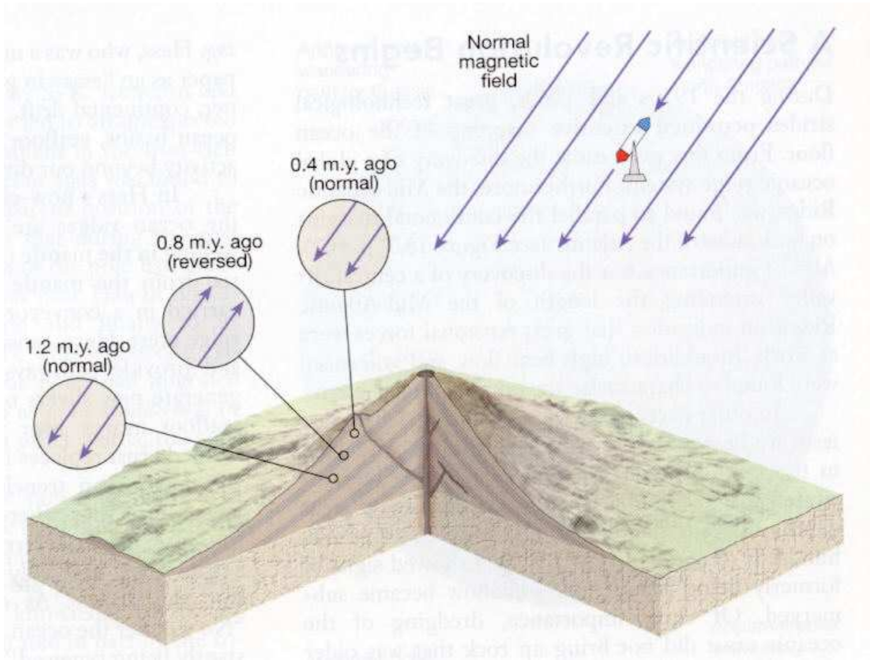
Změny magnetického pole

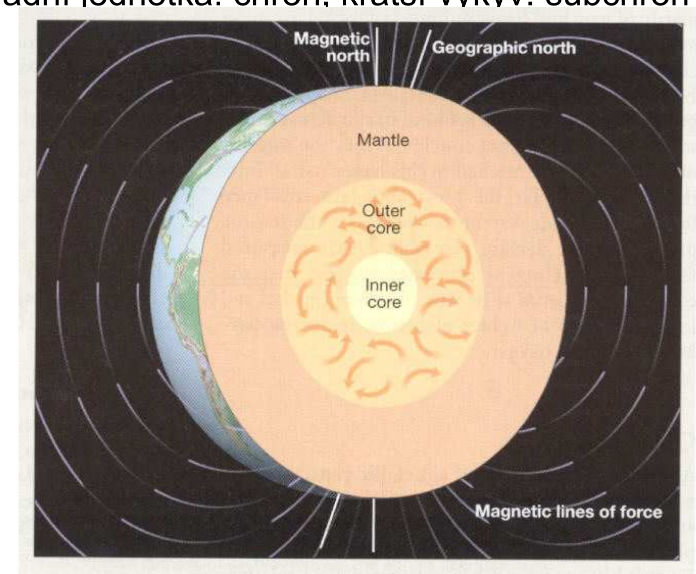
TIME SCALE OF FLUCTUATIONS, OR RECURRENCE INTERVAL	NATURE OF VARIATION	SOURCE
< 5 years	Transient field fluctuations	External (solar activity)
$10^2 - 10^4$ years	Secular variations and geomagnetic 'excursions'	Internal (core processes)
$10^4 - 10^7$ years	Polarity reversals	
$10^7 - 10^8$ years	Polarity bias and reversal frequency.	

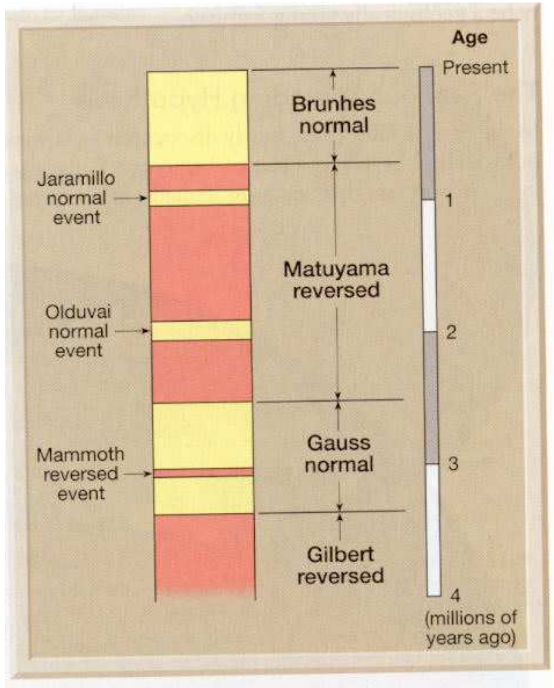
FIG. 3. Variations of the geomagnetic field with time.

Změny orientace magnetického pole

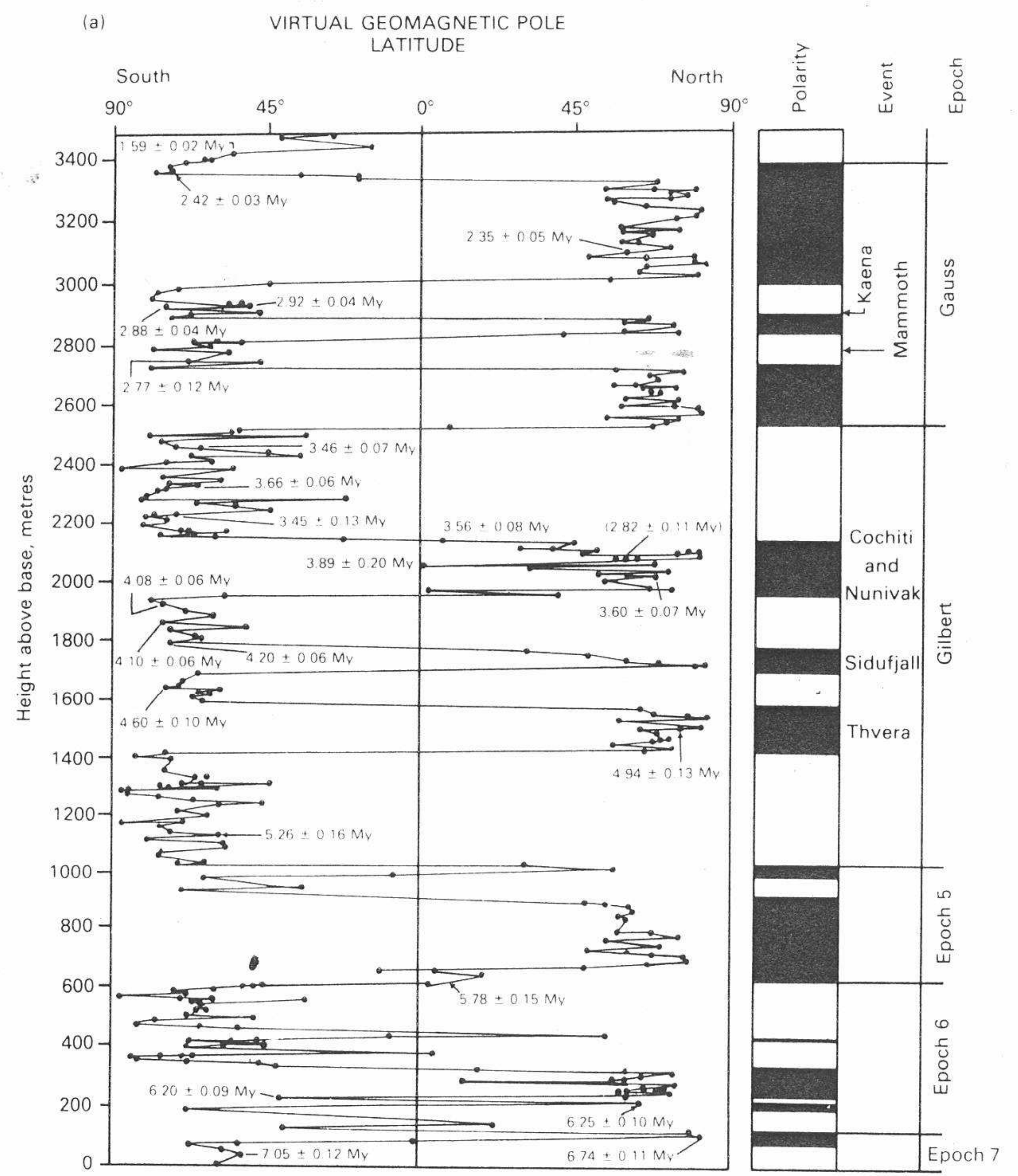
- Celá řada hornin je samovolně magnetizovatelná - feromagnetické minerály se orientují souhlasně se siločarami zemského magnetického pole a vytvářejí tak vlastní magnetická pole.
- Měřením zbytkových magnetických polí změny magnetického pole Země.
- Změny – intenzita, deklinace, přepólování
- období normální magnetické polarity (severní magnetický pól u severního pólu rotace)
- Období reverzní magnetické polarity (severní magnetický pól poblíž jižního pólu rotace).
- Poslední přepólování : 790 000 let, kdy se změnila polarita z reverzní na normální (dnešní).
- Základní jednotka: chron, kratší výkyv: subchron







Magnetostratigrafie



Magnetostratigrafické jednotky

- Chron

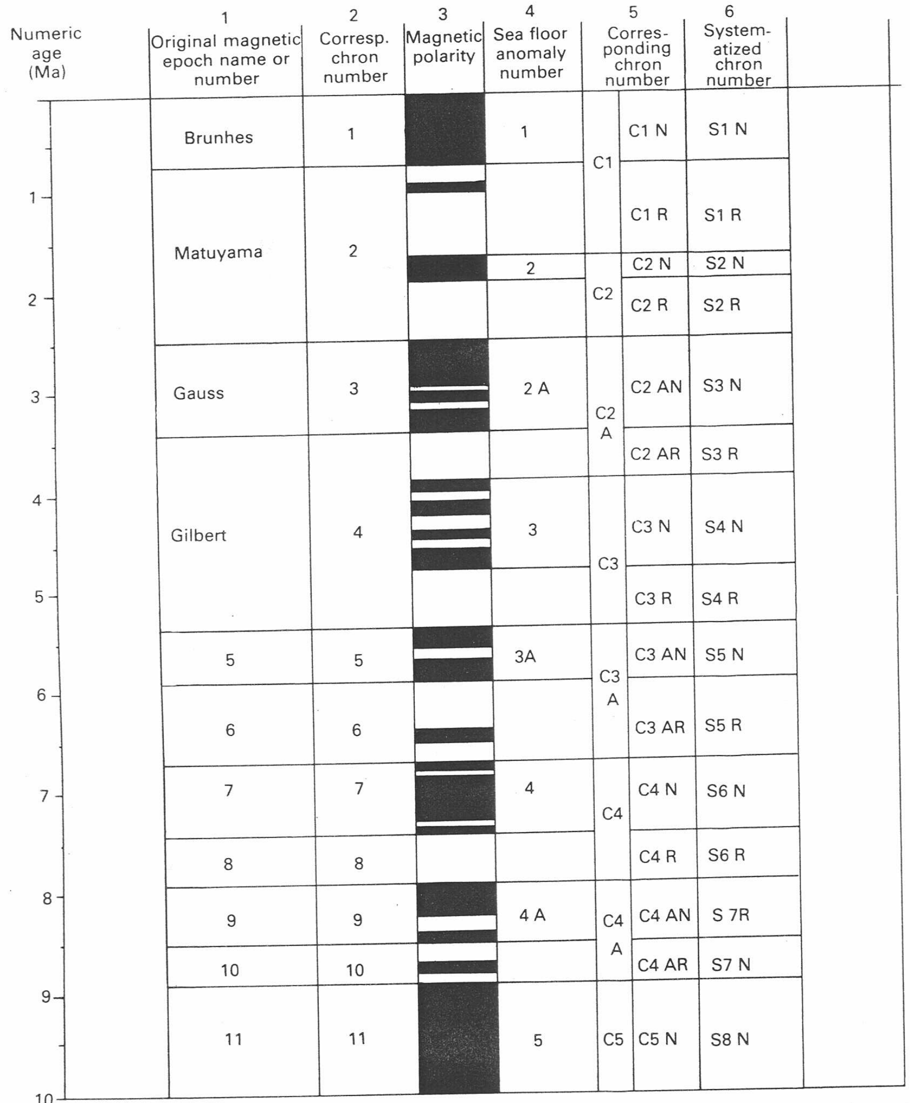


FIG. 18. Comparison of labelling and numbering schemes used for magnetic epochs and chrons. The schemes in columns 1 and 2 are based on the magnetostratigraphic record of sediment and lava sequences. Those in columns 4–6 are based on marine magnetic anomalies. Correlation of columns 2 and 5 is that proposed by Berggren *et al.* (1985). (After Hailwood, *in press*.)

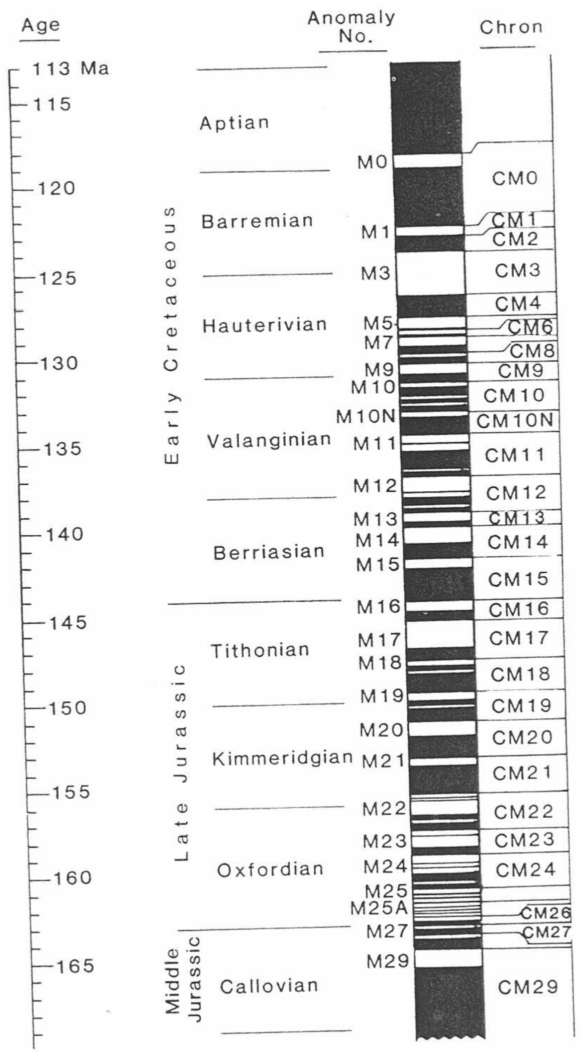
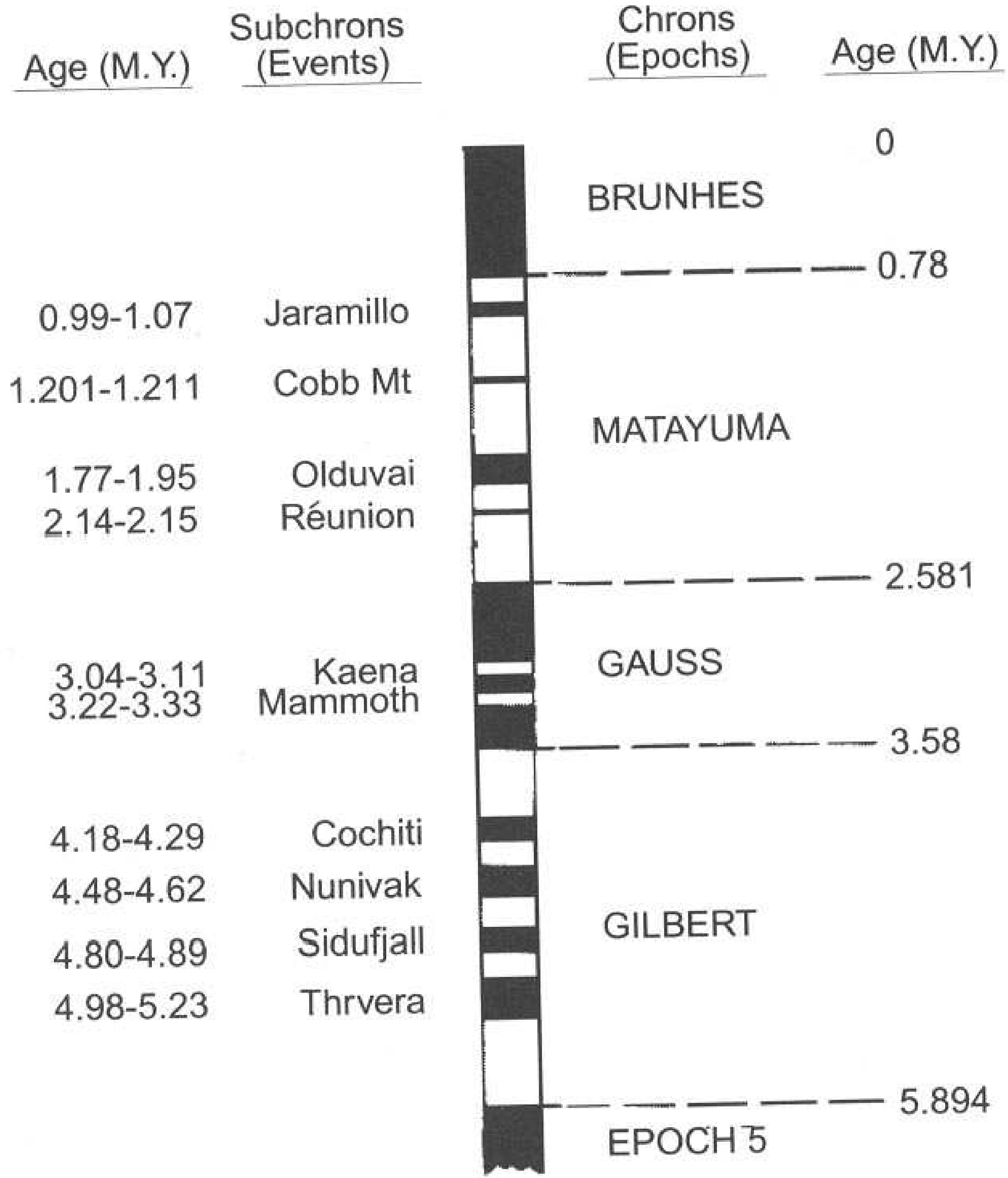


FIG. 20. Mesozoic chron nomenclature (adapted from Cox 1982).

Magneto-stratigrafické jednotky plio-pleistocénu



Vývoj magnetostratigrafické škály

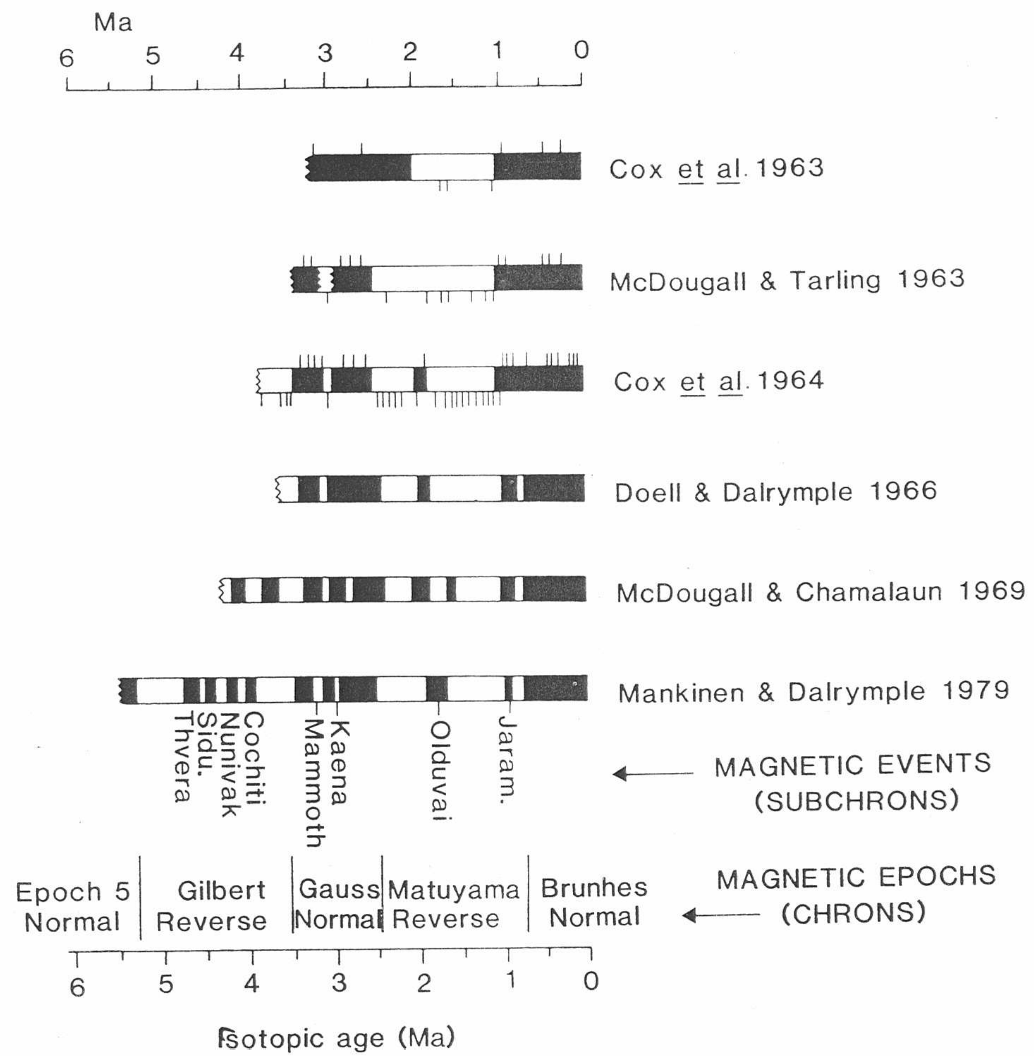


FIG. 9. Some successive versions of the isotopically dated polarity time scale. Note changes in structure of scale as short period magnetic events were discovered progressively. Ticks on upper and lower margins of bars represent positions on time scale of isotopically dated rocks having a normal or reverse polarity characteristic magnetization, respectively. On bars normal polarity intervals are shaded and reverse polarity intervals are white.

Magnetostratigrafická korelace

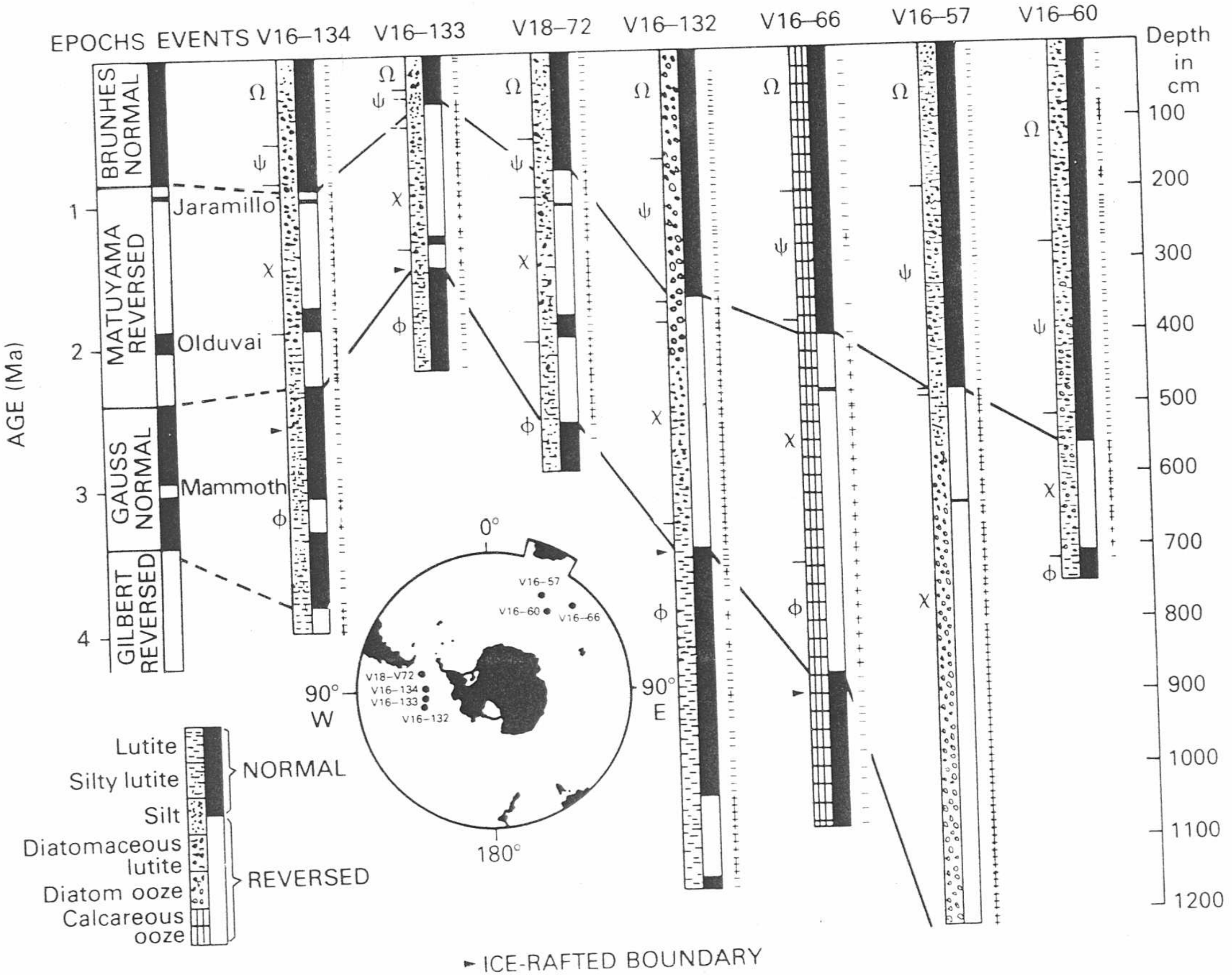


FIG. 11. Correlation of magnetozones in seven deep sea cores from the Antarctic by Opdyke *et al.* (1966). Minus signs indicate normally magnetized specimens; plus signs reversely magnetized. Greek letters denote radiolarian faunal zones. Note consistent relationship between faunal and magnetostratigraphic boundaries in different cores. Numerical ages of the faunal boundaries can be determined from the magnetostratigraphic correlation with the isotopically dated polarity time scale shown at the left.

Magnetostratigrafická korelace

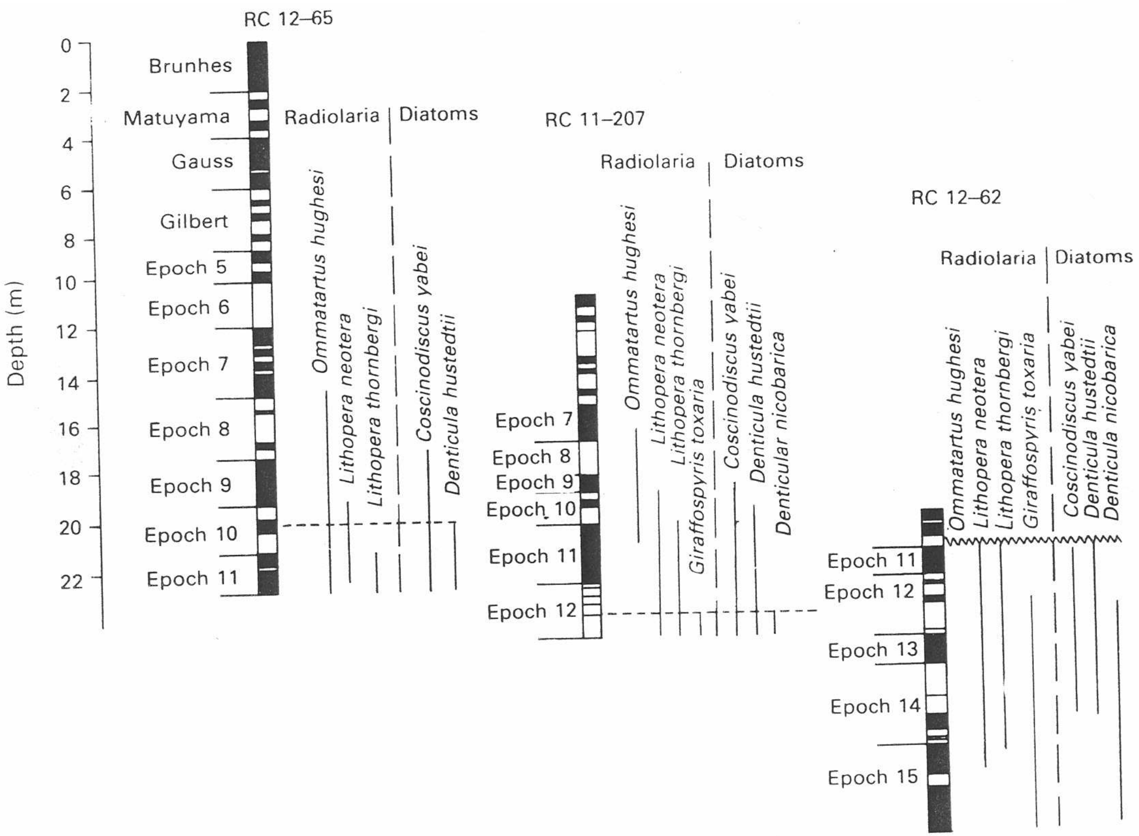
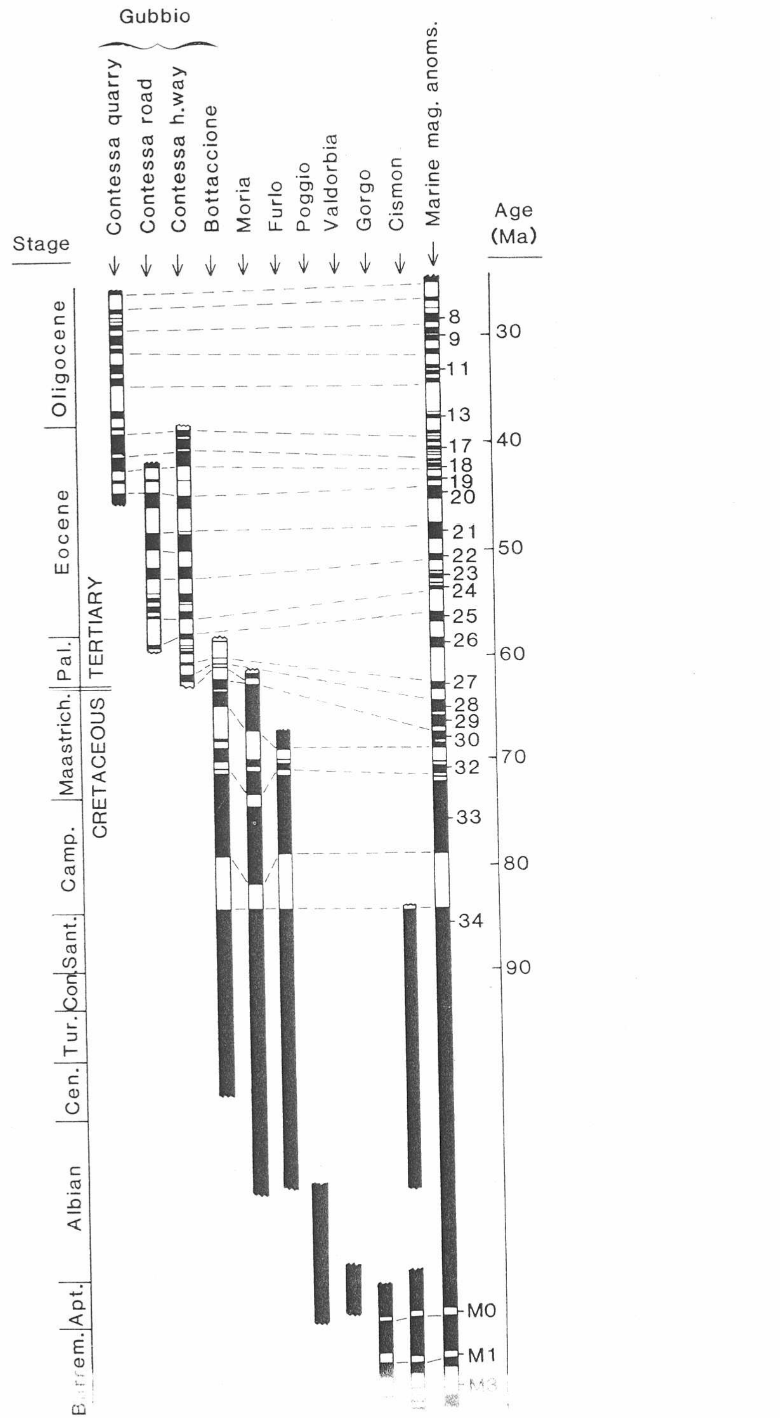


FIG. 12. Extension of biostratigraphically calibrated polarity time scale back to Epoch (Chron) 15 (mid Miocene) through correlation of biostratigraphically dated magnetozones in three cores from the central Pacific (from Opdyke 1972).



Correlation of magnetic reversal sequences in ten sections of pelagic limestones spanning the time inter n to Oligocene in the Umbrian Appenines and southern Alps. The magnetostratigraphic zones are link floor magnetic anomaly sequence shown on the right. (After Lowrie & Alvarez 1981.)

Magnetostratigrafická korelace K/T boundary

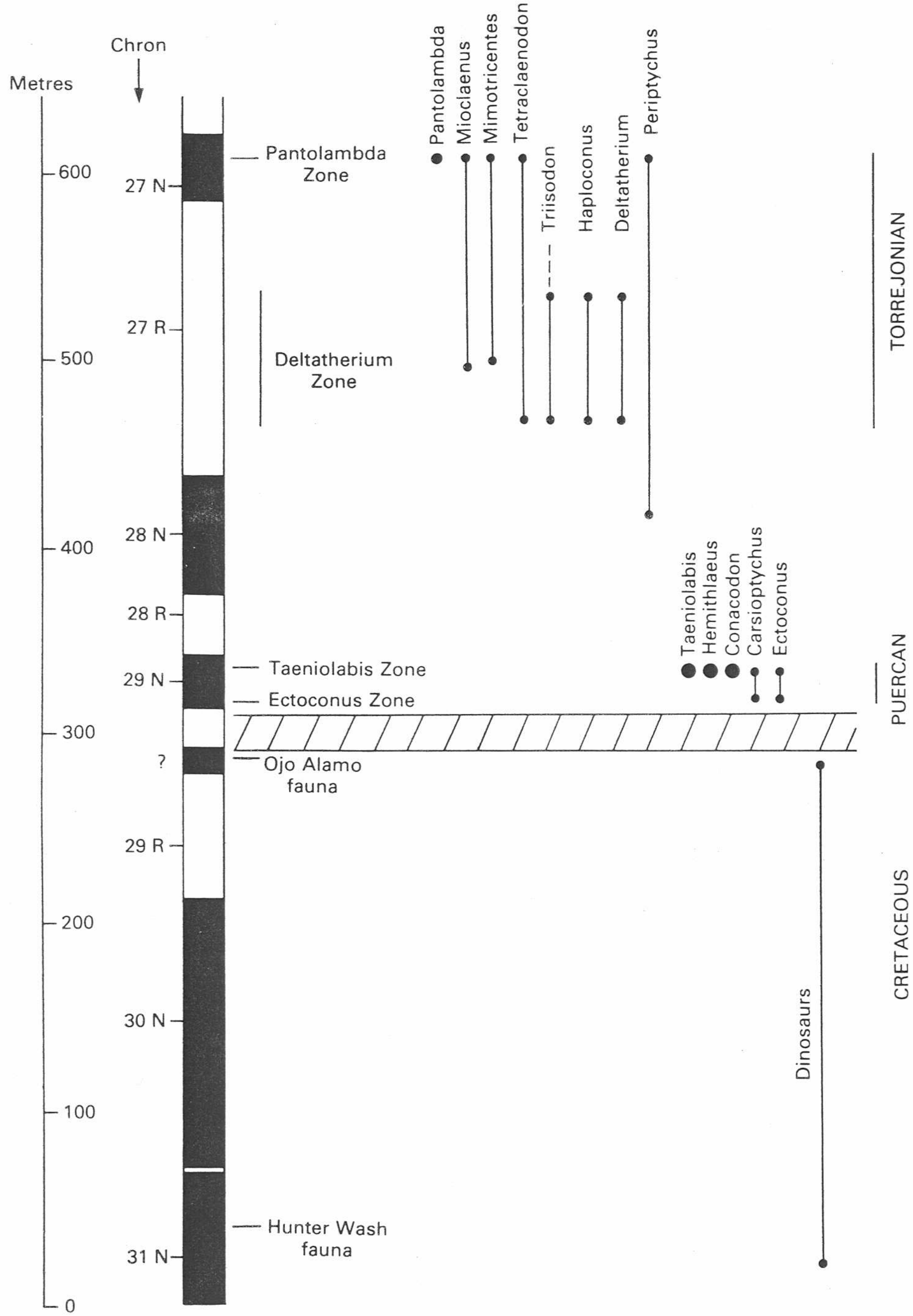


FIG. 32. Location of Cretaceous–Tertiary (K/T) boundary (shown in hachure) in non-marine sediments of the western interior of the USA relative to the magnetic polarity time scale (based on magnetostratigraphic studies of these sediments). Stratigraphical ranges of important fossil species used to define the position of the K/T boundary are shown. (After Lindsay *et al.* 1978 and Butler & Lindsau 1985.)

Sea-floor spreading

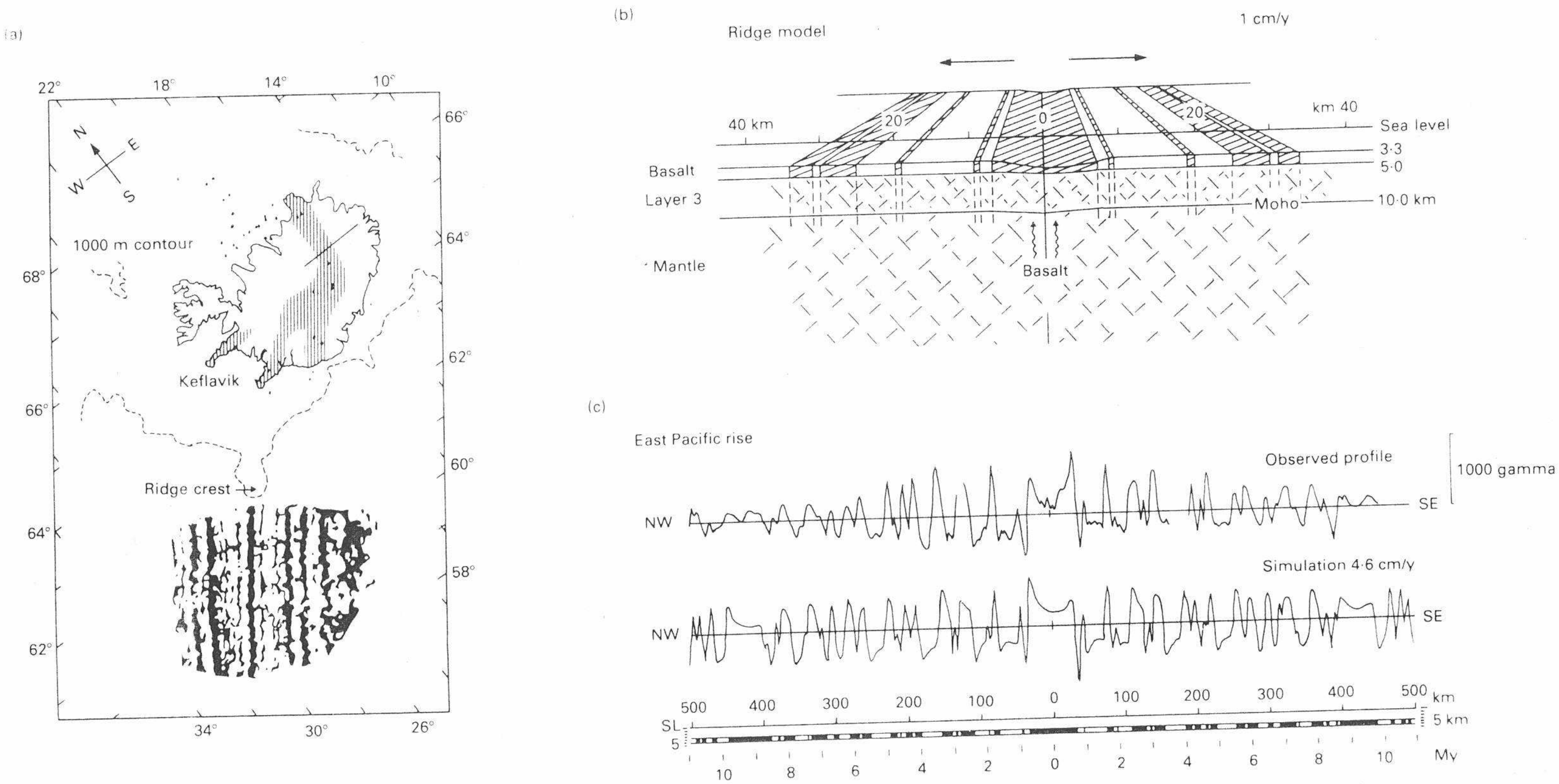


FIG. 15. (a) Patterns of magnetic anomalies over the Reikjanes Ridge south of Iceland (after Heirtzler *et al*. 1966). Note symmetry of pattern either side of ridge crest. (b) Interpretation of observed marine magnetic anomaly patterns in terms of sea floor spreading coupled with geomagnetic polarity reversals. (c) Typical marine magnetic anomaly profile over the East Pacific Rise showing how it can be matched by the similated profile shown underneath, corresponding to the 'block-model' for magnetization in the oceanic crust shown at the bottom (black: normal polarity, white: reverse polarity crust).

Sea-floor spreading

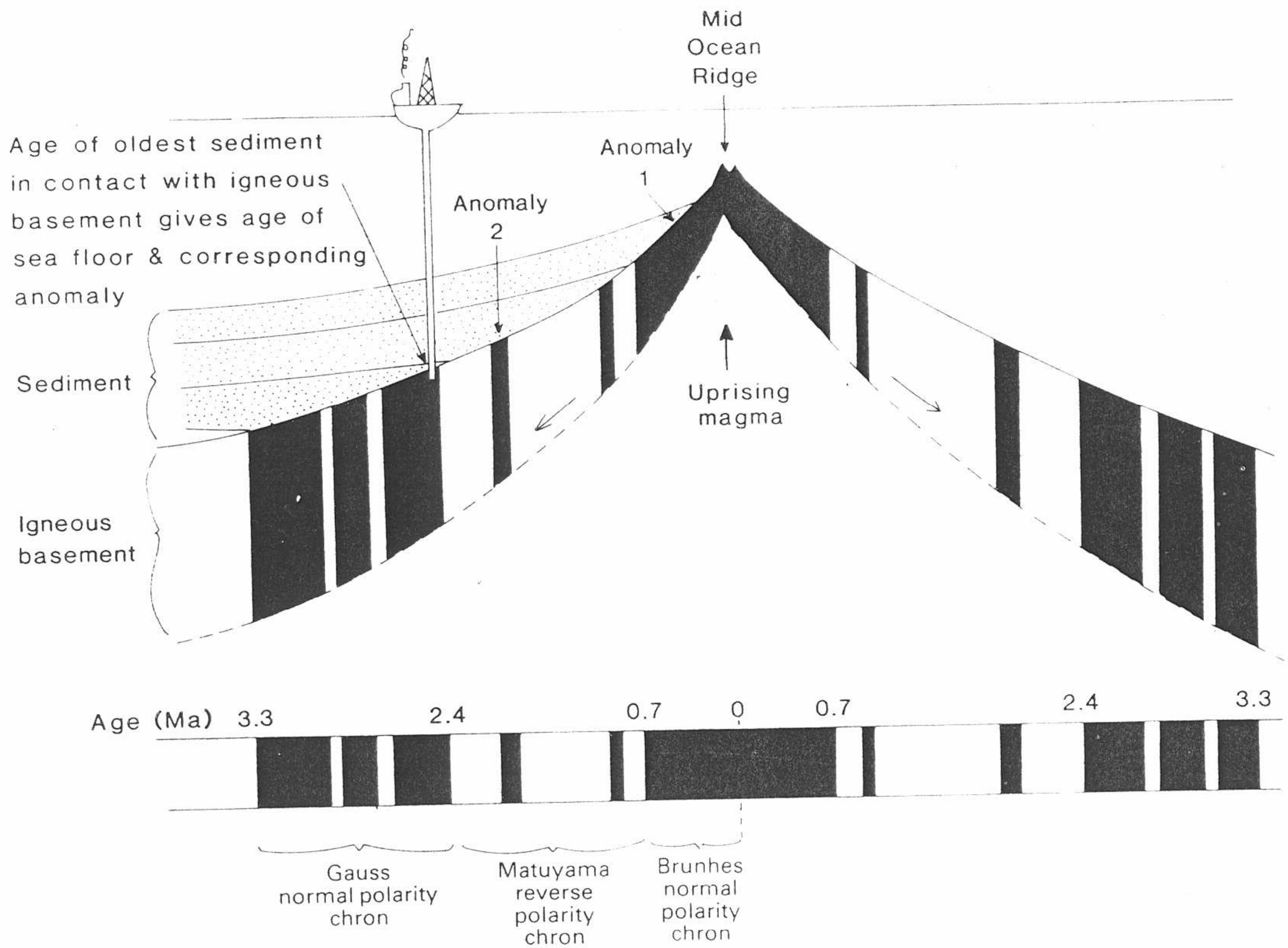


FIG. 17. Schematic diagram illustrating the principle by which the biostratigraphical age of sediment overlying igneous basement can be used to date a particular marine magnetic anomaly, utilizing deep sea drilling.

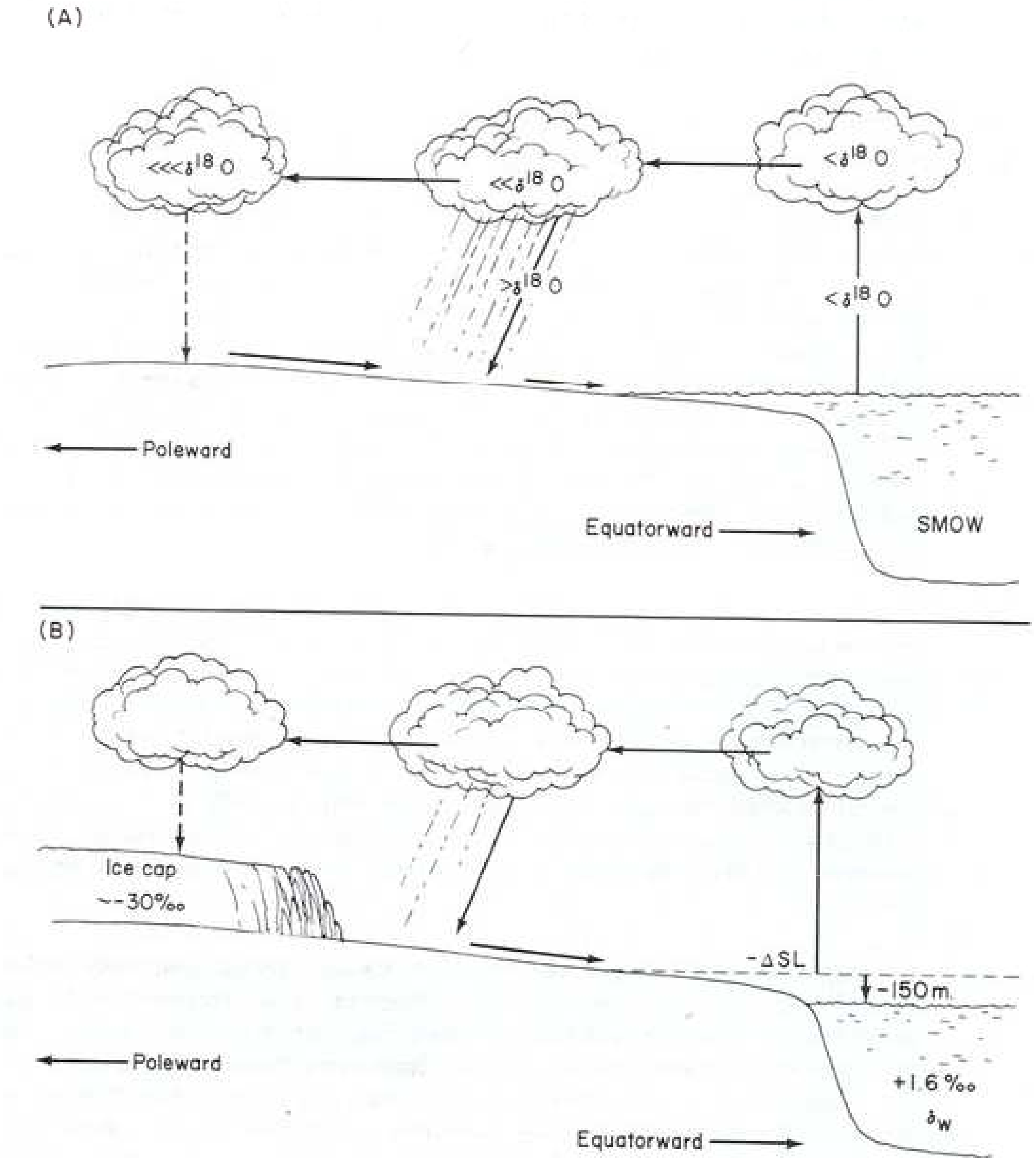
Problémy paleomagnetismu

- DRM is not instantaneous
- Sediments are subject to bioturbation (especially effecting post-depositional DRM)
- Overturned sediment may give false excursions
- Post-Depositional magnetic changes due to chemical recrystallization

Chemostratigrafie: izotopy kyslíku

- A small fraction of water molecules contain the heavy isotope ^{18}O instead of ^{16}O.
- $^{18}O/^{16}O \approx 1/500$
- This ratio is not constant, but varies over a range of several percent.
- Vapor pressure of $H_2{}^{18}O$ is lower than that of $H_2{}^{16}O$, thus $H_2{}^{16}O$ is more easily evaporated.

Frakcionace $^{18}O/^{16}O$ v koloběhu vody



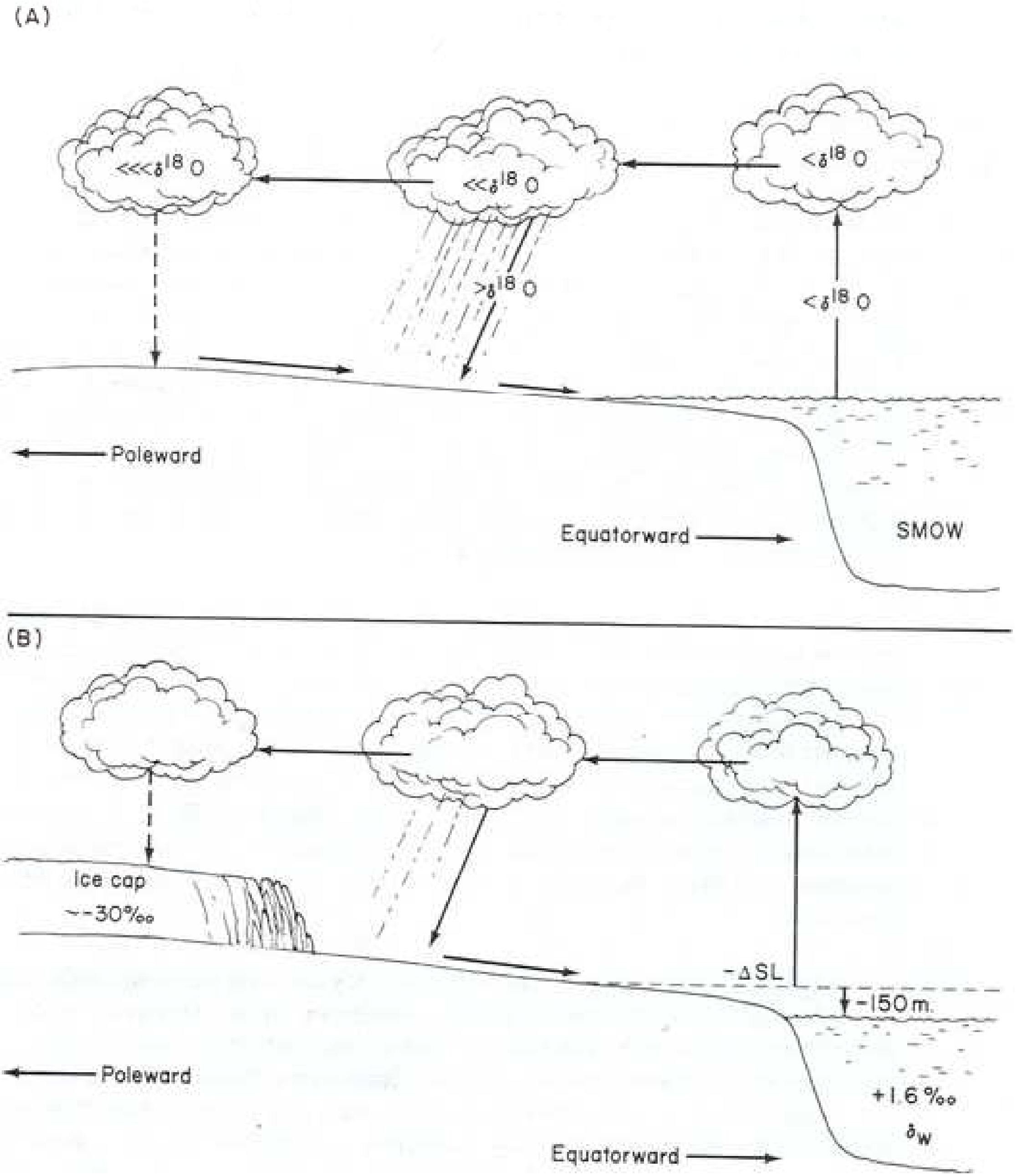
H_2O is evaporated from sea water. The oxygen in the H_2O is enriched in the lighter O_{16}.

This H_2O condenses in clouds,falling on land as precipitation.

Thus, H_2O that is part of the terrestrial water cycle is enriched in the light O_{16} isotope and

Sea water is enriched in the heavier O_{18} isotope

Klimatický význam frakcionace $^{18}O/^{16}O$



Glacial ice is therefore made up primarily of water with the light O_{16} isotope. This leave the oceans enriched in the heavier O_{18}, or "more positive."

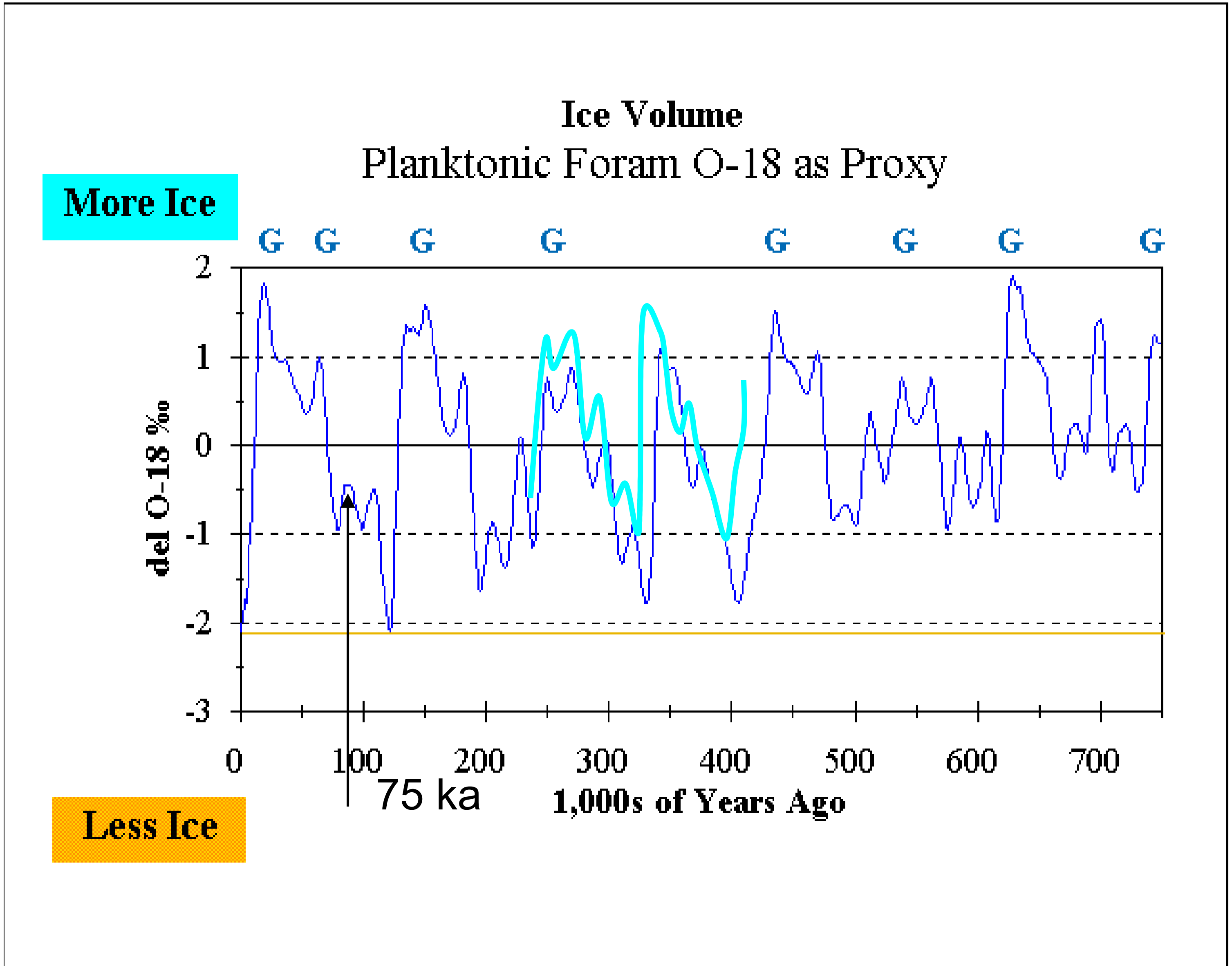
During glacial periods, more O_{16} is trapped in glacial ice and the oceans become even more enriched in O_{18}.

During interglacial periods, O_{16} melts out of ice and the oceans become less O_{18} rich, or "more negative" in O_{18}

$^{18}O/^{16}O$ a globální objem ledu

- As ice sheets grow, the water removed from the ocean has lower $\delta^{18}O$ than the water that remains.
- Thus the $\delta^{18}O$ value of sea water in the global ocean is linearly correlated with ice volume (larger $\delta^{18}O \rightarrow$ larger ice sheets).
- A time series of global ocean $\delta^{18}O$ is equivalent to a time series of ice volume.

Záznam izotopů kyslíku v mořských sedimentech za posledních 700 tisíc let

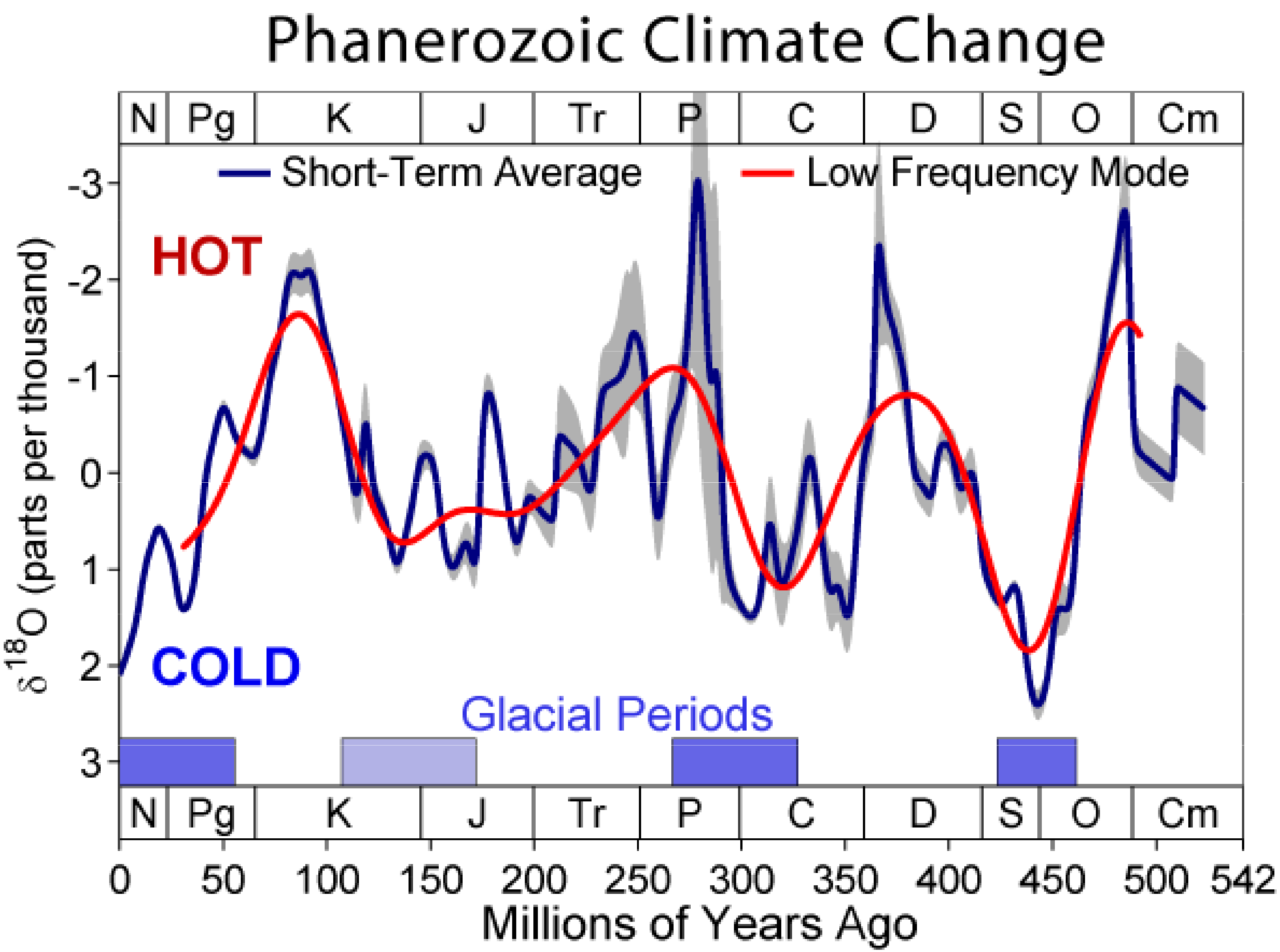


Vrtné projekty DSDP a ODP

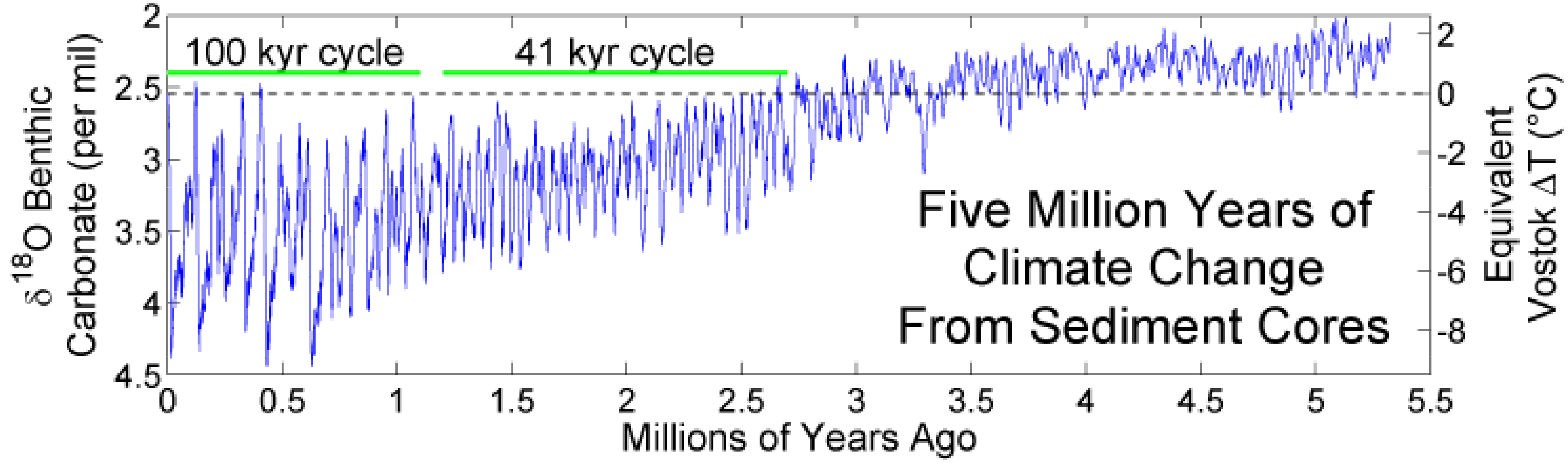
Pelagické sedimenty, cca konstantní rychlost sedimentace, datování

^{18}O v schránkách plaktonních foraminifer ($CaCO_3$)

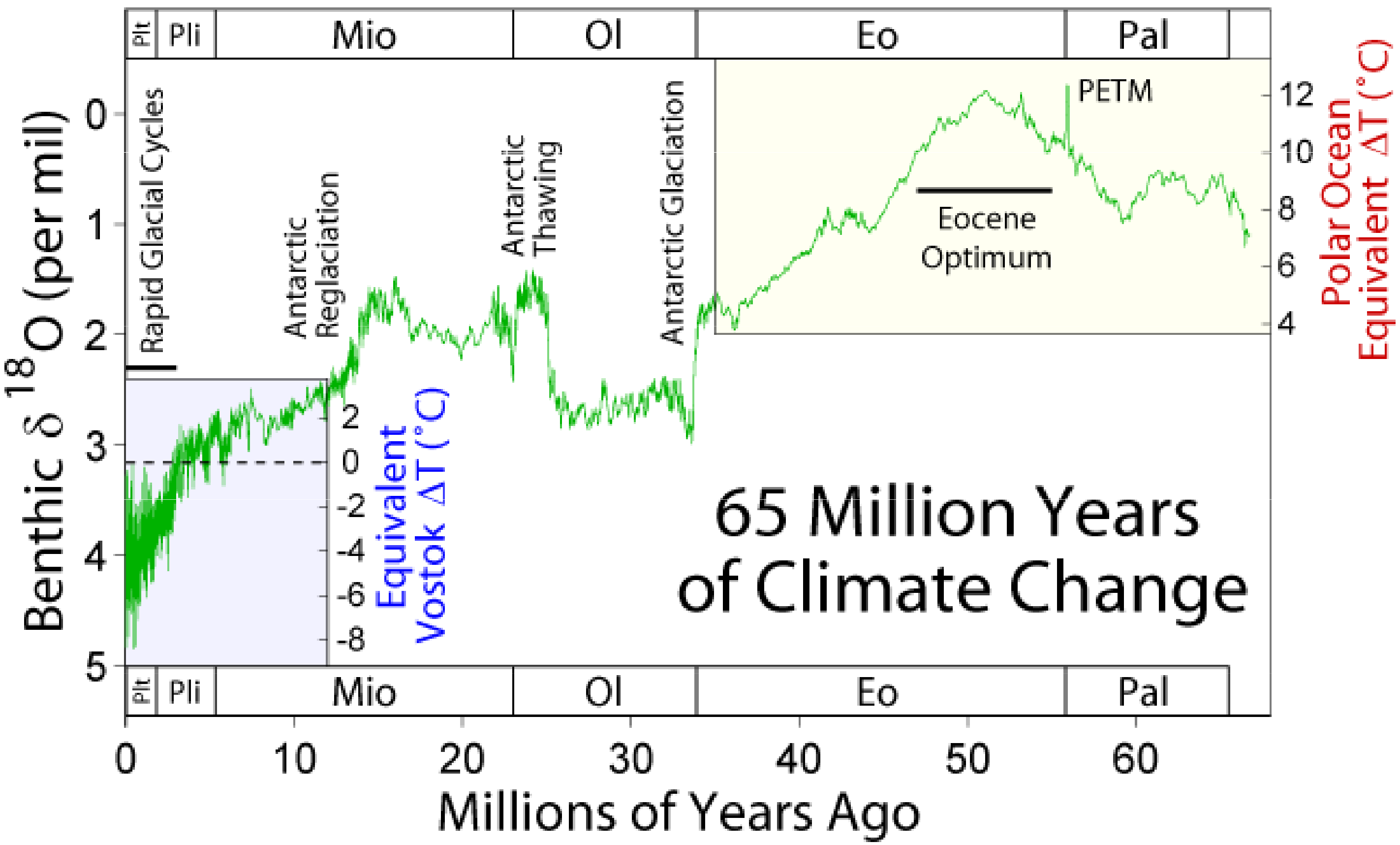
Časové řady



Phanerozoic Climate Change
N
Pg
K
J
Tr
P
C
D
S
O
Cm
Short-Term Average
Low Frequency Mode
HOT
COLD
Glacial Periods
-3
-2
-1
0
1
2
3
δ18O (parts per thousand)
0
50
100
150
200
250
300
350
400
450
500
542
Millions of Years Ago



100 kyr cycle
41 kyr cycle
Five Million Years of
Climate Change
From Sediment Cores
δ18O Benthic
Carbonate (per mil)
Equivalent
Vostok ΔT (°C)
Millions of Years Ago



Plt
Pli
Mio
Ol
Eo
Pal
Rapid Glacial Cycles
Antarctic
Reglaciation
Antarctic
Thawing
Antarctic Glaciation
PETM
Eocene
Optimum
65 Million Years
of Climate Change
Benthic δ18O (per mil)
Equivalent
Vostok ΔT (°C)
Polar Ocean
Equivalent ΔT (°C)
Millions of Years Ago

Chemostratigrafie: stratigrafie izotopů stroncia (SIS)

- Metoda číselného datování
- Poměr izotopů $^{87}Sr/^{86}Sr$
- Chemicky – biochemicky srážené minerály (kalcit): začlenění Sr do krystalové mřížky
- Mořské prostředí (v kontinentálním prostředí lokální vlivy)
- Foraminifery, belemniti, brachiopodi, čistá psací křída
- Poměr 87Sr/86Sr je v moderních oceánech a mořích homogenní
- Další geologické informace z $^{87}Sr/^{86}Sr$ křivek

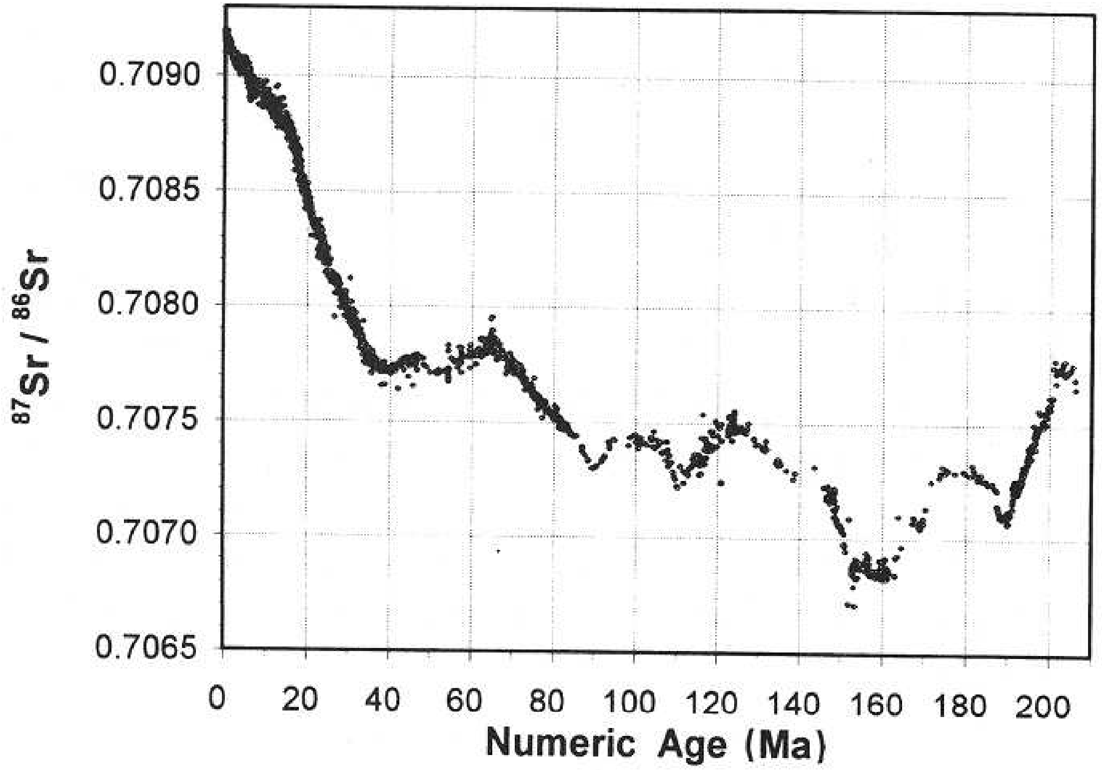


Figure 8.1 *Variation of $^{87}Sr/^{86}Sr$ during the past 206 Ma*

Původ stroncia v mořské vodě

Zdroje:

- Hydrotermální cirkulace na středooceánských hřbetech (plášť)
- Přísun z kontinentu řekami (kontinentální kůra)
- Advekce stroncia z pórových vod během rekrystalizace karbonátů

Časová variabilita:

- Změny v množství přísunu z těchto tří zdrojů
- Změny v izotopickém poměru z pórových vod a v řekách

Source of Sr	Mid-oceanic ridges	Recrystallization of carbonate sediment	Rivers
Amount per year (metric tonnes)	1×10^6	0.3×10^6	3×10^6
$^{87}Sr/^{86}Sr$	0.704	0.708	0.712

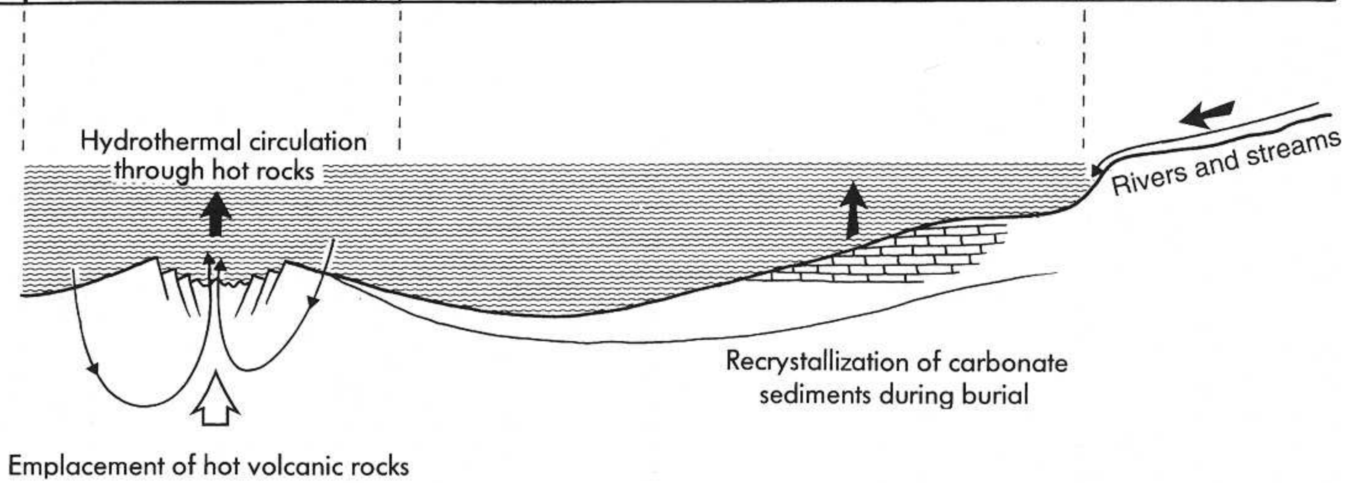


Figure 8.2 *Schematic cross-section through the earth's crust showing the major sources of supply of Sr to the oceans. The amount supplied each year, and the ratio of each source, is shown in the boxed section [Reproduced with permission of Academic Press, Inc, from: McArthur (1992)]*

Analytické metody: spolehlivost materiálu

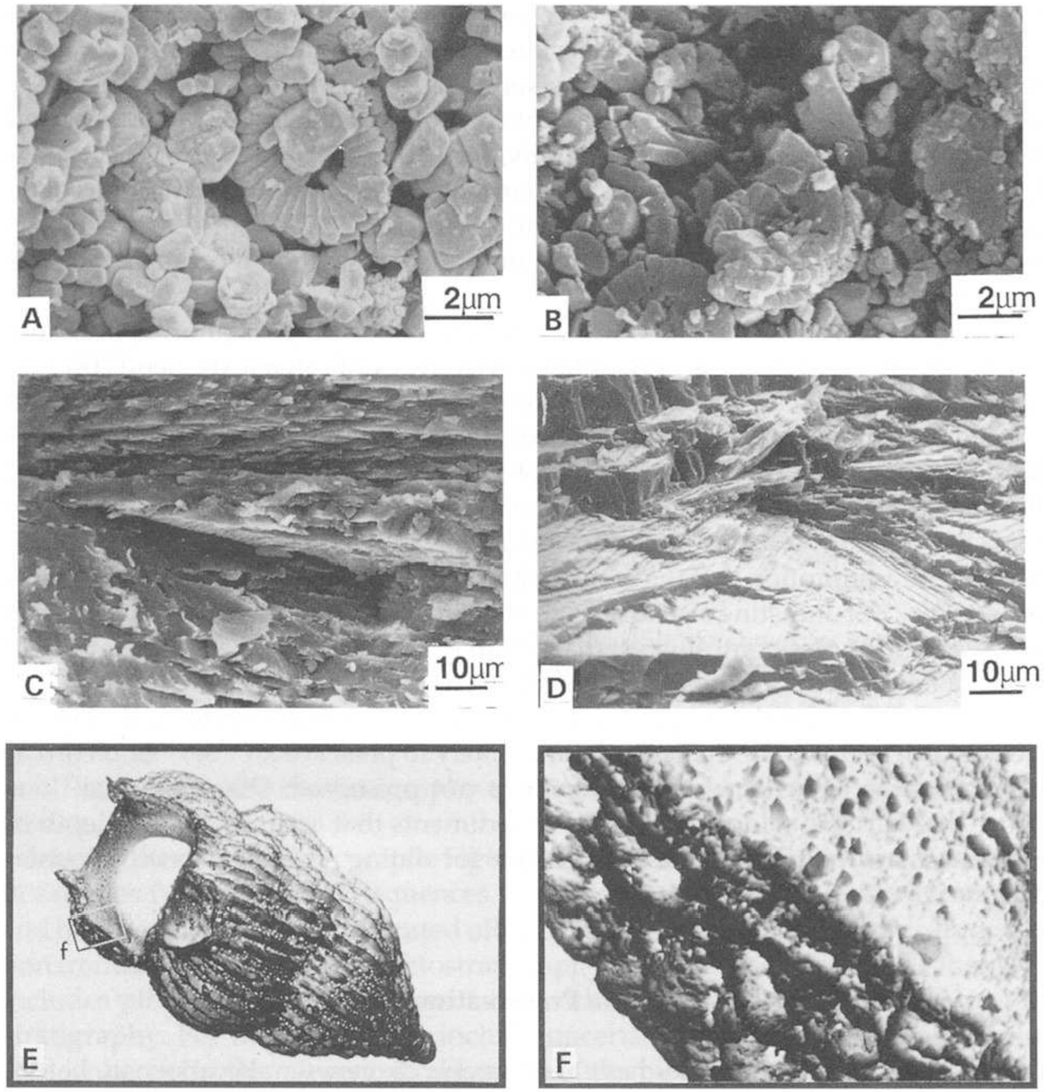


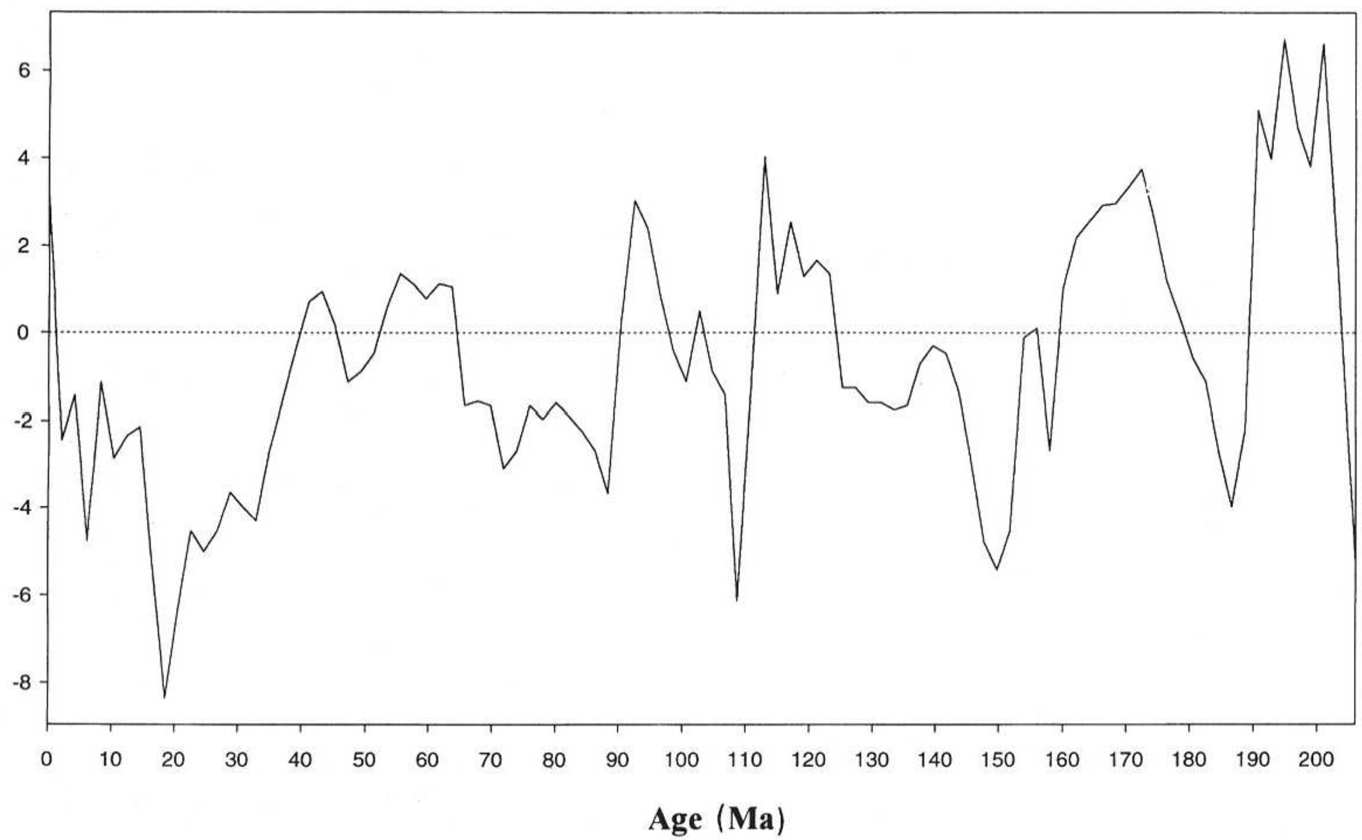
Figure 8.4 *SEM photomicrographs demonstrating good preservation for SIS:* ***A****. Chalk from Lagerdorf, Germany; some overgrowth is seen in both but spar is rare.* ***B****. Chalk, from Kjølby Gaard, Denmark;* ***C****. and* ***D****. different specimens of* Pycnodonte *form K/T boundary sediments on Seymour Island, Antarctica, showing unaltered compact layering in calcite.* ***E****. good preservation of a specimen of* Pseudotextularia deformis *(200 mm long axis) from 1 m below the K/T boundary in the Danish chalk, Kjølby Gaard.* ***F****. detail of aperture in* ***E****. showing only minor nucleation of calcite on the specimen's surface.*

$^{87}Sr/^{86}Sr$ křivky:

- Relativní datování (stejné hodnoty v různých obdobích)
- Číselné datování: kombinace s jinými stratigrafickými metodami (bio-, magneto-stratigrafie atd.)

Metody prezentace dat:

- $^{87}Sr/^{86}Sr$
- $\delta^{87}Sr$: $^{87}Sr/^{86}Sr$(standard) – $^{87}Sr/^{86}/Sr$(vzorek) x 10^5
  - Standard: Modern Seawater Strontium (MSS): 0,709175



Relativní datování

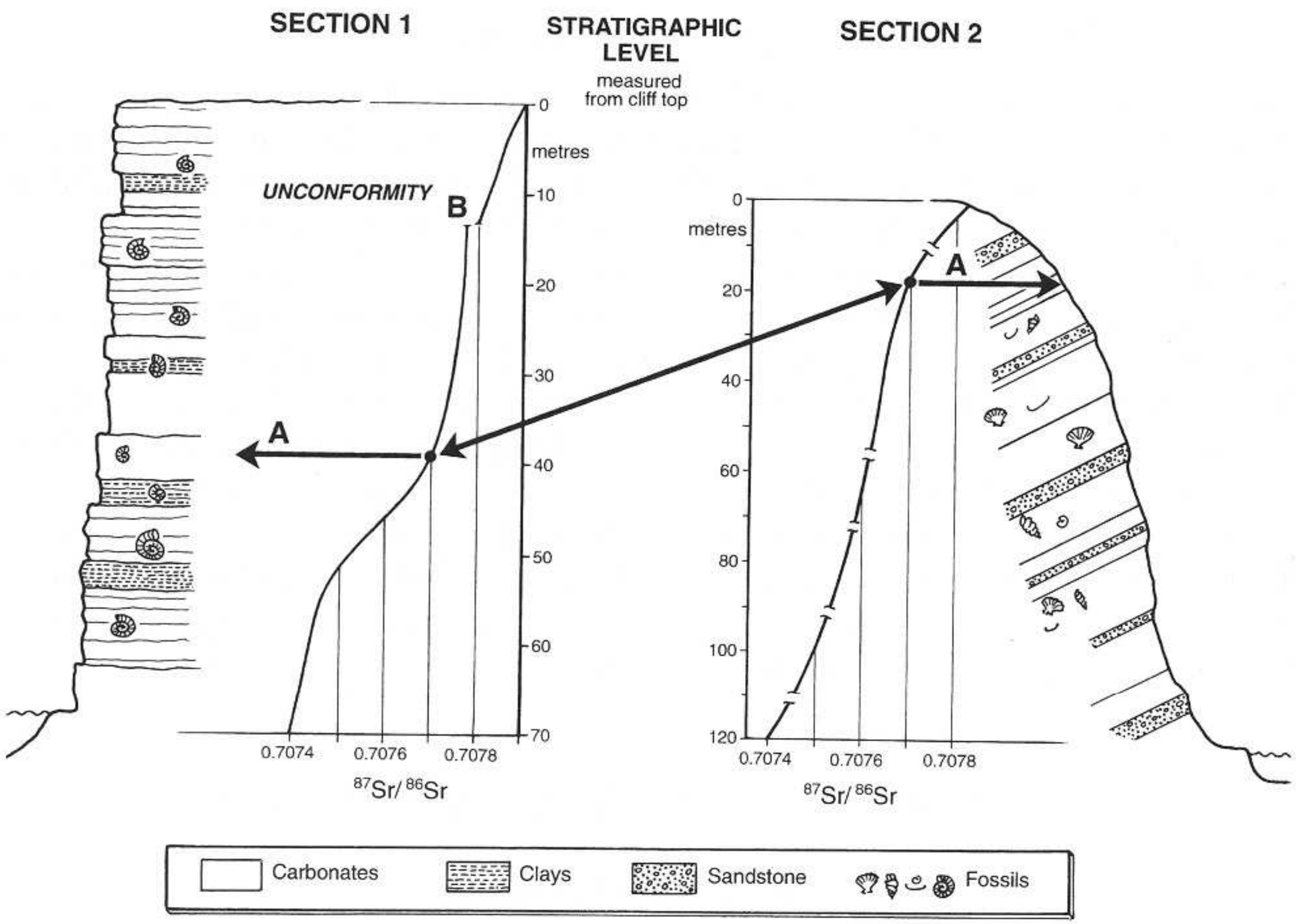


Figure 8.3 Correlating rocks with Sr isotopes: using $^{87}Sr/^{86}Sr$ curves for two widely separated imaginary cliff sections. Levels in the sequences with identical $^{87}Sr/^{86}Sr$ formed at the same time and therefore correlate; for example, the rocks at level A

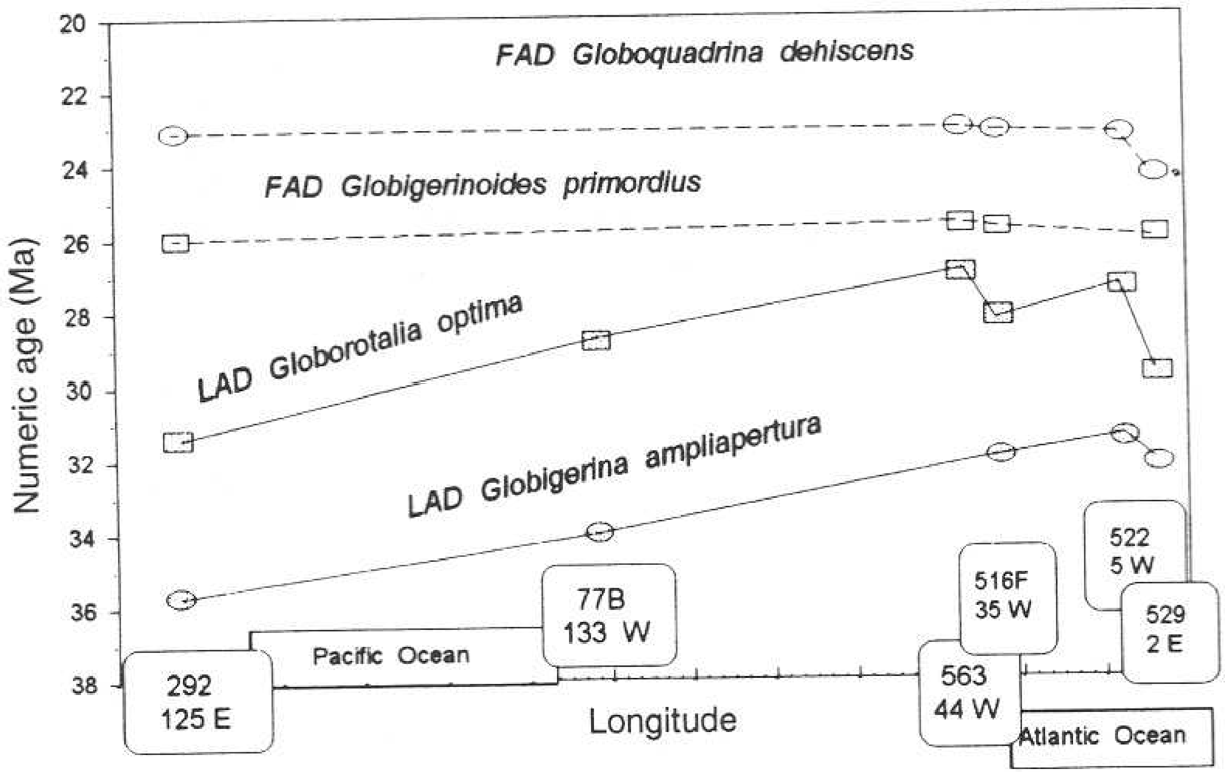


Figure 8.8 *Diachroneity and synchroneity of biostratigraphical boundaries revealed by SIS. Last appearances of* Globigerina ampliapertura *and* Globorotalia optima *young eastward, whilst the first appearances of* Globigerinoides primordius *and* Globoquadrina dehiscens *are synchronous. Site localities: 292, western Philippine Basin; 593, Tasman Sea; 77B, equatorial Pacific; 563, central North Atlantic; 516, 516F, western South Atlantic; 522, 529, eastern South Atlantic. [Reproduced with permission of the American Geophysical Union, from Hess* et al. *(1989)]*

Číselné datování

Table 8.1 *Numerical ages predicted for $^{87}Sr/^{86}Sr$ values 0.707790 to 0.707984; extract from the look-up table of Howarth & McArthur (1997). The table was generated from a statistical LOWESS fit to the data shown in Figure 8.1*

$^{87}Sr/^{86}Sr$	Minimum age	Mean age	Maximum age
0.707970	>30.20	30.49	<30.79
0.707971	>30.18	30.46	<30.77
0.707972	>30.15	30.44	<30.74
0.707973	>30.13	30.41	<30.71
0.707974	>30.11	30.38	<30.68
0.707975	>30.08	30.36	<30.65
0.707976	>30.06	30.33	<30.63
0.707977	>30.03	30.31	<30.60
0.707978	>30.01	30.28	<30.57
0.707979	>29.98	30.26	<30.55
0.707980	>29.96	30.23	<30.52
0.707981	>29.93	30.20	<30.50
0.707982	>29.90	30.18	<30.47
0.707983	>29.88	30.15	<30.44
0.707984	>29.86	30.13	<30.42

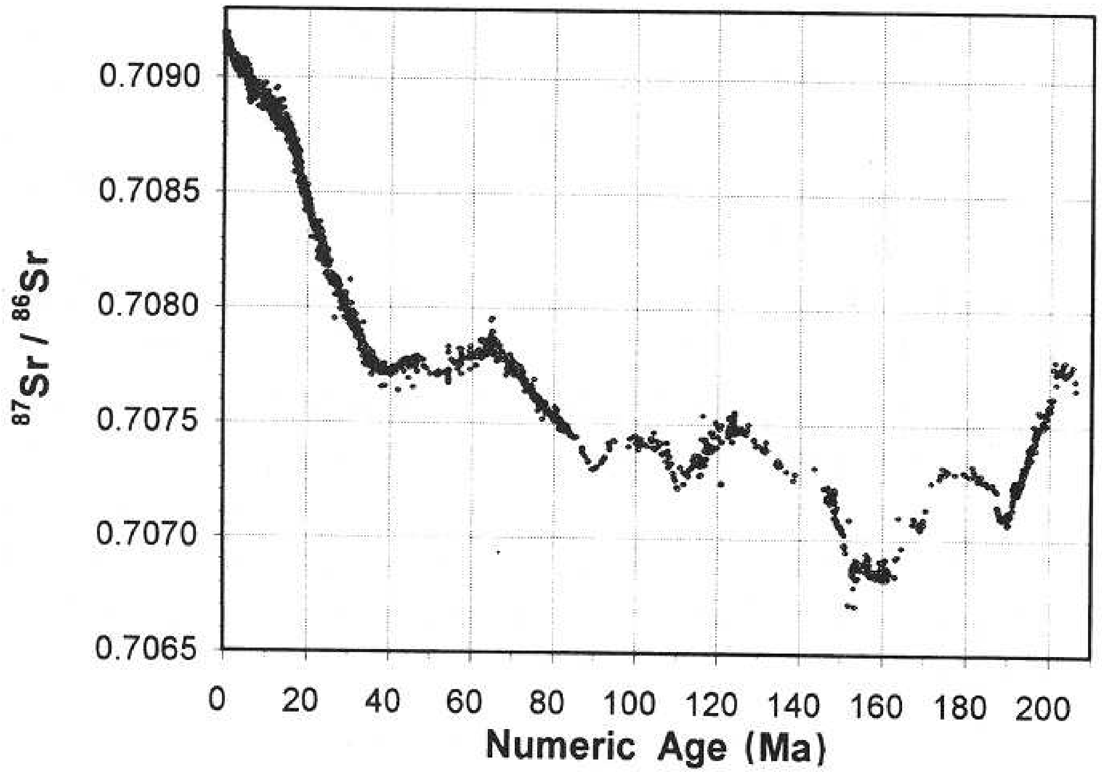


Figure 8.1 *Variation of $^{87}Sr/^{86}Sr$ during the past 206 Ma*

Omezení

- Limity číselného datování doprovodných metod

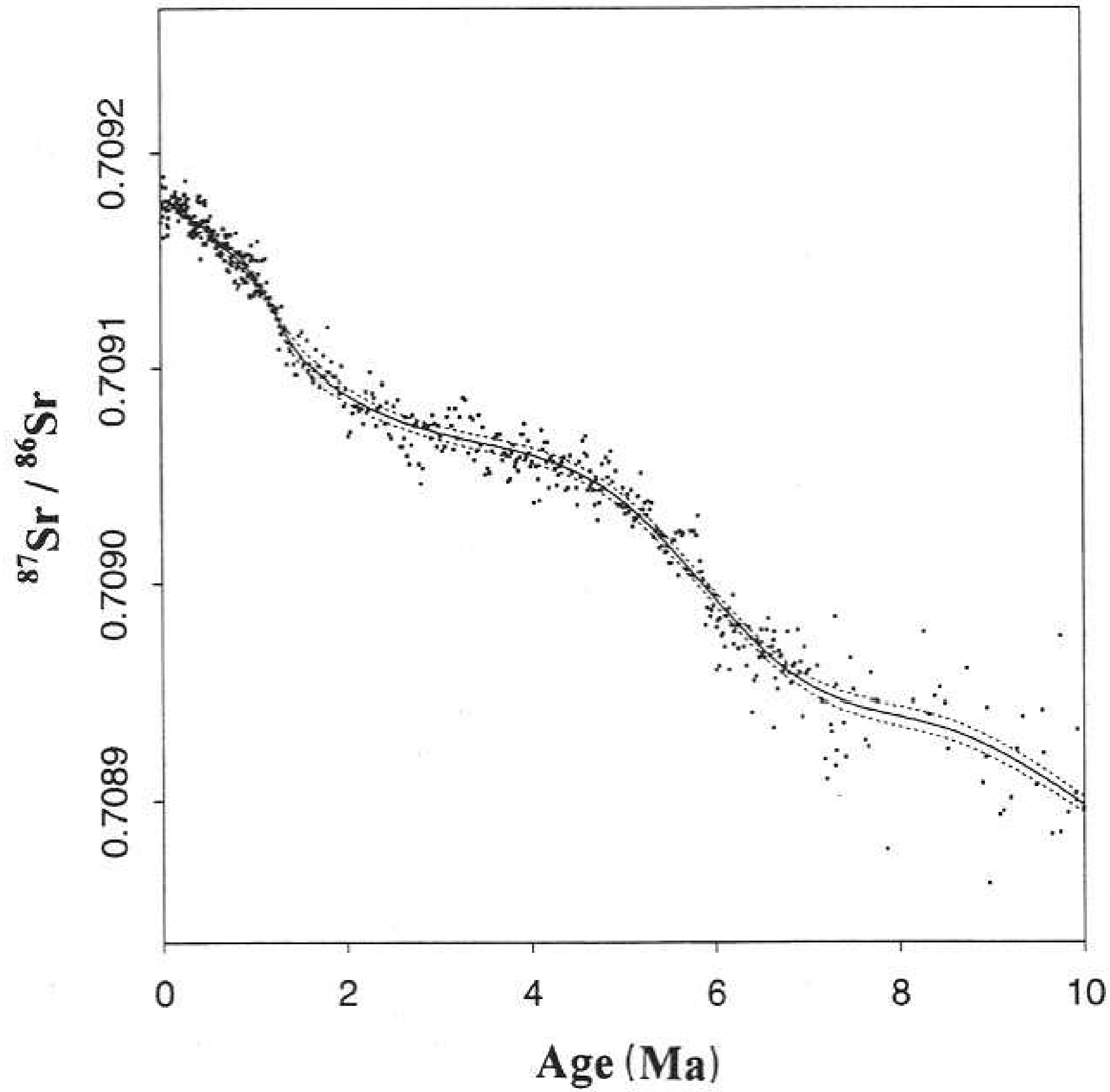


Figure 8.9 A robust LOWESS fit for the interval from 0 to 10 Ma. The central solid line denotes the mean of the data. Confidence limits of 2 s.e. about the mean value are shown as dotted lines. These limits represent the confidence with which the position of the mean is known and say little about the distribution of the data

Metody číselného datování

absolute age (numerical)

- natural clock is necessary

    --radiometric dating

    (nuclear clock: decay of radioactive isotopes)

    --dendrochrolonology

    --fission-track dating

    --varve chronology

    --lichenometry

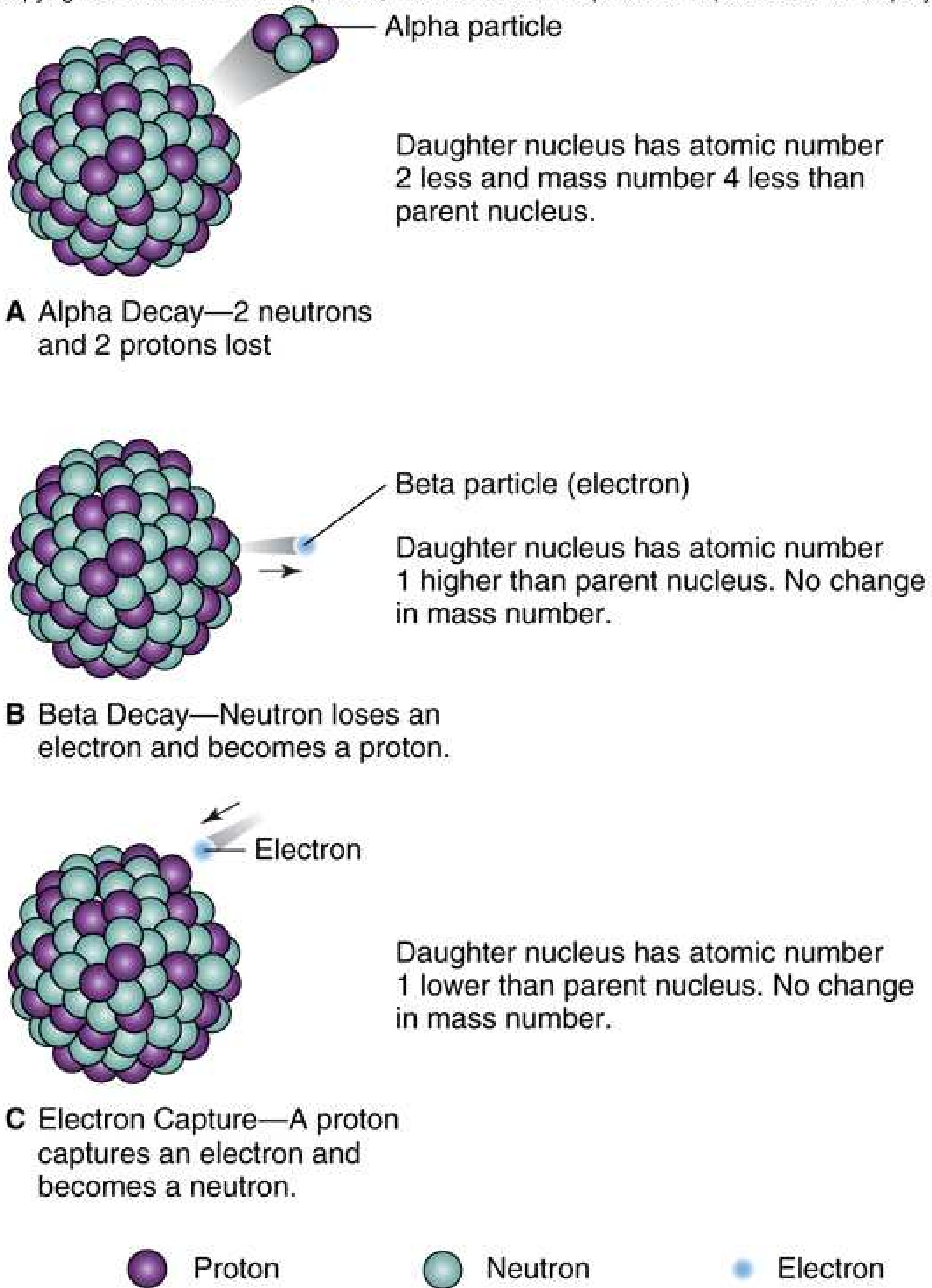
    --surface-exposure dating

Radiometrické datování

radioactive isotopes: have nuclei that spontaneously decay by emitting or capturing subatomic particles

parent: decaying radioactive isotope
daughter: decay daughter

parent ⟶ *daughter*
loss or gain



3 primary ways of decay

alpha decay

particle has 2 neutrons and 2 protons

U^{238} → Th^{234}

92 protons → 90 protons

beta decay

breakdown of neutron into an electron and a proton and loss of the electron to leave a proton (result is gain of one proton)

K^{40} → Ca^{40}

19 protons → 20 protons

electron capture

capture of an electron by a proton and change of proton to neutron (result is loss of proton)

K^{40} → Ar^{40}

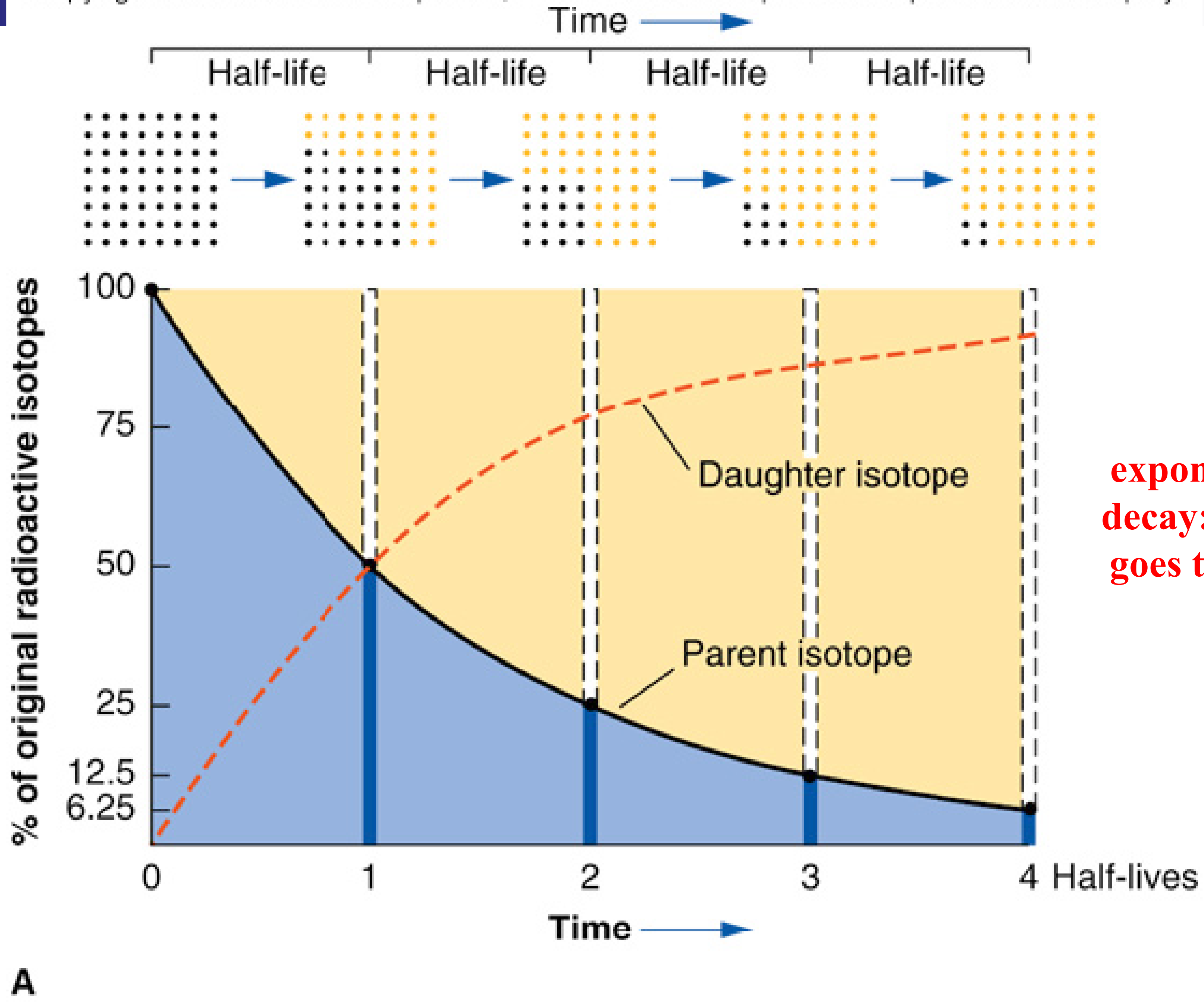
19 protons → 18 protons

Radiometrické datování

- uses continuous decay to measure time since rock's formation
- as minerals crystallize in magma; they may trap atoms of radioactive isotopes in their crystal structures
- …will begin to decay immediately and continuously…
- as time passes, rock will contain less parent and more daughter

POLOČAS ROZPADU (τ)
amount of time it takes for half the atoms of the parent isotope to decay is the isotope's half-life

ROZPADOVÁ KONSTANTA (λ)
Rychlost, jakou se mateřský izotop rozpadá na dceřinný izotop
Stanovuje se laboratorně



exponential decay: never goes to zero

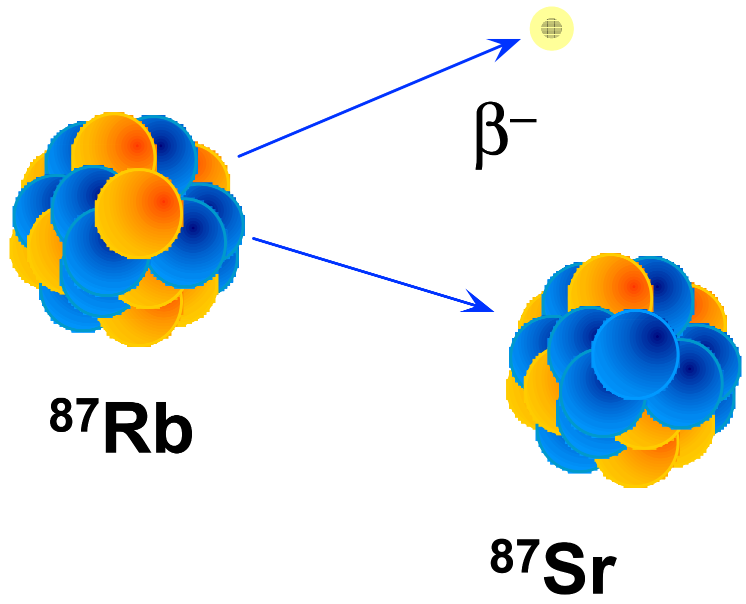
predictable ratios at each half-life: exponential decay (half always remains)

Radioaktivní rozpad a radiogenní izotopy

- "Radiogenic" isotope ratios are functions of both time and parent/daughter ratios. They can help infer the chemical evolution of the Earth.

- Radioactive decay schemes

^{87}Rb-^{87}Sr	τ: 4,88 Ma	λ: 1,42 x 10^{-11} (let^{-1})
^{147}Sm-^{143}Nd	τ: 108 Ga	λ: 6,54 x 10^{-12} (let^{-1})
^{238}U-^{206}Pb	τ: 4.468 Ma	λ: 1,551 x 10^{-10} (let^{-1})
^{235}U-^{207}Pb	τ: 704 Ma	λ: 9,848 x 10^{-10} (let^{-1})
^{232}Th-^{208}Pb	τ: 14 Ga	λ: 4,947 x 10^{-11} (let^{-1})



- "Extinct" radionuclides
  - "Extinct" radionuclides have half-lives too short to survive 4.55 Ga, but were present in the early solar system.

Základní předpoklady geochronologie

- Rozpad je v průběhu času konstantní.
  - good reasons to believe this is correct from nuclear physics
  - measurements of decay sequences in ancient supernovae yield the same values as modern lab measurements.

- Systém zůstává uzavřený vzhledem k mateřským a dceřinným izotopům
  - To závisí na izotopickém systému a typu měřené horniny (minerálu)
  - Pro správnou interpretaci výsledků je nutná pečlivá příprava vzorku a důkladná charakteristika vstupního materiálu

Pro datování jsou nejvhodnější vyvřelé horniny
Metamorfóza může způsobit ztrátu dceřinných produků
Datování sedimentů udává věk zdrojových hornin

Příprava vzorku a analýza

- **Hmotnostní spektrometrie:** měří koncentrace specifických nuklidů na základě jejich atomové hmotnosti.
  - technique requires ionization of the atomic species of interest and acceleration through a strong magnetic field to cause separation between closely similar masses (*e.g.* ^{87}Sr and ^{86}Sr). …count individual particles using electronic detectors...
  - TIMS: thermal ionization mass spectrometry
  - SIMS: secondary ionization mass spectrometry - bombard target with heavy ions or use a laser
- **Příprava vzorku pro TIMS**
  - Rozpuštění vzorku v HF, HNO_3, příprava rozpustného chloridu , další separace na Rb a Sr
  - Rozpuštění a evaporace chloridu Sr a Rb na kovovém (wolfram, rhenium) vlákně spektrometru
  - Zahřívání a ionizace vlákna ve spektrometru

Clean Lab - Chemical Preparation

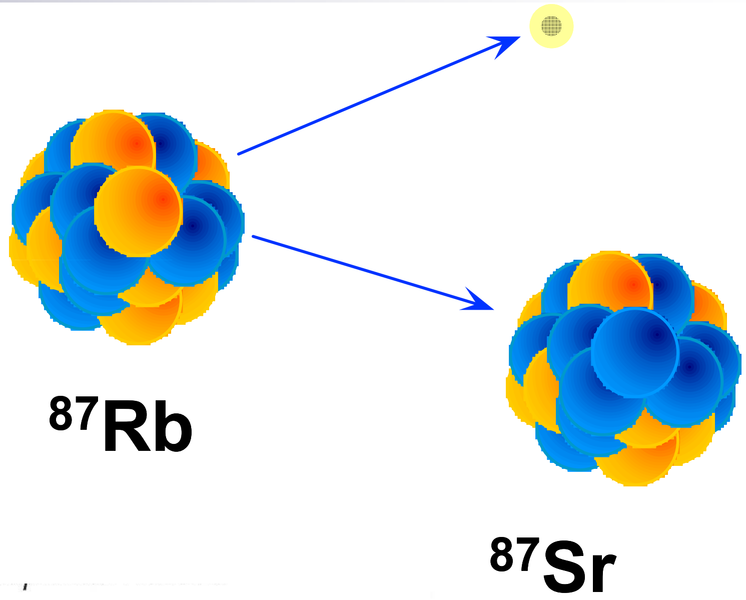
http://www.es.ucsc.edu/images/clean_lab_c.jpg

Thermal Ionization Mass Spectrometer (TIMS)

From: http://www.es.ucsc.edu/images/vgms_c.jpg

Metoda $^{87}Rb/^{87}Sr$

- “whole rock“ analysis
- Parciální krystalizace: nárůst koncentrace Rb a Sr ve zbytkové tavenině
- Plagioklas uzavírá Sr v krystalové mřížce, avšak ne Rb
- Různé poměry Rb/Sr v různých krystalových jedincích



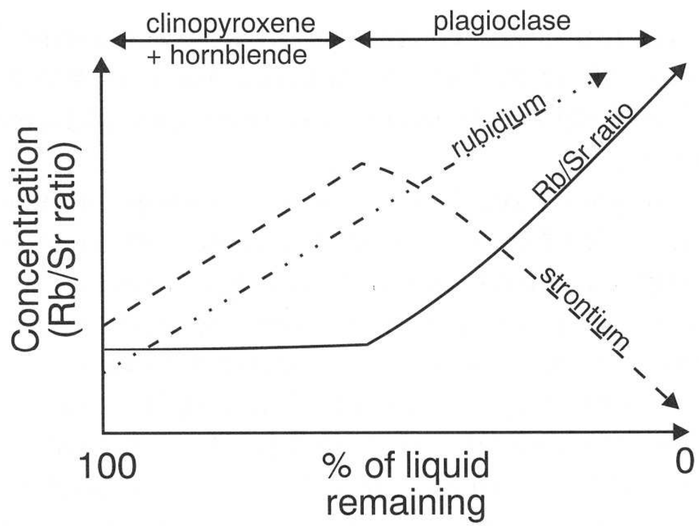


Figure 12.1 *Diagrammatic representation of the concentrations of Rb and Sr, and variations in the Rb/Sr ratio during the crystallization of a granitic magma. Note that for a crystallizing assemblage of clinopyroxene and amphibole, both Rb and Sr are incompatible and thus their concentrations increase with an increasing amount of crystallization. Once plagioclase is stable on the liquidus, because* $k_D Sr_{plag}$ *is* > 1*, the Sr concentration decreases, Rb continues to increase and thus the Rb/Sr ratio of the system increases. This gives a final suite of rocks with variable Rb/Sr ratios*

Rb-Sr izochrona

- Rovnice:
- $^{87}Sr/^{86}Sr_m = {}^{87}Rb/^{86}Sr_m\,(e^{\lambda t} - 1) + {}^{87}Sr/^{86}Sr_i$ (R_0 = initial ratio)
- y = ax + b, kde a = sklon přímky
  b = průsečík s osou y
- $t = 1/\lambda \times \ln(\text{sklon} + 1)$

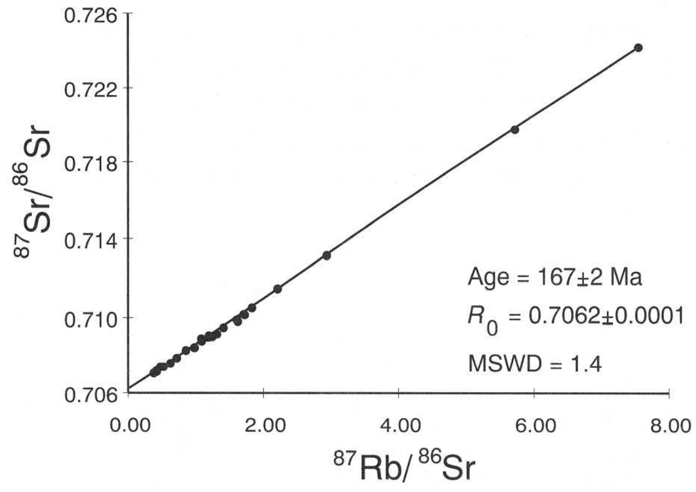


Figure 12.3 *Rb–Sr isochron for a zoned diorite–granodiorite–adamellite intrusion at Bildad Peak, Graham Land, Antarctic Peninsula. Note the broad spread of $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{87}Sr$ ratios, which gives a statistically precise fit of the data to the isochron equation, and thus a low MSWD. [Based on data in: Pankhurst (1982)]*

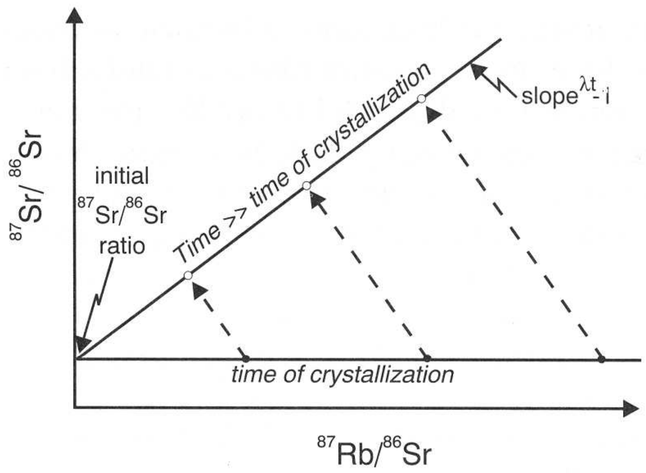


Figure 12.2 *Diagrammatic representation of an isochron diagram showing the evolution of $^{87}Sr/^{87}Sr$ and $^{87}Rb/^{86}Sr$ from the time of crystallization (solid circles) to a time much later than that of crystallization (open circles). Note that $^{87}Sr/^{86}Sr$ increases though time whereas $^{87}Rb/^{86}Sr$ decreases. The age of the intrusion (specifically, the time since crystallization) can be calculated from the slope of the isochron by applying equation (2). The intercept is the $^{87}Sr/^{86}Sr$ ratio of the system at the time of crystallization and has petrogenetic significance*

Stáří růstu jednotlivých minerálů

- Metamorfóza vyvřelých hornin
- Při zahřátí: difůze Sr a Rb, izotopická homogenizace
- Po zchlazení: zastavení difůze a nastavení „hodin“
- Iontové poměry v hornině stálé – stáří „whole rock“ jsou platná
- „blokovací teplota“ minerálů

Table 12.2 *Blocking (closure) temperatures for common minerals for different isotopic systems. FT = fission track method*

Mineral	Method	Closure temperature for mineral systems, *T* (°C)
Zircon	U–Pb	>800
Baddeleyite	U–Pb	>800
Monazite	U–Pb	700
Titanite	U–Pb	600
Garnet	U–Pb	>550
Garnet	Sm–Nd	>550
Hornblende	K–Ar	500
Muscovite	Rb–Sr	500
Muscovite	K–Ar	350
Apatite	U–Pb	350
Biotite	Rb–Sr	300
Biotite	K–Ar	280
K-Feldspar	K–Ar	200
Zircon	FT	200
Apatite	FT	120

Whole rock vs. single grain ages
Příklad:

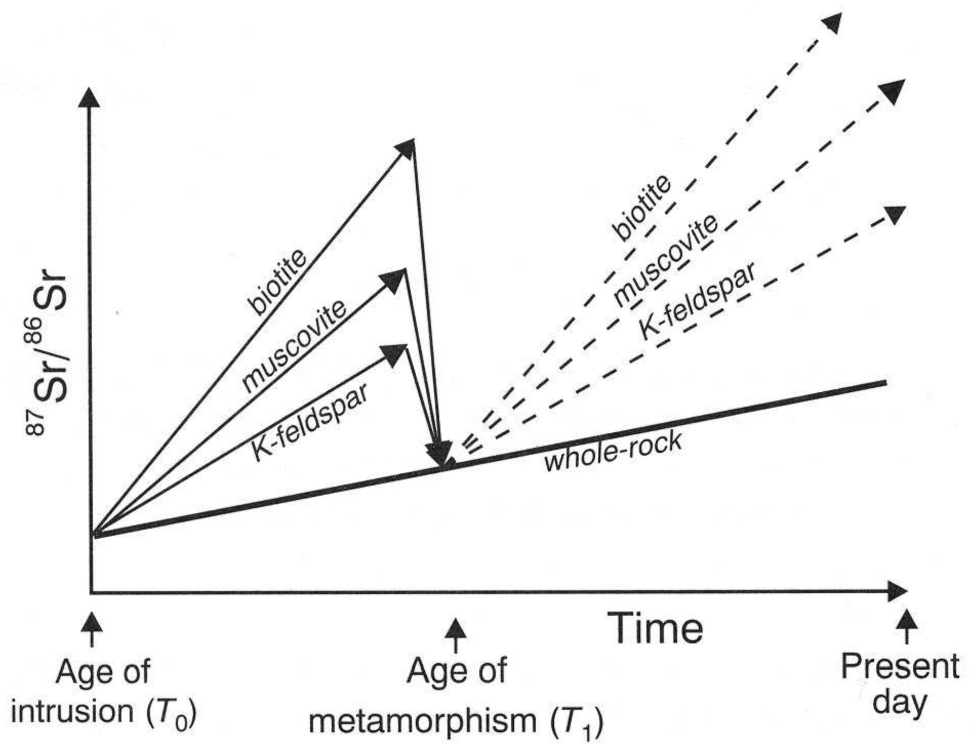


Figure 12.4 *Diagrammatic representation of a whole-rock isochron which has undergone a period of low-grade metamorphism during which the biotite, muscovite and K-feldspar have been taken above their blocking temperatures (Table 12.2) and thus have undergone isotopic homogenization. Post-metamorphism, once all the minerals have once again cooled below their respective blocking temperatures,* in situ *isotopic decay once again takes place. Note that the slope of the whole-rock isochron is undisturbed by the metamorphic event. A mineral isochron will yield the age when the minerals cooled below their blocking temperatures and the whole-rocks will yield the original age of crystallization*

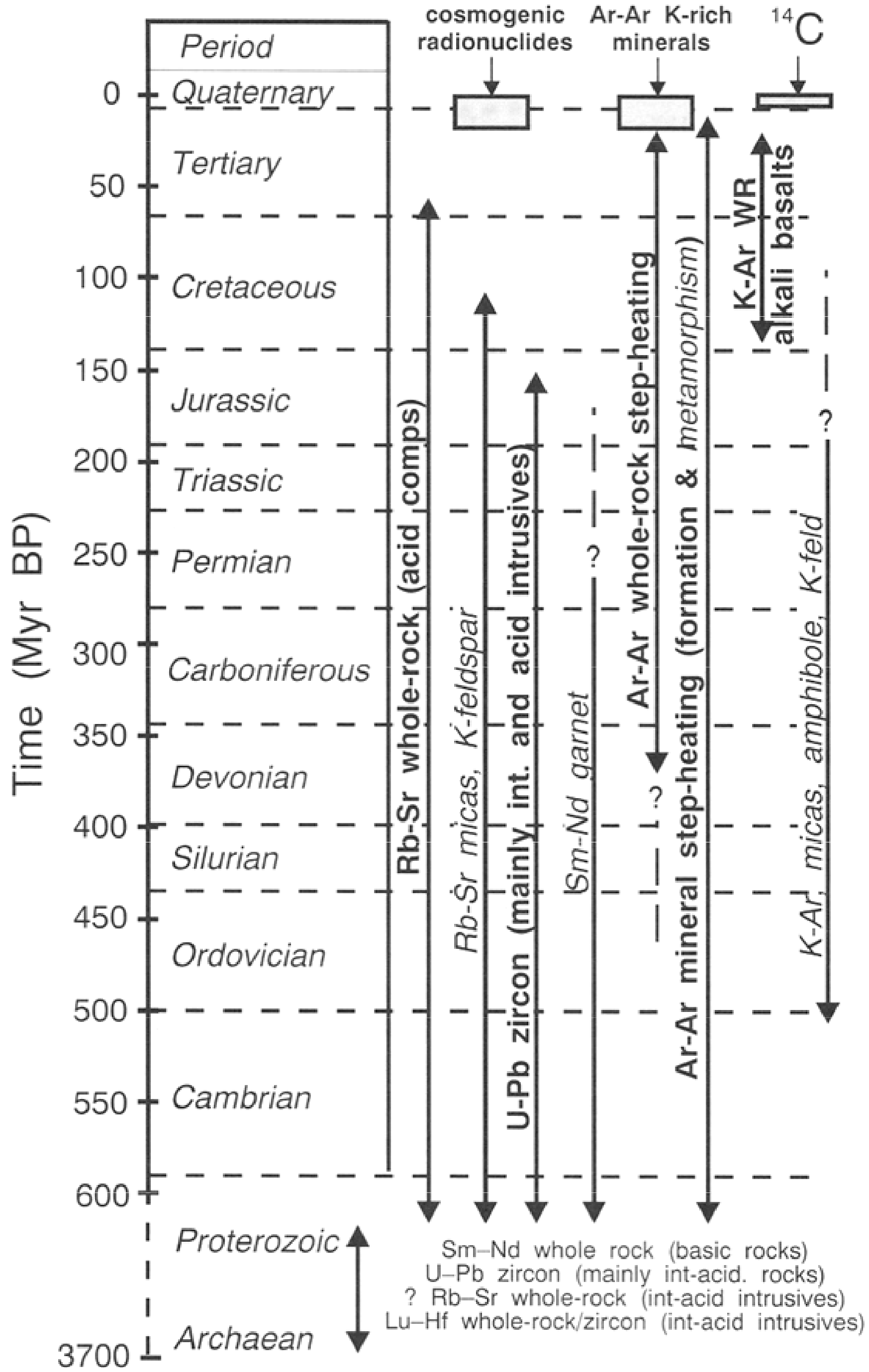
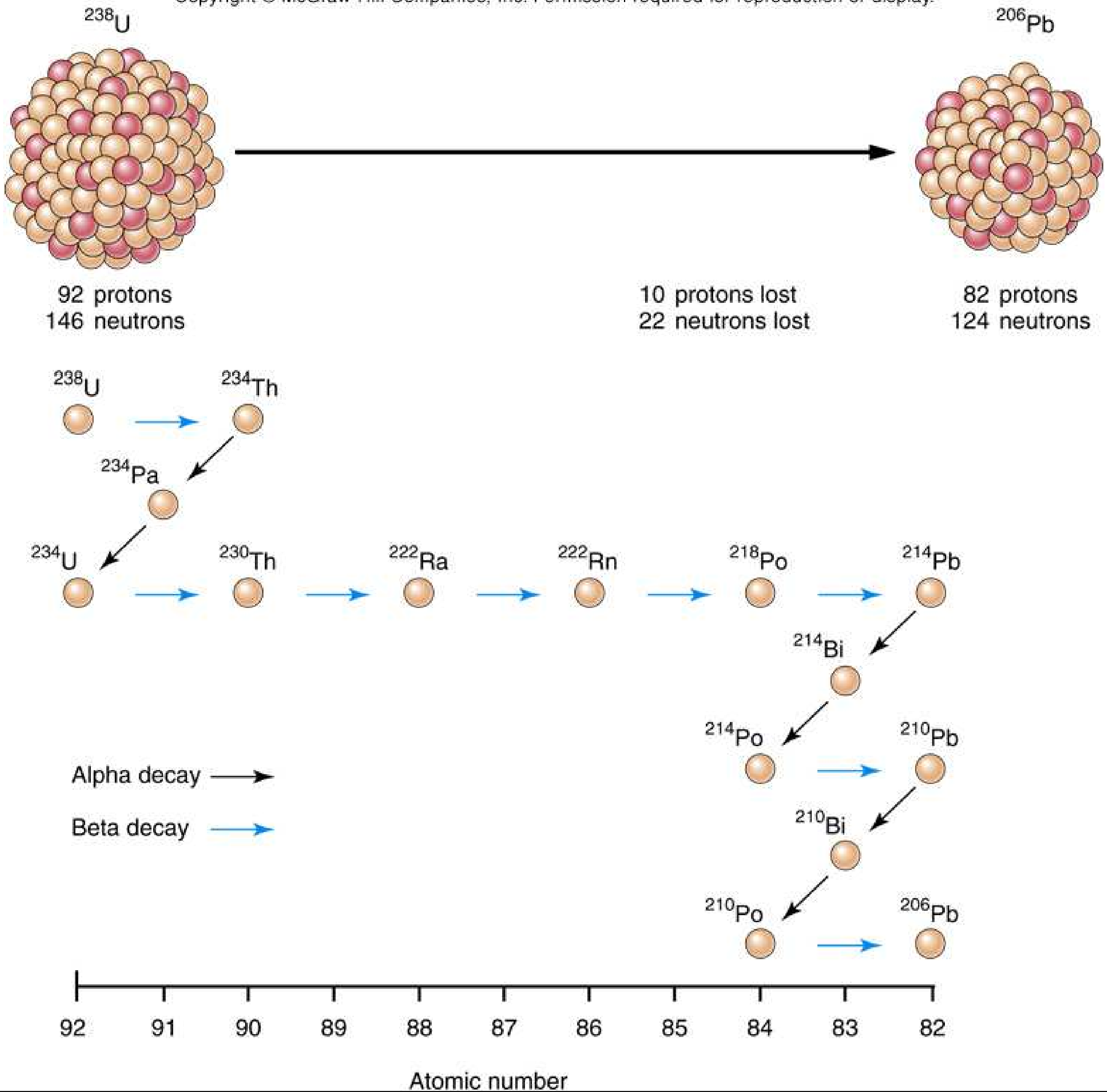


Figure 12.11 *Application of different methods of radiogenic isotope geochronology to different rock types of differing ages. Methods in italics will yield dates that are likely to reflect predominantly metamorphic/uplift events, whereas methods in normal text are more likely to reflect magmatic crystallization*

Uranium 238 Decay Scheme (several steps) to stable Lead 206



Lutetium – hafnium method

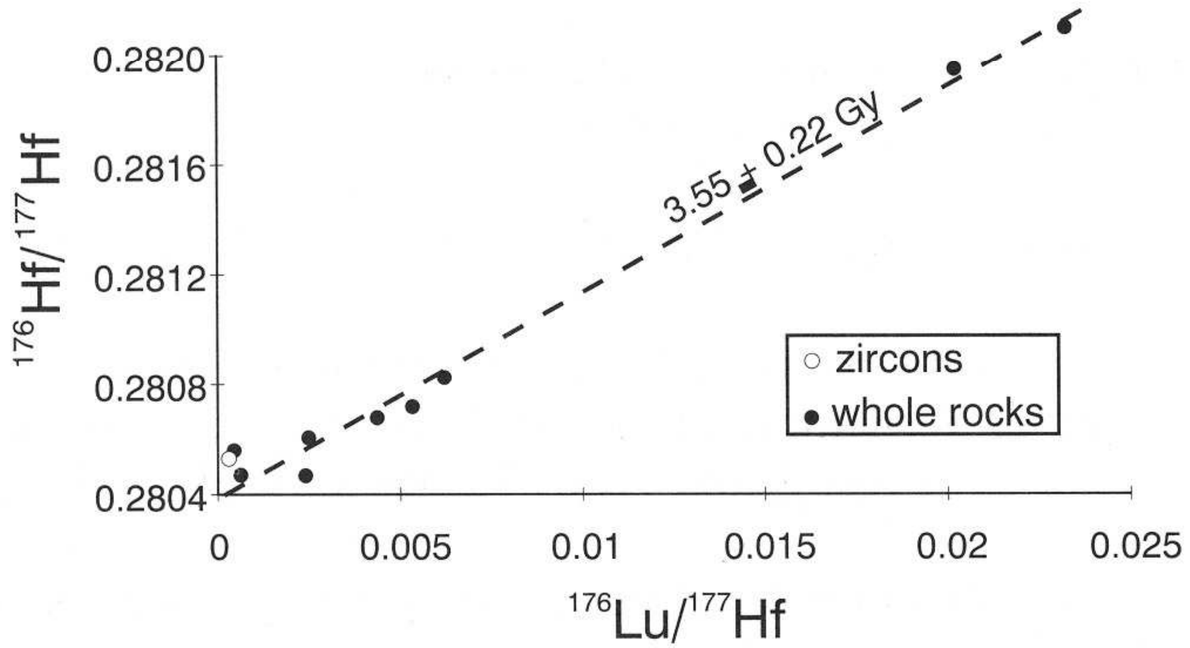
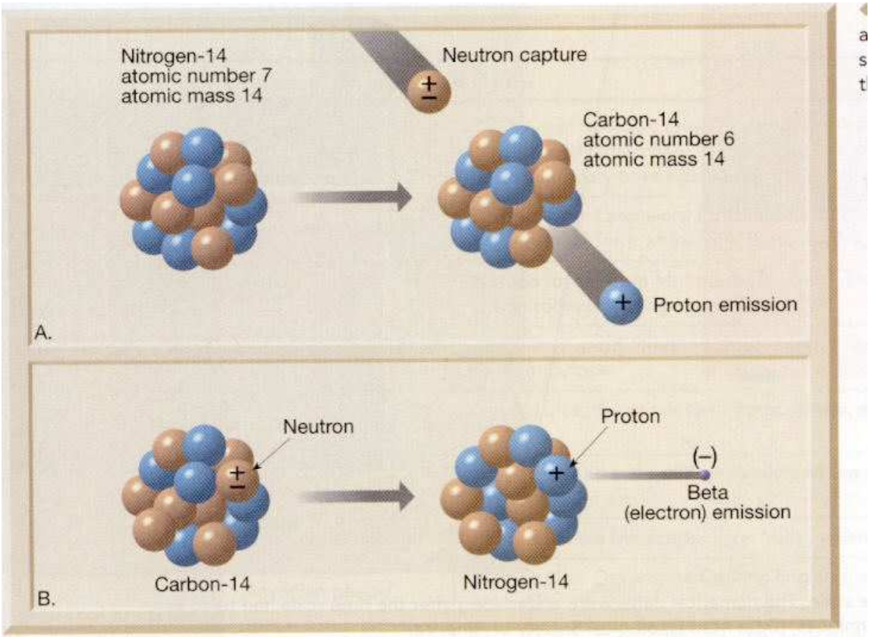
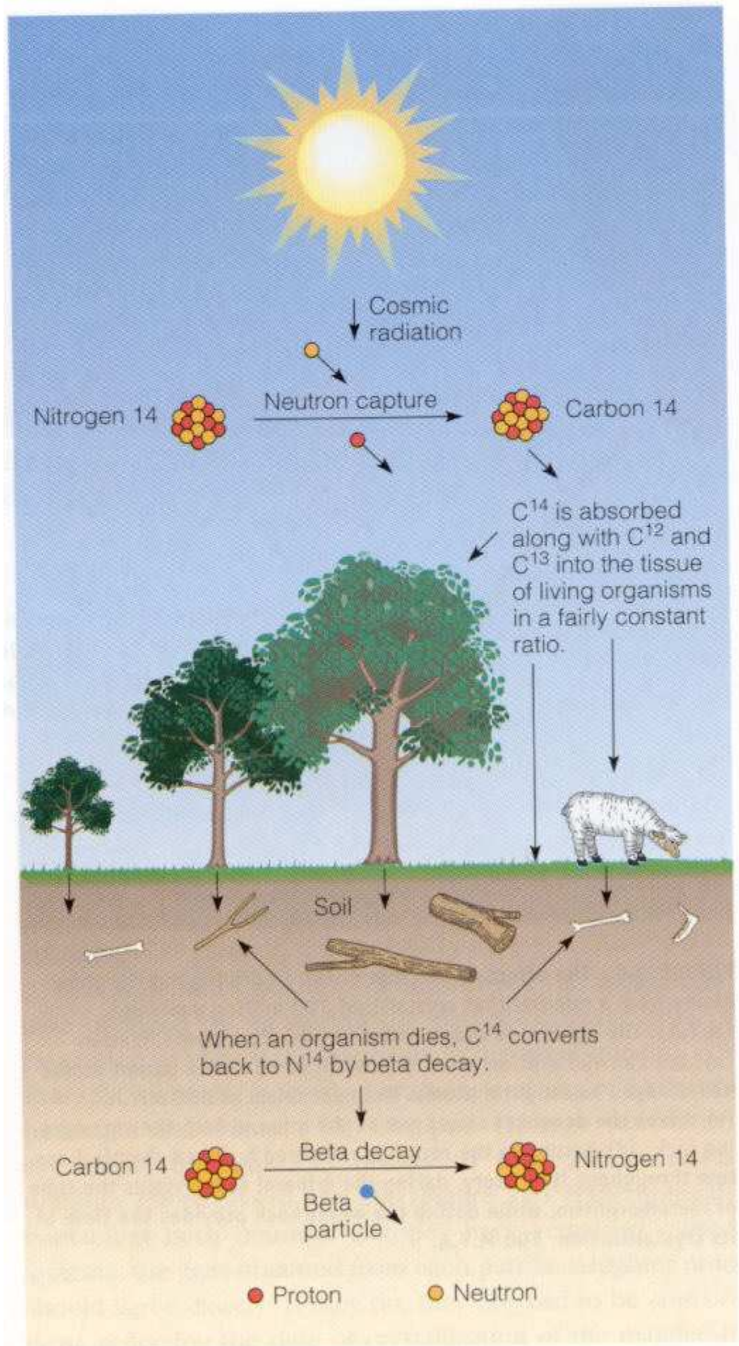


Figure 12.8 *Lu–Hf whole-rock–zircon isochron for the Amitsôq gneiss, West Greenland. Note the limited spread in $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ ratios, which is considerably less than that for the Sm–Nd isochron for the Target Hill gniesses (Figure 12.6). Nevertheless, this isochron yields a relatively precise age of 3.55 ± 0.22 Ga; an age that is concordant with U–Pb zircon and Rb–Sr whole-rock ages from the same locality. [Based on data in: Pettingill* et al. *(1981)]*

Metoda radiouhlíku

- **Willard F. Libby (1906 – 1980), Nobelova cena za chemii 1960**
- **Organická hmota, poločas rozpadu 5700 let, použití: holocén, svrchní pleistocén**
- **N14 -> C14,**
- **fixace C14 do organické hmoty**
- **C14 -> N14**





half-lives of previous are too long to date rocks < 100,000 years old

C-14 has half-life of 5,730 years (changes to N-14)

…date material from 100 to 70,000 years old

C-14 combines with O to form carbon dioxide (CO2) along with the stable isotope of carbon, C-12

some CO2 with C-14 dissolved in oceans, lakes, etc. where organisms drink the water and plants remove it directly from the atmosphere

all living organisms have some C-14 in their cells

…while organism is alive, it continues to replenish C-14…

…when organism dies, the amount of C-14 diminishes…

…thus date age since death of organism…

a note regarding C-14….

C-14 forms naturally by cosmic ray bombardment of nitrogen

when C-14 is combined with other techniques,
…a systematic error is noted that results from changes
in cosmic-ray bombardment in the past
(this varies with solar-energy output and Earth's magnetic field)

dates either are corrected by comparison to another technique (i.e. dendrochronology) or are reported in C-14 years

some items dated by C-14

- cloth wrapped around Dead Sea Scrolls: 2000-2200 years
- papyrus from ancient Egypt: 2100 years old

other absolute-dating techniques:

- fission-track dating

…division of radioactive atom's nucleus into 2 pieces of approximately equal size…

…when this happens, the particles move at high speeds and leave behind tears in crysal called fission tracks..

…can count number of fission tracks to determine age…

…tracks are erased at temperatures > 250°C…

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Metoda štěpných stop (fission track)

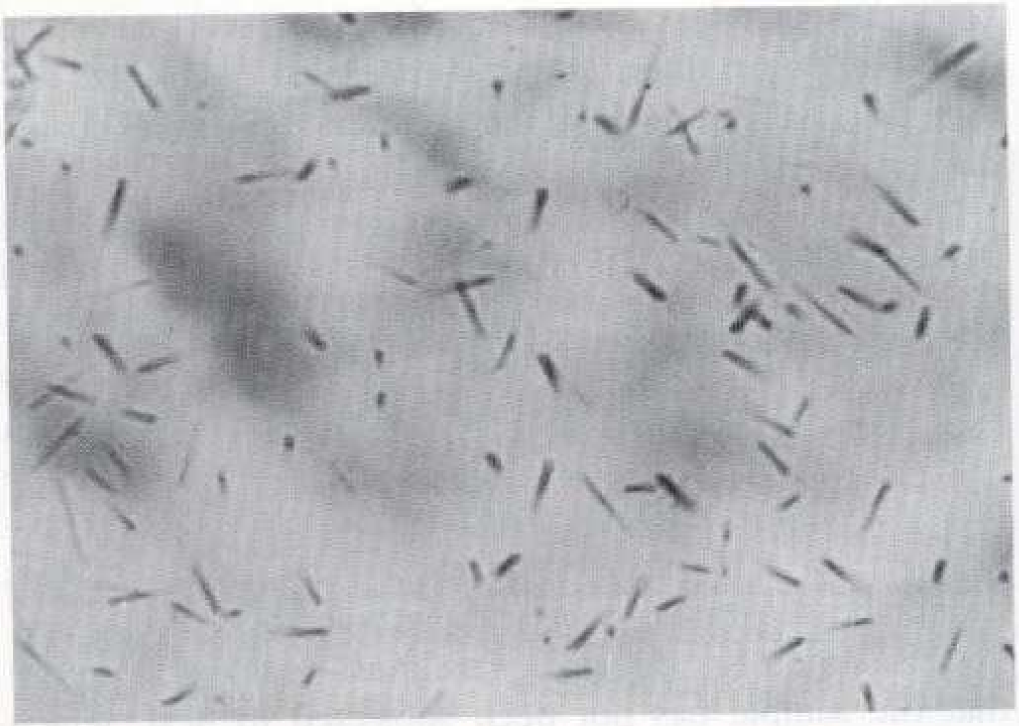


FIGURE 2.10 Each fission track (about 16 μm in length) in this apatite crystal is the result of the radioactive decay of a uranium atom. The crystal, which has been etched with hydrofluoric acid to make the fission tracks visible, comes from one of the dikes at Shiprock, New Mexico, and has a calculated age of 27 million years.

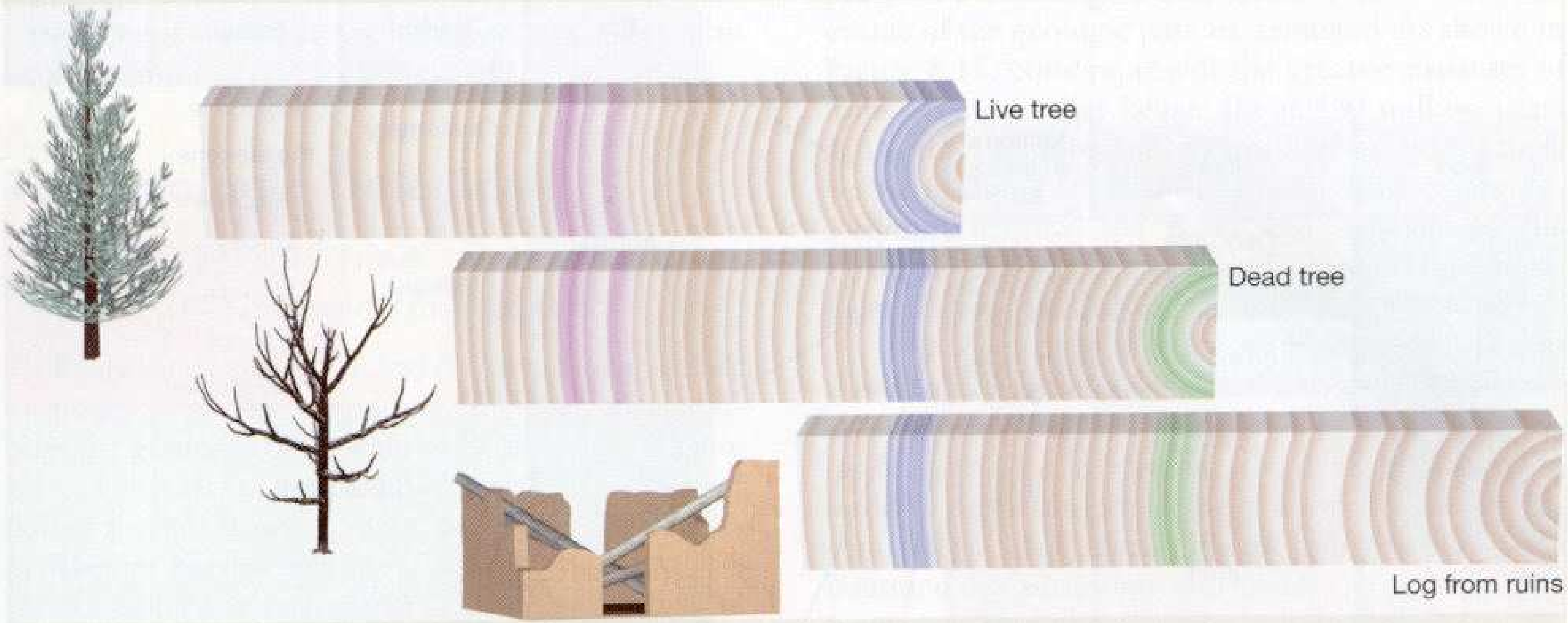
- dendrochronology (tree-ring dating)

annual growth of trees produces concentric rings
…dates back to 9000 years are possible…

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Dendrochronologie

- **Proces: růst letokruhů dřeva**
- **Doba cyklu: 1 rok (sezónní přírůstek)**
- **Použití: do – 5 000 let**



◆ **Figure 8.E** Cross dating is a basic principle in dendrochronology. Here it was used to date an archaeological site by correlating tree-ring patterns for wood from trees of three different ages. First, a tree-ring chronology for the area is established using cores extracted from living trees. This chronology is extended further back in time by matching overlapping patterns from older, dead trees. Finally, cores taken from beams inside the ruin are dated using the chronology established from the other two sites.

- varve chronology

varves: paired layers of sediment

1) thick, light, coarse layer from summer
2) thin, dark, fine layer from winter

…common in glacial lackes that have large inflow of water in summer and freeze in winter…

…count pairs to determine age (drill cores in sediment)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

OTHER NUMERICAL DATING TECHNIQUES

VARVE CHRONOLOGY

Lakes can produce annual layers.

Usually occur in glacial lakes or those that freeze over in winter.

Coarser sediments are deposited in summer.

Winter-summer layers are called **COUPLETS**.

Couplets in lakes are known as **VARVES**.

Count the couplets back from the sediment surface to determine numerical age.

OTHER NUMERICAL DATING TECHNIQUES

VARVE CHRONOLOGY

RTG densitometrie varvitů

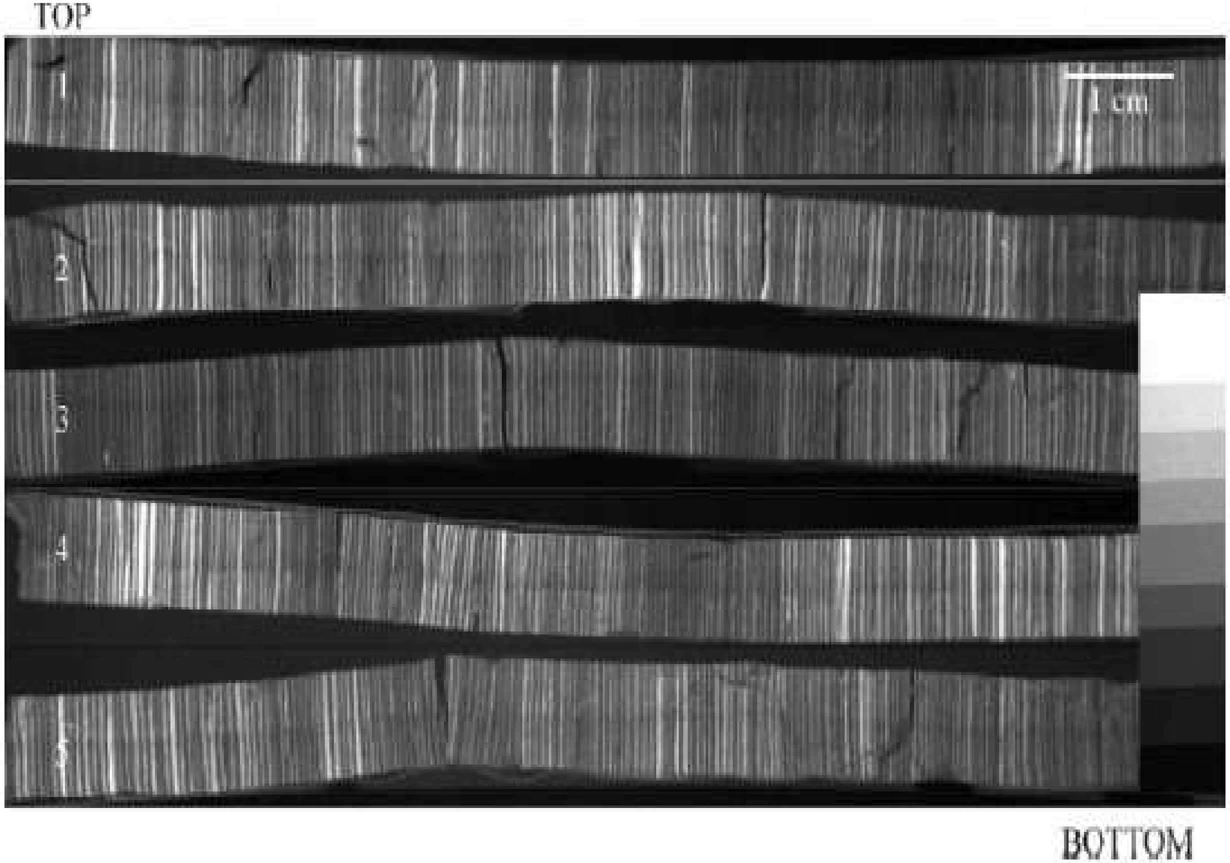
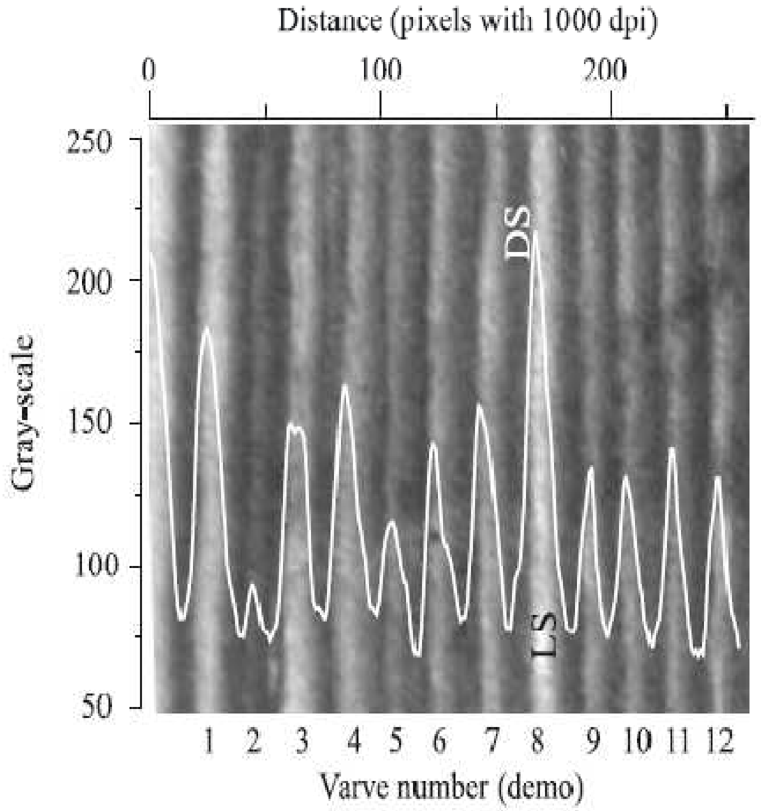


Figure 3. X-ray images of clastic-organic varves from Lake Nautajärvi representing the period from ca. AD 200 to 600 BC. Radiographs are taken from epoxy-embedded slabs of uniform 2-mm thickness. A calibration sample made of glass is seen in the right-hand corner.



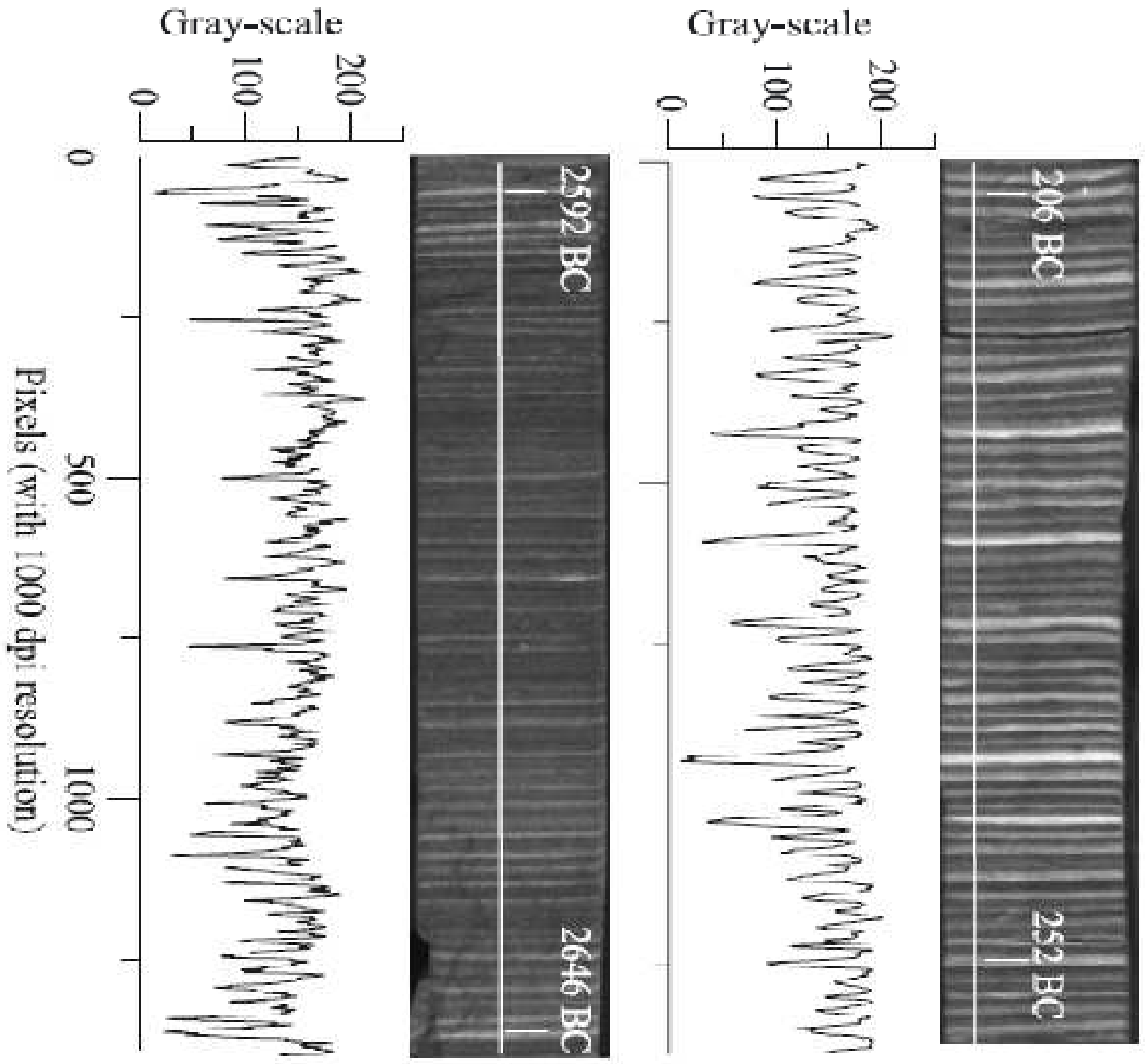
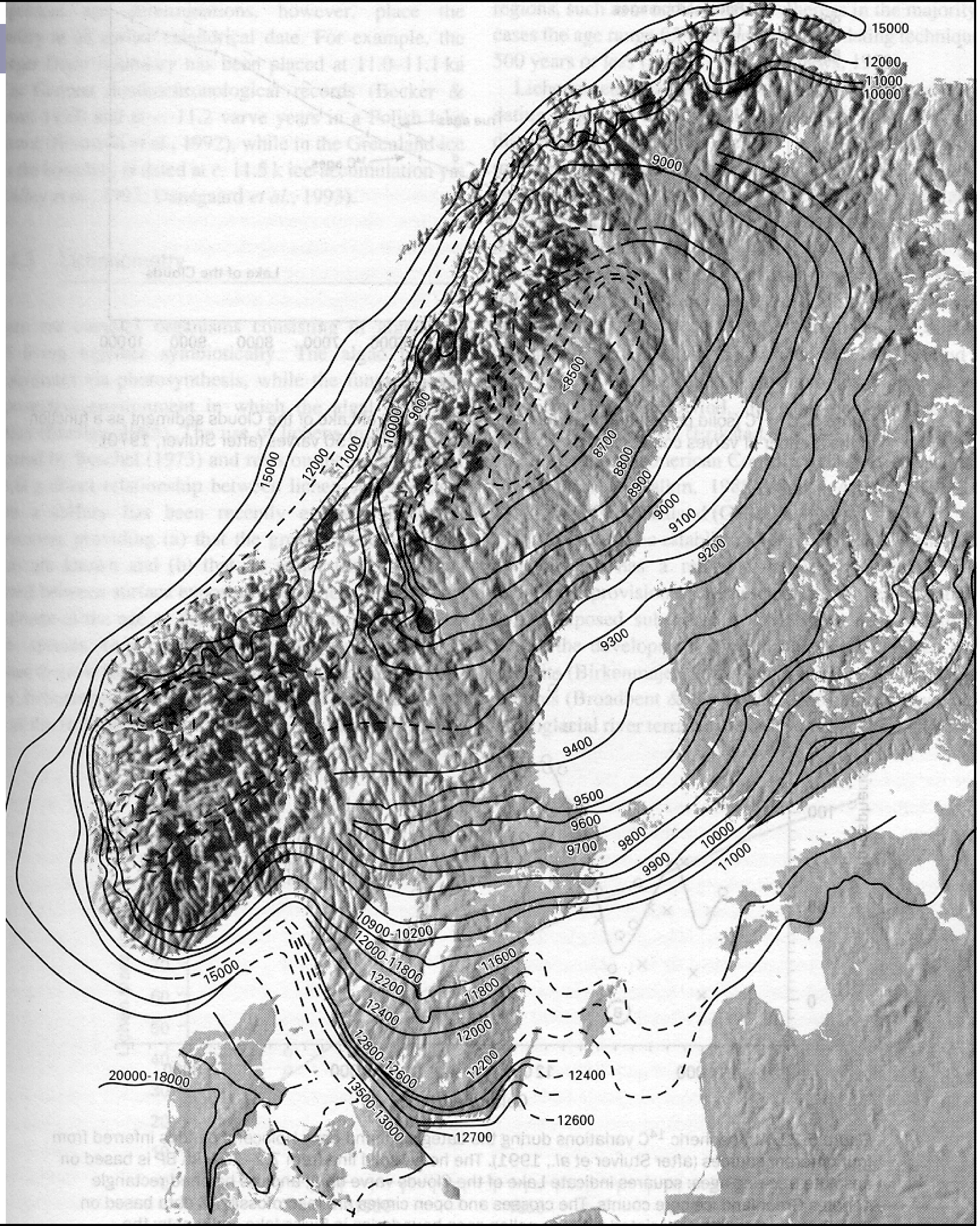


Figure 5. Two X-ray radiographs from 206 to 252 BC and 2592 to 2646 BC of Lake Nautajärvi sediment show that the visually striking components, mineral-rich and organic laminae, are far from perfect throughout the sequence for studies of automated line-scan image analysis. Therefore, it is also necessary to estimate the error in the varve chronology.

Uses of varve chronology (1)

- Patterns of deglaciation
  - Used extensively in both Scandinavia and North America as a means of dating the deglaciation of major ice sheets.
  - Varve sequences in different lakes can be linked on the basis of relative thicknesses of particular annual layers (e.g. thicker layers in warmer years).
  - Comparison of varve chronology with dates from other methods on the same sediments (e.g. ^{14}C) can improve confidence in dating framework.
- Varves in other sediment systems
  - Rhythmic sediments exist in other sediment systems.
  - Sedimentation and biological activity can show seasonal patterns in many lakes and can result in annual sediment layers.
  - E.g. diatom blooms during spring/summer can produce **organic** varves in some lake sediments.

Deglaciace Skandinávie



Uses of varve chronology (2)

- Calibration of ^{14}C timescale
  - Where varves have a significant organic component, comparisons can be made between the varve chronology and a ^{14}C chronology.
  - E.g. Wolfarth *et al*., (1993); Boreas, 22, 113-128. Comparison of varve (calendar) years and ^{14}C years shows possible calibration errors in the ^{14}C method.
- Duration of particular 'events'
  - e.g. Younger Dryas (Loch Lomond Stadial) event in Europe estimated to have lasted *c*. 1140 +/- 20 years in Poland on the basis of varve chronology.
  - Same event represented by between 900 and 1000 varves in Sweden.

OTHER NUMERICAL DATING TECHNIQUES

LICHENOMETRY

Lichens are plant-like organisms that grow on rocks.

Grow at a measurable rate.

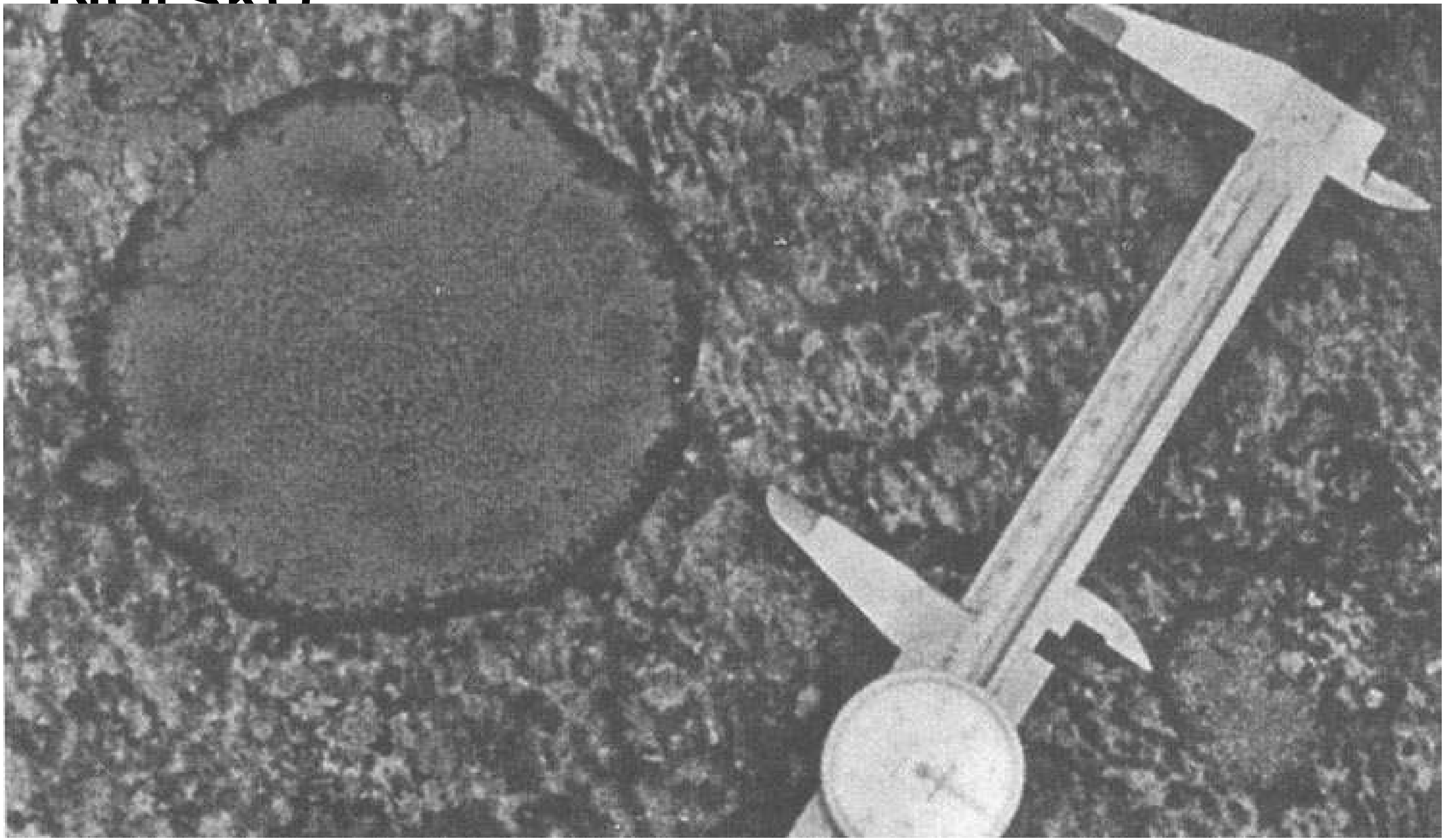
By measuring size on items of known date, the size is plotted against size on unknown aged objects.

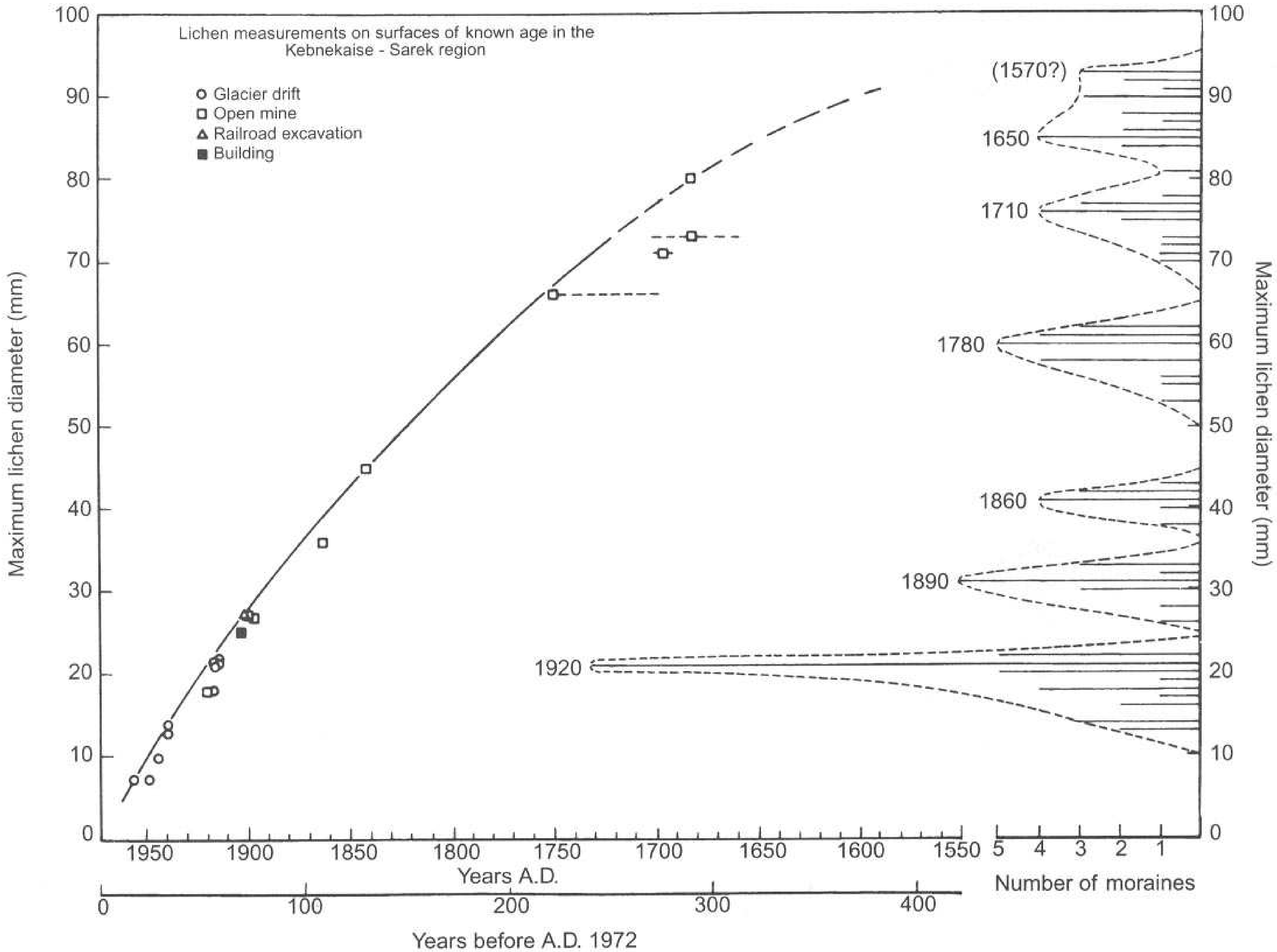
Good for the last 9000 years.

OTHER NUMERICAL DATING TECHNIQUES

LICHENOMETRY

Rhizocarpon geographicum, Norsko





Lichen measurements on surfaces of known age in the
Kebnekaise - Sarek region
Glacier drift
Open mine
Railroad excavation
Building
Maximum lichen diameter (mm)
Years A.D.
Years before A.D. 1972
Number of moraines
(1570?)
1650
1710
1780
1860
1890
1920

• surface exposure dating

…designed to measure when surfaces are first exposed…

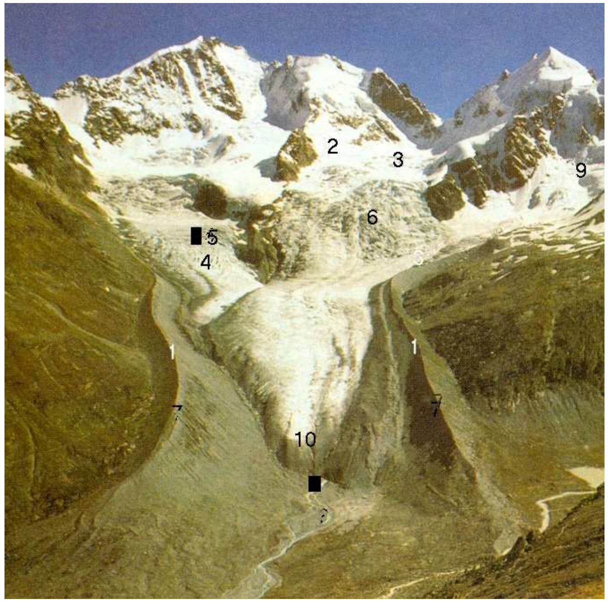
cosmogenic isotopes: those that are produced in small quantities in surface exposures from cosmic-ray bombardment

…intergalactic radiation, predominantly neutrons, hits atoms and converts them into cosmogenic isotopes

Si, Mg, Fe, Al……convert to beryllium 10
K, Ca, Cl……convert to chlorine 36
Be-10 and Cl-36 then also decay into daughter products

10Be has t1/2 of ~ 300,000 years.
36Cl has t1/2 of ~ 1.5 million years.
Fills the gap between 14C and K-Ar.
…much more complicated than radiogenic methods…
--parent material is continuously produced (must know production rate)--
--erosion may remove material--
--very small amounts present to be measured--

OTHER NUMERICAL DATING TECHNIQUES



Moraine

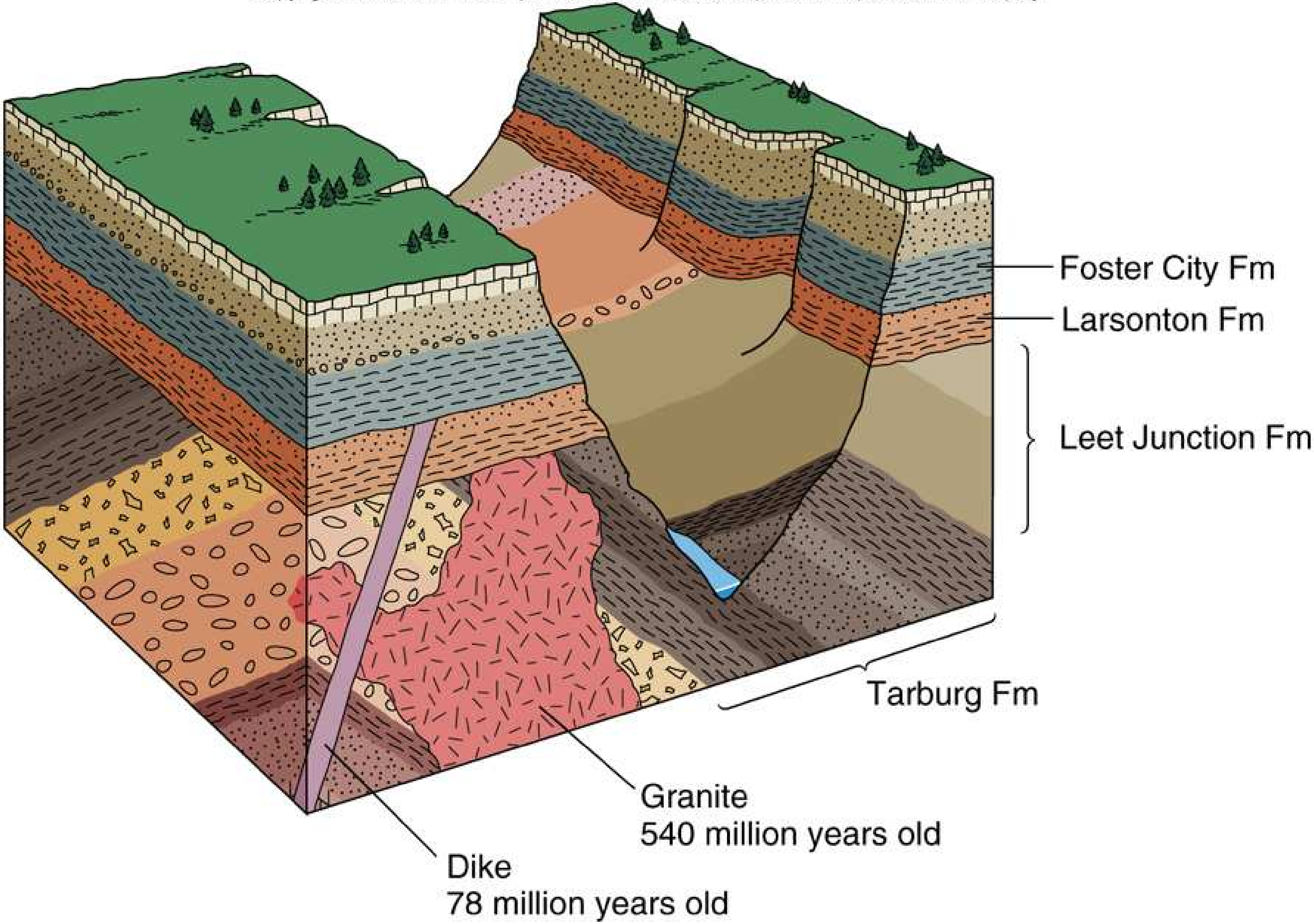
Alluvial fan

Datování ^{137}Cs

- ^{137}Cs: antropogenní izotop, vzniká jako produkt umělých radioaktivních rozpadů (jaderné elektrárny, jaderné výbuchy)

- Černobyl 1986
- Pacific nuclear weapon tests 1960-61

relative and absolute dates combined



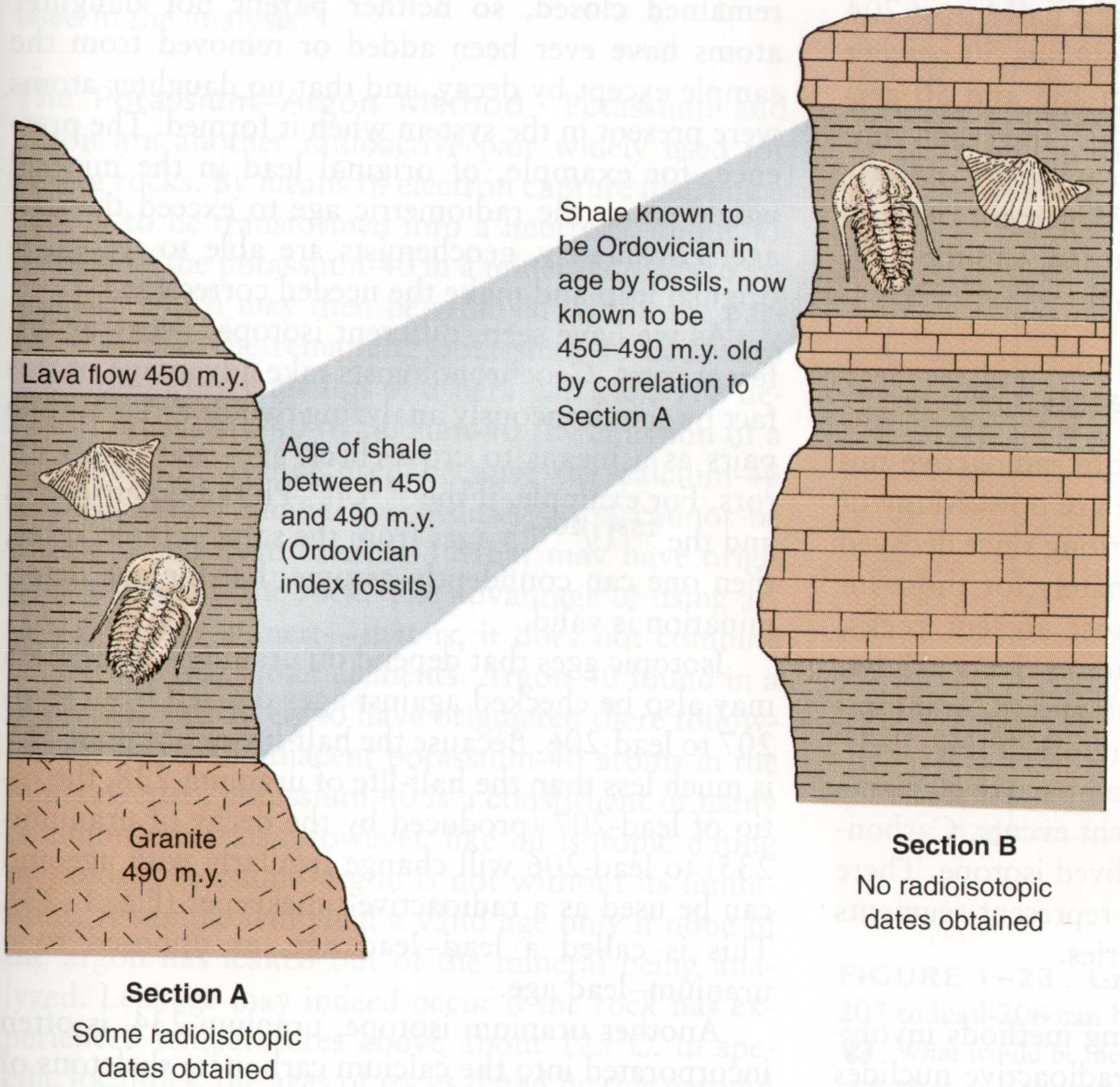


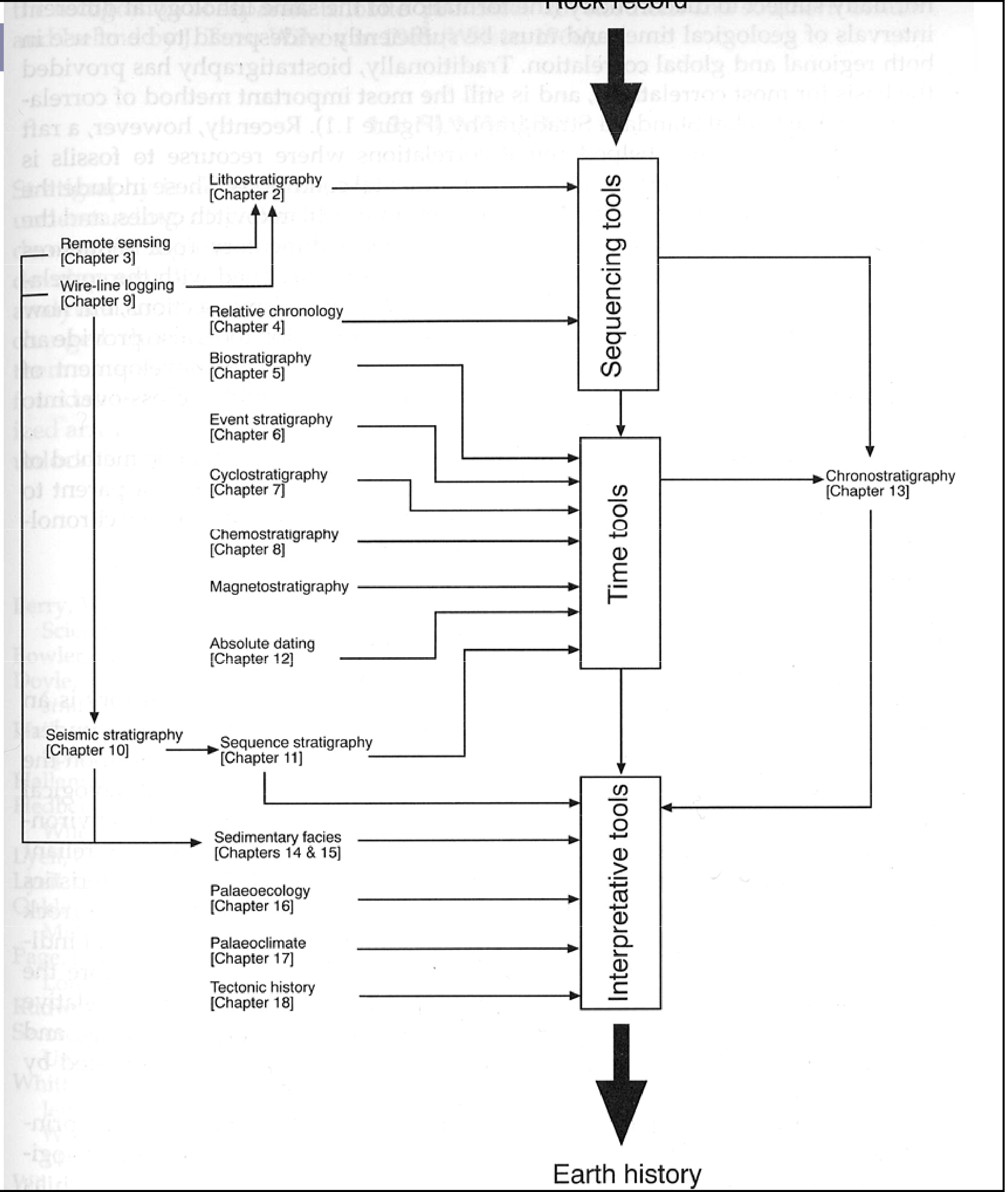
FIGURE 1–21 The actual age of rocks that cannot be dated isotopically can sometimes be ascertained by correlation.

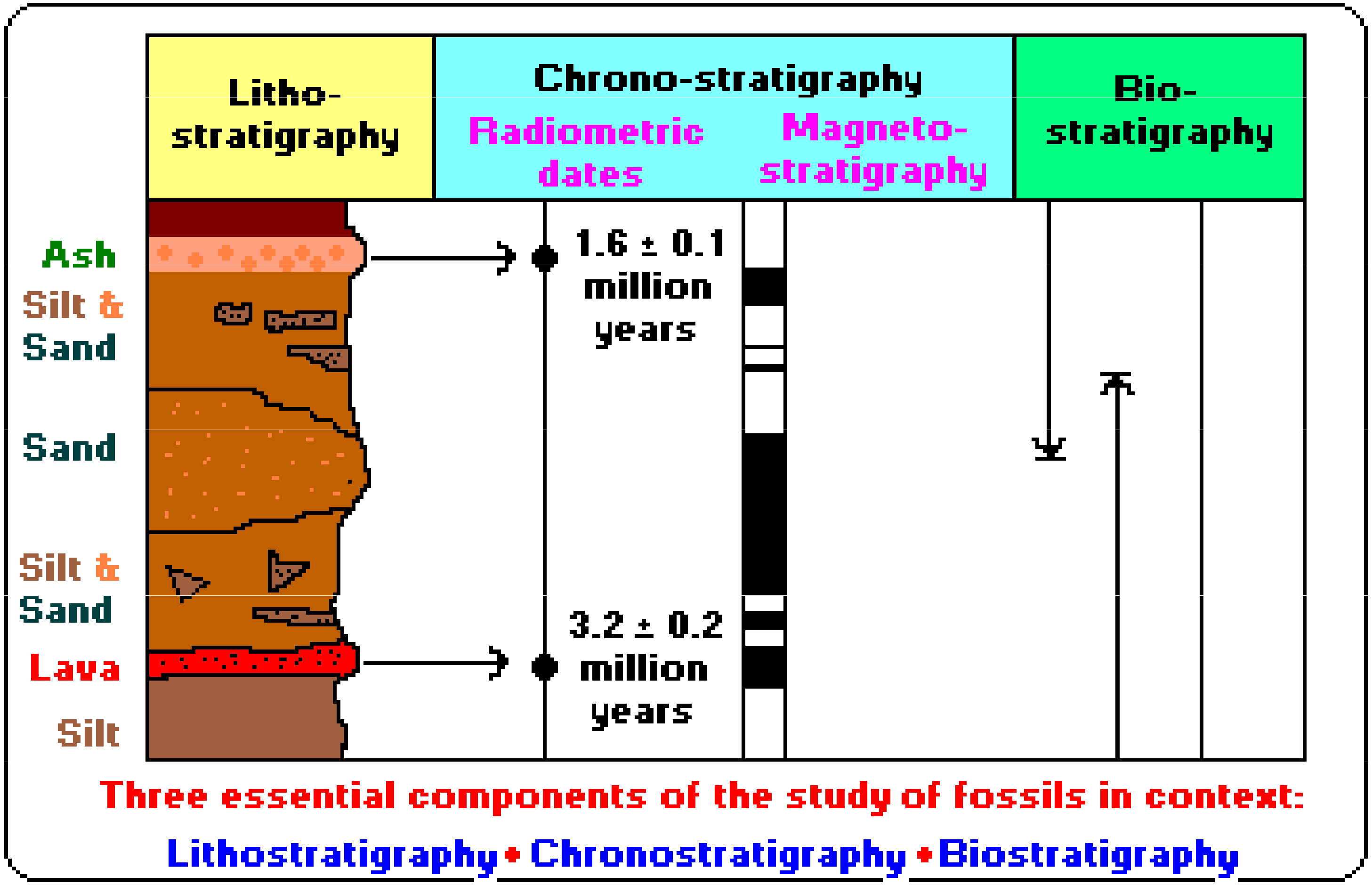
Chronostratigrafie (globální standardní stratigrafie)

- integruje data ze stratigrafických metod
- standard pro globální stratigrafickou korelaci
- dělení horninového záznamu na časově-horninové jednotky – chronostratigrafické jednotky
- Historické hledisko

Stratigraphic tool kit

- Vytvoření sekvence
  - Sled „událostí“
  - Časové nástroje
- Interpretace záznamu



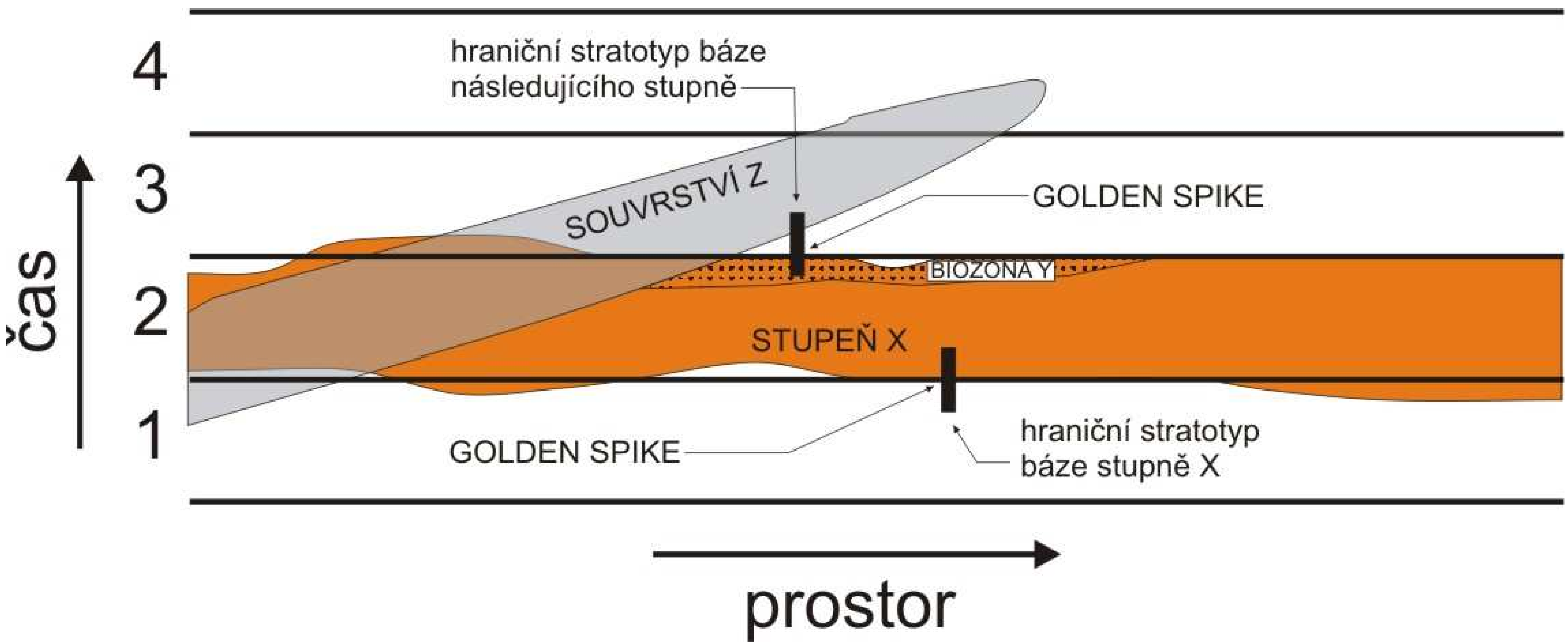


Litho-stratigraphy
Chrono-stratigraphy
Radiometric dates
Magneto-stratigraphy
Bio-stratigraphy
Ash
Silt & Sand
Sand
Silt & Sand
Lava
Silt
1.6 ± 0.1 million years
3.2 ± 0.2 million years
Three essential components of the study of fossils in context:
Lithostratigraphy • Chronostratigraphy • Biostratigraphy

Chronostratigrafie: historie

- Definice prvních útvarů: 19. stol
- Názvy: geografické (devon, perm), etnografické (silur, ordovik), časové (trias, terciér), litologické (křída, karbon), na základě litologie, později smíšení s biostratigrafií a časovým významem jednotek – zmatek
- 1941: definice časově-horninových jednotek (Schenck and Muller 1941)
- American Code of Stratigraphic Nomenclature (1970)
- International Stratigraphic Guide (Hedberg 1976, 1967):
  Chronostratigraphic units are „bounded by isochronous surfaces“
- 1972: definice prvního mezinárodního hraničního stratotypu: kopec Klonk, Barandién, stanovení kritérií pro výběr hranic jednotek
- Stanovení „golden spike“ (zlatý hřeb) – geometricky nekonečně malý bod na profilu, který určuje stanovenou hranici
- Zásady České stratigrafické klasifikace (3. vydání), Chlupáč I, Štorch P (1997). Věst. Čes. Geol. Úst, 72(2), 193-204

Časové vztahy mezi chronostratigrafickými, litostratigrafickými a biostratigrafickými jednotkami



by Yin Hongfu[1], Zhang Kexin[1], Tong Jinnan[1], Yang Zunyi[2] and Wu Shunbao[1]

The Global Stratotype Section and Point (GSSP) of the Permian-Triassic Boundary

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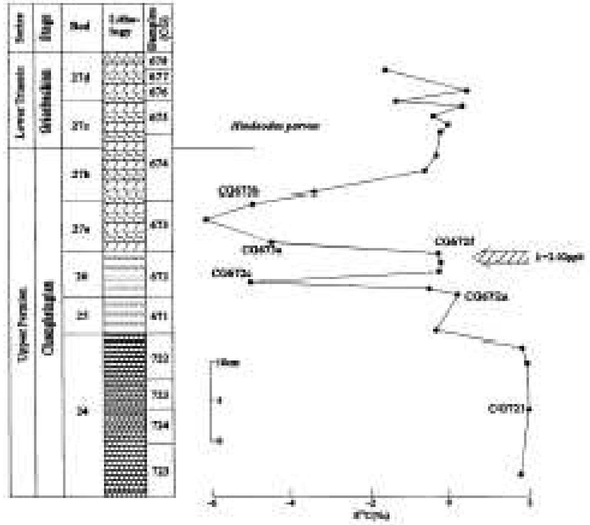

Figure 8. Stable carbon isotope values across the PTB at Meishan section (from Xu and Yan, 1993).

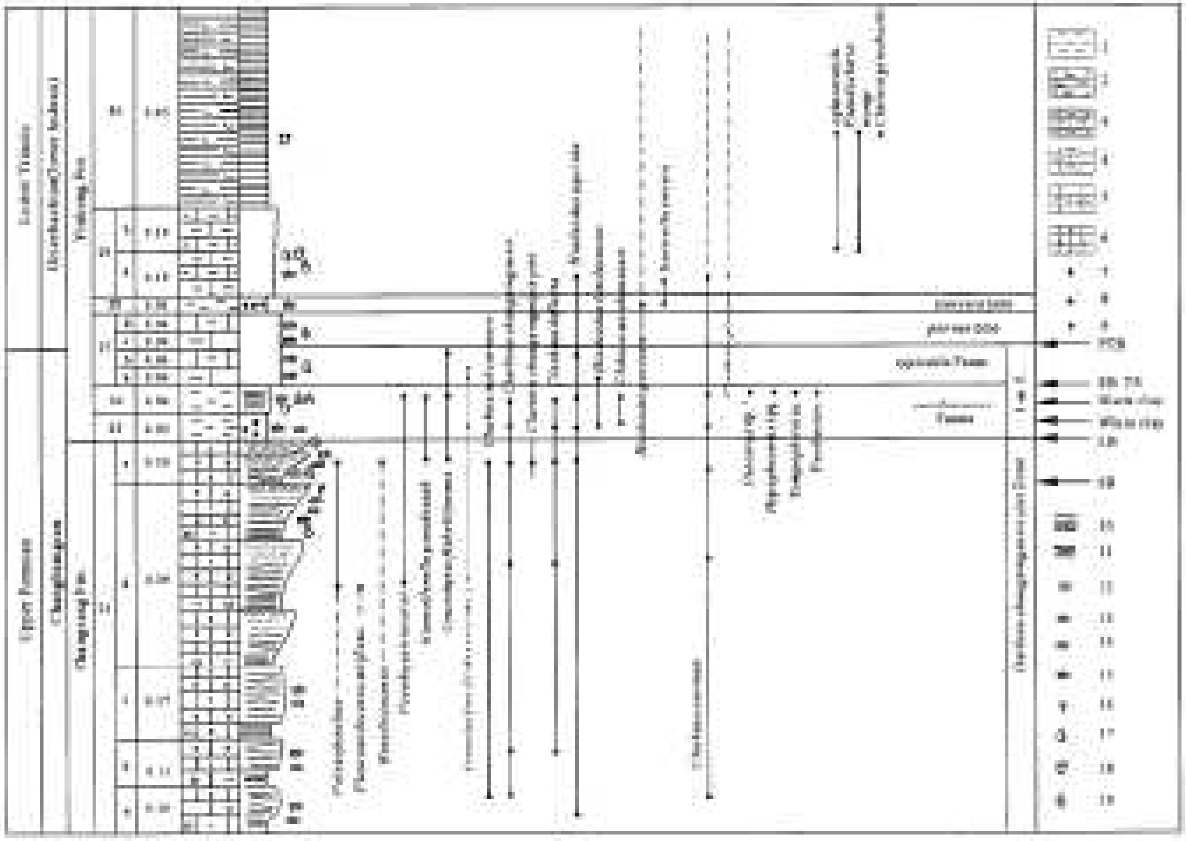

Figure 3. Litho- and biostratigraphic column of PTB strata of Meishan section D. Lm. Z. Hindeodus latidentatus-Clarkina meishanensis Zone, SB sequence surface, LB lithostratigraphic boundary, EB eventostratigraphic boundary, TS transgressive surface, PTB Permian-Triassic boundary. 1. clay, 2. calcareous mudrock, 3. marl, 4. argillaceous micrite, 5. siliceous micrite, 6. bioclastic micrite, 7. highquartz, 8. zircon, 9. microspherules, 10. horizontal bedding, 11. wavy bedding, 12. convolute bedding, 13. fusulinids, 14. foraminifers, 15. conodonts, 16. calcareous algae, 17. brachiopods, 18. bivalves, 19. ammonoids.

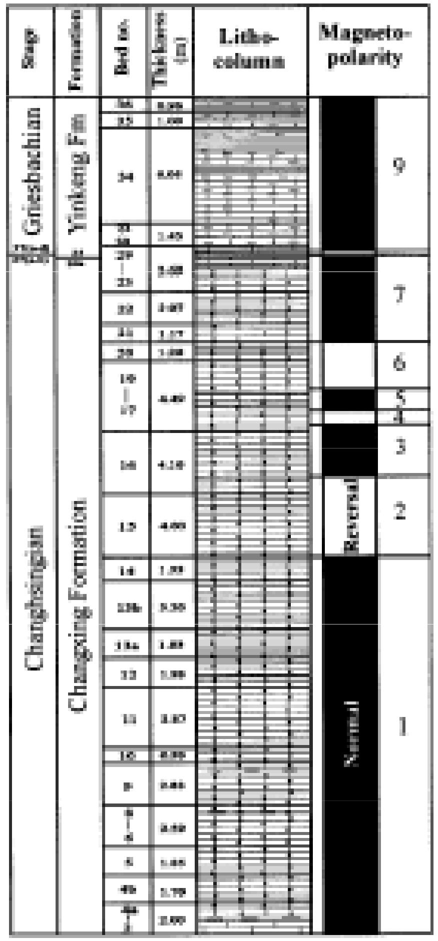

Figure 7. Magnetostratigraphy of Meishan Section D.

Hierarchie chronostratigrafických jednotek

- všechny vrstvy (horniny) na celém světě vznikly v daném časovém intervalu
- Časově-horninové jednotky (chronostratigrafické jednotky)
- Časové vyjádření (geochronologické jednotky)

Príklad:	Chronostratigrafické jednotky	Geochronologické jednotky	Oblastné litostratigrafické jednotky	Rýdzo biostratigrafické jednotky
fanerozoikum	eonotem	eon		
mezozoikum	eratem	era		
jura	útvar	perioda	skupina	
lias	oddelenie	epocha	súvrstvie	rôzne druhy biostratigrafických
toark	stupeň	věk	člen	zón
Hildoceras bitrons	chronozóna	chron		(subzóna)
			vrstva (horizont)	(biohorizont)

Obr. 23a. Prehľad hlavných stratigrafických jednotiek. Chronostratigrafické a geochronologické jednotky si vzájomne zodpovedajú a ich obsah je presne stanovený. Oblastné litostratigrafické a biostratigrafické jednotky sú nezávislé od iných stupníc a hierarchické usporiadanie je relatívne

Hierarchie chronostratigrafických jednotek

- STUPEŇ (STAGE)

- 2 – 10 mil. let, časové vyjádření: věk (age)
- Teoreticky aplikovatelný celosvětově (ICS), někdy pouze regionální platnost
- Interregionální korelace
- Definován stratotypy spodní a svrchní hranice
- Mořské sedimenty, nepřerušený sled, faciálně monotónní, význačné horizonty (biozóny) –možnost široké korelace
- Název: geografický, historické aspekty

Hierarchie chronostratigrafických jednotek

- ODDĚLENÍ (SERIES)

- 13 – 35 mil. let, časové vyjádření: epocha (epoch)
- Součástí útvaru (2 – 6 oddělení v útvaru)
- aplikovatelné celosvětově (ICS),
- spodní hranice definována spodní hranicí nejnižšího stupně
- Horní hranice definována horní hranicí nejvyššího stupně
- Název: spodní (Lower), střední (Middle), svrchní (Upper), geografický, historické aspekty

Hierarchie chronostratigrafických jednotek

- ÚTVAR (SYSTEM)

- 30 – 80 mil. let (s výjimkou kvartéru), časové vyjádření: perioda (period)
- Chronostratigrafické jednotky s celosvětovou platností
- Součástí útvaru (2 – 6 oddělení v útvaru)
- aplikovatelné celosvětově (ICS),
- spodní hranice definována spodní hranicí nejnižšího stupně
- Horní hranice definována horní hranicí nejvyššího stupně
- Název: význam geografický, etnografický, litologický, časový, historické názvy

Hierarchie chronostratigrafických jednotek

- ERATEM (ERATHEM)

- časové vyjádření: éra
- spodní hranice definována spodní hranicí nejnižšího stupně
- horní hranice definována horní hranicí nejvyššího stupně
- Název: historické názvy, hlavní změny ve vývoji života

- EONOTEM (EONOTHEM)

- časové vyjádření: eon
- Název: historické názvy, hlavní změny ve vývoji života

Hierarchie chronostratigrafických jednotek

- CHRONOZÓNA (CHRONOZONE)

- Soubor hornin vzniklý kdekoli na světě v daném časovém intervalu, který odpovídá jiné formální stratigrafické jednotce (biozóně, zóně magnetické polarity, apod)
- Časové vyjádření: chron
- Není jednoznačně přijímáno, rozpory

Adjektiva:

Čeština

- Spodní, střední, svrchní

Angličtina:

- Časově - horninové jednotky: Lower, Middle, Upper
  - Lower Carboniferous limestones, Upper Famennian conodonts

- Časové (nehmotné) určení: Early, Middle, Late
  - Late Triassic climatic changes, Late Proterozoic orogenic phase, foraminifers of Late Cretaceous age

Table 1

Summary of Categories and Unit-Terms in Stratigraphic Classification*

Stratigraphic Categories	Principal Stratigraphic Unit-terms	Equivalent Geochronologic Units
Lithostratigraphic	Group Formation Member Bed(s), Flow(s)	
Unconformity-bounded	Synthem	
Biostratigraphic	Biozones: Range zones Interval zones Lineage zones Assemblage zones Abundance zones Other kinds of biozones	
Magnetostratigraphic polarity	Polarity zone	
Other (informal) stratigraphic categories (mineralogic, stable isotope, environmental, seismic, etc.)	-zone (with appropriate prefix)	
Chronostratigraphic	Eonothem Erathem System Series Stage Substage (Chronozone)	Eon Era Period Epoch Age Subage (or Age) (Chron)

* *If additional ranks are needed, prefixes Sub and Super may be used with unit-terms when appropriate, although restraint is recommended to avoid complicating the nomenclature unnecessarily.*

INTERNATIONAL STRATIGRAPHIC CHART

ICS

International Commission on Stratigraphy

IUGS

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
Phanerozoic	Cenozoic	Quaternary * / Neogene	Holocene		0.0118
			Pleistocene	Upper	0.126
				Middle	0.781
				Lower	1.806
			Pliocene	Gelasian	2.588
				Piacenzian	3.600
				Zanclean	5.332
			Miocene	Messinian	7.246
				Tortonian	11.608
				Serravallian	13.65
				Langhian	15.97
				Burdigalian	20.43
				Aquitanian	23.03
		Paleogene	Oligocene	Chattian	28.4 ±0.1
				Rupelian	33.9 ±0.1
			Eocene	Priabonian	37.2 ±0.1
				Bartonian	40.4 ±0.2
				Lutetian	48.6 ±0.2
				Ypresian	55.8 ±0.2
			Paleocene	Thanetian	58.7 ±0.2
				Selandian	61.7 ±0.2
				Danian	65.5 ±0.3
	Mesozoic	Cretaceous	Upper	Maastrichtian	70.6 ±0.6
				Campanian	83.5 ±0.7
				Santonian	85.8 ±0.7
				Coniacian	89.3 ±1.0
				Turonian	93.5 ±0.8
				Cenomanian	99.6 ±0.9
			Lower	Albian	112.0 ±1.0
				Aptian	125.0 ±1.0
				Barremian	130.0 ±1.5
				Hauterivian	136.4 ±2.0
				Valanginian	140.2 ±3.0
				Berriasian	145.5 ±4.0

* proposed by ICS

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
					145.5 ±4.0
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian	150.8 ±4.0
				Kimmeridgian	155.7 ±4.0
				Oxfordian	161.2 ±4.0
			Middle	Callovian	164.7 ±4.0
				Bathonian	167.7 ±3.5
				Bajocian	171.6 ±3.0
				Aalenian	175.6 ±2.0
			Lower	Toarcian	183.0 ±1.5
				Pliensbachian	189.6 ±1.5
				Sinemurian	196.5 ±1.0
				Hettangian	199.6 ±0.6
		Triassic	Upper	Rhaetian	203.6 ±1.5
				Norian	216.5 ±2.0
				Carnian	228.0 ±2.0
			Middle	Ladinian	237.0 ±2.0
				Anisian	245.0 ±1.5
			Lower	Olenekian	249.7 ±0.7
				Induan	251.0 ±0.4
	Paleozoic	Permian	Lopingian	Changhsingian	253.8 ±0.7
				Wuchiapingian	260.4 ±0.7
			Guadalupian	Capitanian	265.8 ±0.7
				Wordian	268.0 ±0.7
				Roadian	270.6 ±0.7
			Cisuralian	Kungurian	275.6 ±0.7
				Artinskian	284.4 ±0.7
				Sakmarian	294.6 ±0.8
				Asselian	299.0 ±0.8
		Carboniferous: Pennsylvanian	Upper	Gzhelian	303.9 ±0.9
				Kasimovian	306.5 ±1.0
			Middle	Moscovian	311.7 ±1.1
			Lower	Bashkirian	318.1 ±1.3
		Carboniferous: Mississippian	Upper	Serpukhovian	326.4 ±1.6
			Middle	Visean	345.3 ±2.1
			Lower	Tournaisian	359.2 ±2.5

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
					359.2 ±2.5
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	374.5 ±2.6
				Frasnian	385.3 ±2.6
			Middle	Givetian	391.8 ±2.7
				Eifelian	397.5 ±2.7
			Lower	Emsian	407.0 ±2.8
				Pragian	411.2 ±2.8
				Lochkovian	416.0 ±2.8
		Silurian	Pridoli		418.7 ±2.7
			Ludlow	Ludfordian	421.3 ±2.6
				Gorstian	422.9 ±2.5
			Wenlock	Homerian	426.2 ±2.4
				Sheinwoodian	428.2 ±2.3
			Llandovery	Telychian	436.0 ±1.9
				Aeronian	439.0 ±1.8
				Rhuddanian	443.7 ±1.5
		Ordovician	Upper	Hirnantian	445.6 ±1.5
				Stage 6	455.8 ±1.6
				Stage 5	460.9 ±1.6
			Middle	Darriwilian	468.1 ±1.6
				Stage 3	471.8 ±1.6
			Lower	*Stage 2*	478.6 ±1.7
				Tremadocian	488.3 ±1.7
		Cambrian	Furongian	*Stage 10*	
				Stage 9	
				Paibian	501.0 ±2.0
			Series 3	*Stage 7*	
				Stage 6	
				Stage 5	
			Series 2	*Stage 4*	
				Stage 3	
			Lower Series	*Stage 2*	
				Stage 1	542.0 ±1.0

This chart was drafted by Gabi Ogg.

	Eonothem Eon	Erathem Era	System Period	Age Ma
				542
Precambrian	Proterozoic	Neo-proterozoic	Ediacaran	~630
			Cryogenian	850
			Tonian	1000
		Meso-proterozoic	Stenian	1200
			Ectasian	1400
			Calymmian	1600
		Paleo-proterozoic	Statherian	1800
			Orosirian	2050
			Rhyacian	2300
			Siderian	2500
	Archean	Neoarchean		2800
		Mesoarchean		3200
		Paleoarchean		3600
		Eoarchean	Lower limit is not defined	

Subdivisions of the global geologic record are formally defined by their lower boundary. Each unit of the Phanerozoic (~542 Ma to Present) and the base of Ediacaran are defined by a basal Global Standard Section and Point (GSSP), whereas Precambrian units are formally subdivided by absolute age (Global Standard Stratigraphic Age, GSSA). Details of each GSSP are posted on the ICS website (*www.stratigraphy.org*).

International chronostratigraphic units, rank, names and formal status are approved by the International Commission on Stratigraphy (ICS) and ratified by the International Union of Geological Sciences (IUGS).

Numerical ages of the unit boundaries in the Phanerozoic are subject to revision. Some stages within the Ordovician and Cambrian will be formally named upon international agreement on their GSSP limits. Most sub-Series boundaries (e.g., Middle and Upper Aptian) are not formally defined.

Colors are according to the United States Geological Survey (USGS).

The listed numerical ages are from 'A Geologic Time Scale 2004', by F.M. Gradstein, J.G. Ogg, A.G. Smith, et al. (2004; Cambridge University Press).