



Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

Curriculum: Esplorazione Geologica

Anno accademico 2021 - 2022

Analisi di Bacino e Stratigrafia Sequenziale (426SM)

Docente: Michele Rebesco

Modulo 1.4

Outline:

Scales

Sedimentary structures (cm) to sedimentary basin (10^3 km)

Sequence stratigraphy & lithostratigraphy

Depositional architecture (systems, elements, ...)

Facies

Facies sequence

Facies model

Seismic stratigraphy

Seismic facies analysis

Scale

Non si po' avere tutto in un colpo solo!

Pensate alle mappe (es. GoogleMaps): non si può avere assieme il dettaglio, e la visione d'insieme, e una via di mezzo non ci da nessuna delle prime due...

Pensate alla simica: o risoluzione, o penetrazione, o un compromesso tra le due

Ricordate che abbiamo nominato le tre scale di indagine, sia sul terreno che in sismica

Ebbene, per una analisi completa servono tutte e tre le scale. Come per andare in un posto sconosciuto vi servono tutti e tre i livelli di informazione:

Nazione

Città

Via e n° Civico



Scales of sedimentary basin analysis

Horizontal
scale

1.000 km Sedimentary basin
(a thick sequence of sedimentary rocks)

>10 km Depositional system
(three-dimensional assemblage of
facies formed within a particular
depositional environment)

100 m Outcrop
(a visible exposure of sedimentary
deposits)

m Bed
(layers of sedimentary rocks)

cm Sedimentary structure
(features in sediments formed at the
time of deposition)

Traditional
seismics

Hi-Resolution
Seismics

attribute
analysis

Sub-bottom

Field

Lab

The sedimentary structures found in sedimentary rocks are important keys to the interpretation of their depositional setting as they are formed in response to the processes that deposited the sediment (primary sedimentary structures) or modified them during or following deposition (secondary sedimentary structures). Primary sedimentary structures are mainly produced by the migration of bedforms, which are extremely diverse and valuable indicators of depositional process, water depth, current type and velocity.

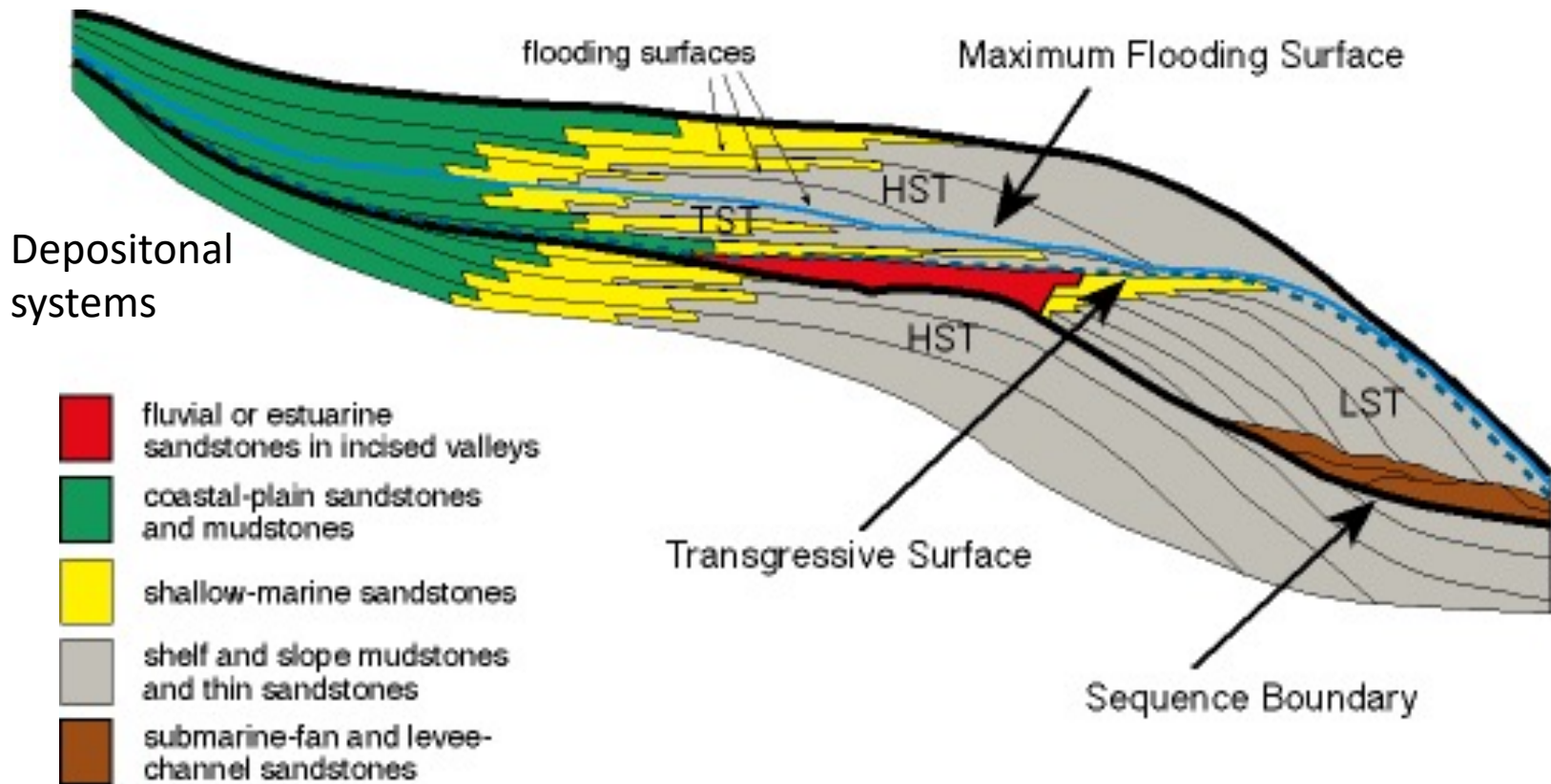
Sedimentary structures

They are three-dimensional features found within the sedimentary section and/or on the bedding plane (bedforms) and have visible characteristic fabrics, textures, arrangements of sediments within a rock.



Sequence Stratigraphy

is the analysis of sedimentary deposits in a time-stratigraphic context



?? 100 – 1000 km ??



Lithostratigraphy

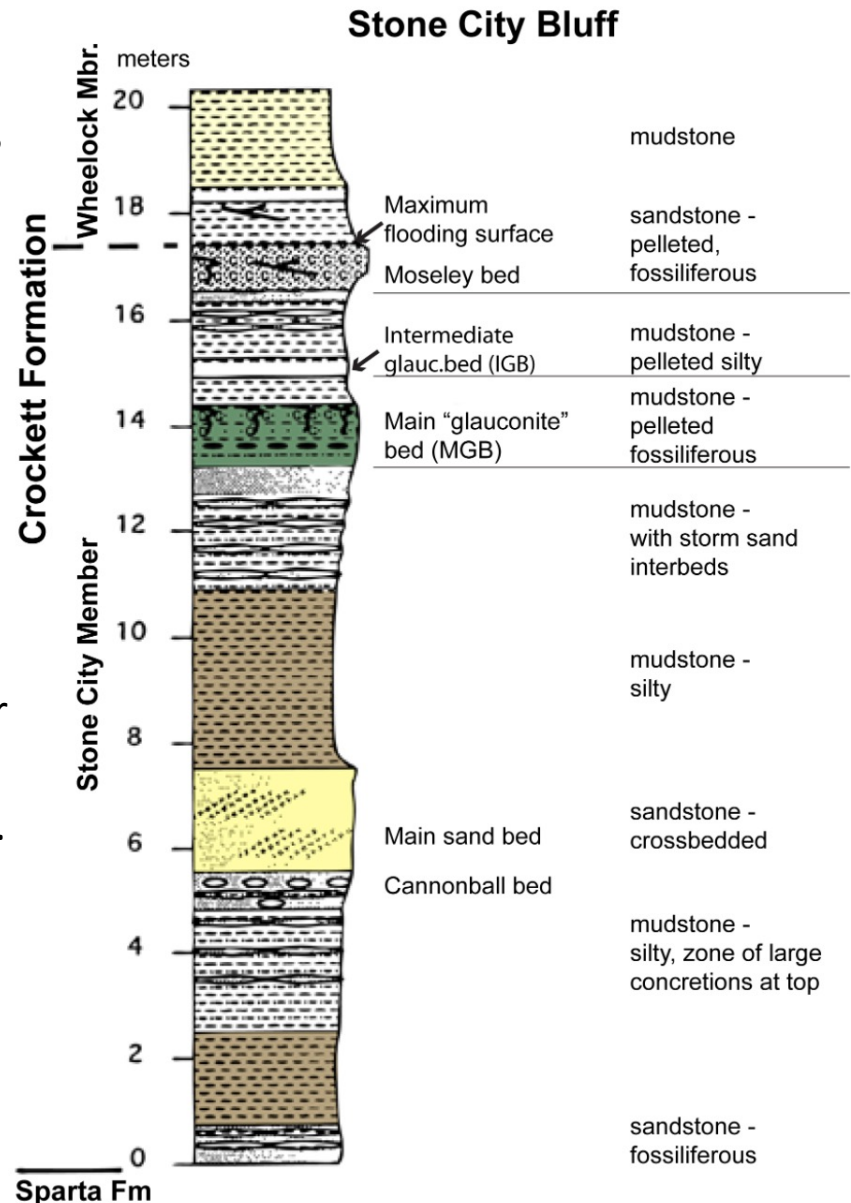
The lithostratigraphy is the study of rock layers (physical characteristics as type, color, mineral composition, grain size...).

Its fundamental unit is the geological formation.

A formation is a body of rock having a consistent set of physical characteristics (lithology) that distinguish it from adjacent bodies of rock, and which occupies a particular position in the layers of rock exposed in a geographical region (the stratigraphic column).

A formation must be large enough to be mapped (in surface or subsurface).

Formations may be combined into groups of strata or divided into members.



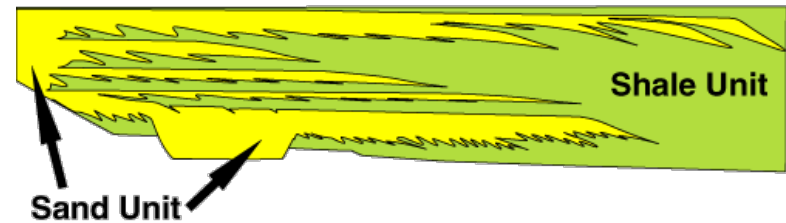
Lithostratigraphy versus Sequence Stratigraphy

Lithostratigraphy maps these sedimentary rocks solely on the basis of their lithology and does not necessarily consider that these rocks may have accumulated over a particular period of time. In contrast allostratigraphy maps the rock units on the basis of the timing of their accumulation.

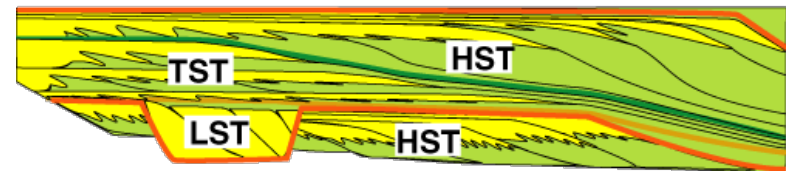
The "sequence stratigraphic" approach is a higher order of allostratigraphy that assumes a connection of the discontinuities and surfaces used to subdivide the sedimentary section to changes in base level.

A sequence is a **cyclic** succession of rocks composed of genetically related units of strata.

Correlations based on Lithology - Lithostratigraphic



Correlations based on Bounding Surfaces - Allostratigraphic



Key

- mfs (Maximum Flooding surface)
- TS (Transgressive Surface)
- SB (Sequence Boundary)
- LST Lowstand System Tract
- TST Transgressive System Tract
- HST Highstand System Tract

Discontinuities

Sequences are enveloped by sequence boundaries that are identified as significant erosional unconformities and their correlative conformities. These boundaries are the product of a fall in sea level that erodes the subaerially exposed sediment surface of the earlier sequence or sequences.

Unconformity: a surface separating younger from older strata, along which there is evidence of subaerial erosional truncation and correlative submarine erosion, with a significant hiatus in sedimentation (Vail, et al., 1977).

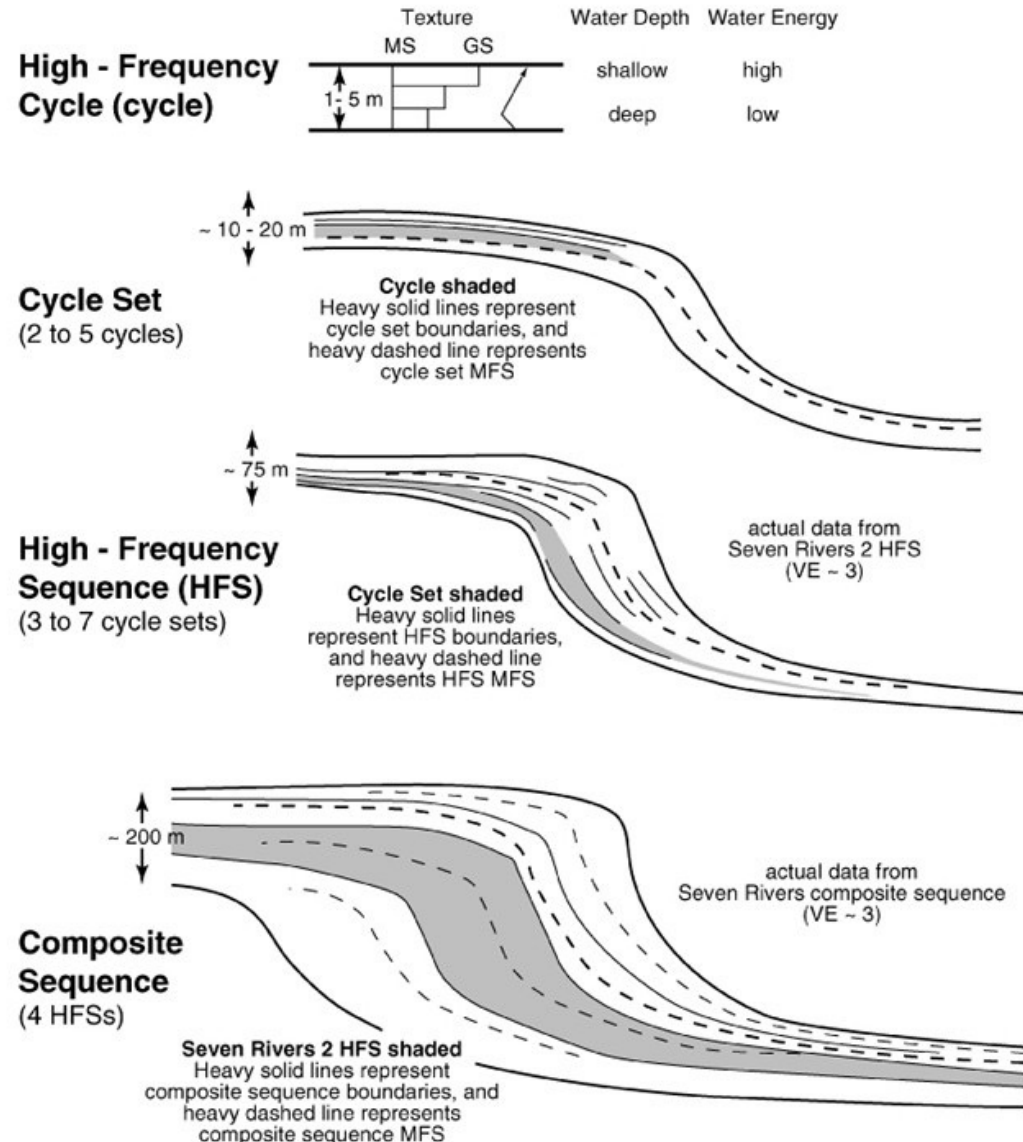


Cyclicality

Stratigraphic cyclicality within a sedimentary succession can be observed at different scales.

This variability of stratigraphic sequences in terms of time spans and physical dimensions is the result of the complex interplay of multiple local and global controls on accommodation and sedimentation.

Most, if not all, stratigraphic successions display repetitions of strata, at different scales, that reflect a succession of related depositional processes and environmental conditions that are repeated in the same order. The repetition of such events is termed cyclic or rhythmic sedimentation, and this leads to the formation of stratigraphic successions



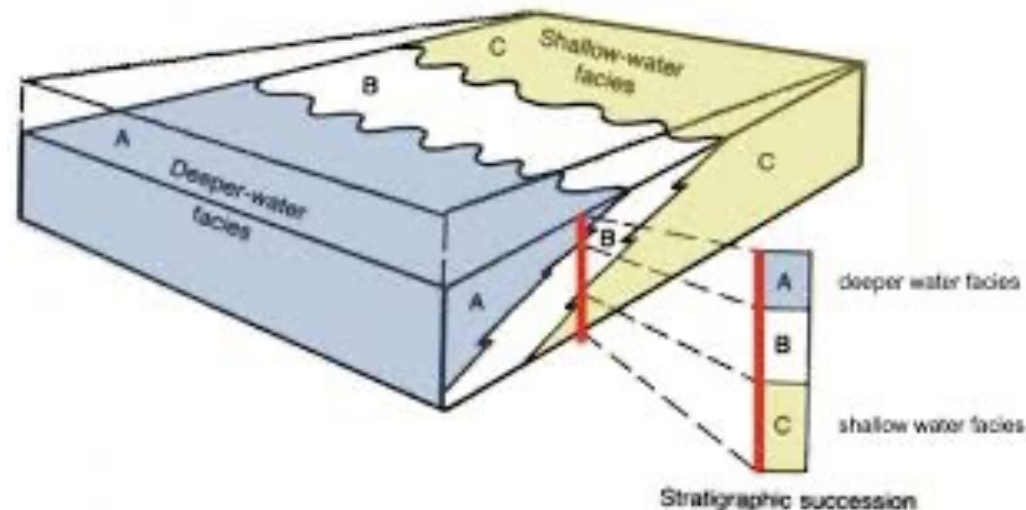
Sedimentary facies

Detectable aspects of a sedimentary body that make it distinguishable from adjacent ones

Aspects include: physical, chemical, biological, organic, structural, seismic...

Detectable either in the field, seismics or lab

- Set of characteristics or rock body?
- with reference to stratigraphic units?
- descriptive or interpretative?



Various components...

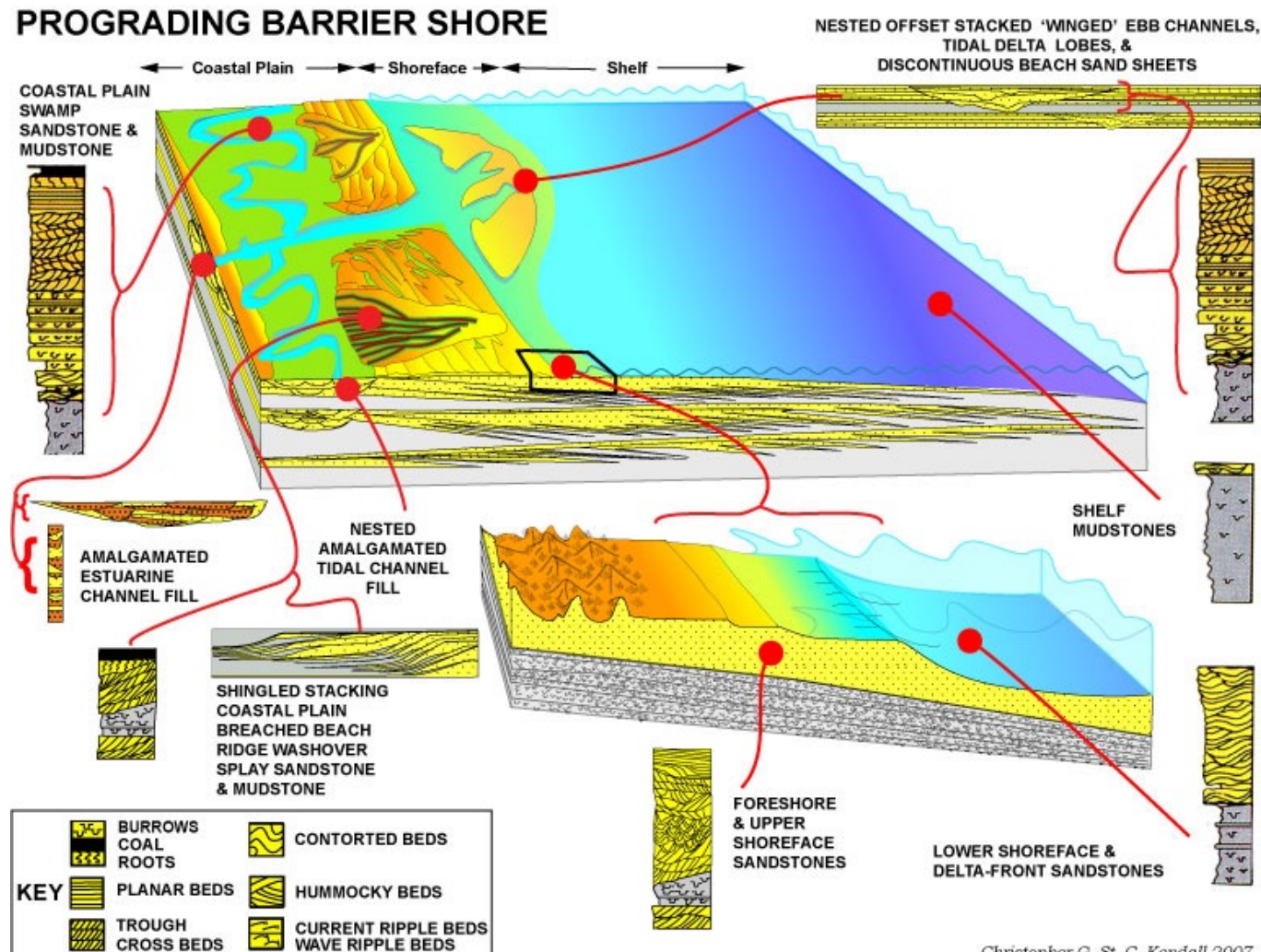
Facies: Detectable aspects of a sedimentary body that make it distinguishable from adjacent ones.

Depositional system: a three-dimensional assemblage of facies

Element: assemblage of bodies of sediment that are genetically related to each other and were generated in a common depositional environment.

Body: general geological term that refers to a mass of sediment that may be a group of beds or elements.

Unit: general geological term that refers to a distinct geologic entity with a lower and upper confining boundary.



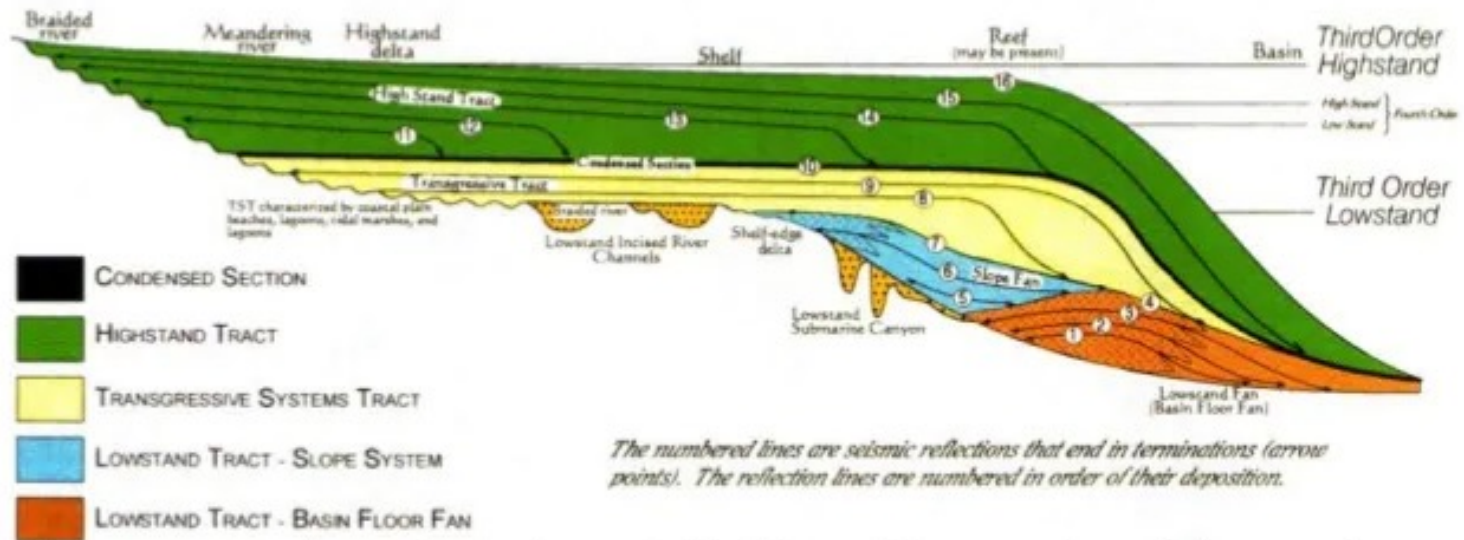
Larger scale components...

Sequence: A relatively conformable succession of genetically related strata bounded at their upper surface and base by unconformities and their correlative conformities

System tracts: subdivisions of sequences that consist of discrete depositional units that differ in geometry and represent different phases of eustatic changes.

Sequence Stratigraphy

SYSTEMS TRACTS DEPOSITED DURING ONE COMPLETE
Third ORDER EUSTATIC SEA-LEVEL CYCLE



Sequence stratigraphy is the subdivision of the stratigraphic record on the basis of bounding discontinuities.

Defining facies

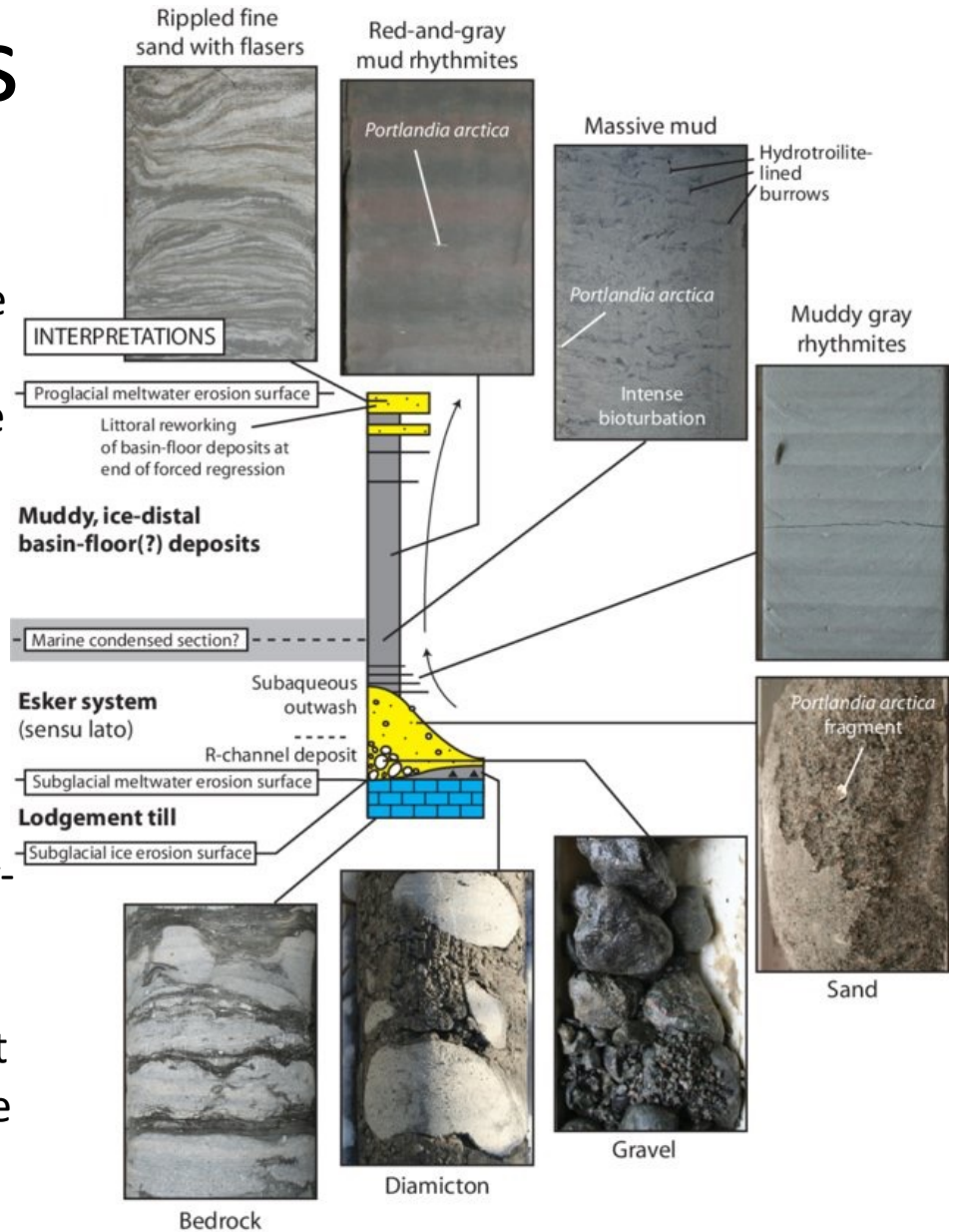
Subdivision (of a rock body) into constituent facies is essentially a classification procedure

The degree of subdivision is governed by the objective of the study

(Roger Walker, 1984. Facies Model, ISBN 978-0919216259

In other words, there are no standard, ready-made facies.

When YOU are in the field (or in a lab) and have to subdivide and classify a rock body, it is YOU that define the facies according to the objective of your study.



Example of facies subdivision

Fjellanger et al., 2005.
 Upper cretaceous basin-floor fans in the Vøring Basin, Mid Norway shelf.
 Norwegian Petroleum Society Special Publications 12:135-164
 DOI: 10.1016/S0928-8937(05)80047-5

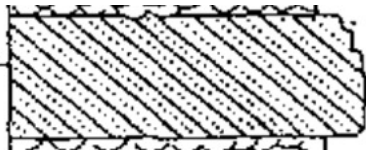
Facies	Observations	Process	Description	Core photo
C1	Massive sandstone or faint inverse graded sandstone	Hyper-concentrated density flow		<div style="display: flex; justify-content: space-between;"> <div style="text-align: center;"> <p>Facies C1</p> </div> <div style="text-align: center;"> <p>Facies T1</p> </div> </div>
C2	Massive or top-only graded sandstone	Hyper-concentrated to concentrated density flow		<div style="text-align: center;"> <p>Facies C2</p> </div>
T1	Graded sandstone with Tabco de Bouma divisions	Concentrated density flow and turbidity flow		<div style="text-align: center;"> <p>Facies T2</p> </div>
T2	Stratified sandstone	Concentrated density flow and turbidity flow modified by currents or waves		<div style="text-align: center;"> <p>Facies S1</p> </div>
H1	Heterolithic sandstone and mudstone	Low density turbidity flow / bottom current		<div style="text-align: center;"> <p>Facies H1</p> </div>
S1	Overtuned / brecciated deposits	Slumping		<div style="text-align: center;"> </div>

Scale: Core width 10 cm

Facies sequence (or association)

It is understood that facies will ultimately be given an environmental interpretation (Middleton, 1978).

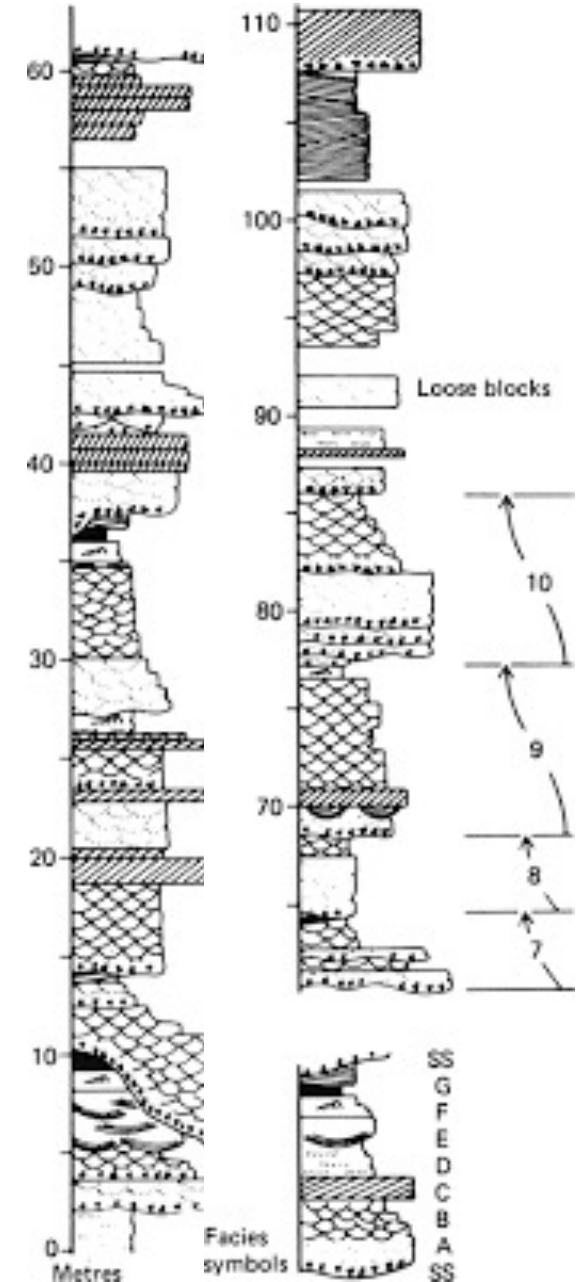
However, most facies have ambiguous interpretations. E.g., a cross-bedded sandstone facies could be formed in several different ways...



Cant and Walker, 1976

But – according to the «Walther’s law - a sequence (or association) of facies with gradational transitions is more informative.

Thus a sequence including this facies may be interpreted as being of fluvial origin

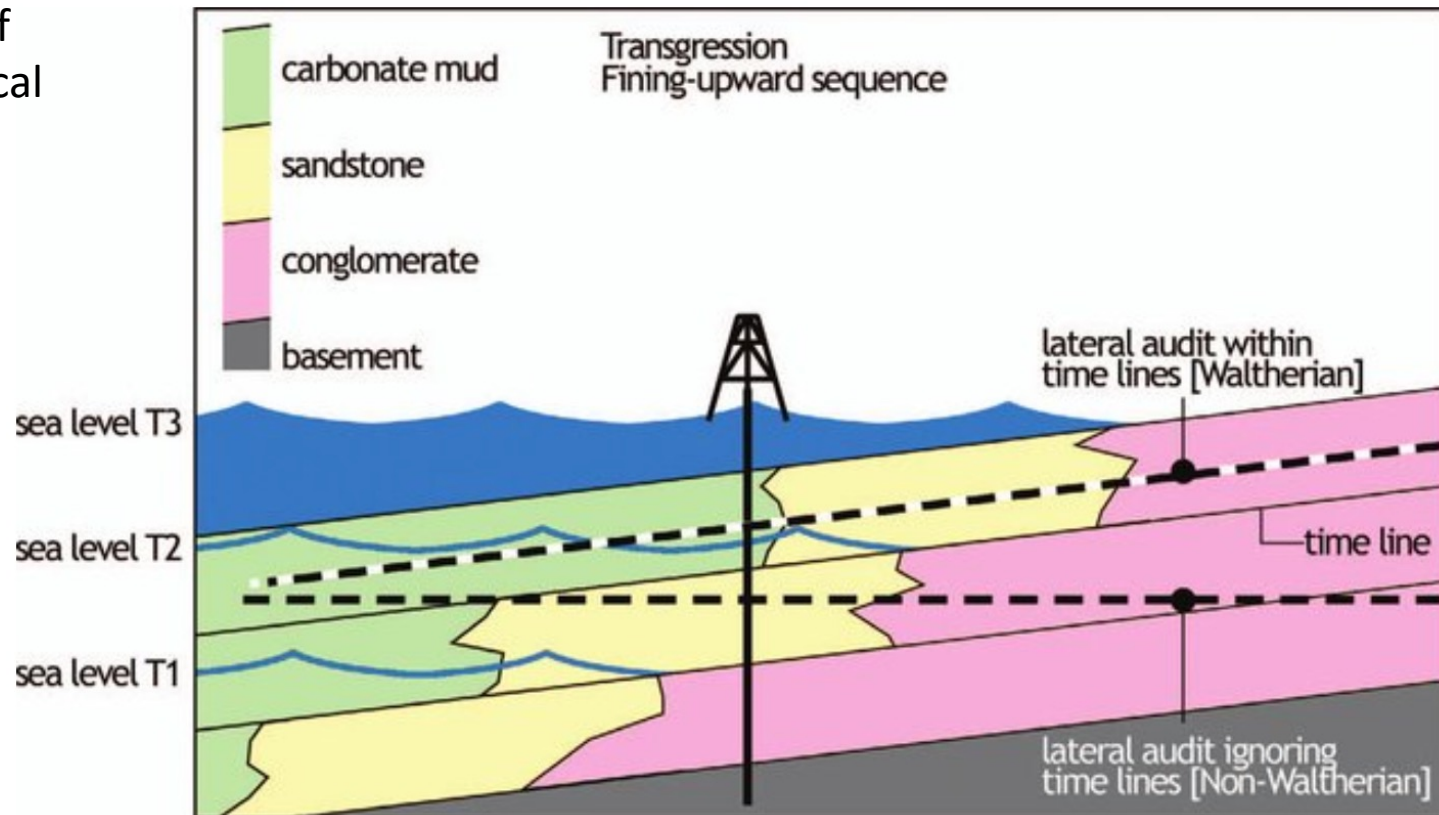


Walther's Law of Facies

The Law of Walther (German geologist, 1860-1937), states that the vertical succession of facies reflects lateral changes in environment. Thus, when a depositional environment "migrates" laterally, sediments of one depositional environment come to lie on top of another.

A classic example of this law is the vertical stratigraphic succession that typifies marine transgressions and regressions.

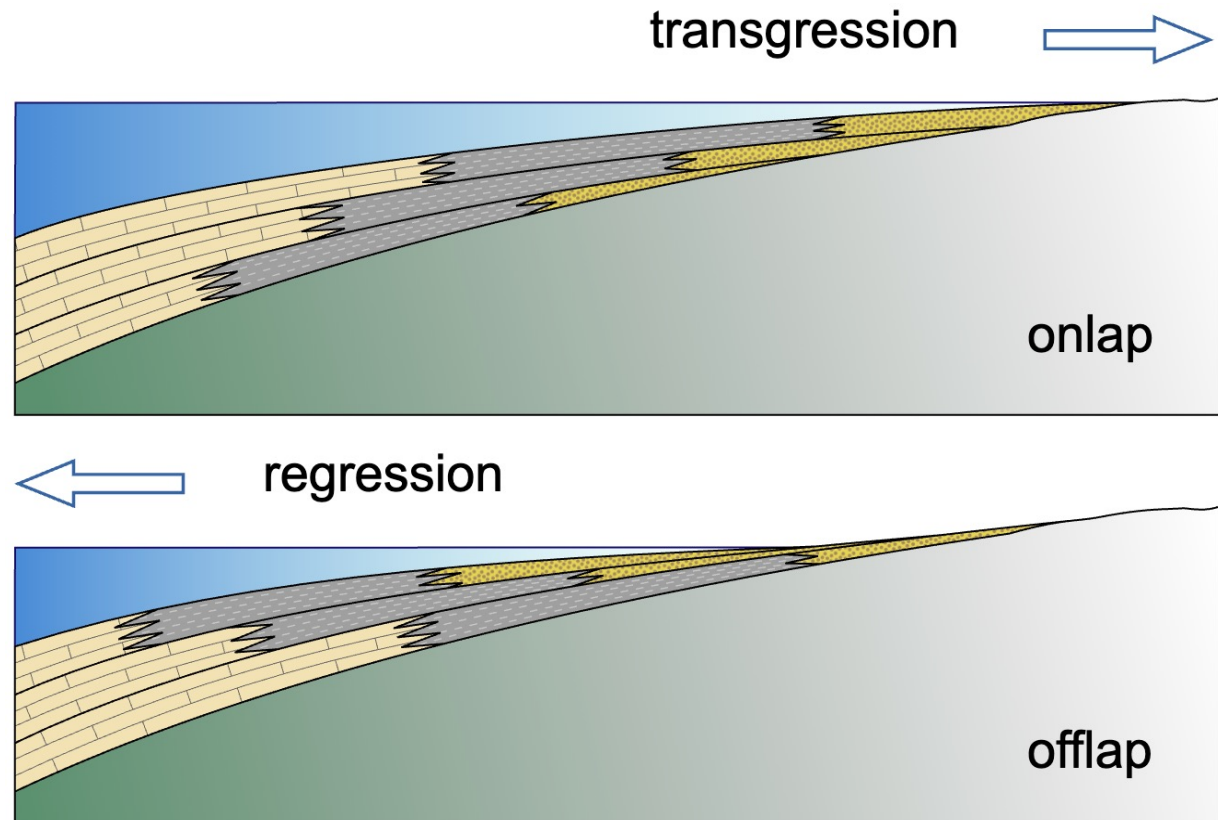
Purkis et al., 2012. Vertical-To-Lateral Transitions Among Cretaceous Carbonate Facies--A Means To 3-D Framework Construction Via Markov Analysis. Journal of Sedimentary Research 82(4):232-243



transgressions and regressions

A transgression is a landward shift of the coastline while regression is a seaward shift. The terms are applied to gradual changes in coast line position without regard to the mechanism causing the change.

Causes include eustatic sea-level changes, subsidence or rebound, in turn due to climate changes or tectonic events.



Facies Model

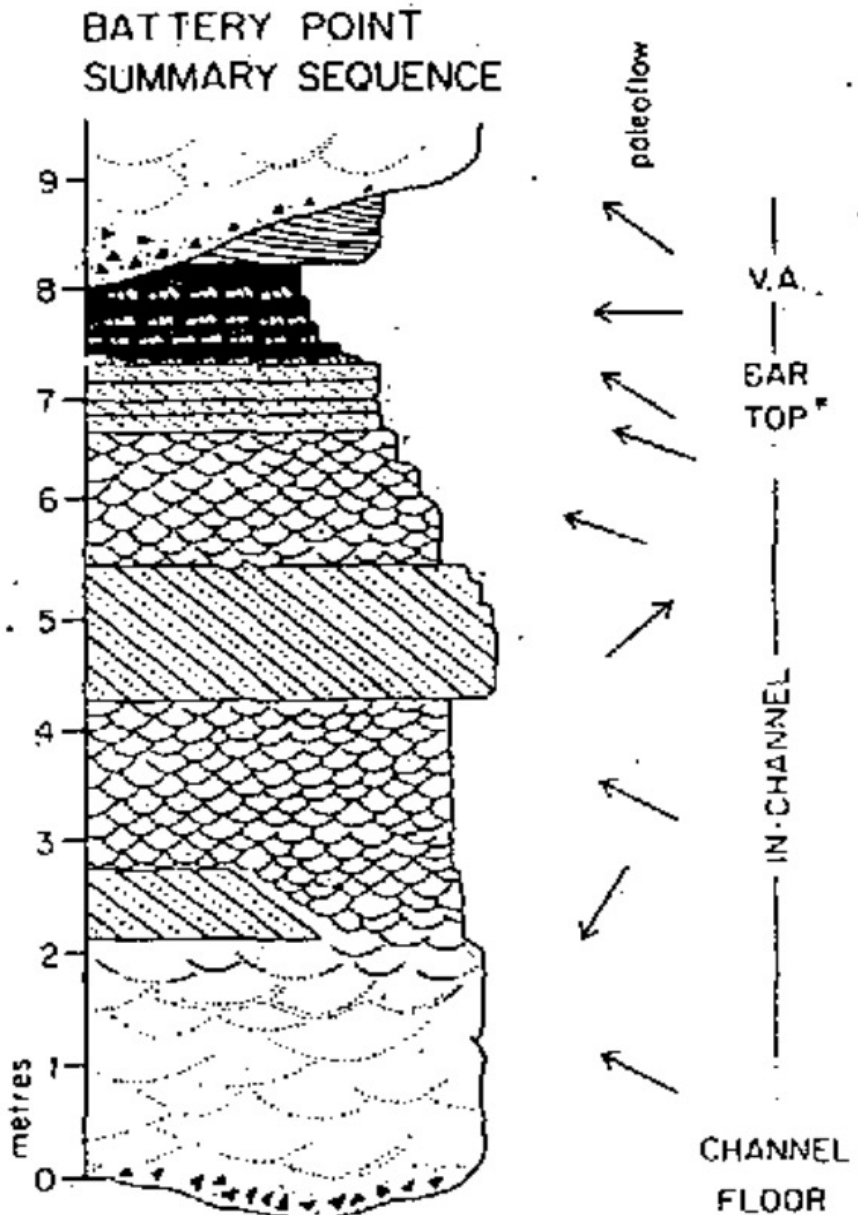
Facies models link many observations from modern environments (the ontological method according to Walther) and ancient deposits into coherent syntheses.

A facies relationship diagram and its stratigraphic section are only local summaries, not general models.

A facies model is a general summary of a specific sedimentary environment, written to be usable in four different ways

A limited amount of local information plus the guidance of well-understood facies models results in significant predictions about that local environment.

Walker, 1984. Facies Model



Cant and Walker, 1976

Attualismo

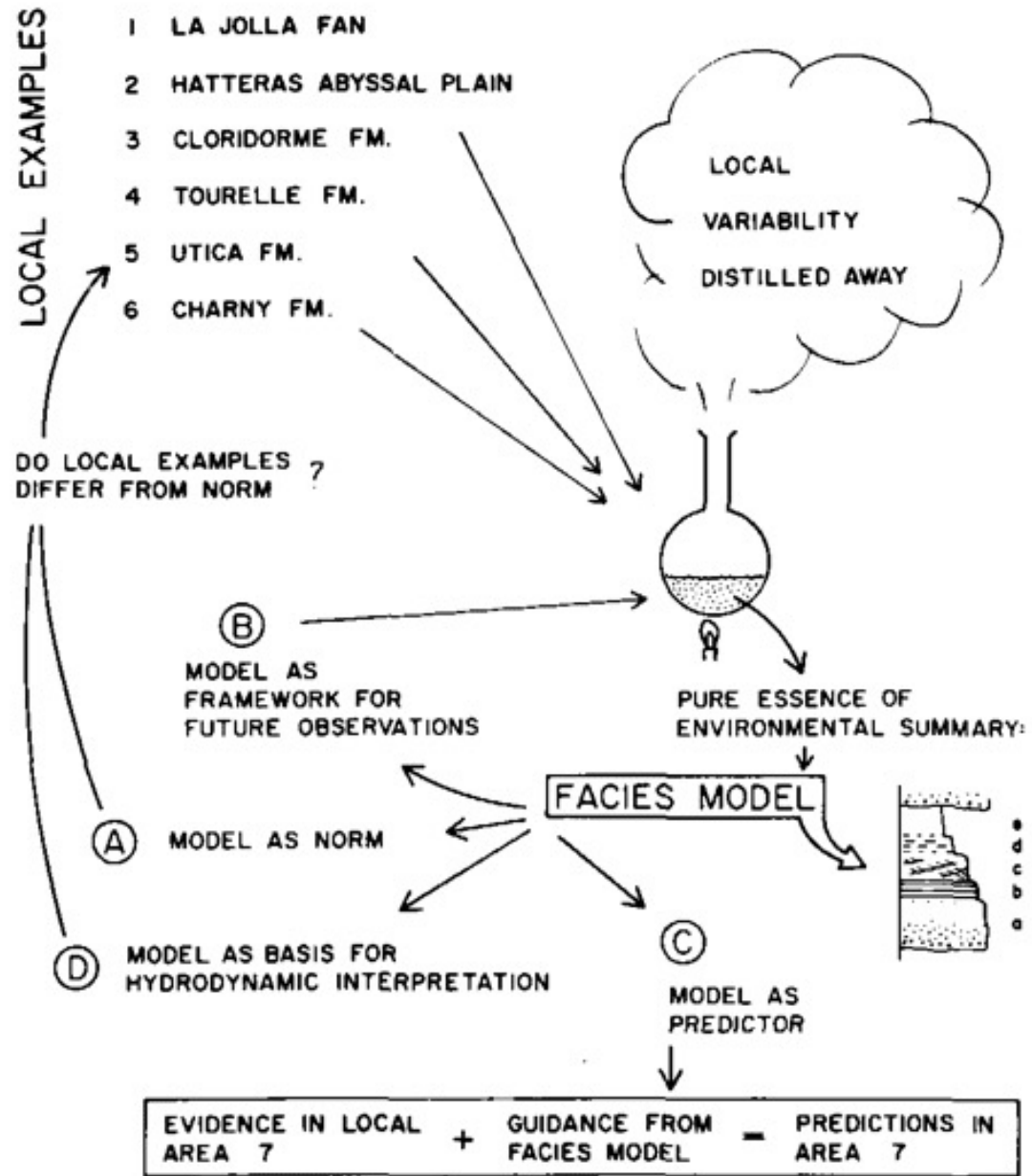
Walther ha affermato che le spiegazioni più soddisfacenti della genesi dei fenomeni antichi erano analogie ai processi geologici moderni, chiamando questa affermazione attualistica il metodo ontologico (poiché l'ontologia è il ramo della filosofia che studia concetti come la realtà).

L'Uniformitarismo (o Attualismo) è il principio secondo il quale i processi naturali che hanno operato nei tempi passati sono gli stessi che possono essere osservati nel tempo presente. Il principio è stato coniato da due geologi scozzesi, James Hutton e Charles Lyell, intorno al 1800



Distillation and use of a facies model

- A: norm, to identify local anomalies
- B: framework, for future observations
- C: predictor (*radiator*)
- D: basis for interpretation (we can ask questions tht could not be asked if we had not used the facies model).

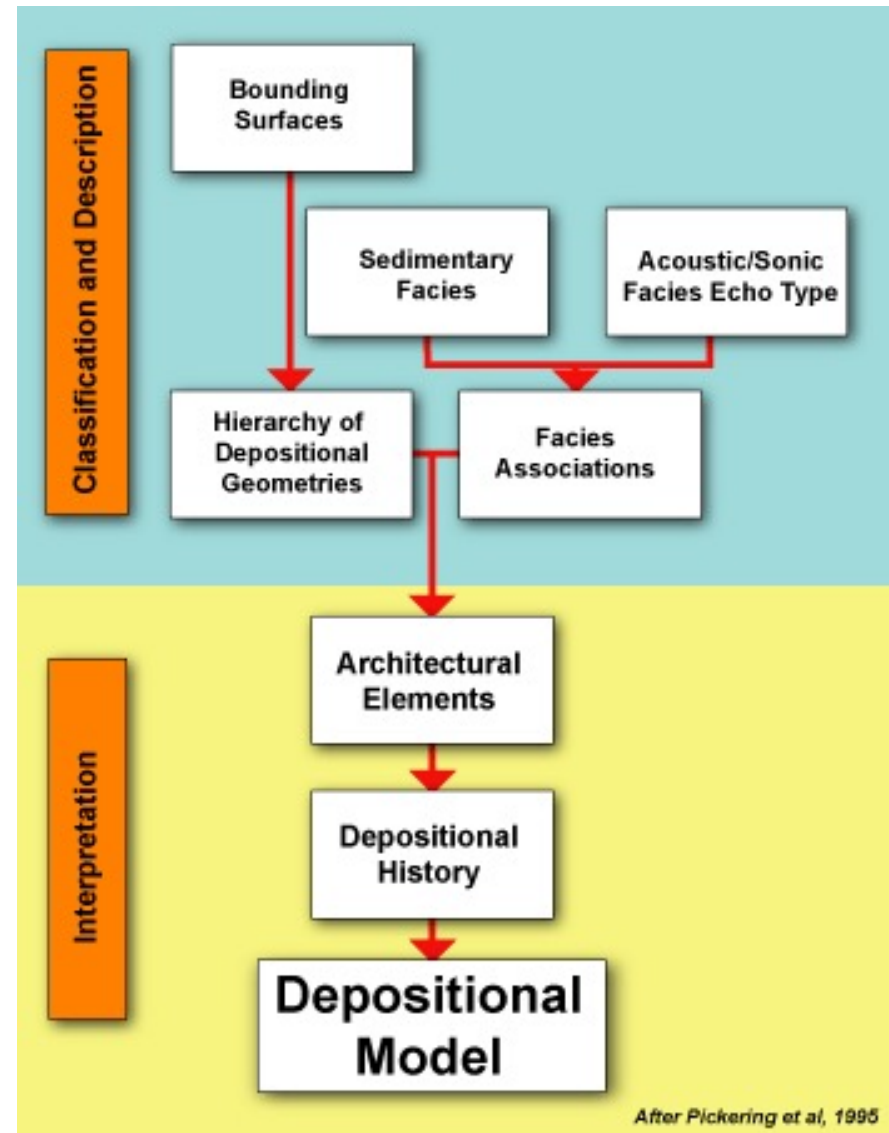


Walker, 1984. *Facies Model*

Description and interpretation

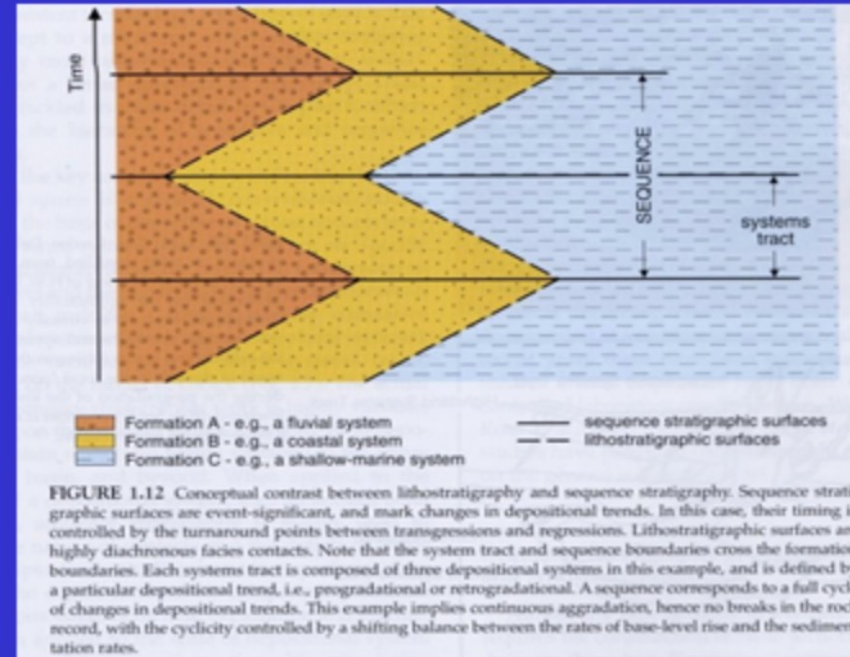
The analysis of complex sedimentary systems involves their description, classification and eventual interpretation.

Sprague et al (2002) have combined the use of both the boundaries and the enclosed sediments to describe a system of hierarchical frameworks that is based solely on the physical stratigraphy of the strata. The architectural framework is thus comprised of both genetically related stratigraphic elements and their associated boundaries.



Sismostratigrafia

Il principio fondamentale della Stratigrafia Sismica (o Sismostratigrafia) è che, entro la risoluzione del metodo, le riflessioni sismiche seguono le stratificazioni principali approssimando le linee del tempo. Il contrasto di impedenza rappresentato sulla sezione sismica è prodotto dalle interfacce tra gli strati e non dalle variazioni laterali di facies.



Alla scala della risoluzione sismica si può assumere che la *facies* cambi all'interno di strati tempo-equivalenti in modo graduale senza generare riflessioni sismiche. Quindi le riflessioni rappresentano superfici tempo in 3 dimensioni, e separano rocce più antiche da rocce più giovani. Alcune eccezioni, già note: contatti tra fluidi diversi, variazioni diagenetiche, *bottom simulating reflector*, fenomeni di *tuning*, etc.

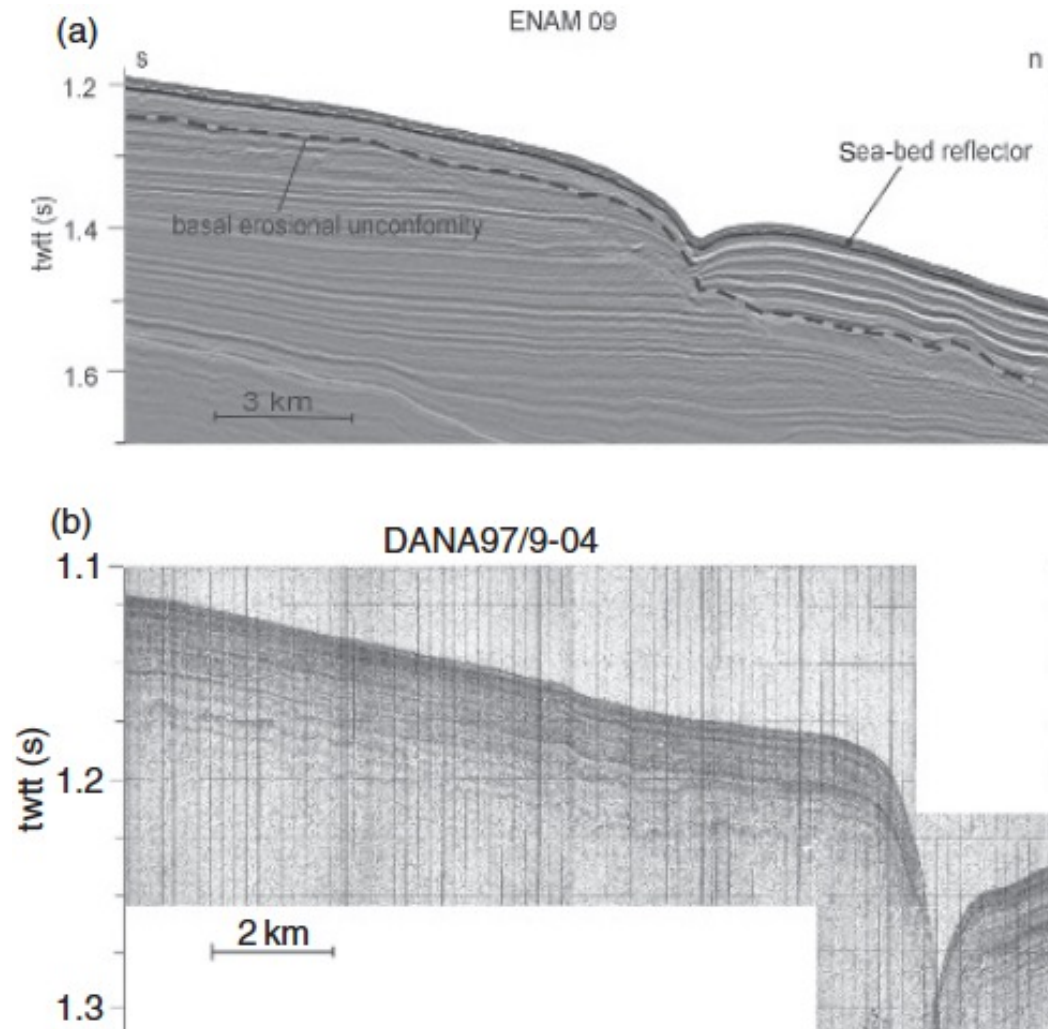
Possiamo quindi dire che le riflessioni sismiche forniscono una informazione di tipo **cronostratigrafico**, mentre le informazioni litologiche possono essere analizzate sulla base di caratteristiche del segnale e geometrie.

SEISMIC METHODS

For correct interpretation of seismic data, it is important to acknowledge the difference between a seismic profile and a geological profile.

Hence the seismic reflectors do not uniquely correspond to actual bed interfaces. Moreover, the horizontal scale on a conventional seismic profile is displayed in the metric system, while the vertical scale is displayed as two-way travel times (twtt). Thus, seismic profiles tend to be highly exaggerated on the vertical scale, leading to distortion of thickness and dip of layers.

Nielsen, Knutz, Kuijpers, 2008.
Seismic Expression of Contourite
Depositional Systems. *Developments
in Sedimentology*, 60, 301–321

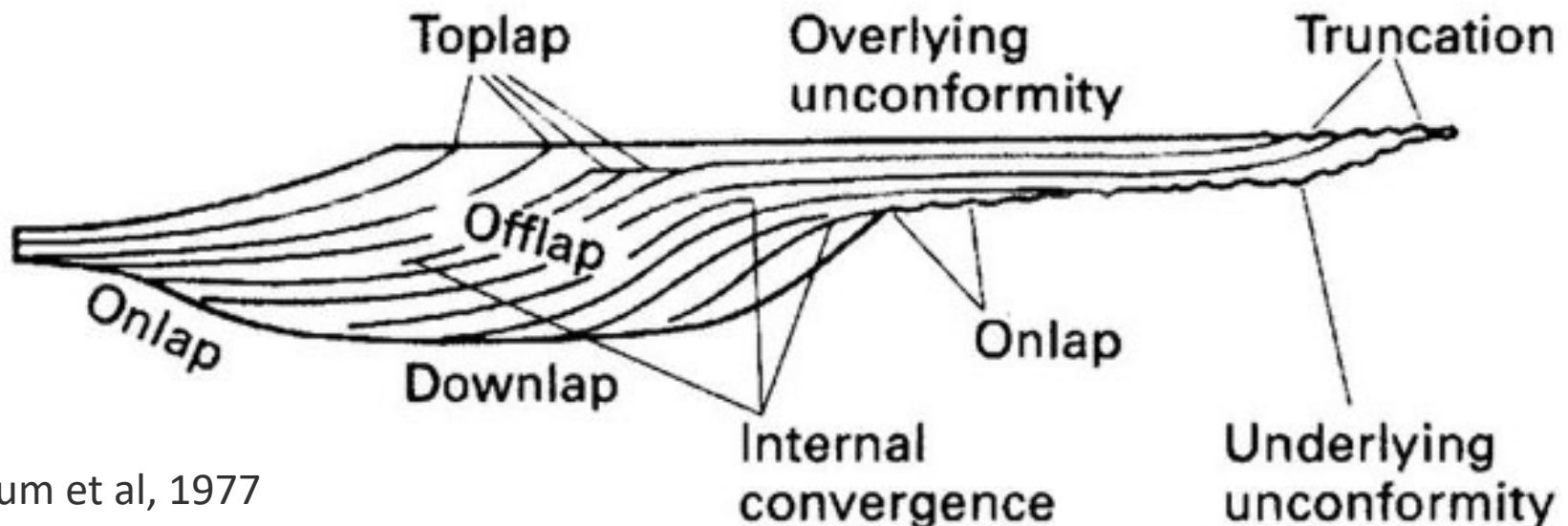


Seismic stratigraphy

The interpretation of seismic stratigraphy is based on the identification of seismic sequences and on seismic facies analysis.

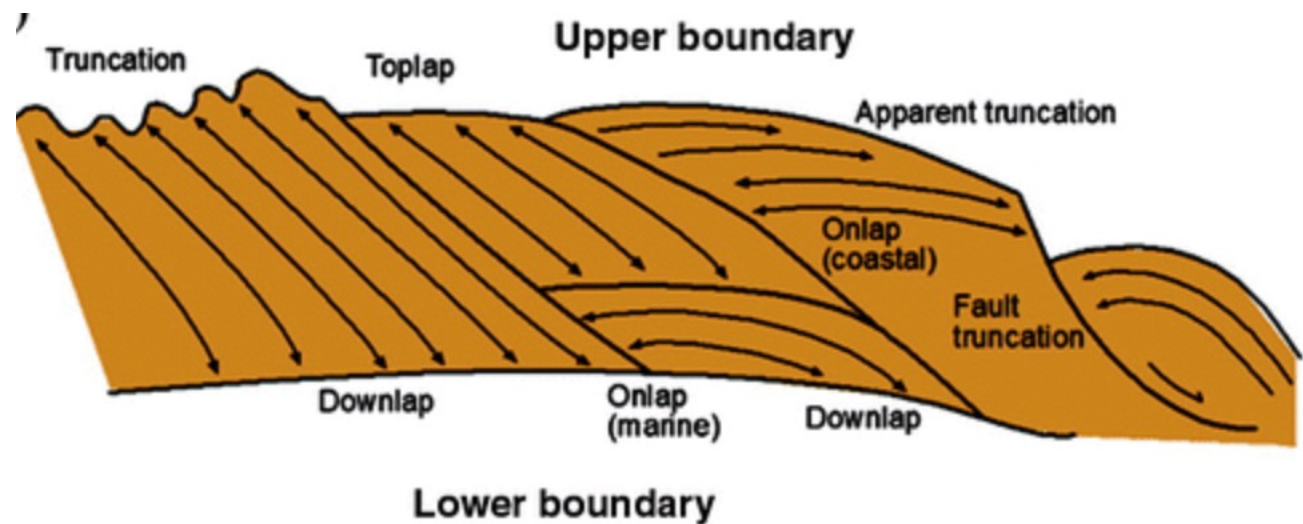
A seismic sequence consists of a succession of reflections that are relatively concordant limited at the base and top by discontinuities shown by the lateral termination of reflectors.

Their limits are often discontinuous due to either a depositional hiatus or an erosional unconformity and could represent anywhere from thousands to millions of years. The identification of seismic sequences is based on the geometry of the termination, at top and bottom, of a group of reflectors, and are interpreted as the lateral termination of strata.

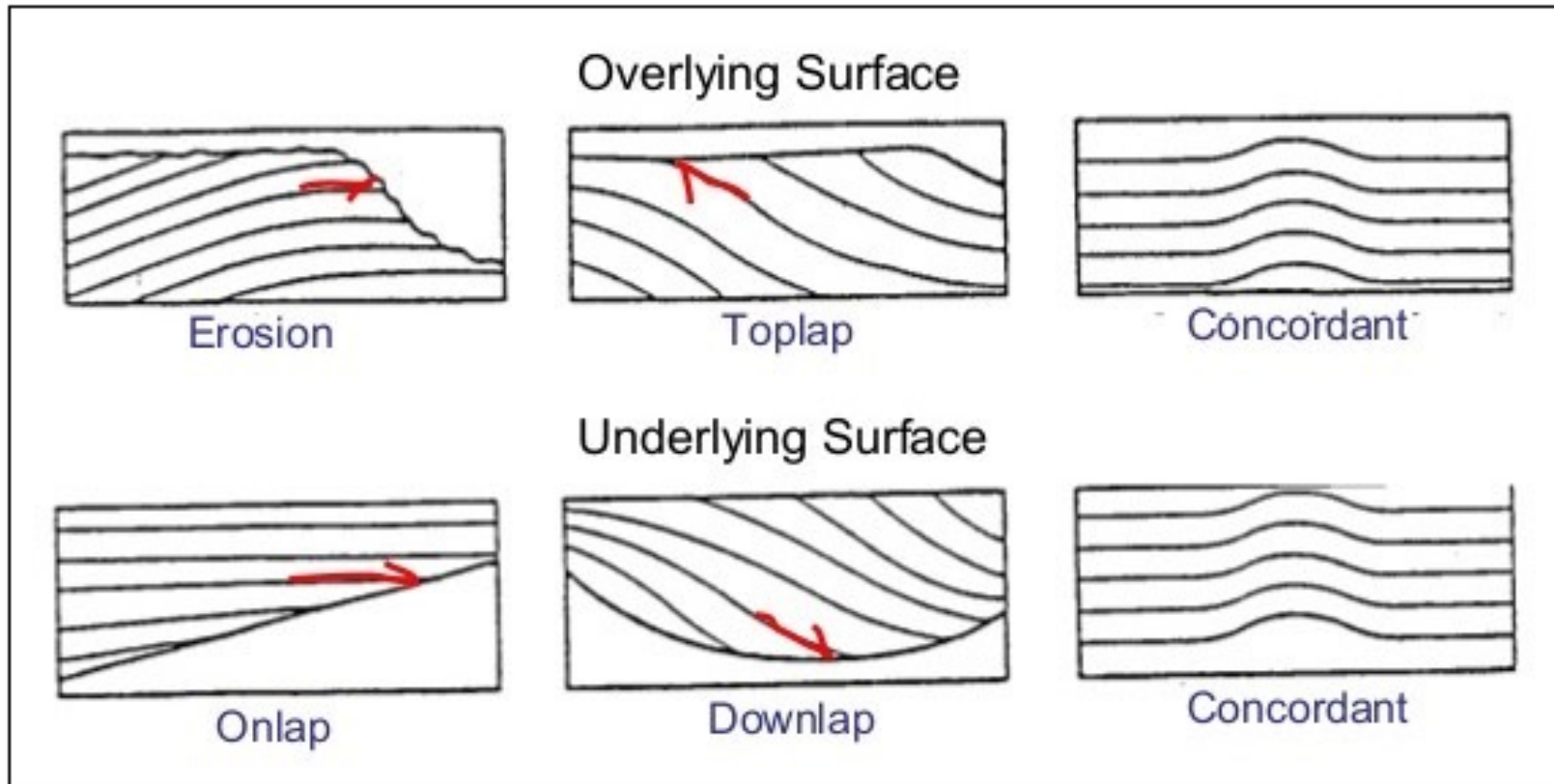


Seismic Reflection Terminations

- Truncation: Reflector termination due to erosion
- Apparent truncation: Disappearance of a reflector because it becomes too thin
- Fault truncation: reflector termination against the fault planes
- Toplap: Reflector termination at an overlying surface or upper boundary
- Onlap: Reflector termination on surfaces with greater dips than that of the overlying beds; lapping onto a structural high
- Downlap: Reflector termination on surfaces which dip less than that of the overlying beds; lapping onto a structural low
- Offlap: Combination of Toplap and Downlap at both surface



Upper and lower boundaries



Bedset terminations are named according to their angular relationship with underlying and overlying bounding surfaces.

Seismic interpretation

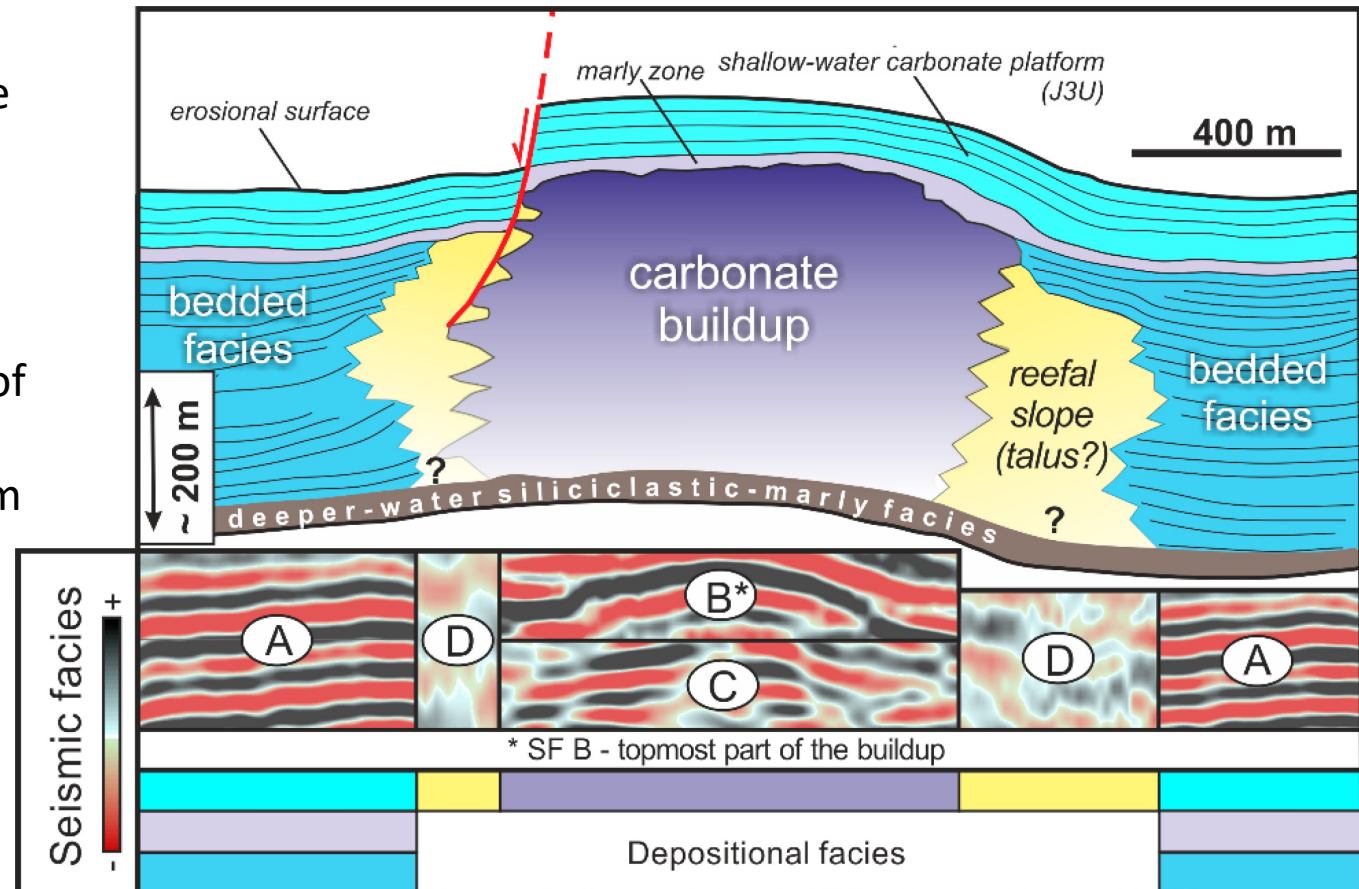
Concurrent with the development of seismic methods (in particular the use of digital 3-D volumes that provides new opportunities for seismic facies analysis), the terminology within seismic interpretation has become increasingly confusing. Terms like “sequence”, “facies” and “attributes” appear in a multitude of contexts to the extent that the scientist must clarify the meaning of these terms within the context of the specific study.

Since the concepts of “seismic stratigraphy” and “seismic sequence stratigraphy” were introduced in the 1970–1980s (Vail et al., 1977a; van Wagoner et al., 1988), a whole set of terms has developed for seismic interpretation that are now widely used. However, the conventional concept of seismic sequence stratigraphy – and the terminology involved – is not always fully applicable to some context (like e.g. contourite studies). We thus suggest the use of the simple term “seismic unit” that is not associated with any specific depositional environment to denote a stratigraphic subdivision of a sedimentary succession. The breakdown into seismic units, in contrast, may be based on analysis of reflection terminations and internal reflector patterns using the traditional technique introduced by Mitchum and Vail (1977) among others.

Seismic facies analysis

After seismic stratigraphic studies of a basin are done to delineate genetically related units, these seismic sequences are further described to define mappable, three-dimensional seismic units composed of groups of reflections whose parameters differ from those of adjacent facies units (Mitchum et al. 1977).

Seismic facies analysis is the description and interpretation of seismic reflection parameters, such as configuration, continuity, amplitude, and frequency, within the stratigraphic framework of a depositional sequence



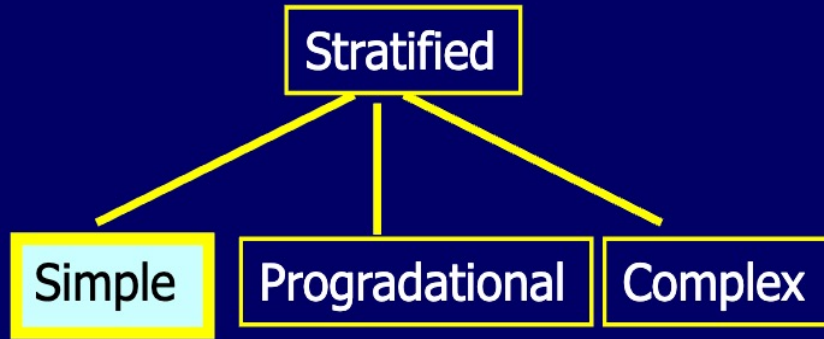
Seismic facies

Analysis of the seismic facies deals with investigation of vertical and lateral variations of internal reflections. Synonymous terms are “seismic reflection pattern”, “acoustic facies” or “echo character” analysis, the latter mostly used in connection with UHR seismic data. The seismic facies is relative to the type of seismic method employed. This means that a seismic facies will display differently on different types of seismic data and will also depend on processing parameters. Moreover, because the reflections result from changes in the physical parameters through the sedimentary succession, there is no unequivocal correlation between seismic facies and sedimentary structures within the facies. A seismic facies characterised by a parallel reflection configuration, for instance, need not necessarily indicate the existence of fine parallel banding or stratification of the sediments.

Basically there are two categories of seismic attributes: those that quantify the geometric aspects and those that quantify the reflectivity components of the seismic data. The geometric attributes reveal information on dip, azimuth and termination of a reflector or horizon, which can in turn be related e.g. to bed forms.

The reflectivity attributes reveal information on reflector amplitude, frequency and phase, which in turn might be related to lithology. As the types of attributes are numerous, so are the computational methods and a variety of seismic attribute analysis techniques exist.

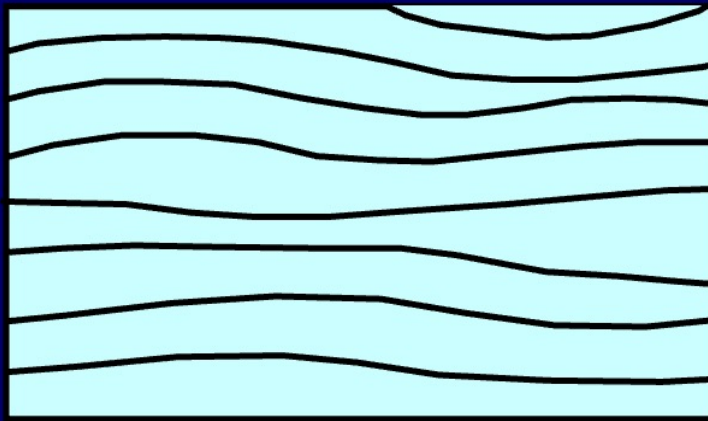
Simple Stratified Internal Configurations



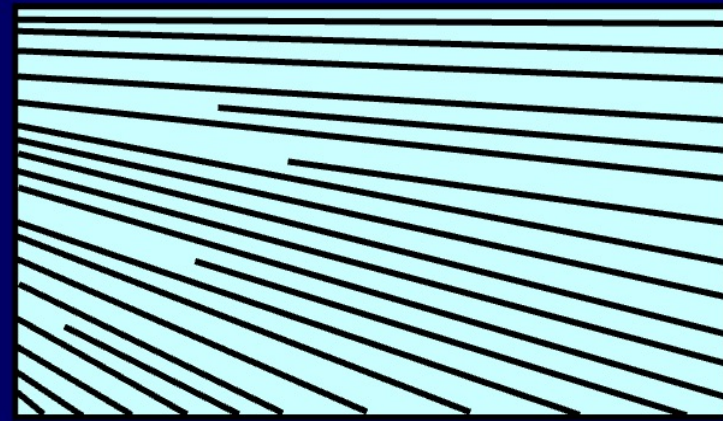
Parallel - Even



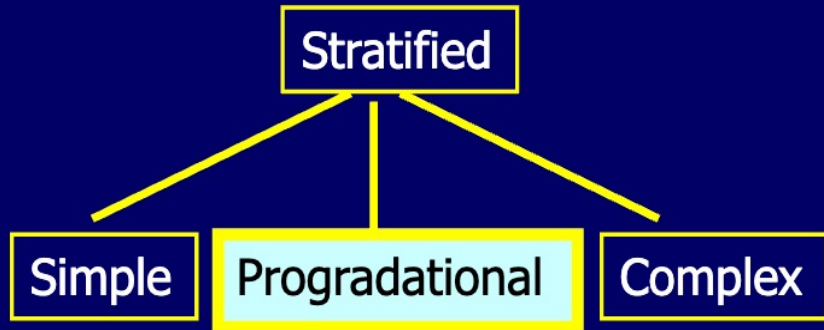
Subparallel



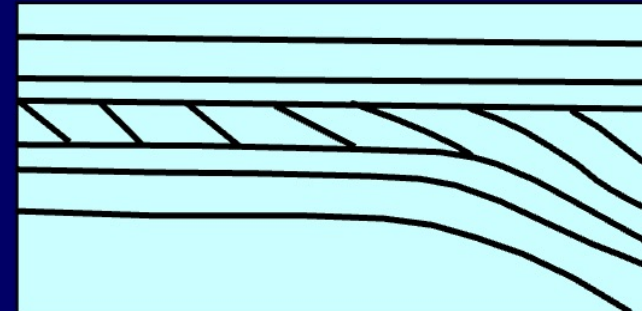
Divergent



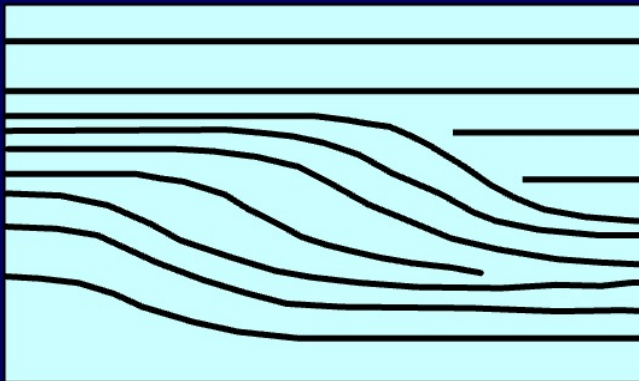
Progradational Internal Configurations



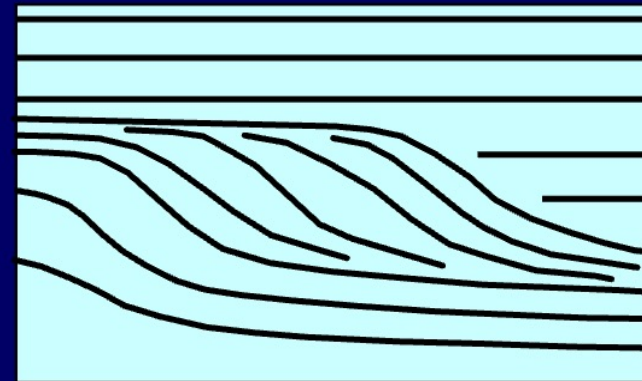
Shingled



Sigmoid



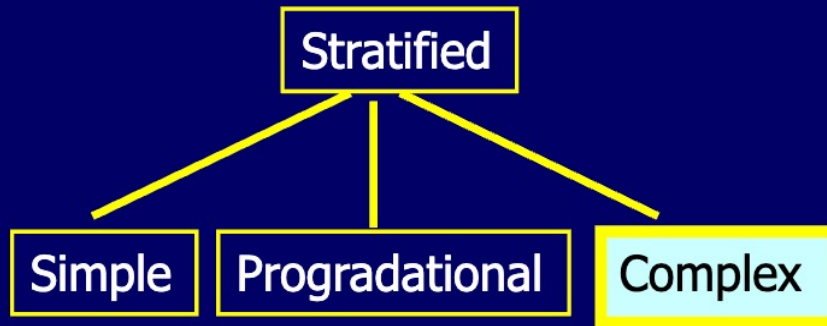
Oblique



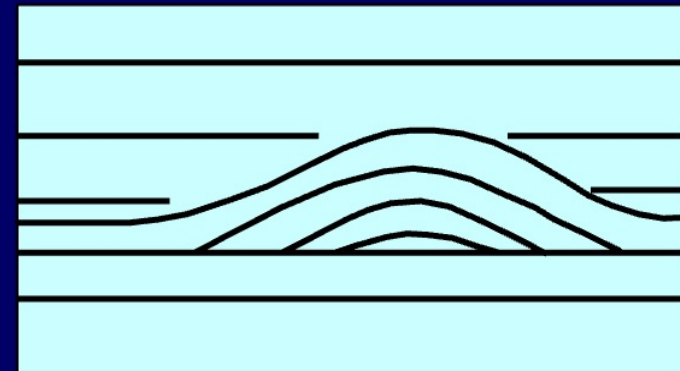
Upbuilding (Aggradation)

**Outbuilding
(Progradation)**

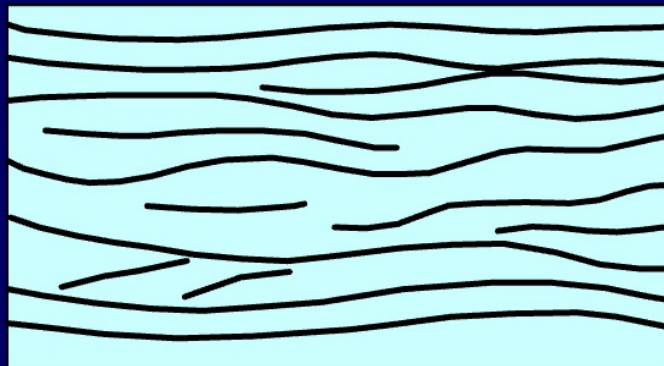
Complex Internal Configurations



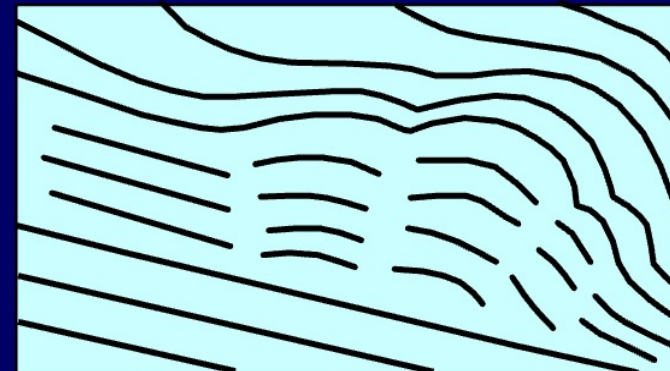
Mounded



Hummocky

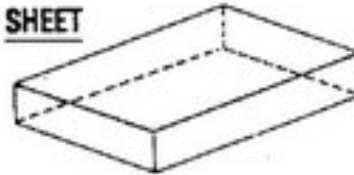


Deformed

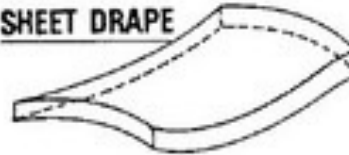


Main types of external forms of seismic units

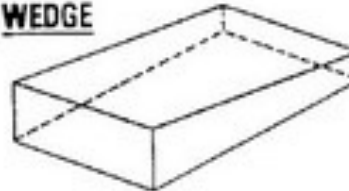
SHEET



SHEET DRAPE



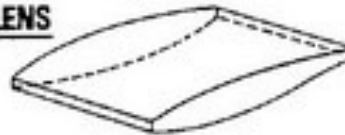
WEDGE



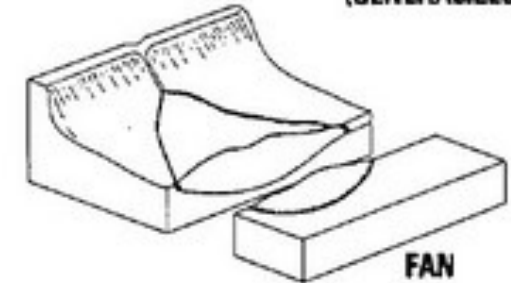
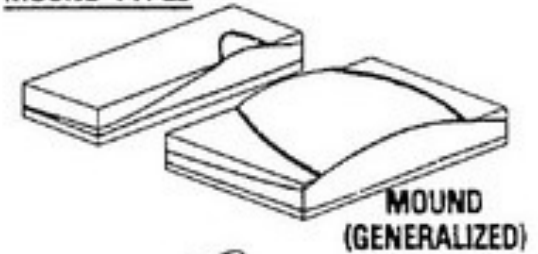
BANK



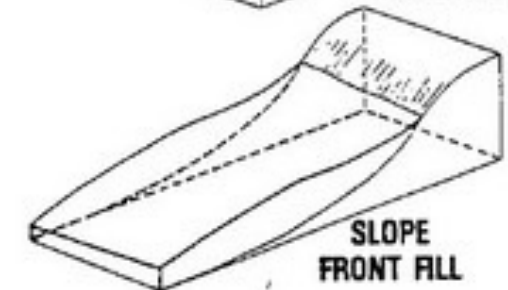
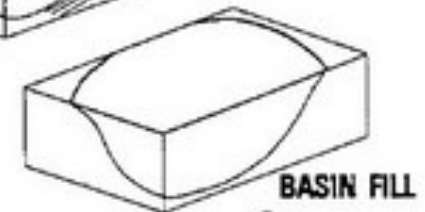
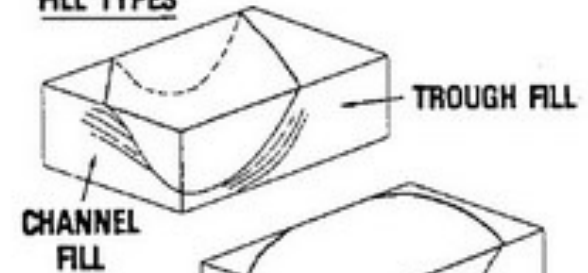
LENS



MOUND TYPES



FILL TYPES



Seismic attributes (reflection parameters)

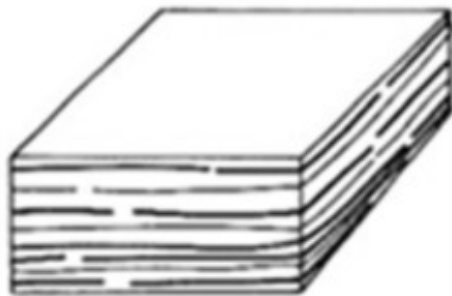
- Amplitude
- Lateral continuity
- Frequency
- Phase
- Polarity

The amplitude and lateral continuity of a seismic horizon depend respectively on the impedance contrast and on extent and nature of the geological layers that define that horizon.

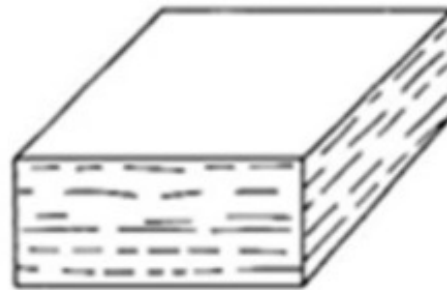
Frequency (distance between reflectors): depends on bed thickness and changes in lithology

Phase: can be used as a good continuity indicator in poor reflectivity areas

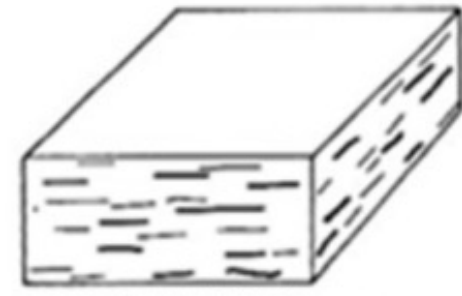
Polarity: it depends on the positive or negative acoustic impedance



**HIGH AMPLITUDE AND CONTINUITY
(INTERBEDDED HIGH
AND LOW ENERGY)**



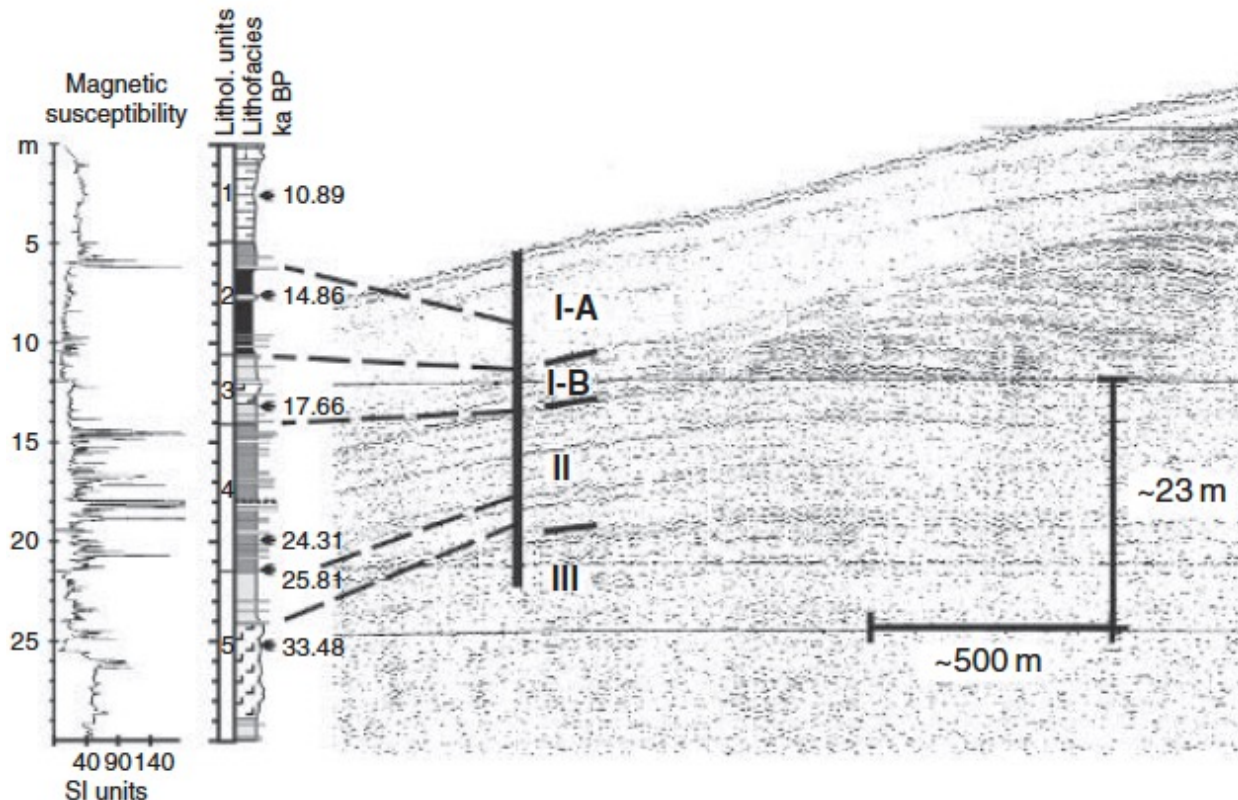
**LOW AMPLITUDE
(UNIFORM ENERGY)**



**LOW CONTINUITY
VARIABLE AMPLITUDE
(VARIABLE ENERGY)**

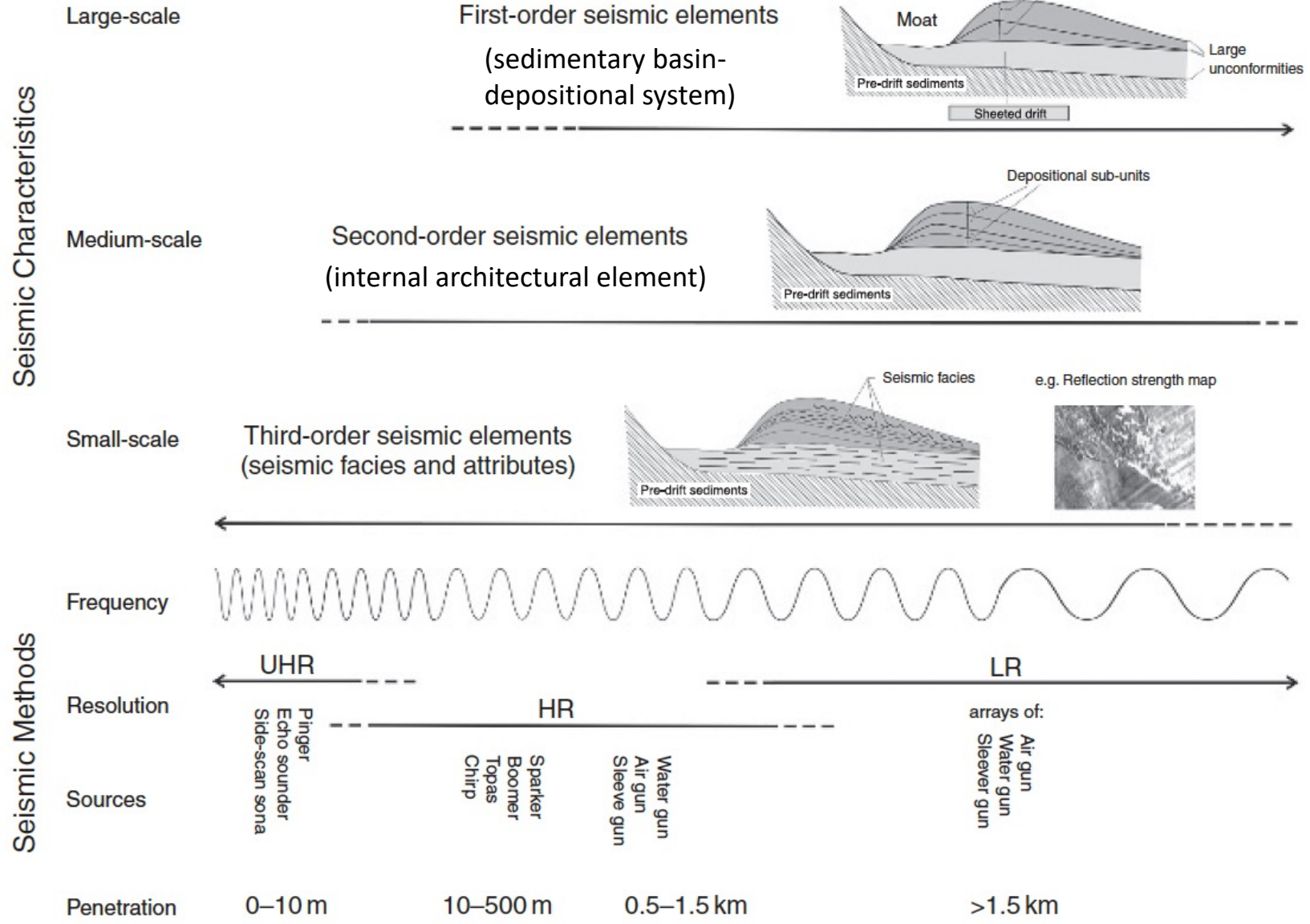
Seismic inversion: converting seismics into geology

Seismic inversion, broadly defined, is the study of acoustic information like velocity, impedance and amplitude to extract geological information of the subsurface layers like density, porosity and compaction. It is a difficult process, since the seismic measurements are limited and the earth extremely complex, and there are many different inversion methods.



In seismic depth conversion, the twtt is converted to depth. This process requires estimation of the seismic velocity, which in fact is the most uncertain link between seismics and geology. Therefore, the use of core and borehole information in combination with seismics requires information on the seismic velocity used for the correlation.

Correlation between the seismic methods, frequency of the seismic source and the seismic characteristics



Modulo	Argomento	Docente	Data
1.1	introduzione al corso e argomenti	Rebesco	05/10/21
1.2	metodi (geofisica, affioramenti, geologia marina, ambienti attuali)	Volpi/Rebesco	06/10/21
1.3	meccanismi di formazione dei bacini (geodinamica, tettonica...)	Lodolo	12/10/21
1.4	Interpretazione sismica, facies e strutture primarie	Rebesco	13/10/21
	Martedì 19 Ottobre non c'è lezione		
1.3	Energy storage e CCS	Volpi/Donda	20/10/21
2.1	processi sedimentari eolici, fluviali e glaciali	Rebesco	26/10/21
2.2	maree e onde	Rebesco	27/10/21
	Martedì 2 Novembre non c'è lezione		
	Mercoledì 3 Novembre non c'è lezione		
2.3	gravità e correnti di fondo, trasporto di massa	Rebesco	09/11/21
3.1	pianure abissali (decantazione emipelagica) e margini continentali	Rebesco	10/11/21
3.2	Conoidi sottomarine (flussi gravitativi dalla scarpata continentale)	Lucchi	16/11/21
3.3	Sediment drifts (correnti di fondo lungo la scarpata continentale)	Rebesco	17/11/21
3.4	Mass transport deposits (accenni a risoluzione/penetrazione)	Ford	23/11/21
3.5	piattaforme continentali (onde, tempeste, tsunami)	Rebesco	24/11/21
3.6	calotte glaciali e ghiacciai marini	De Santis	30/11/21
3.7	Delta, estuari e spiagge e ambienti deposizionali carbonatici	Rebesco	01/12/21
3.8	faglie, vulcani e corpi intrusivi	Civile	07/12/21
	Mercoledì 8 Dicembre non c'è lezione		
3.9	fiumi, laghi e deserti	Rebesco	14/12/21
4	esercitazione	Rebesco	15/12/21
5.1	stratigrafia sequenziale	Zecchin	21/12/21
5.2	livello del mare e spazio di accomodamento	Zecchin	22/12/21
	Dal 23 Dicembre al 9 Gennaio non c'è lezione		
5.3	discontinuità e paraconformità e altre superfici significative	Zecchin	11/01/22
5.4	system tracts (apparati deposizionali) e diversi modelli	Zecchin	12/01/22
5.5	applicazioni (es. reservoirs di idrocarburi)	Zecchin	18/01/22
6	visita a CoreLoggingLAB e/o SEISLAB (assieme a Geologia Marina)	Rebesco	19/01/22