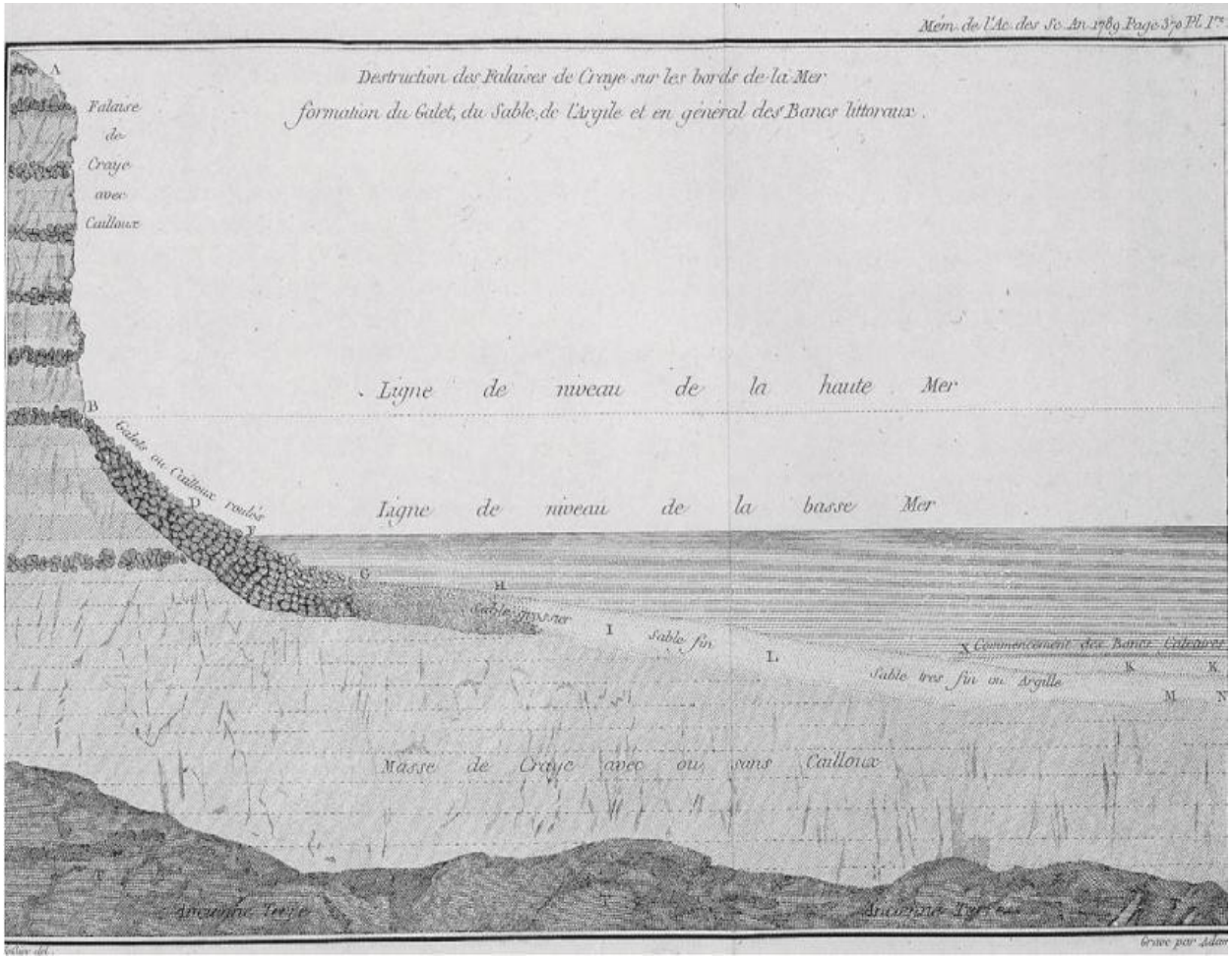
The sedimentary record of sea level variations: towards a sequence stratigraphy approach.

(limited to detritic sediments)



Module de Géologie Marine

L3- département de géosciences de l'Ecole normale supérieure

Mathieu Rodriguez

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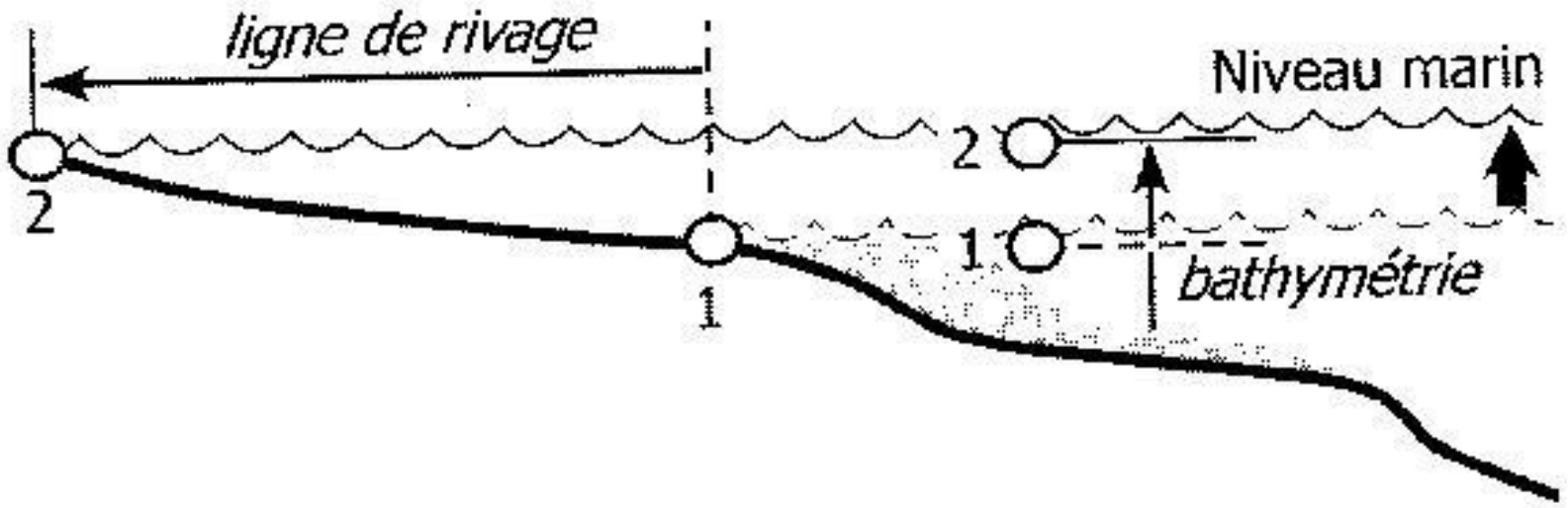
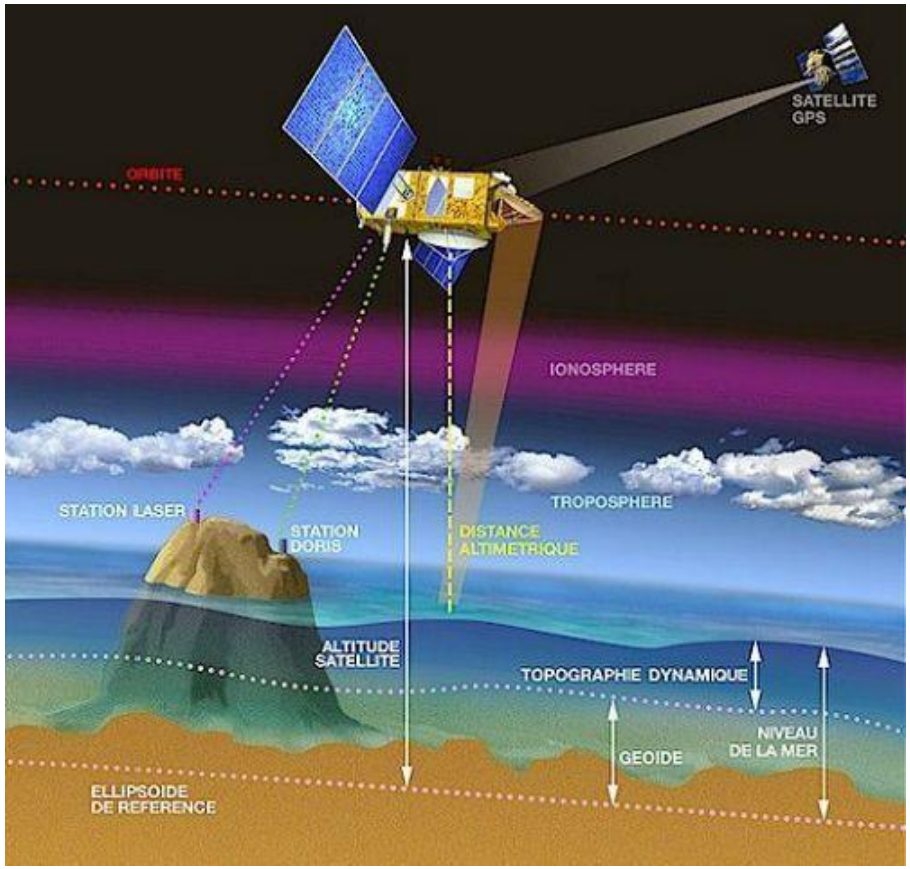
Sea level : what do we measure?

- **Absolute sea level :** variations of the distance between sea level and a reference surface (ellipsoid). Variations of absolute sea level = eustatism
- **Relative sea level** : measured from a reference location on the basement; corresponds to variations in the location of the coastline
- **Bathymetry** : depth of the ocean



Measure of present-day sea level variations by satellite altimetry and tide gauges



eustatism

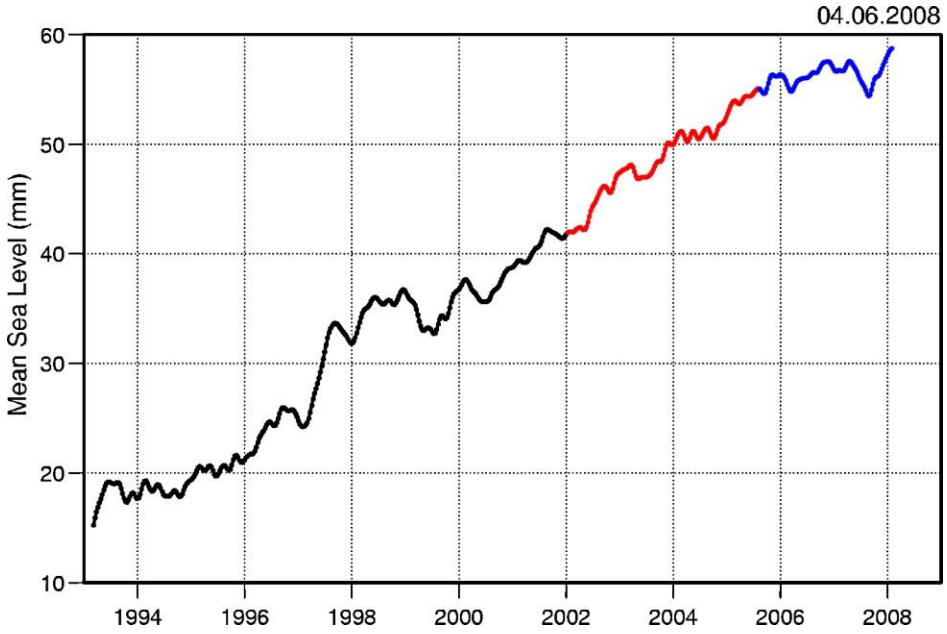
Tide gauge of Marseille, where '0' topography is defined in France

http://fr.wikipedia.org/wiki/Fichier:Maregraphe.jpg

In « La terre vue de l'espace », A. Cazenave

Recent sea level variations measured by satellite and tide gauges

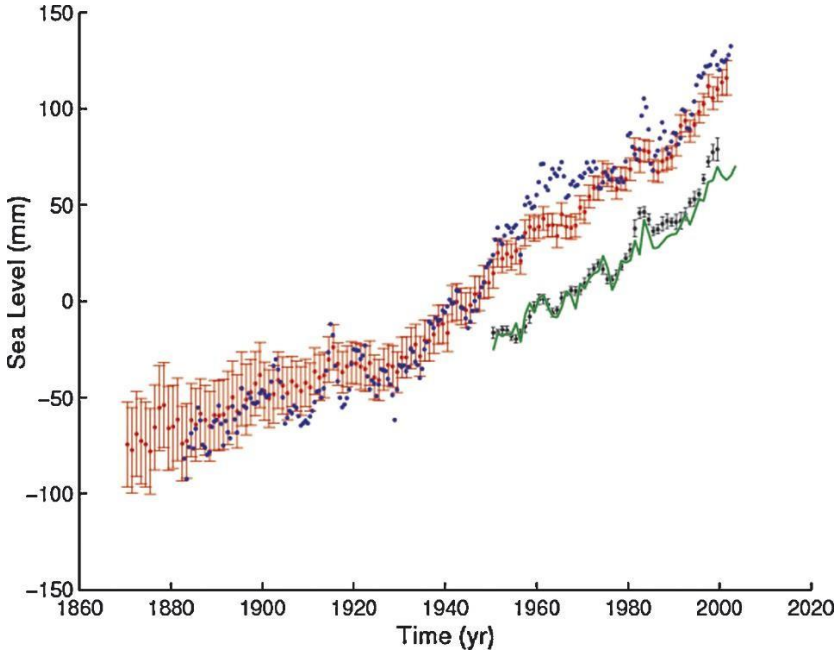
Satellites



~ 3 mm/year since 1993!

Évolution du niveau de la mer, entre 1993 et 2008, mesurée par les satellites altimétriques Topex/Poseidon et Jason-1 (données moyennes sur le domaine 65.8N et 65.8S de latitude ; un lissage sur trois mois a été effectué). Noir : Topex/Poseidon ; rouge : Topex/Poseidon plus Jason-1 ; bleu : Jason-1.
Cazenave et al., 2008.

Tide gauges

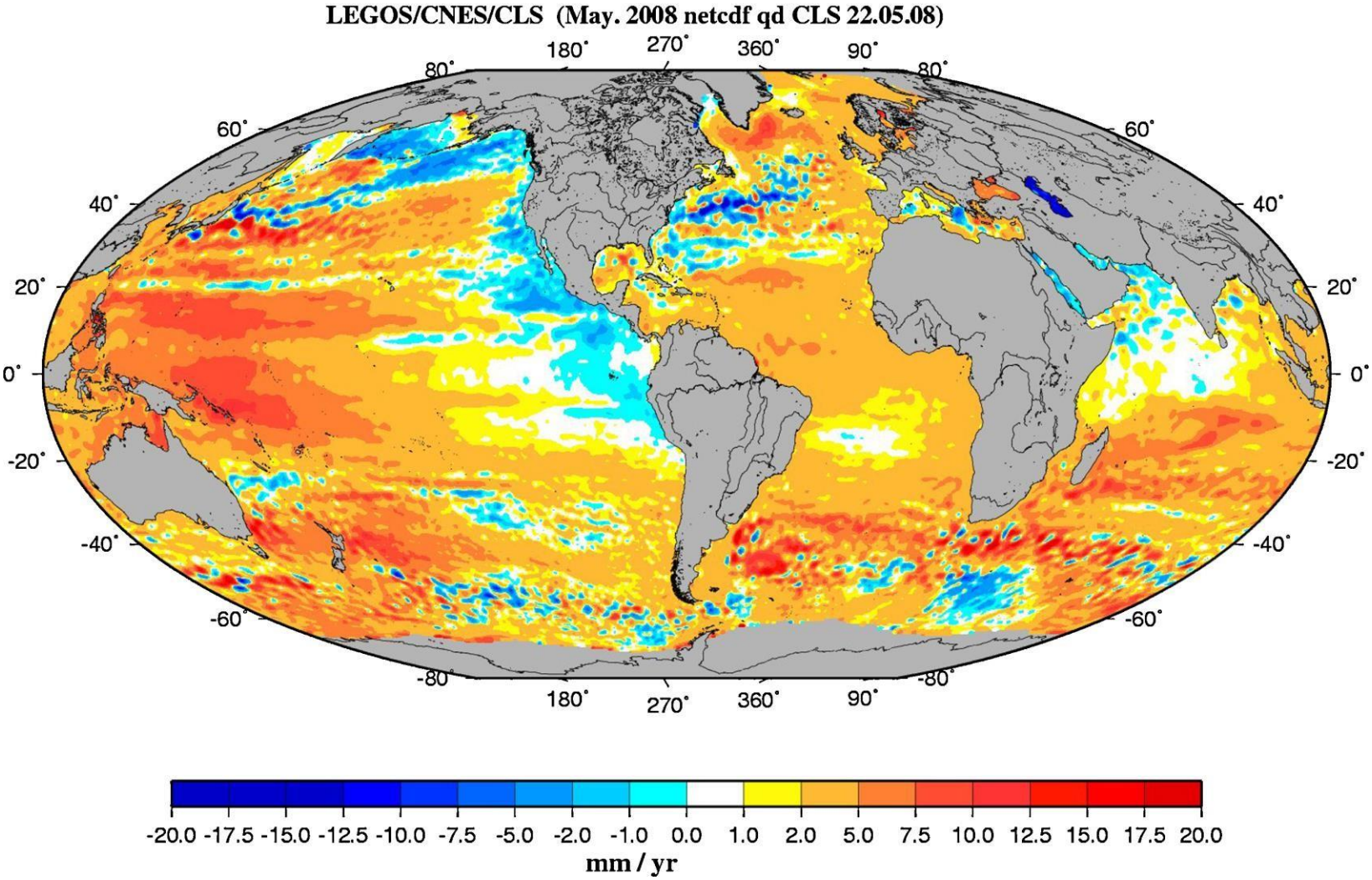


Évolution du niveau de la mer mesurée au cours du XX e siècle d'après diverses reconstructions utilisant les enregistrements marégraphiques.
In ***Cazenave et al., 2008***

Rate of sea level rise from satellite altimetry

Origin : thermic expansion + melting of continental ice sheets

Sea level trends from satellite altimetry (Oct.92-Jan.08)



Distribution géographique des vitesses de variation du niveau de la mer entre 1993 et 2008 basées sur les données altimétriques multisatellites, *in* ***Cazenave et al., 2008.***

Tracking past sea level variations, at the geological time scale

What is recorded in the sedimentary archives?

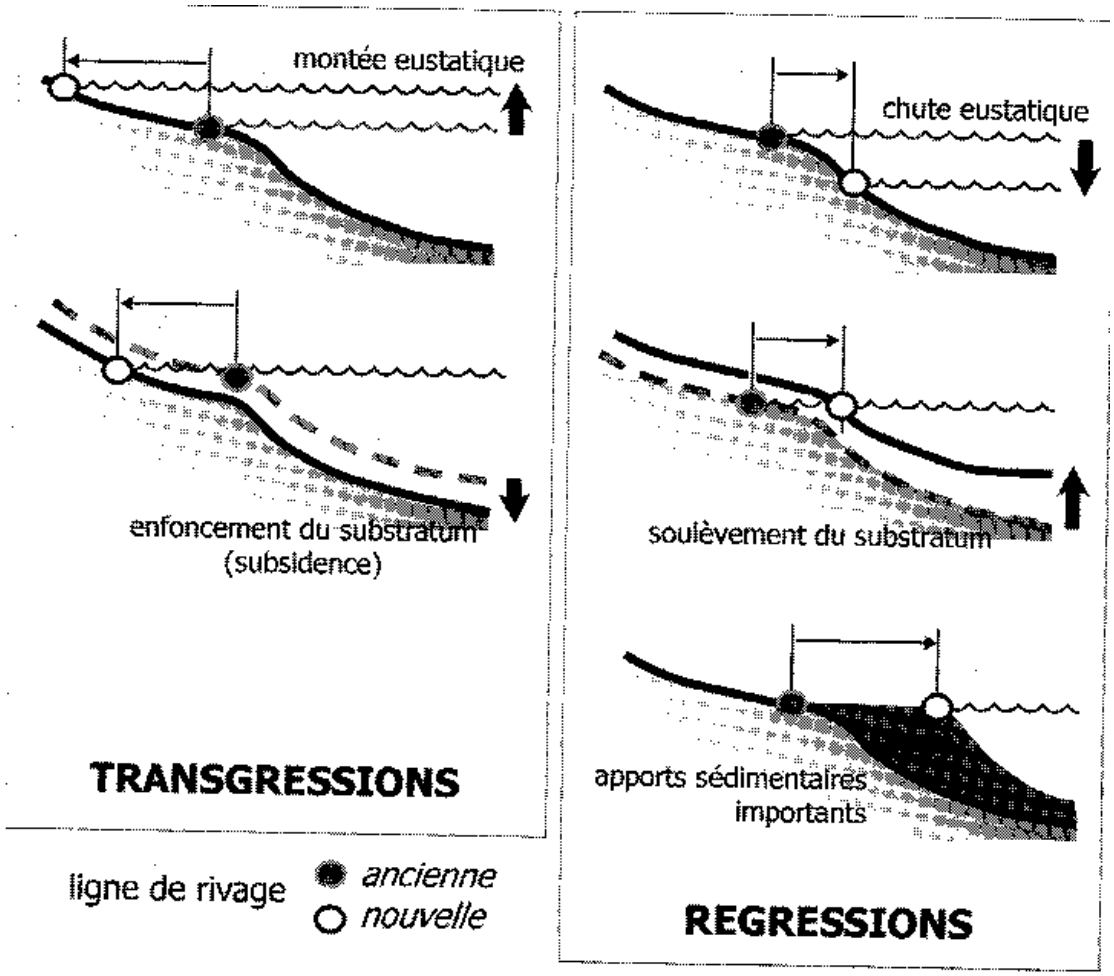


Figure 1.20.

Les différentes manières d'obtenir une transgression ou une régression en faisant varier, indépendamment des autres facteurs, l'eustatisme, la subsidence et les apports sédimentaires.

Relative sea level variations : regression (lowstand) and transgression (highstand)

Tracking past sea level variations, at the geological time scale

Oblique stratifications + unconformity
Ypresian sandstones; Noirmoutiers, Vendée

MAIN QUESTIONS

- How sea level variations are recorded in sediments?
- What is the time resolution of the record?
- How do we reconstruct past sea level curves from the sedimentary record?
- What do we learn from the sedimentary record in terms of past sea level variations?

OUTLINE

- The significance of the sedimentary record of sea level variations : an historical approach
- Tracking sea level variations at the 10^4-10^5 yrs time scale (genetic stratigraphy)
- Tracking sea level variations at the 10^6 time scale (sequence stratigraphy)
- Which processes control sea level variations at the geological time scale? A synthesis

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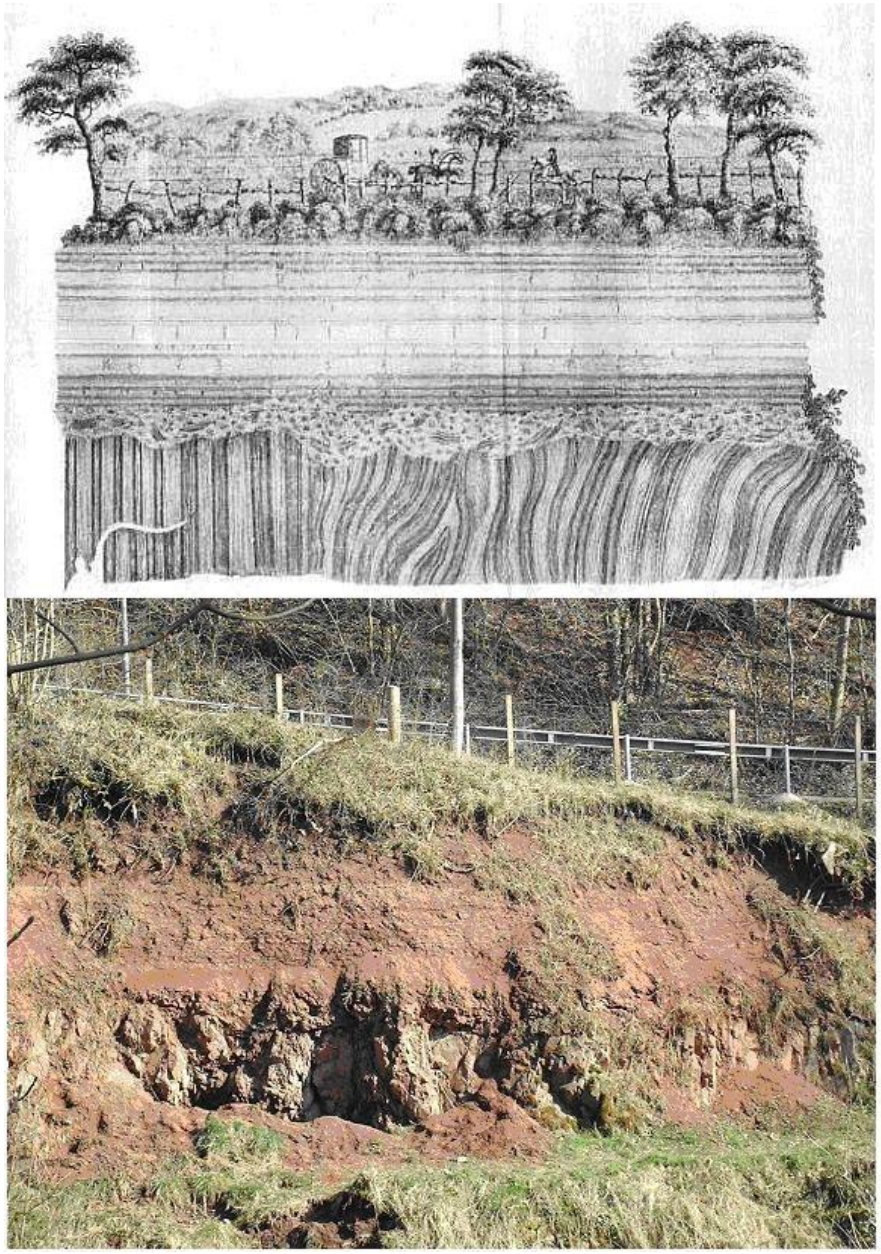
Hutton 1787 : the concept of unconformity



The 'schistus' beds were seen to stand vertically; they were cut off along an irregular surface; the red sandstones and conglomerates lay above them and were inclined gently seawards.

[Siccar point; close to Edinburg, Scotland]

http://all-geo.org/highlyallochthonous/2011/01/the-making-of-an-angular-unconformity-huttons-unconformity-at-siccar-point/

Erosion of an old mountain belt (Caledonides) by the sea…

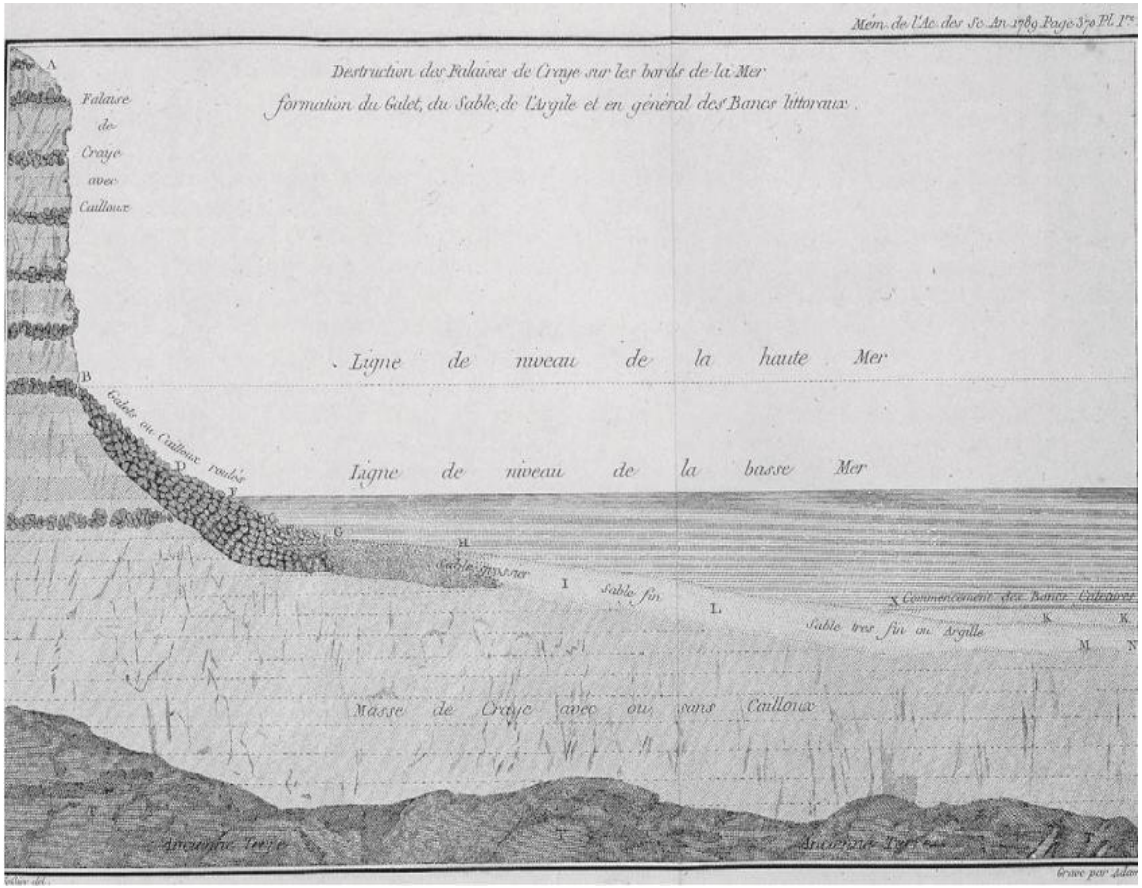
The base of the conglomerates corresponds to the fossil sea level

Hardgrounds (=niveaux condensés/surfaces durcies)

- During highstands, a location that used to be close to the shore and the sediments feeders (rivers…) during the lowstand, may be far from any sedimentary supply.
- The dominant deposits are pelagic, with slow sedimentation rates (often marked by burrows etc…)
- A large amount of time is therefore recorded in a small thickness of sediments

Hardground = high stands

Evidences of cyclic sea level variations from sediment facies analysis : pioneer works by Lavoisier (~1785)



A.L. LAVOISIER, Sur les couches modernes horizontales, qui ont été déposées par la mer, et sur les conséquences qu'on peut tirer de leurs dispositions, relativement à l'ancienneté du globe terrestre. Mém. Acad. Sc. , année 1789 (1793), p. 351-371.

St Gobain outcrop (Alps)

Bottom: sand with shells (well preserved)

=> calm environment, below the depth affected by storms, swell…

Top: round & angular pebbles

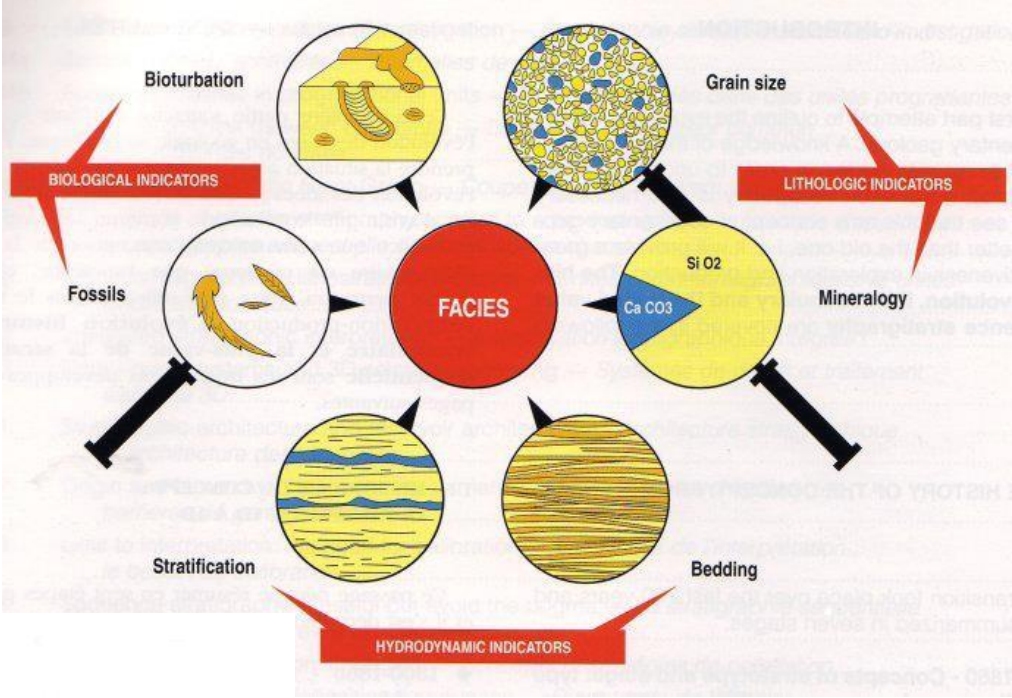
=> rough/choppy environment due to the swell and waves at the shore…

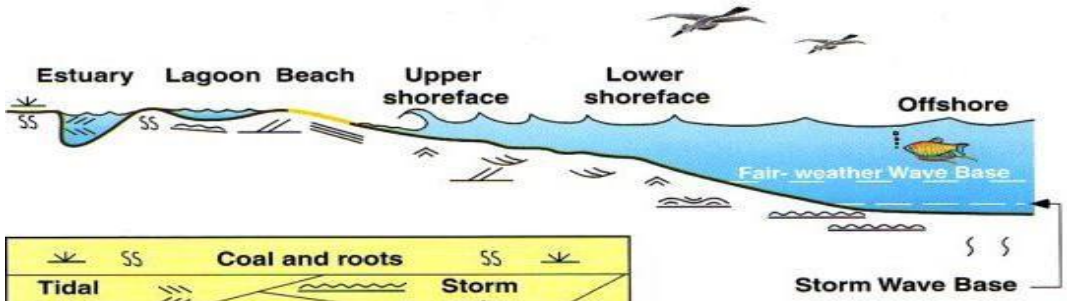
Interpretation: This sedimentary series reflects relative sea level variations.

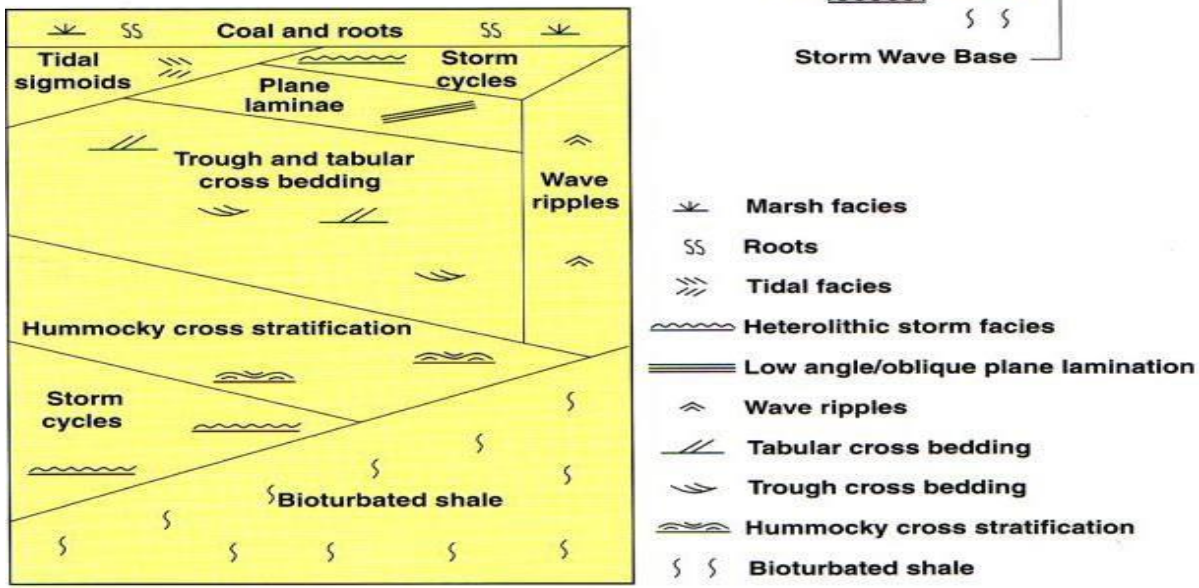
⟹ Evidence of Cyclic sea level variations … & intuition of what will be called later the Milankovitch astronomic parameters…

How sedimentary facies are related to sea level

Facies = biostratigraphic+ hydrodynamics+ lithologic characteristics of a sedimentary rock







Ex. Biostratigraphy : reefs <->shallow water

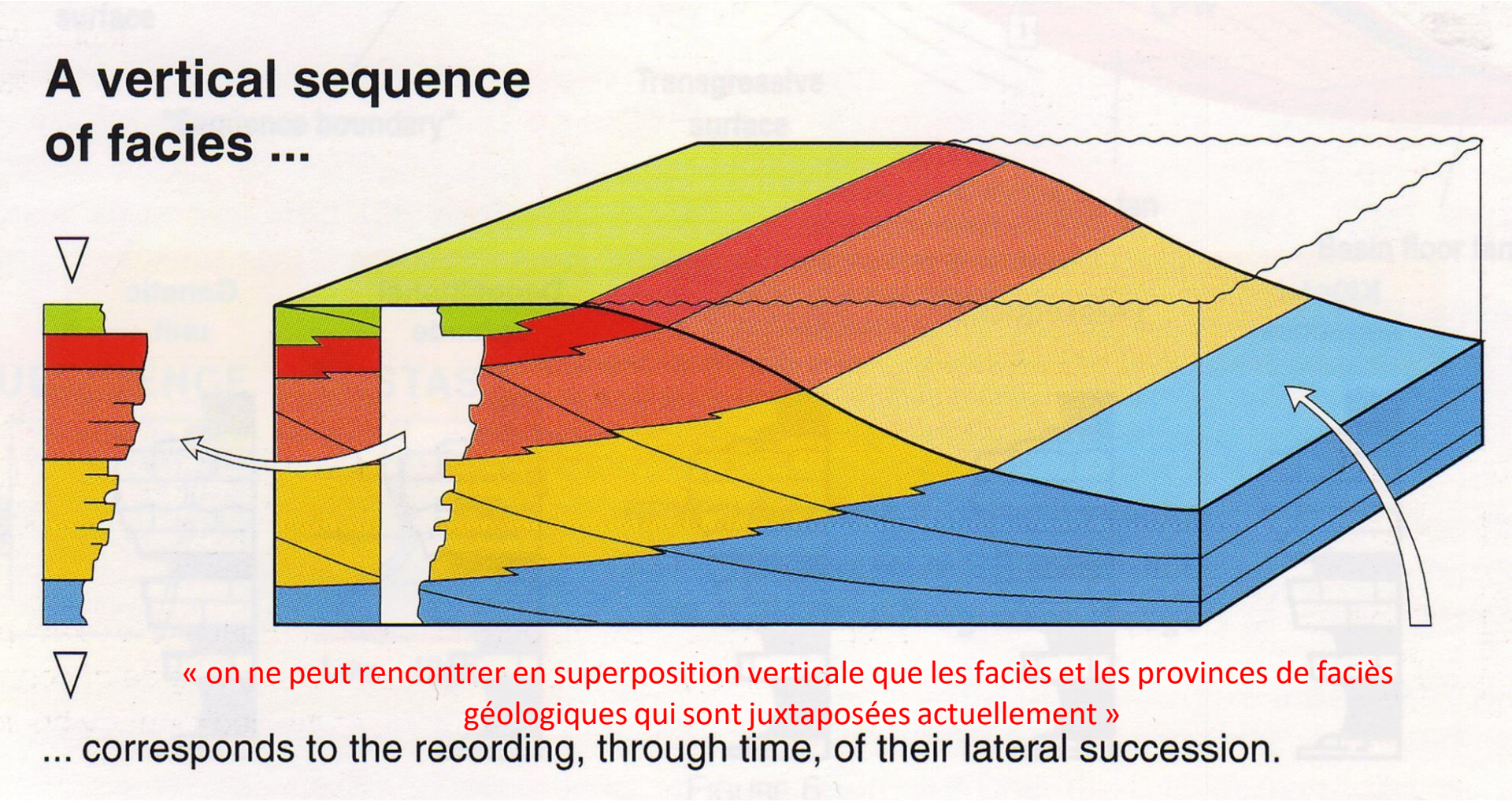
Ex. Lithology : sands <-> shore; marls/shales <->deep water

Ex. Hydrodynamic : well bedded, regular deposits <->deep water; cross bedding : shallow water

Etc…

(Homewood et al., 1999)

How the spatial distribution of sedimentary facies is related to sea level Walther's law (1894)



Walther's law (1894)

Une variation du NMR entraîne au cours du temps un changement de la distribution spatiale des faciès sédimentaires, les variations de la position de la ligne de rivage entraînant des changements de la bathymétrie, de l'hydrodynamique, etc... Avec Walter, l'enregistrement sédimentaire commence à être interprété en 4 dimensions, i.e. en termes de distribution spatiale et temporelle des faciès sédimentaires

How the geometry of sedimentary deposits record sea level changes :

Emile Haug 1907

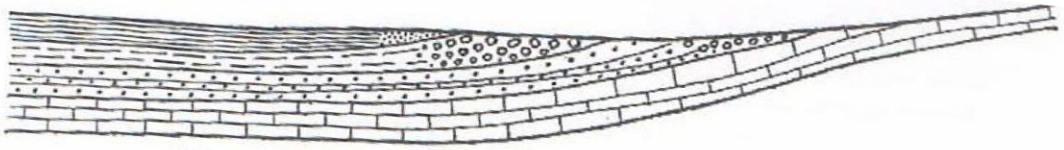


Fig. 192. — Retrait graduel des couches constituant une série régressive.

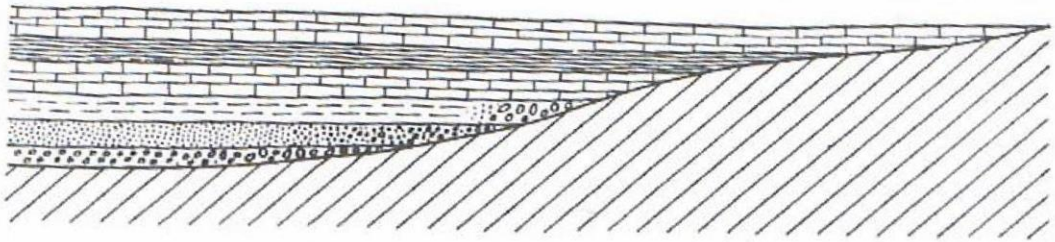
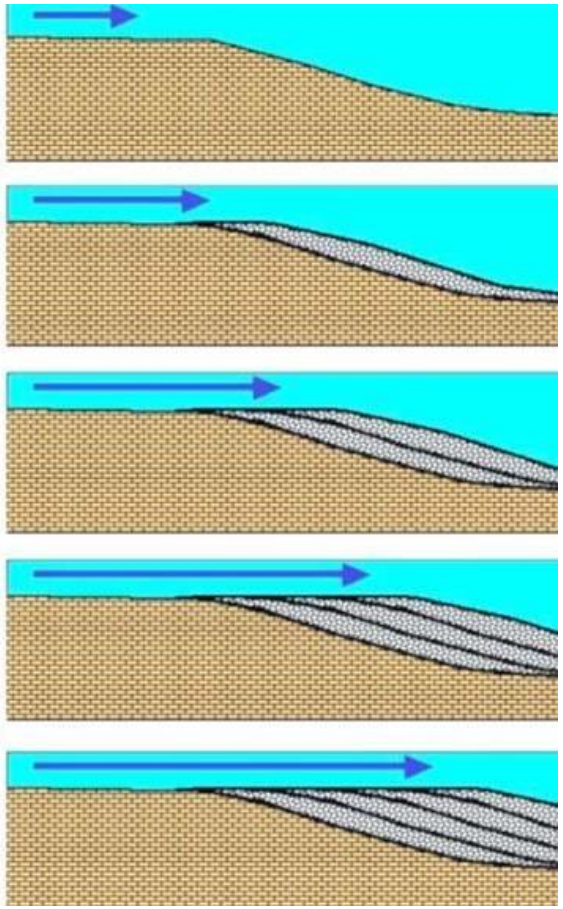


Fig. 191. — Transgressivité graduelle des couches successives déposées dans une mer qui envahit une région précédemment exondée.

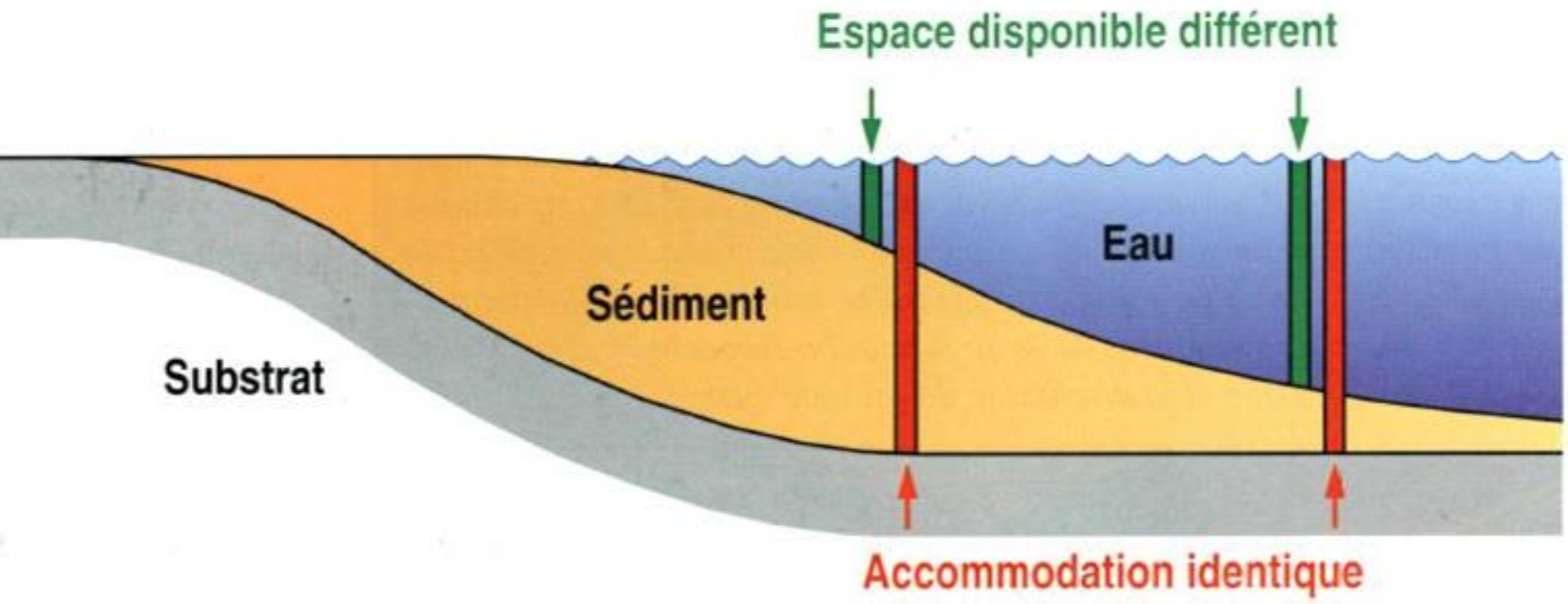
Figure 1.21.

Dessins de Emile Haug, tirés de son livre *Traité de géologie*, montrant des géométries de sédiments interprétées comme étant liées aux transgressions et régressions (Haug, 1907).



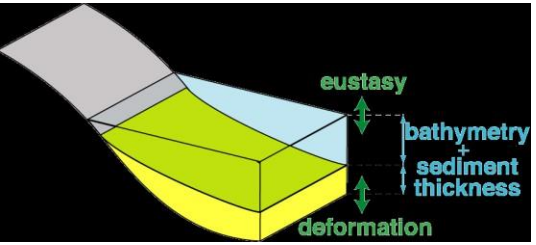
In Merzeraud, 2009

How the geometry of sedimentary deposits record sea level changes

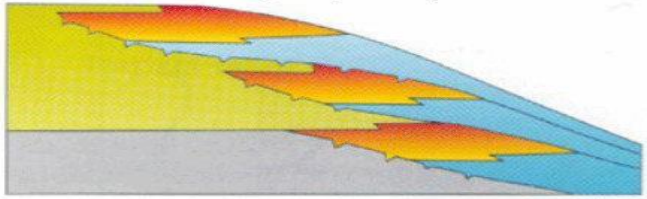
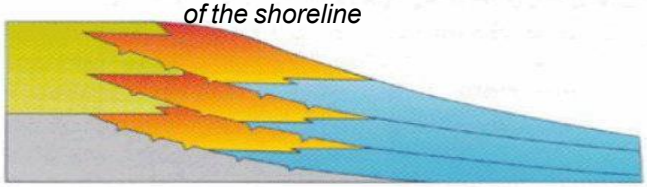
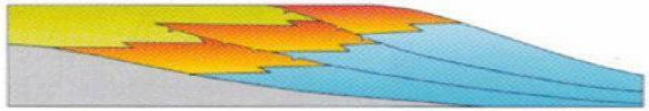
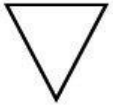
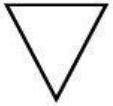
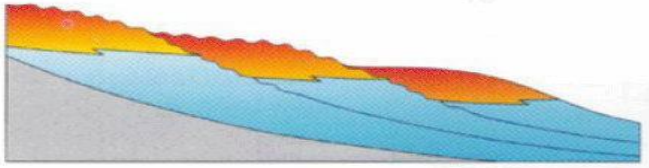
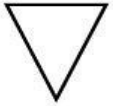


D'après Vade Mecum de Stratigraphie Séquentielle, Elf Exploration, 1996

How the geometry of sedimentary deposits record sea level changes



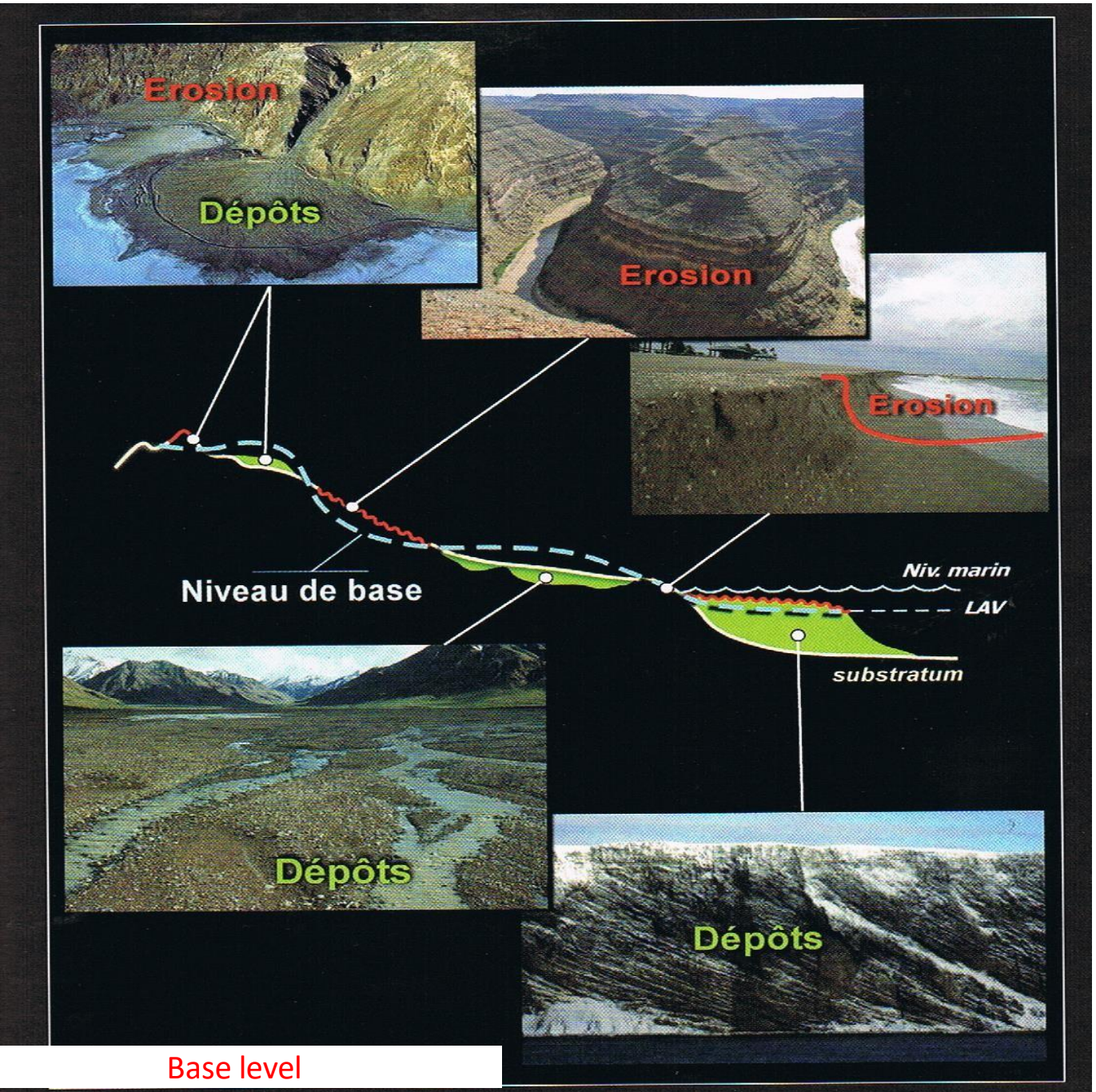
accommodation

a/s accommodation sedimentation	architecture stratigraphique	représentation
a/s > 1 **rétrogradation**		
a/s = 1 **aggradation**		
0 < a/s < 1 **progradation**		
a/s = 0 **progradation**		
a/s < 1 **progradation**		

Stable location of the shoreline

(Homewood et al., 1999)

How landscapes are affected by sea level changes : the concept of base level by Powell (~1870)



Base level

Base level :

virtual surface with no deposition/no erosion

Inland : mainly influenced by tectonic processes + ice sheets etc…

Close to the sea : mainly influenced by sea level fluctuations…

How landscapes are affected by sea level changes : the concept of base level by Powell (~1870)

River's morphology evolves according to the slope gradient…

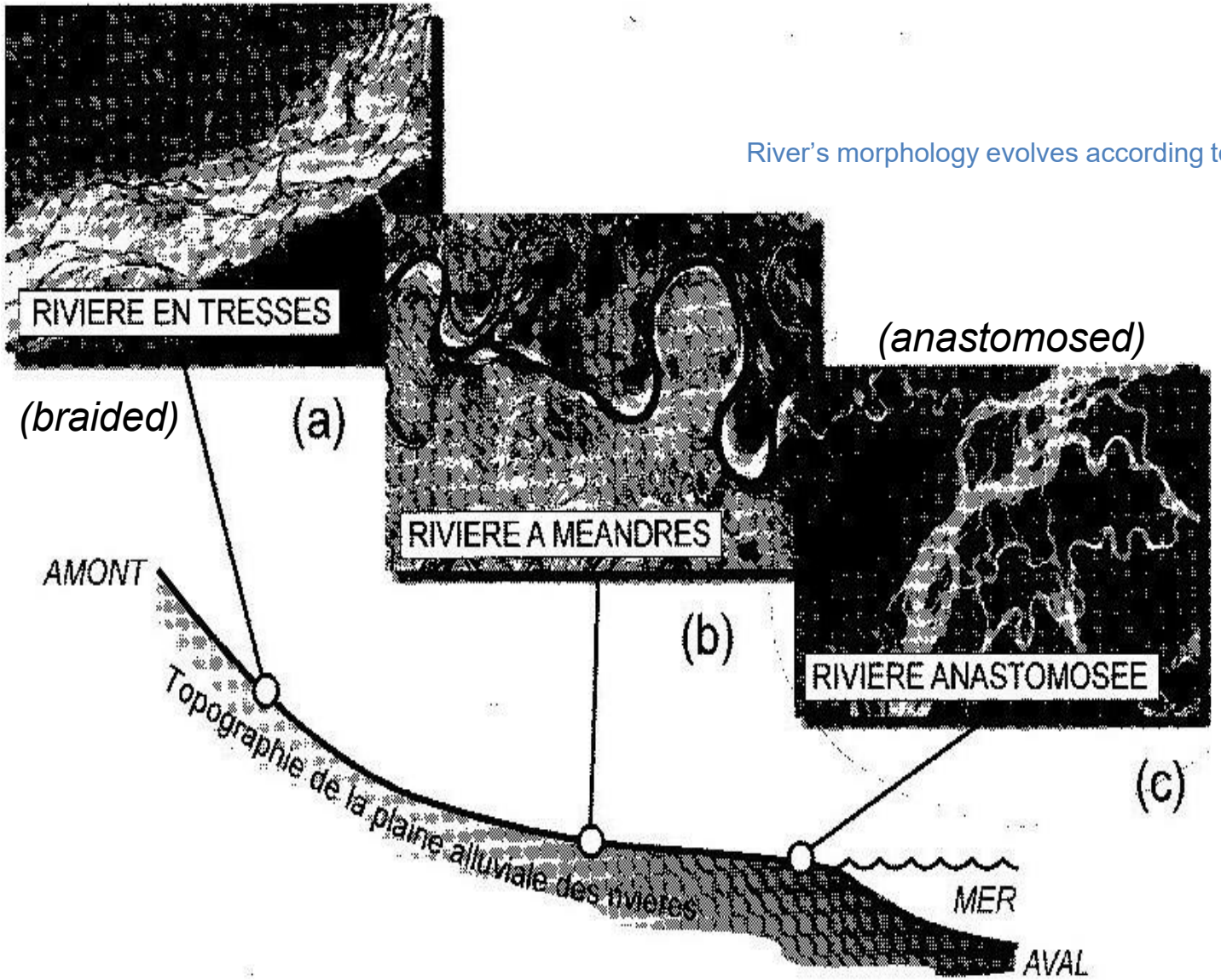


Figure 3.22. Morphologie des rivières suivant la pente sur laquelle se fait l'écoulement.

In Merzeraud, 2009

How landscapes are affected by sea level changes : the concept of base level by Powell (~1870)

A change in sea level is expressed by a change in the base level

For a sea level rise, the deposition lowers the slope gradient and therefore the river's morphology

The change in river's morphology is recorded in sediment facies

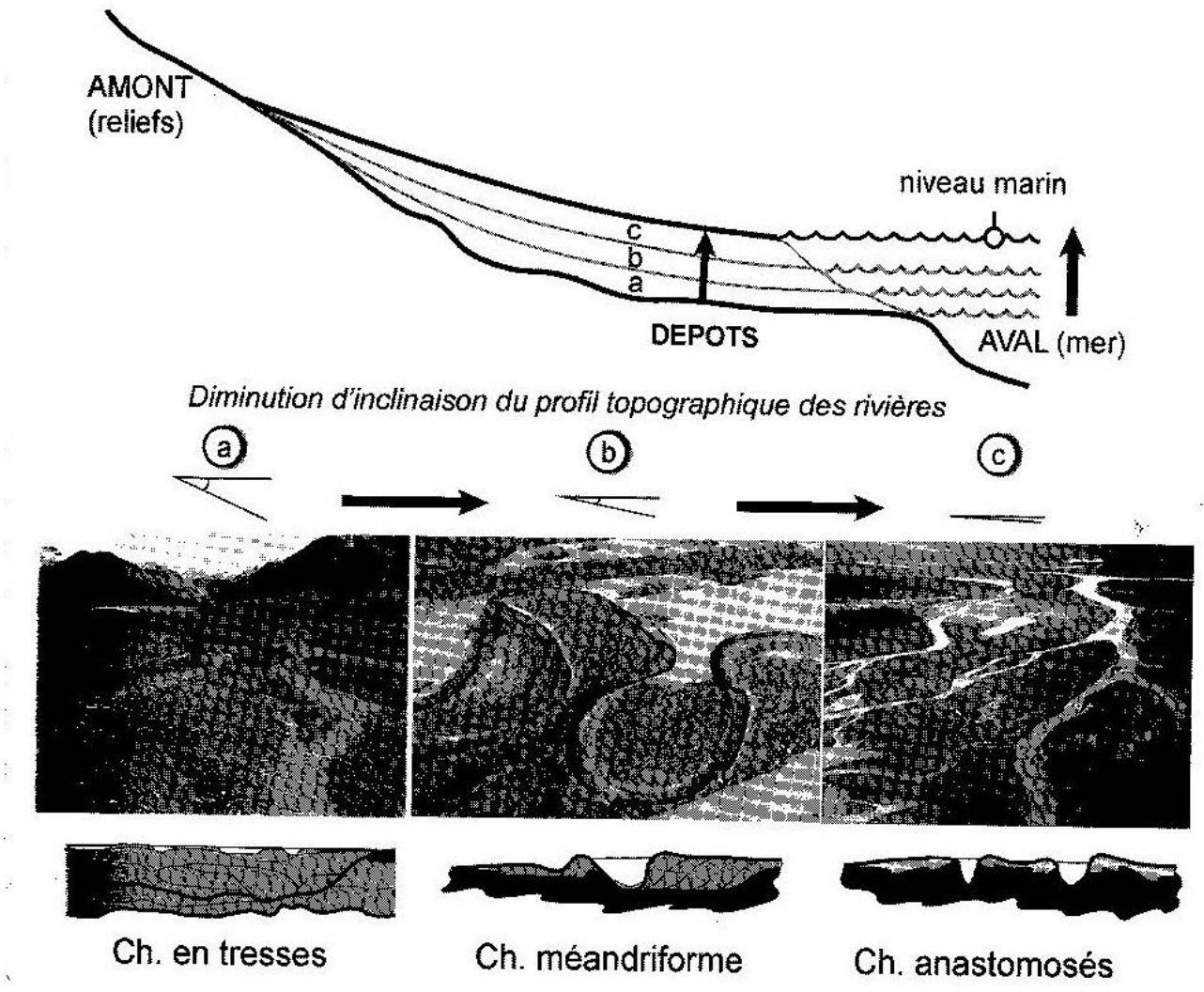


Figure 3.23. Réponse des rivières à une hausse niveau marin.

Les nappes phréatiques s'élèvent et la sédimentation va remplir le lit des rivières en diminuant ainsi leur pente. Les photographies illustrent l'évolution possible des morphologies fluviatiles. Sous les photographies, un schéma représente l'aspect des accumulations sédimentaires dans les chenaux fossiles vus en coupes transversales (argiles en noir et sable en gris).

In Merzeraud, 2009

Definition of a sequence

L. Sloss 1949:

«*l'ensemble des dépôts ayant eu lieu pendant un cycle de transgression/régression (couplé à la subsidence ou à la remontée du fond du bassin), limité à la base et au sommet par une discontinuité* ».

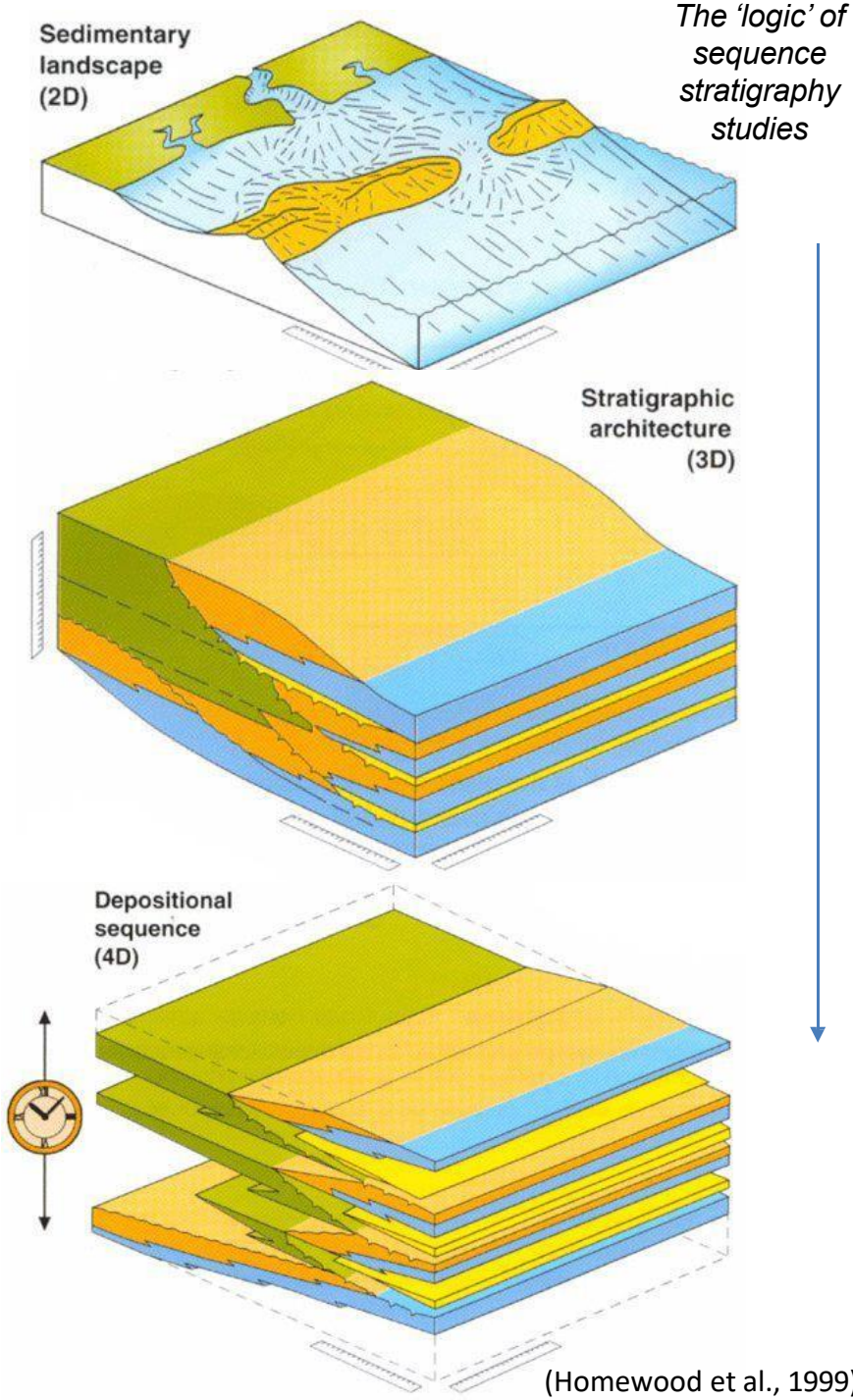
« group of deposits that occurs during a cycle of sea level rise and fall, bounded at the bottom & top by a discontinuity »

- -lateral changes in facies does not help spatial correlation…
- -major discontinuities are easier to track…but at the scale of a basin, they become difficult to identify or they disappear… an erosive surface can lateraly evolve into a deposition surface

The advent of seismic reflection helped the study of sediment deposits at the basin scale, and allowed the development of sequence stratigraphy

-> Vail's model in the 1970's

The 'logic' of sequence stratigraphy studies



(Homewood et al., 1999)

What is an isochron

A surface bounding coeval sedimentary environments

(*whatever the facies, the sedimentary rocks bounded by the isochron have been deposited at the same time*)…

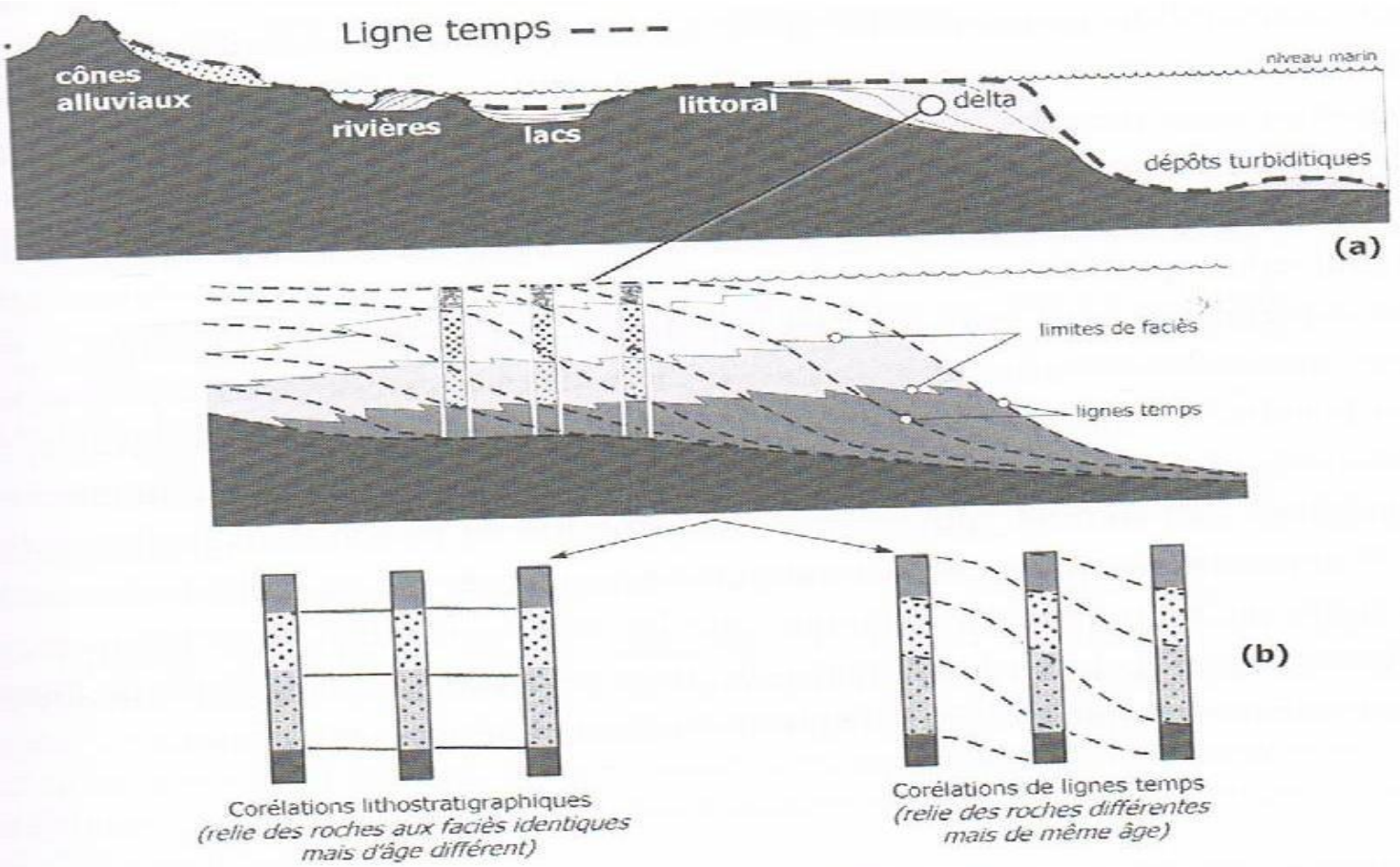
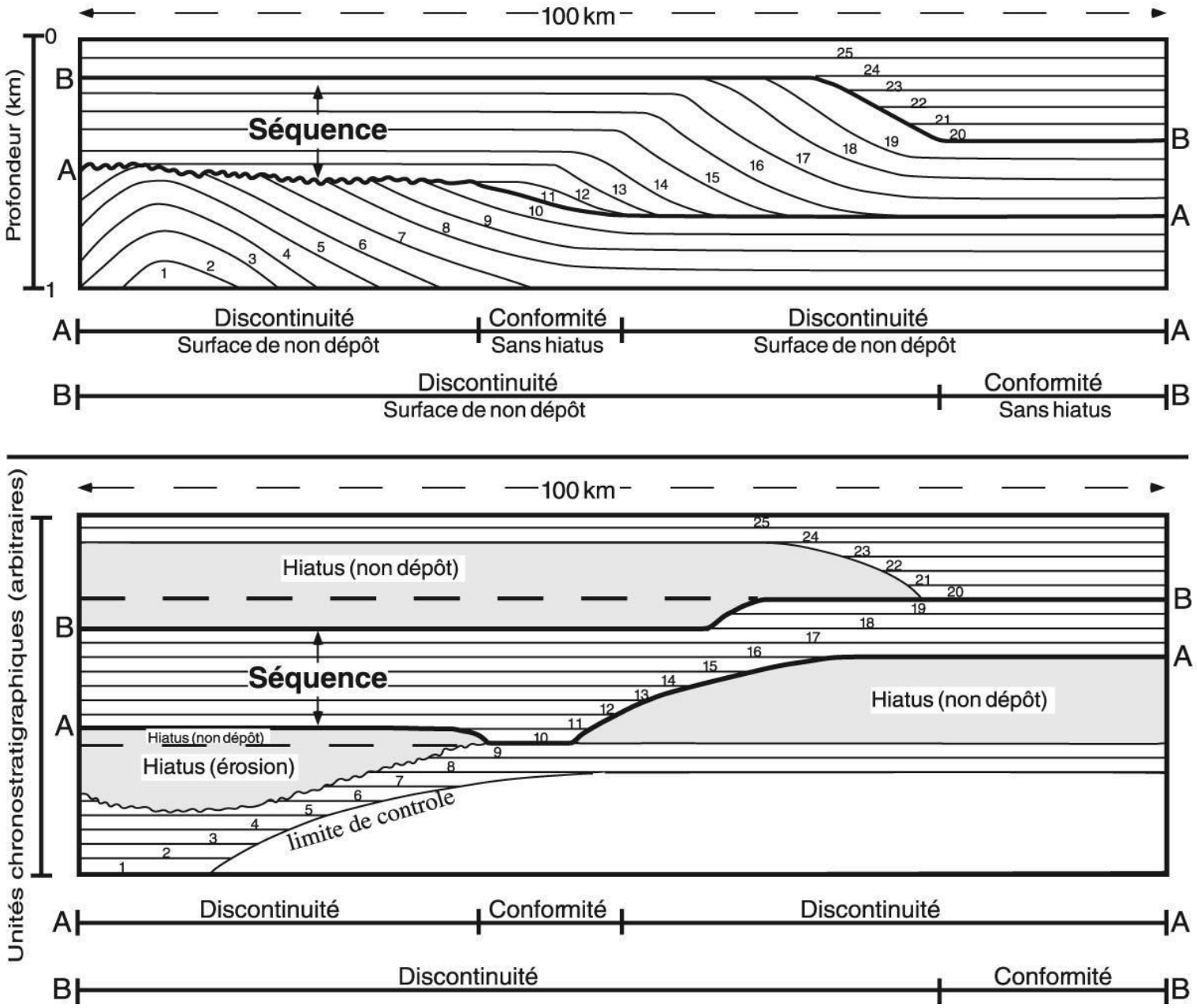


Figure 2.5. La notion de ligne temps.

(a) C'est une limite qui recouvre et relie latéralement des terrains ou des faciès différents. (b) Dans un delta, les lignes temps encadrent et relient des roches variées (sables, argiles) mais d'âge identique. Sous l'effet de la progradation, le principe de superposition stratigraphique ne s'applique plus, car les argiles ne sont pas toujours plus vieilles que les grès sus-jacents : certaines ont le même âge.

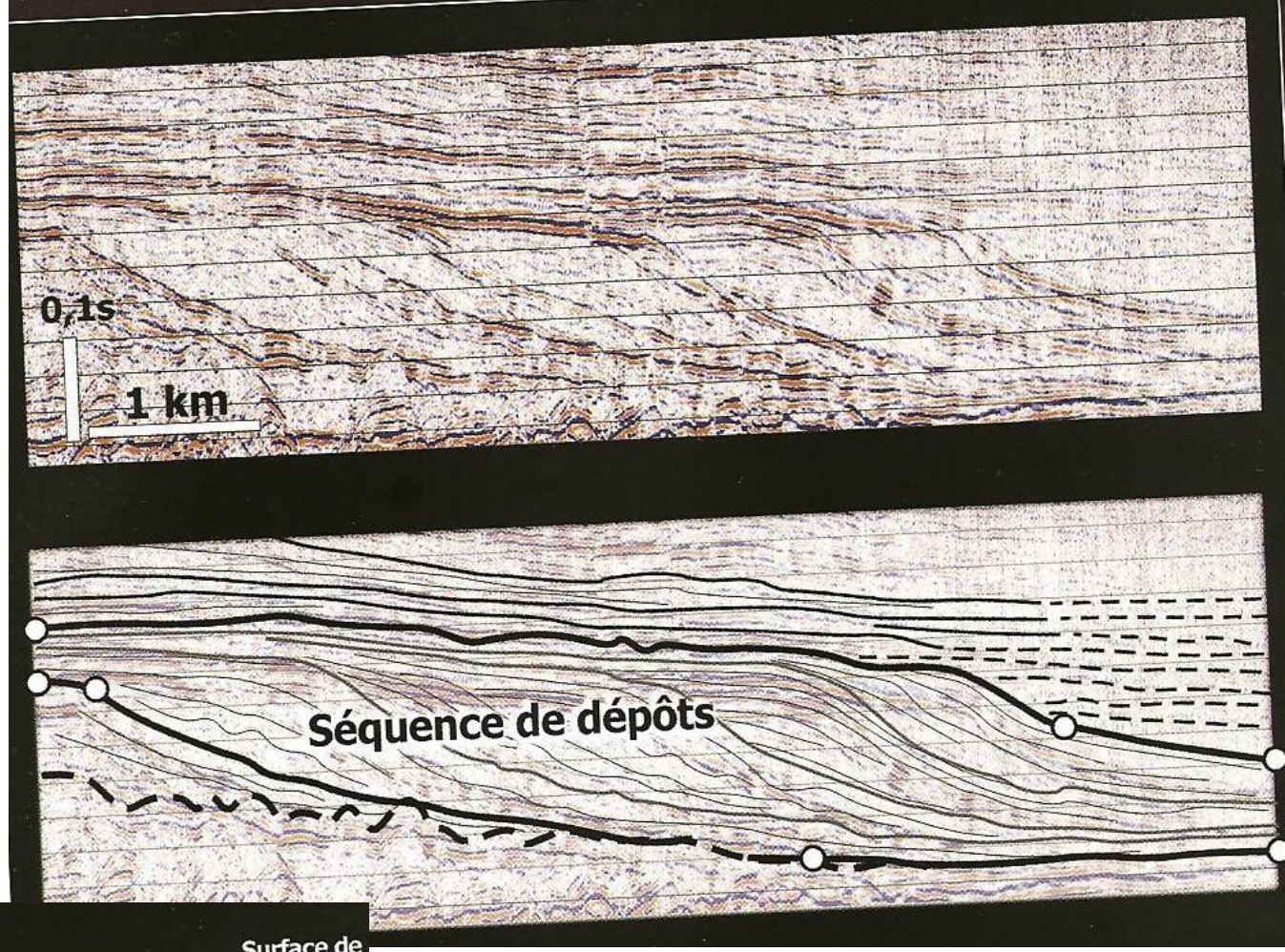
Wheeler's diagram

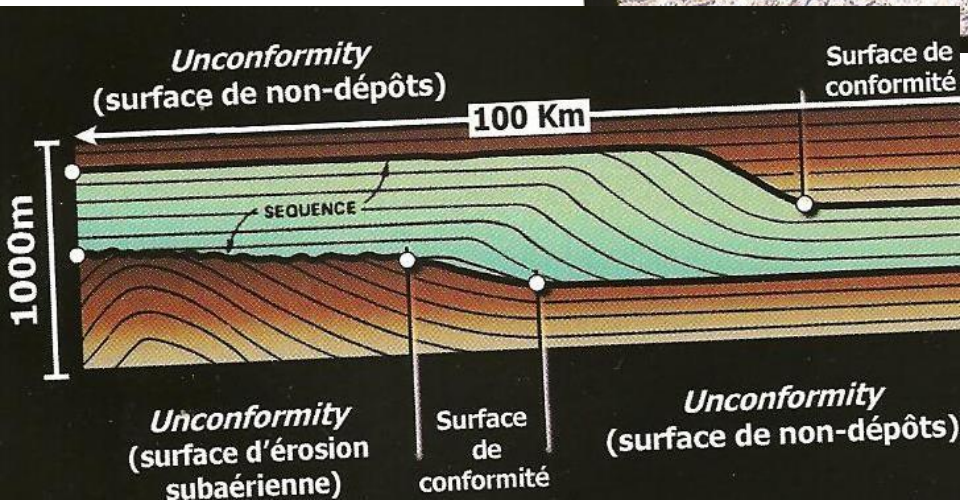


Time record may be discontinuous at a given location…but time is always recorded somewhere!

Correlations allow to determine the time recorded by an erosive surface…

Vail ‘s model of sequence stratigraphy, based on seismic lines





Définition d’une séquence selon Vail, 1977 : « unité stratigraphique composée de strates relativement conformes et génétiquement liées, encadrées par deux surfaces de discordances passant latéralement à des surfaces concordantes »

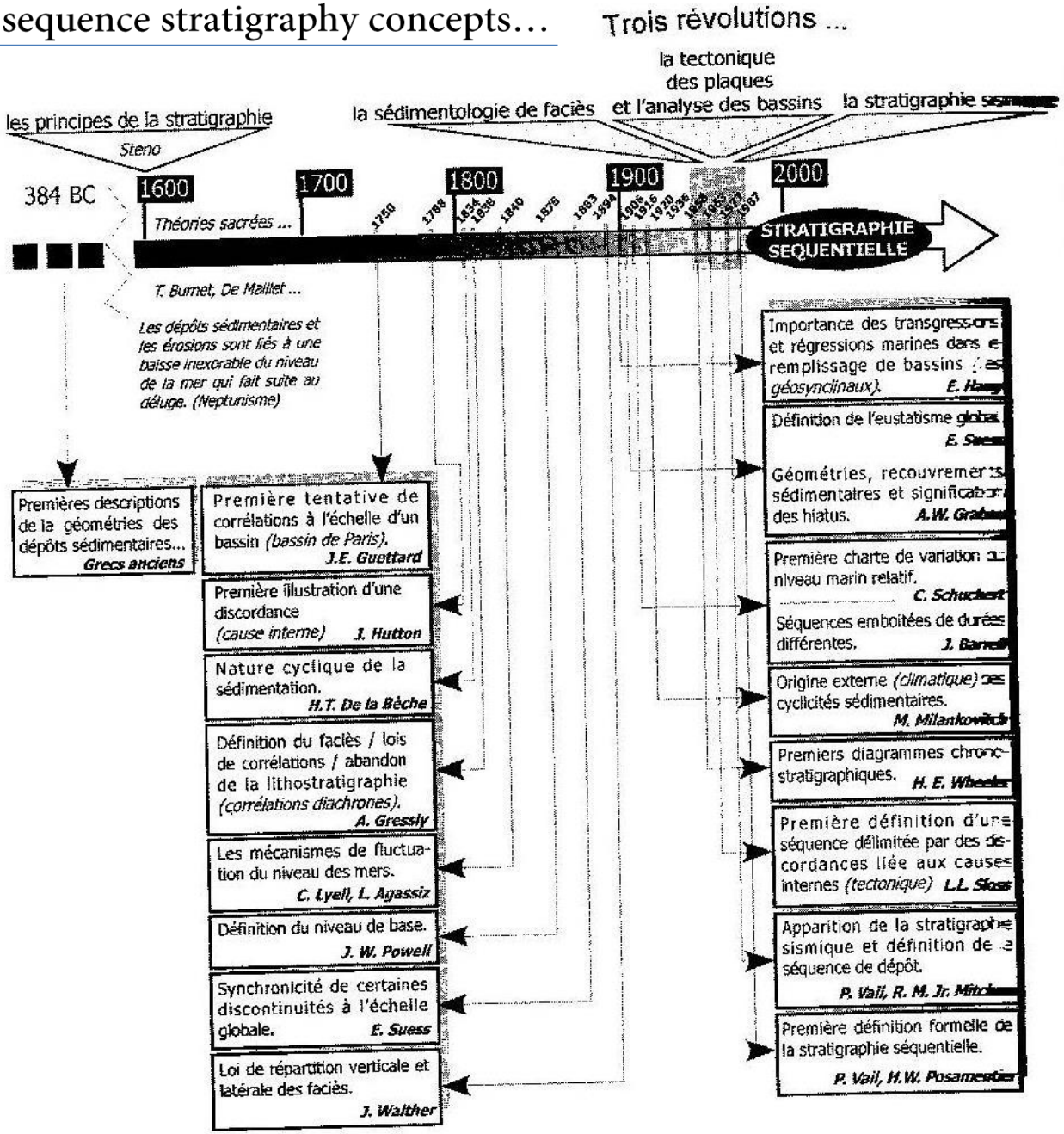


Figure 5.1. Quelques-unes des grandes découvertes, l'évolution des idées et des concepts qui ont abouti à la mise au point de la stratigraphie séquentielle.

Tracking past sea level variations, at the geological time scale

Oblique stratifications + unconformity
Ypresian sandstones; Noirmoutiers, Vendée

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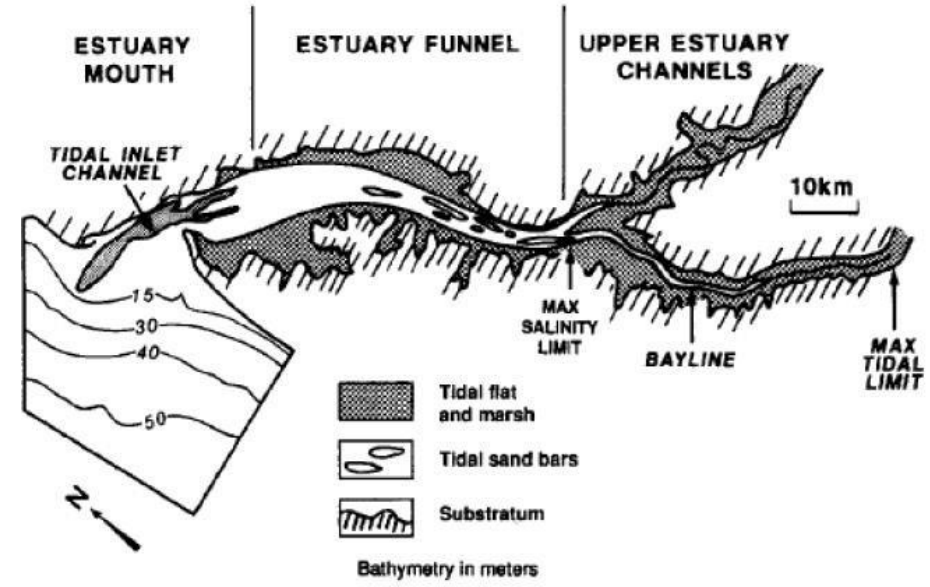
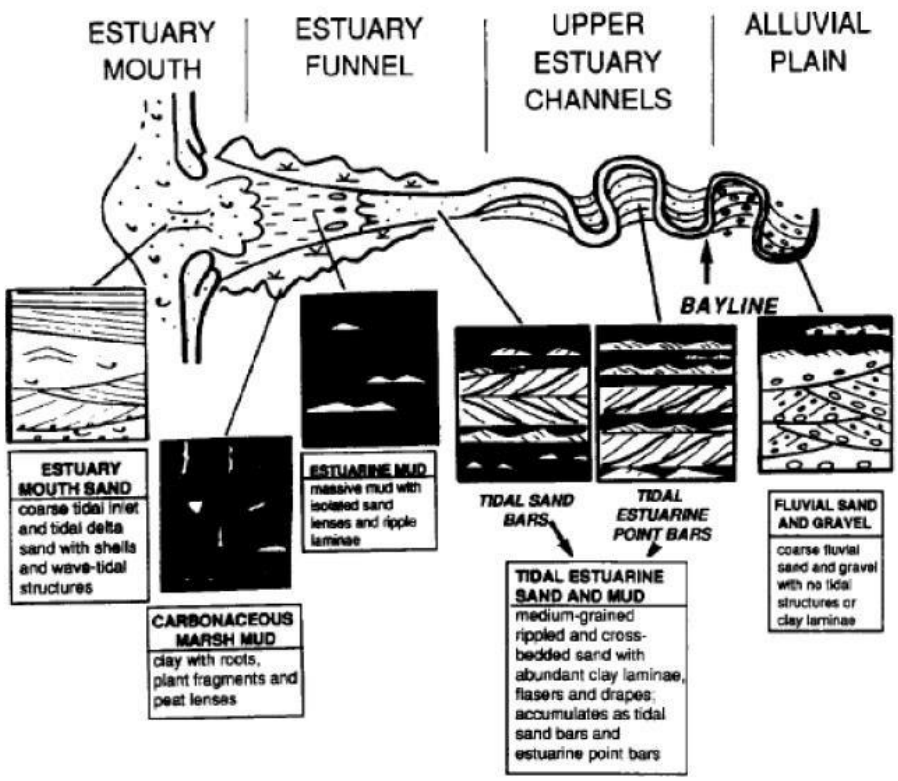
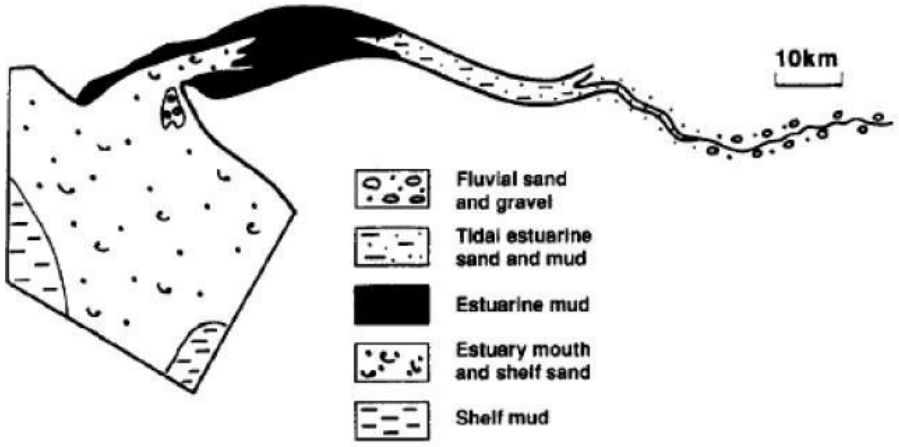
Tracking sea level variations at the 10^4-10^5 yrs time scale : the case of the Gironde estuary (France)

Tracking sea level variations at the 10^4-10^5 yrs time scale : the case of the Gironde estuary (France)



Allen & Posamentier 1993





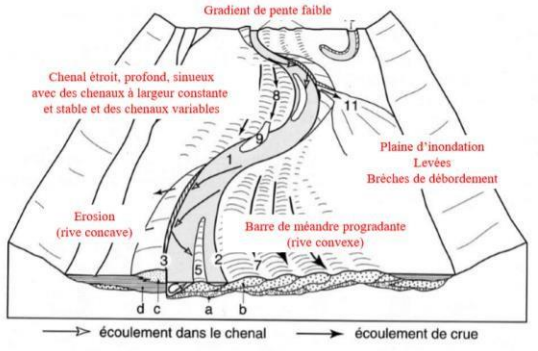
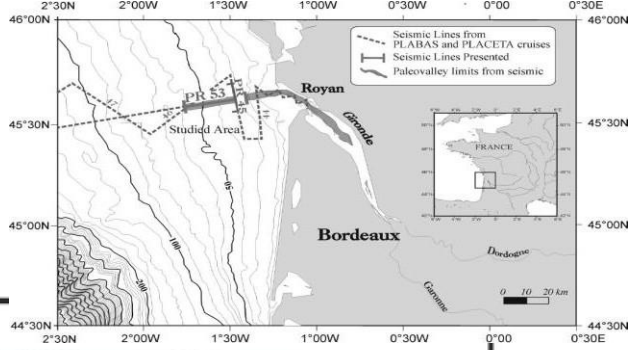


FIG. 2.—Top: Morphology and depositional environments of the present Gironde estuary; depth contours are in meters below mean sea level. The maximum landward limits of tides and salinity also are indicated, as well as the location of the bayline (see discussion in text). Bottom: present-day sediment distribution. Modified from Allen (1991).

The present-day distribution of sedimentary deposits along the Gironde estuary

Tracking sea level variations at the 10^4-10^5 yrs time scale : the case of the Gironde estuary (France)



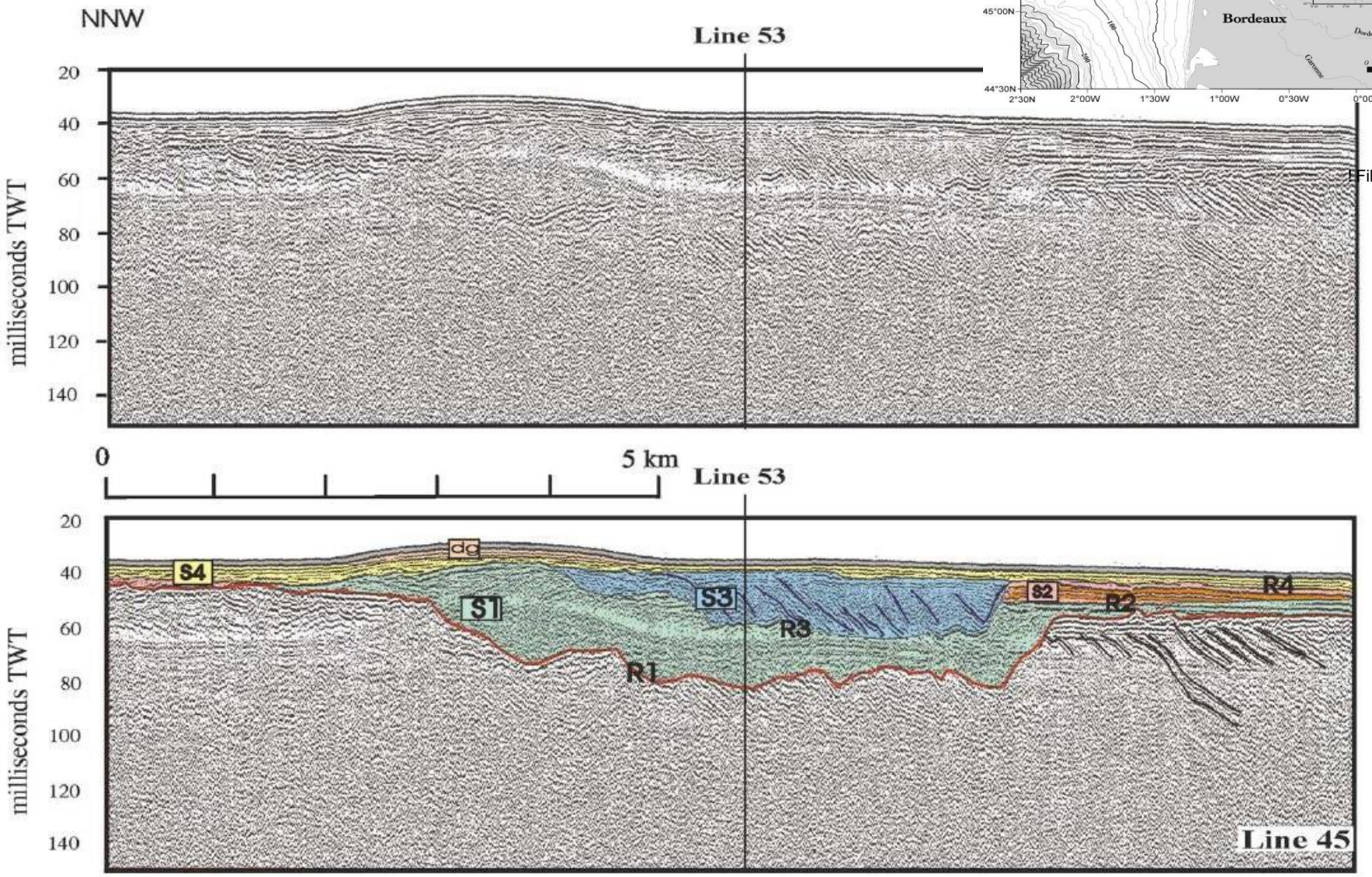


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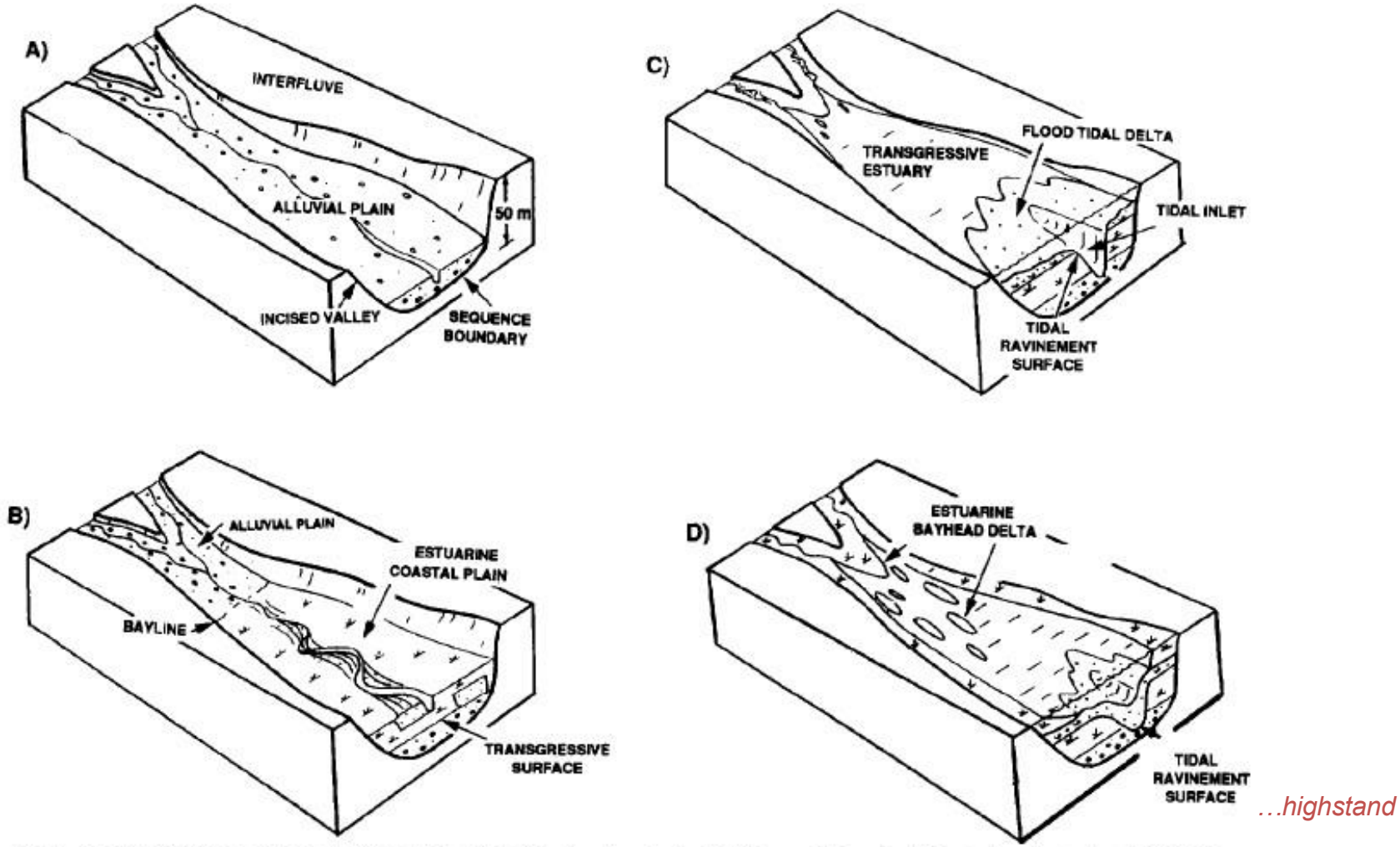
Fig. 3. Seismic line 45 processed and its interpretation. only 12 km of the line are presented. R1, sequence boundary; R2, transgressive surface; R3, tidal ravinement surface; R4, wave ravinement surface. S1, Lowstand Systems Tract; S2, Transgressive Systems Tract; S3, Tidal Infill (TST member); S4, Highstand Systems Tract; dg, dredging dumping.

Tracking sea level variations at the 10^4-10^5 yrs time scale : the case of the Gironde estuary (France)

Lowstand…



…highstand

FIG. 7.—Schematic illustration of the geological evolution of the Gironde estuary during the Würm eustatic cycle. **A)** Lowstand: prior to about 18,000 BP coarse fluvial sediment bypassed the incised valley en route to the lowstand shoreline located at the continental shelf. **B)** Initiation of transgression: at about 10,000 BP the incised valley was transgressed and became an estuary, with estuarine coastal-plain deposits onlapping onto the alluvial plain as the bayline migrated up the valley. **C)** Maximum marine flooding occurred at about 4000 BP and resulted in a blanket of estuarine mud in the funnel zone and landward migration of the tidal inlet at the estuary mouth. **D)** Stillstand: since about 4000 BP relative sea level has remained almost stable, and a regressive tidal-estuarine bayhead delta has prograded into the upper estuary, gradually filling it with sediment.

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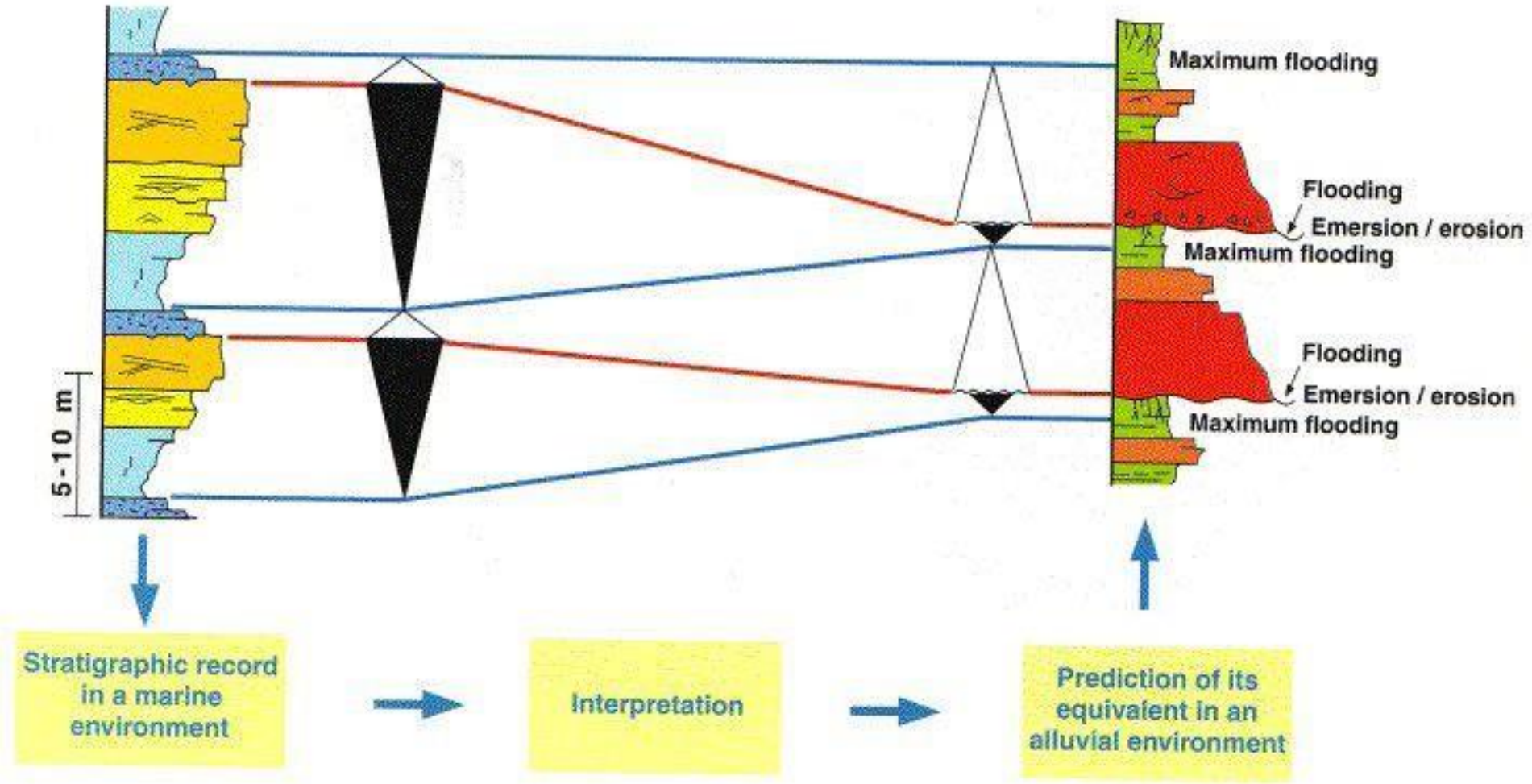
Graphical Representation of genetic stratigraphy models



(Homewood et al., 1999)

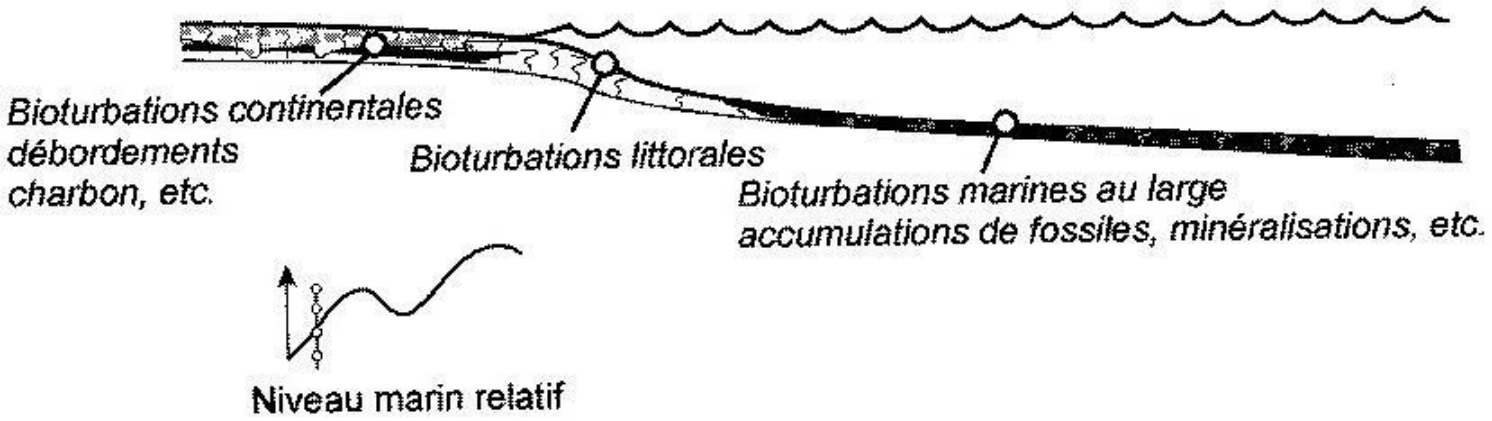


Figure 3.29. Mise en place de la limite de séquence génétique (surface d'inondation maximale).

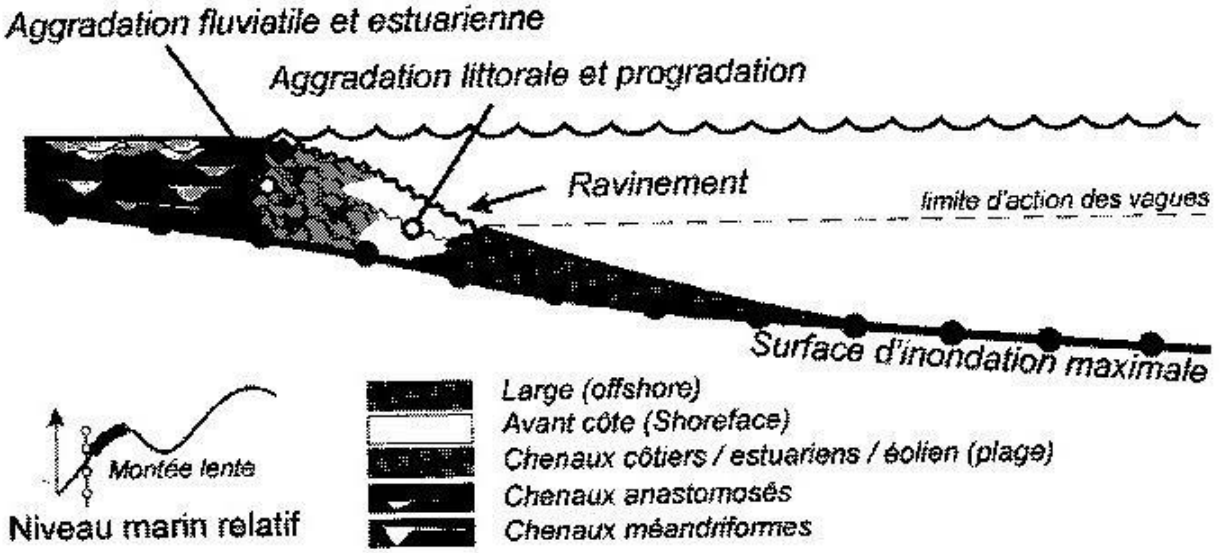


Figure 3.30. Montée lente du niveau marin relatif (début de la phase régressive).

Over 1,5 eustatic cycle

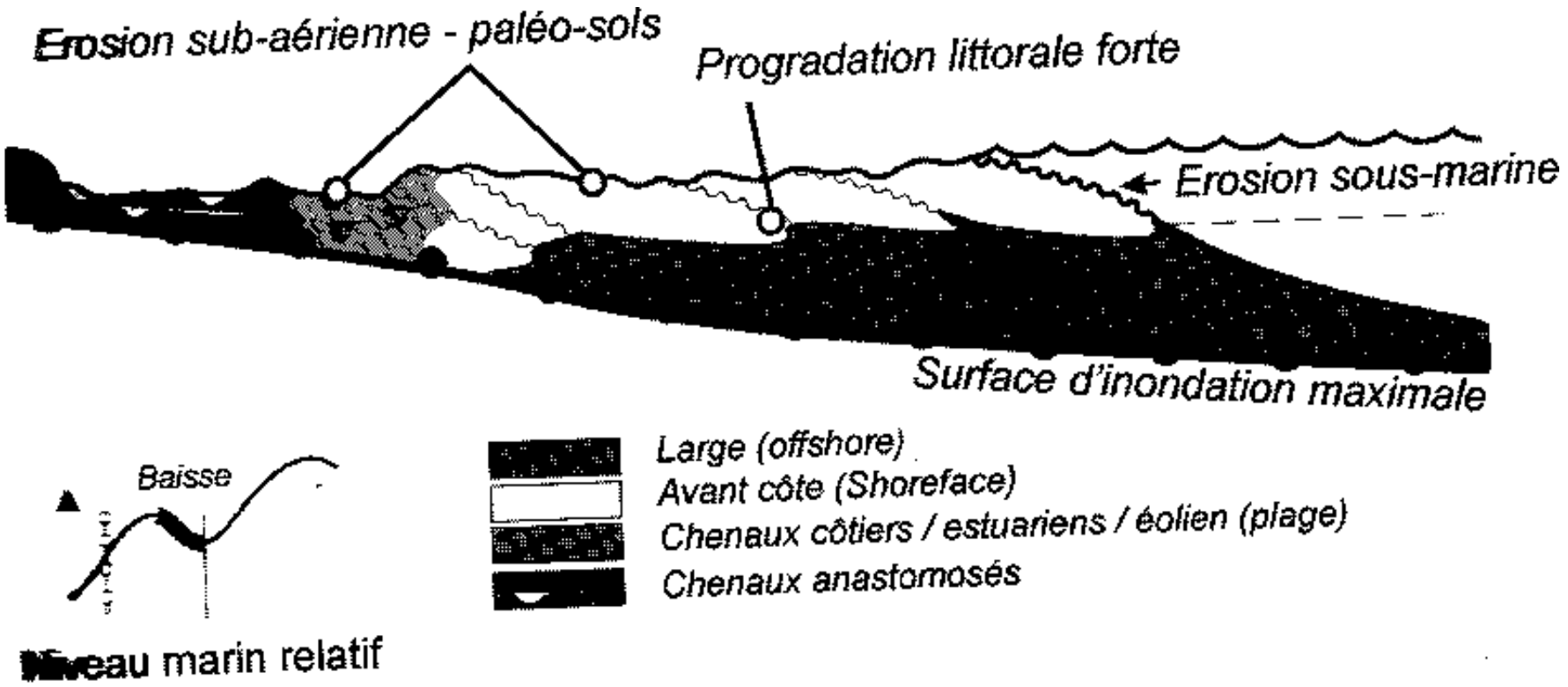


Figure 3.31. Baisse du niveau marin relatif (phase régressive).