Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

Curriculum: Esplorazione Geologica

Anno accademico 2022 - 2023

Analisi di Bacino e Stratigrafia Sequenziale (426SM)

Docente: **Michele Rebesco**

Module	Topic	Teacher	Date
1.1	Introduction to the course	Rebesco	03/10/22
1.2	Methods (geophysics, but not only)	Volpi/Rebesco	06/10/22
6.1	Visit to the icebreaker Laura Bassi (along with Geologia Marina)	Rebesco	10/10/22
1.3	Mechanisms of basin formation (geodynamics, tectonics…)	Lodolo	13/10/22
1.4	Seismic interpretation, facies and primary structures	Rebesco	17/10/22
	No lesson: 20th October		
1.5	Energy storage & CCUS	Volpi/Donda	24/10/22
	No lesson: 27th		
2.1	Sedimentary processes in river & deltas	Rebesco	31/10/22
	No lesson: 3rd November		
2.2	Action of tides and waves, wind and ice	Rebesco	07/11/22
2.3	Density currents, bottom currents and mass transport	Lucchi/Rebesco	10/11/22
3.1	Alluvial deposits, lakes and deserts	Rebesco	14/11/22
3.2	Barrier systems and incised valleys	Rebesco	17/11/22
3.3	Continental shelves (wases, storms, tsunamis)	Rebesco	21/11/22
3.4	Submarine fans (gravity flows on the continental slope)	Lucchi/Rebesco	24/11/22
3.5	Sediment drifts (bottom currents along the continental slope)	Rebesco	28/11/22
3.6	Mass transport deposits	Ford	01/12/22
3.7	Abyssal plains (hemipelagic fallout) and continental margins	Rebesco	05/12/22
	No lesson on Thursday 8 th December		
3.8	Glacial depositional systems	De Santis	12/12/22
3.9	Carbonatic environments, faults, volcans	Rebesco	15/12/22
4.1	Sequence stratigraphy: introduction	Rebesco	19/12/22
	No lessons from 23 rd December to 8 th January		
4.2	Sequence stratigraphy: closer view	Rebesco	09/01/23
4.3	Sequence stratigraphy: applications (e.g. hydrocarbon reservoirs)	Rebesco	12/01/23
5	Excercise	Rebesco	13/01/23
6.2	Visit to CoreLoggingLAB (along with Geologia Marina)	Rebesco	20/01/23
6.3	Visit to OGS and SEISLAB (along with Geologia Marina)	Rebesco	27/01/23

Module 1.4
(Seismic) stratigraphy and facies

Outline:

Scales

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

Sequence stratigraphy & lithostratigraphy

Depositional architecture (systems, elements, …)

Facies

Facies sequence

Facies model

Seismic stratigraphy

Seismic facies analysis

Scale

You can't have it all in one go!

Think of the maps (eg GoogleMaps): you cannot have the detail and the overview together, and a middle ground give us neither of the two ...

Think of the simic: either resolution, or penetration, or a compromise between the two

Remember that we have named the three survey scales, both on the ground and in seismic

Well, for a complete analysis you need all three scales. Like going to an unfamiliar place, you need all three levels of information:

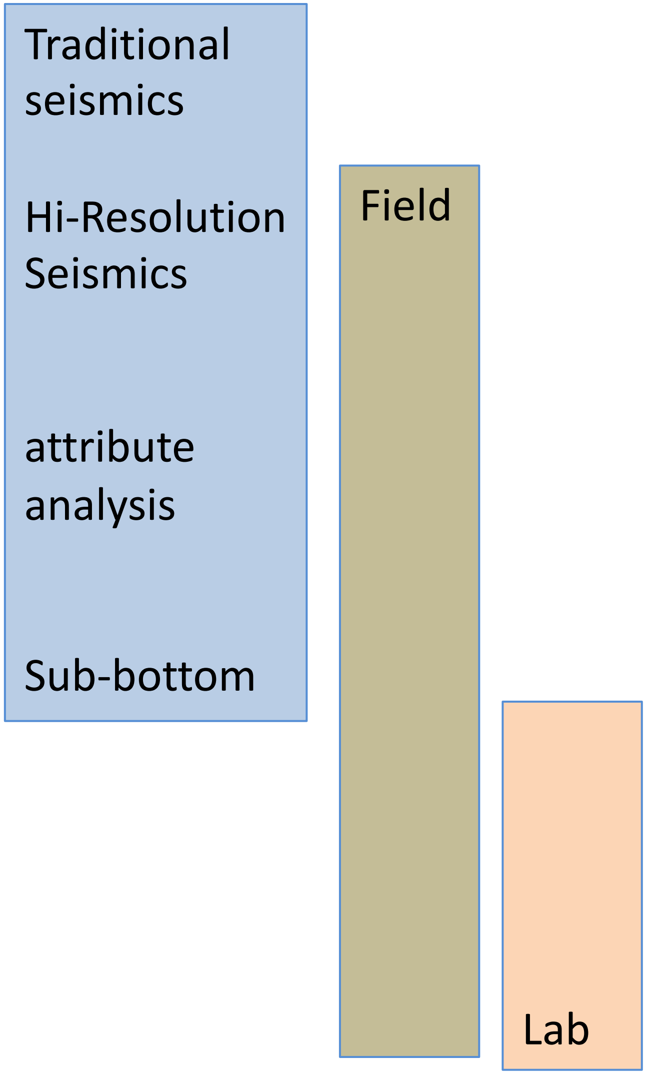
Country

City

Street and number

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)



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Sedimentary structures

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.

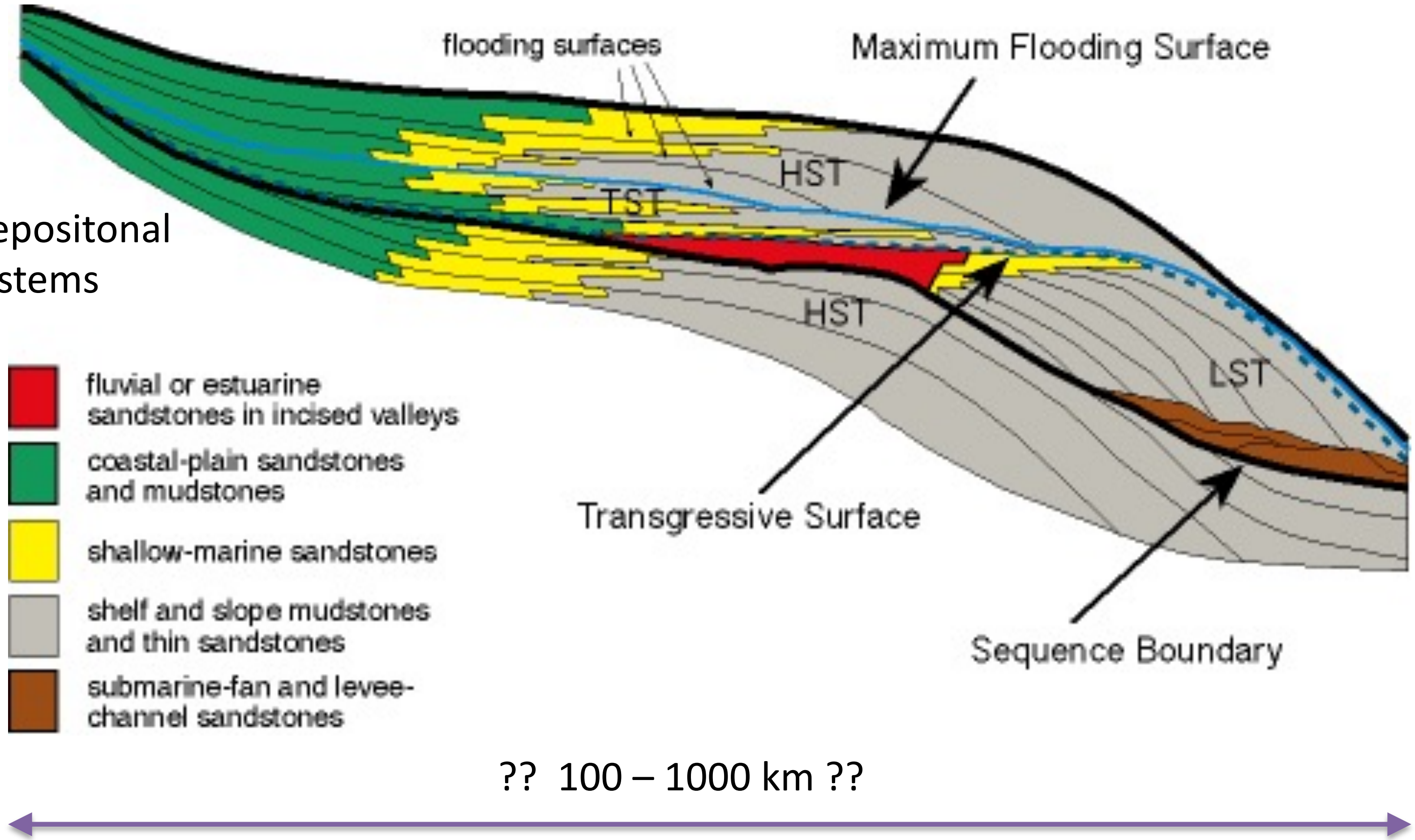
They are three-dimensional features found within the sedimentary section and/or on the bedding plane (bedforms) and have visible characteristic fabrics, textures, arrangements of sediments within a rock.

http://www.sepmstrata.org/Terminology.aspx?id=sedimentary%20structures

Sequence Stratigraphy

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

Depositonal systems



?? 100 – 1000 km ??

Lithostratigraphy

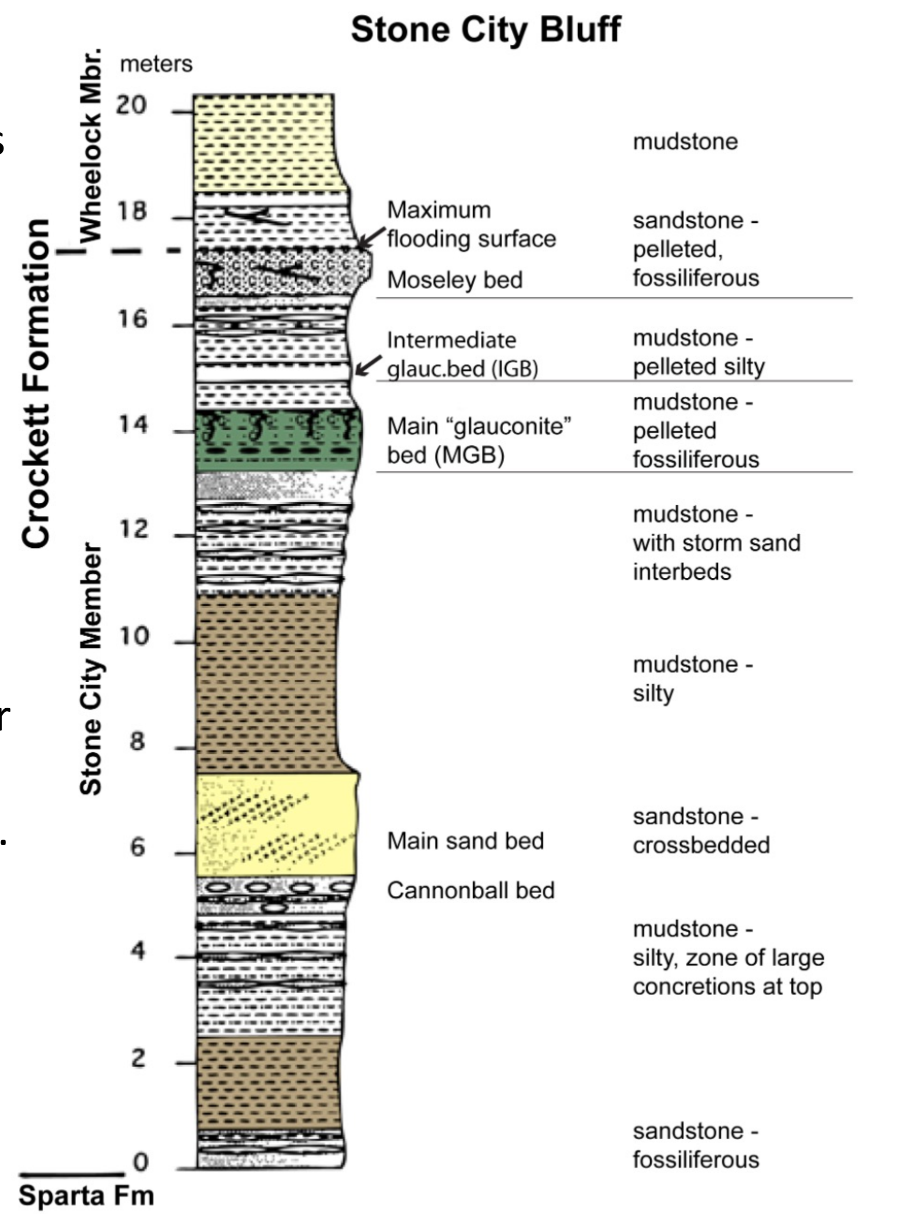
The lithostratigraphy is the study of rock layers (physical characteristics as type, color, mineral composition, grain size…).

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.



Modified after Yancey & Davidoff (1994)

Lithostratigraphy versus Sequence Stratigraphy

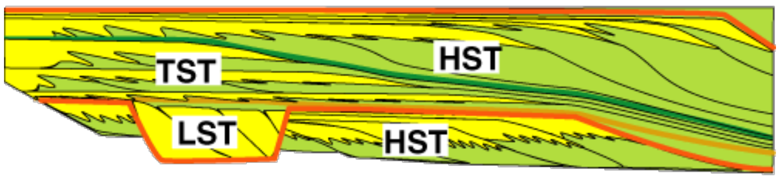
Lithostratigraphy maps these sedimentary rocks solely on the basis of their lithology and does not necessarily consider that these rocks may have accumulated over a particular period of time. In contrast allostratigraphy maps the rock units on the basis of the timing of their accumulation.

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.

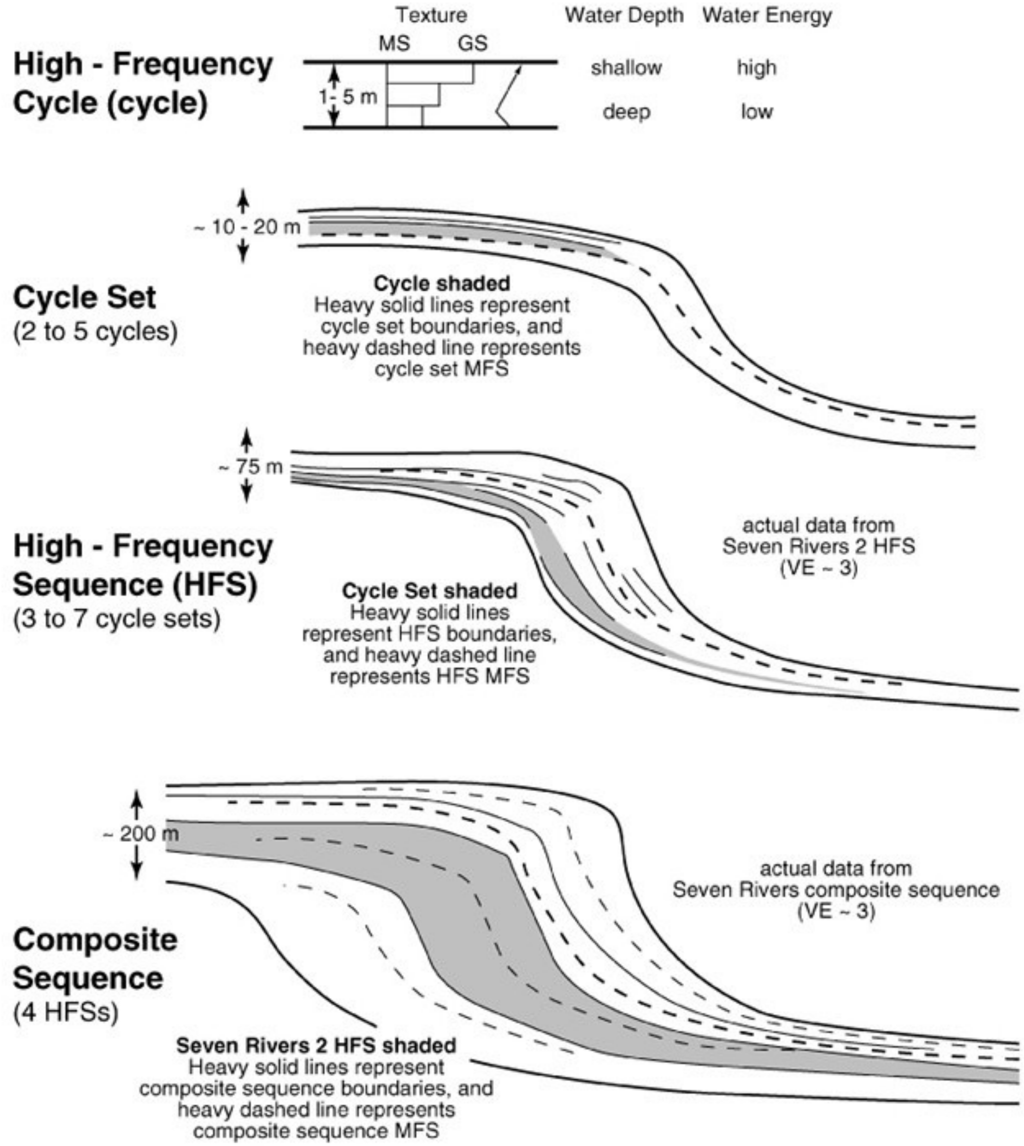
Unconformity: a surface separating younger from older strata, along which there is evidence of subaerial erosional truncation and correlative submarine erosion, with a significant hiatus in sedimentation (Vail, et al., 1977).

Cyclicity

Stratigraphic cyclicity 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

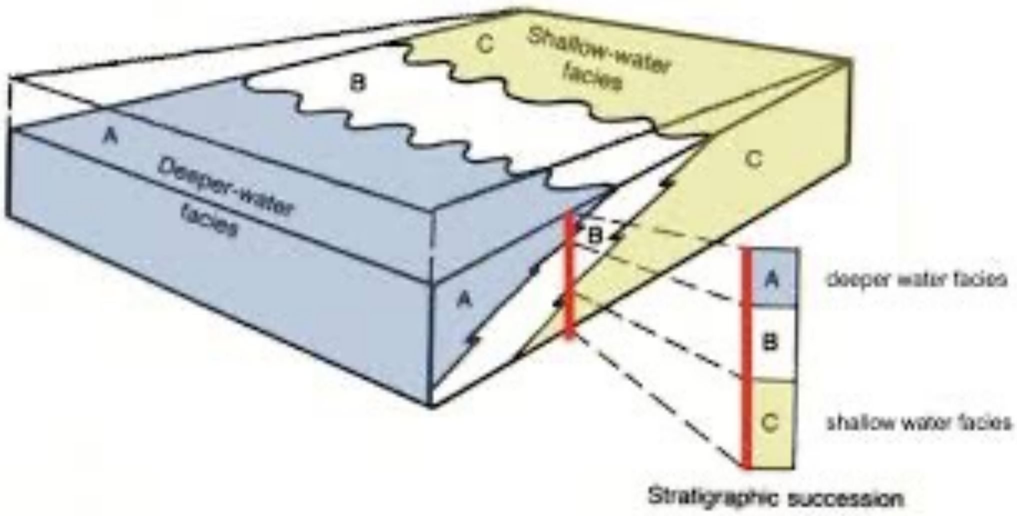
Aspects include: physical, chemical, biological, organic, structural, seismic…

Detectable either in the field, seismics or lab

- Set of characteristics or rock body?

- with reference to stratigraphic units?

- descriptive or interpretative?



Various components…

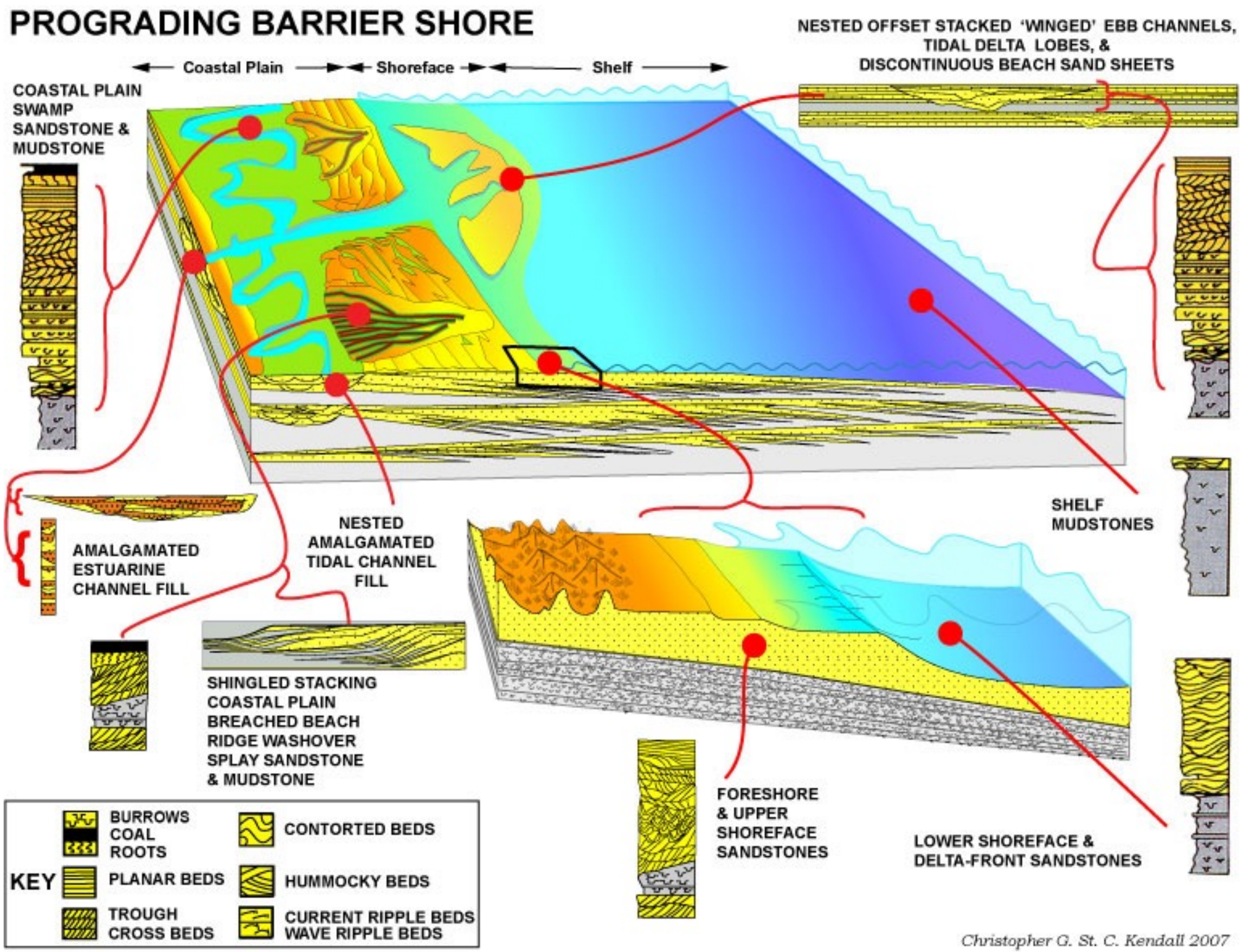
Facies: Detectable aspects of a sedimentary body that make it distinguishable from adjacent ones.

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.



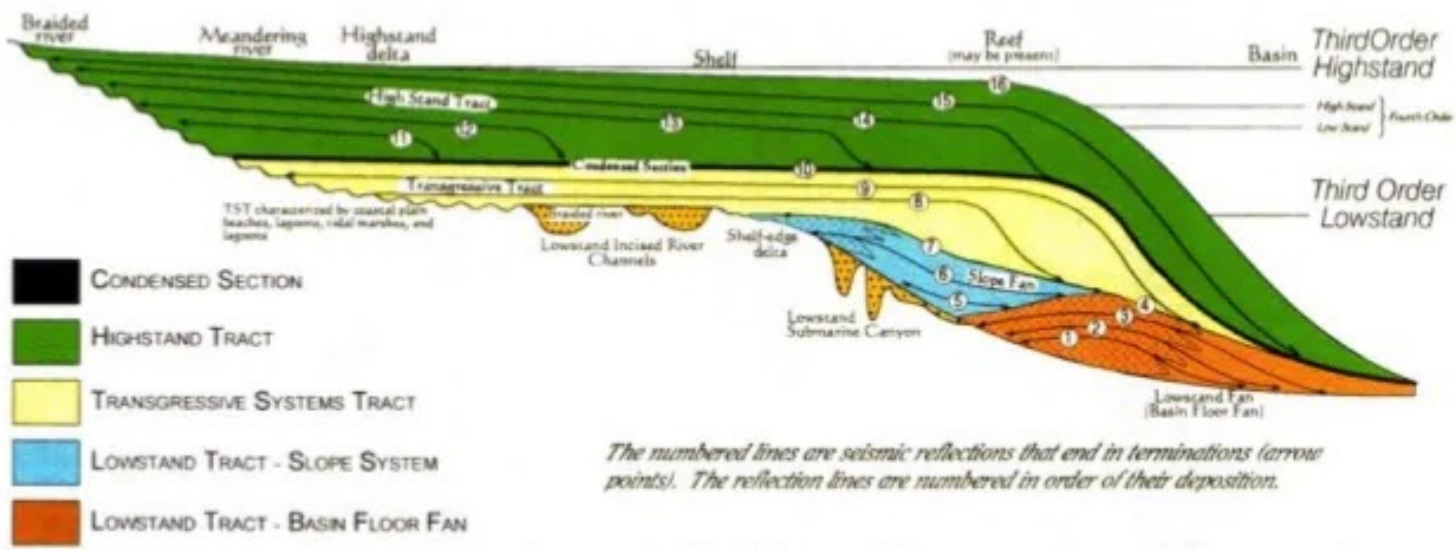
Larger scale components…

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.

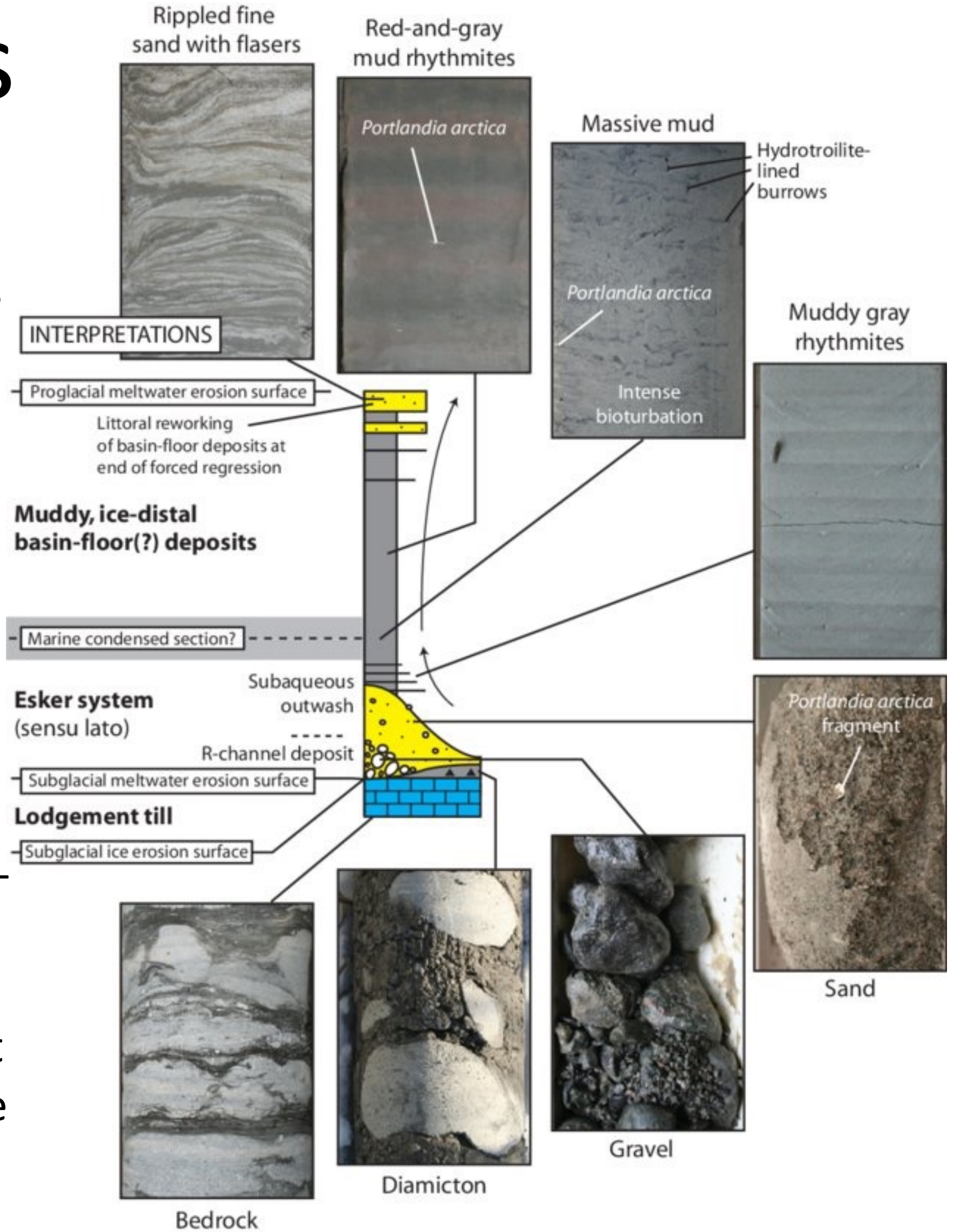
Defining facies

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

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

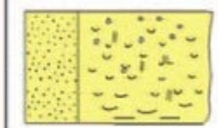
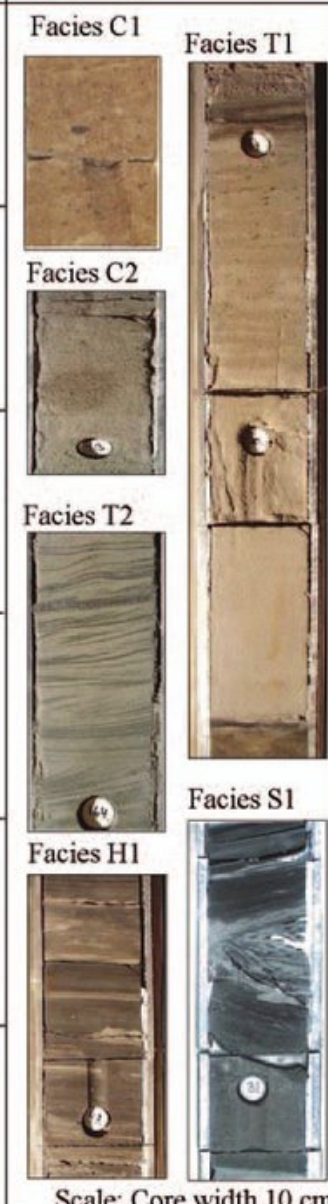
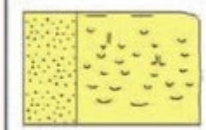
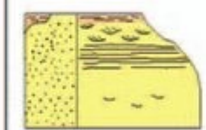
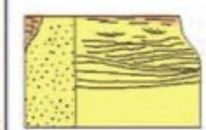
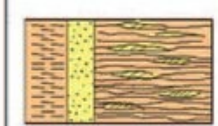
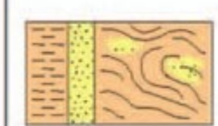
(Roger Walker, 1984. Facies Model, ISBN 978-0919216259

In other words, there are no standard, ready-made facies.
When YOU are in the fied (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

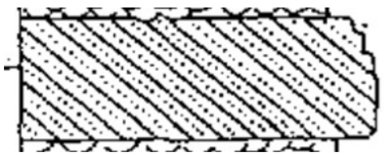
Fjellanger et al., 2005. Upper cretaceous basin-floor fans in the Vøring Basin, Mid Norway shelf. Norwegian Petroleum Society Special Publications 12:135-164
DOI: 10.1016/S0928-8937(05)80047-5

Facies	Observations	Process	Description	Core photo
C1	Massive sandstone or faint inverse graded sandstone	Hyper-concentrated density flow		
C2	Massive or top-only graded sandstone	Hyper-concentrated to concentrated density flow		
T1	Graded sandstone with Tabcde Bouma divisions	Concentrated density flow and turbidity flow		
T2	Stratified sandstone	Concentrated density flow and turbidity flow modified by currents or waves		
H1	Heterolithic sandstone and mudstone	Low density turbidity flow / bottom current		
S1	Overturned / brecciated deposits	Slumping		

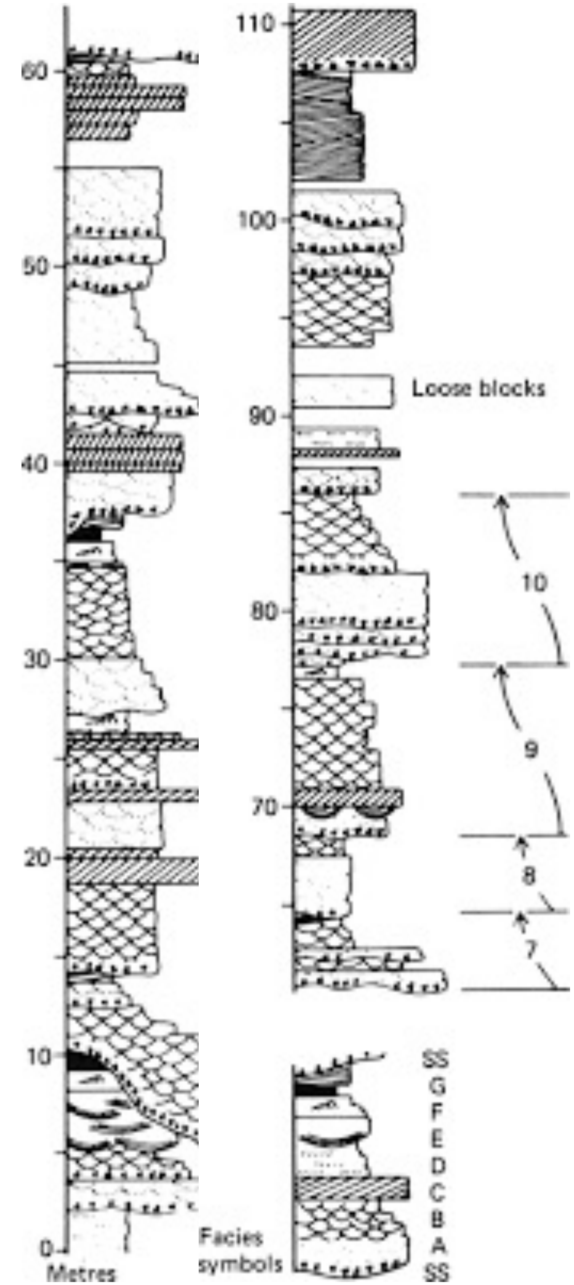
Facies sequence (or association)

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

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



Cant and Walker, 1976



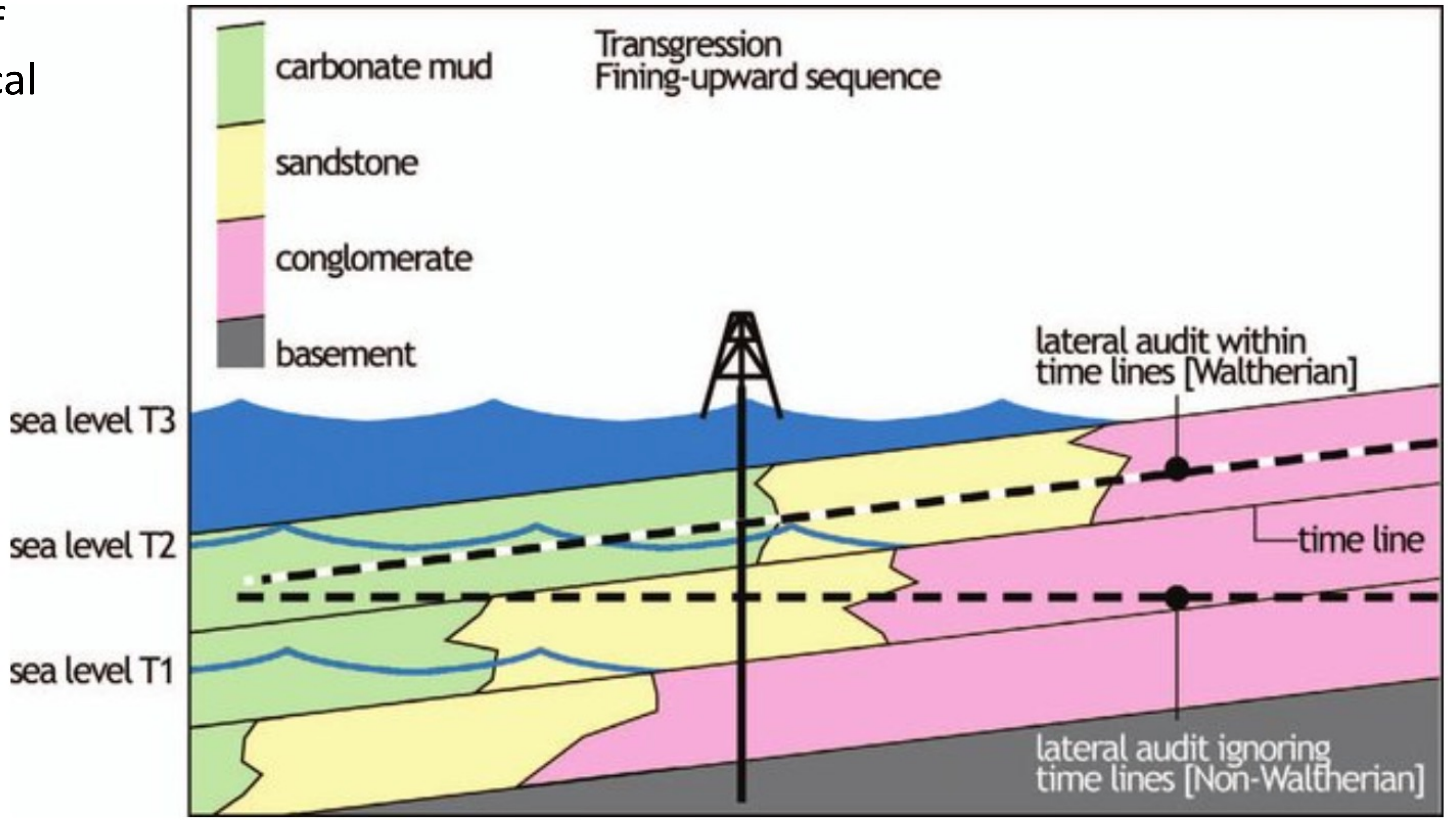
But – according to the «Walther's law - a sequence (or association) of facies with gradational transitions is more informative.

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.

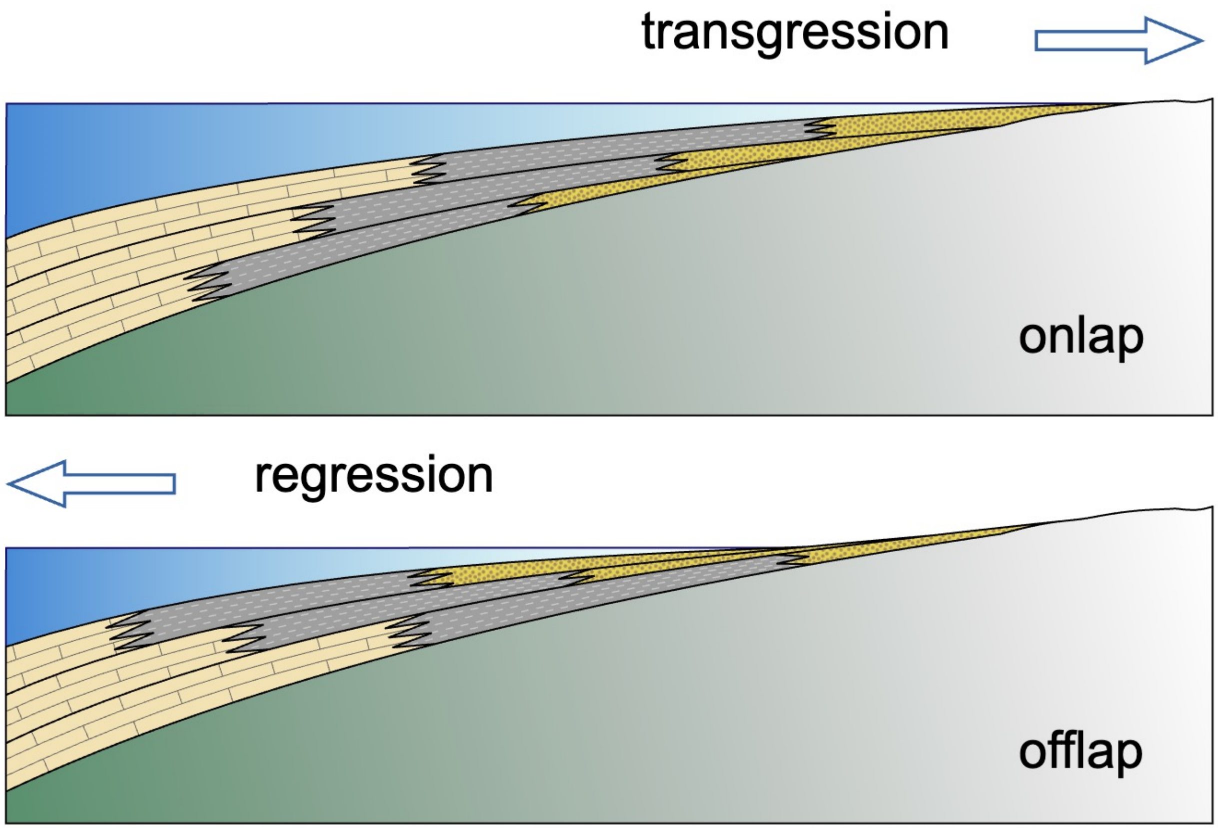


Purkis et al., 2012. Vertical-To-Lateral Transitions Among Cretaceous Carbonate Facies--A Means To 3-D Framework Construction Via Markov Analysis. Journal of Sedimentary Research 82(4):232-243

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.



https://en.wikipedia.org/wiki/Marine_transgression

Facies Model

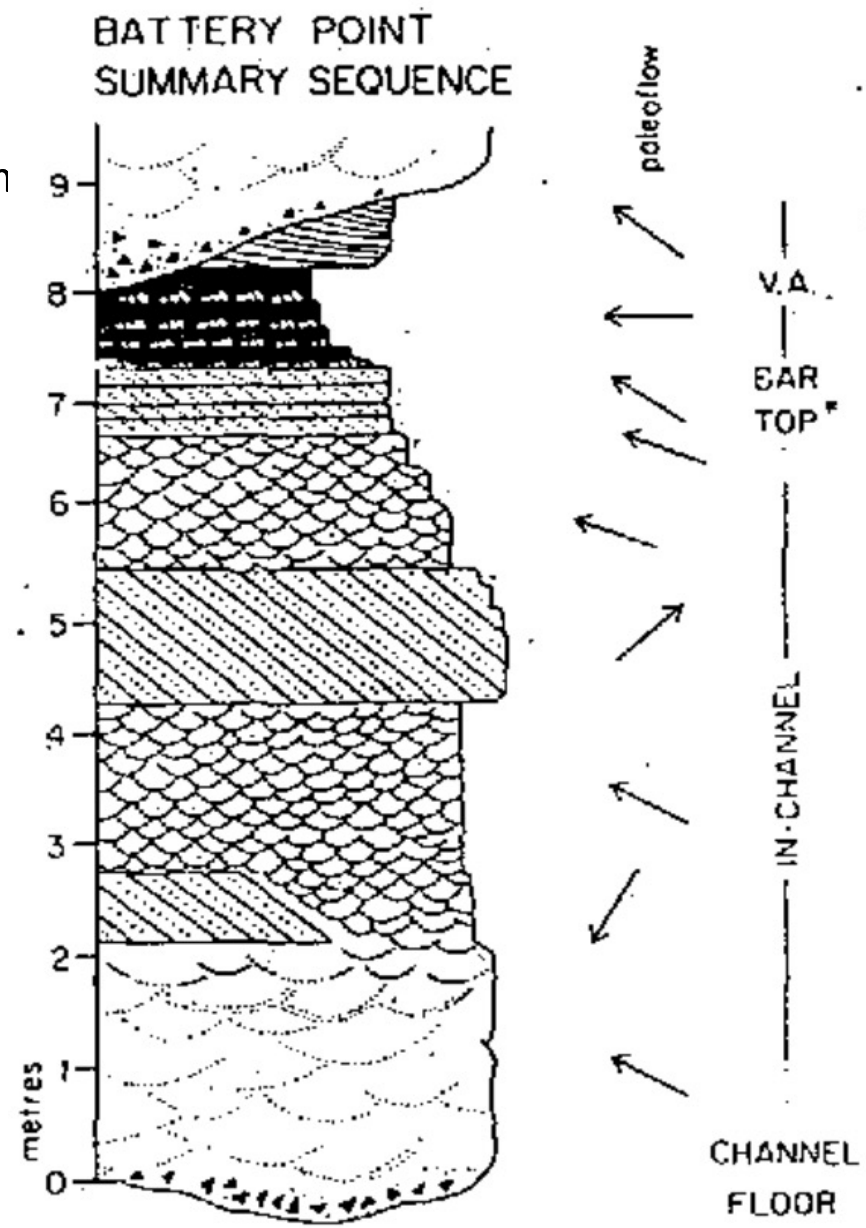
Facies moldels link many observations from modern environments (the ontological method according to Walther) and ancient deposits into coherent syntheses.

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

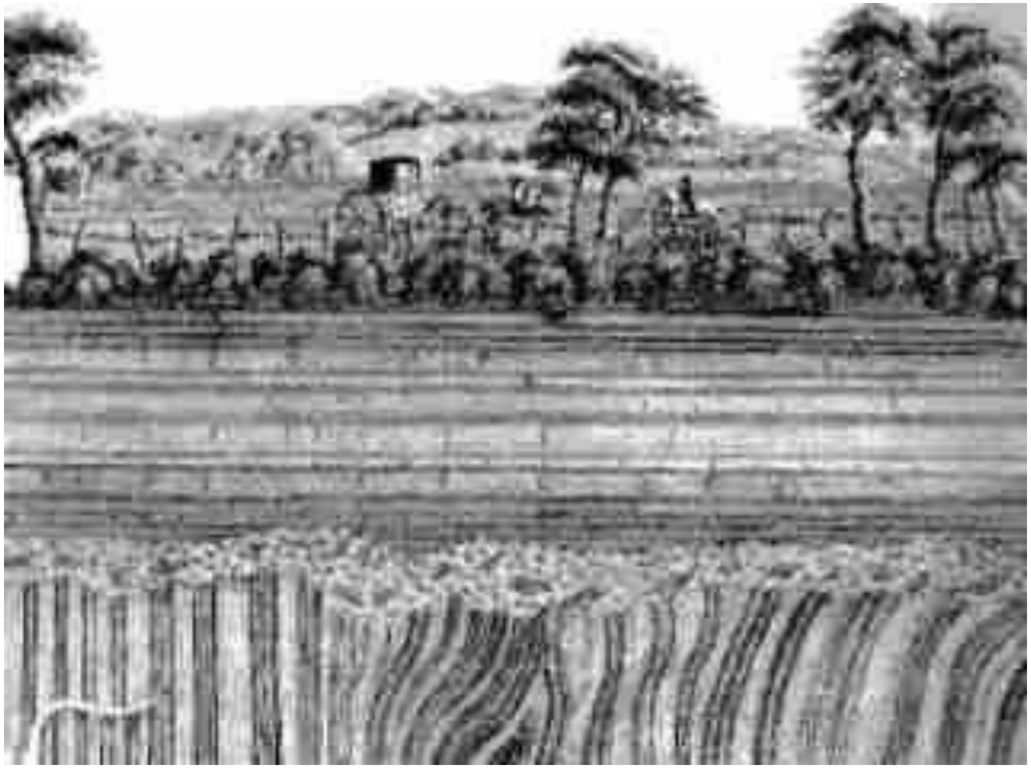
Walker, 1984. Facies Model



Cant and Walker, 1976

Actualism

Uniformitarianism (or Actualism) is the principle according to which the natural processes that have operated in past times are the same that can be observed in the present time. The principle was coined by two Scottish geologists, James Hutton and Charles Lyell, around 1800

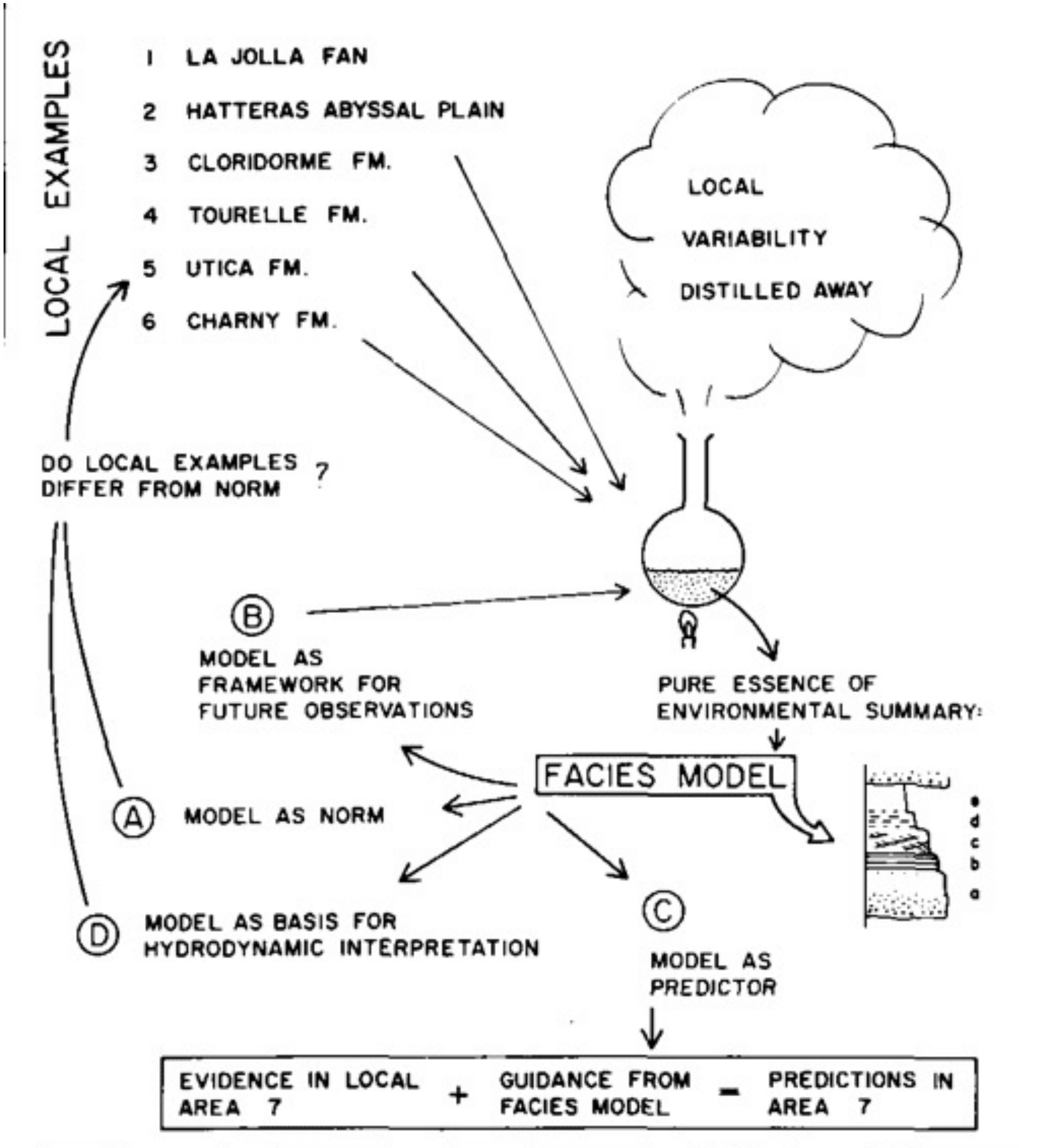


Walther argued that analogues to modern geological processes are the most satisfying explanations for the genesis of ancient phenomena. He thus regarded the actualism as the ontological method (since ontology is the branch of philosophy that studies concepts such as reality).

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).

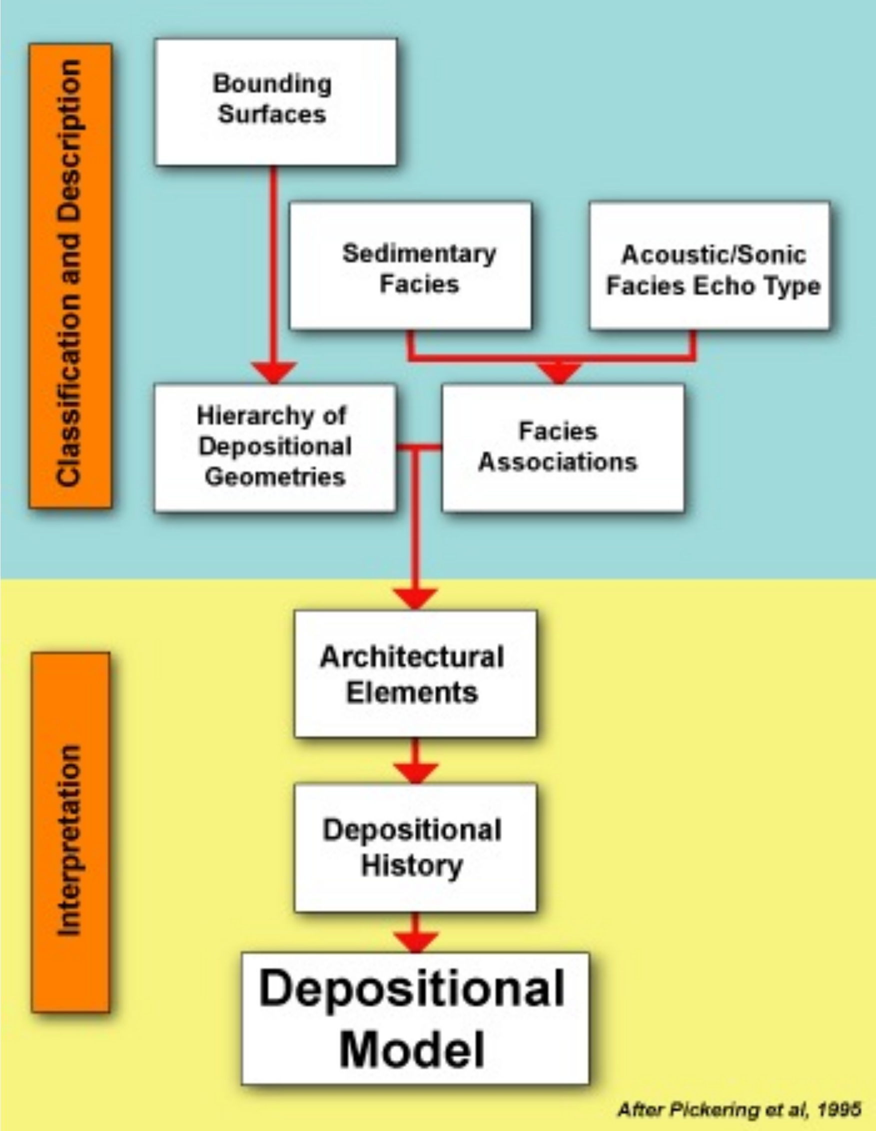
Walker, 1984. Facies Model



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.

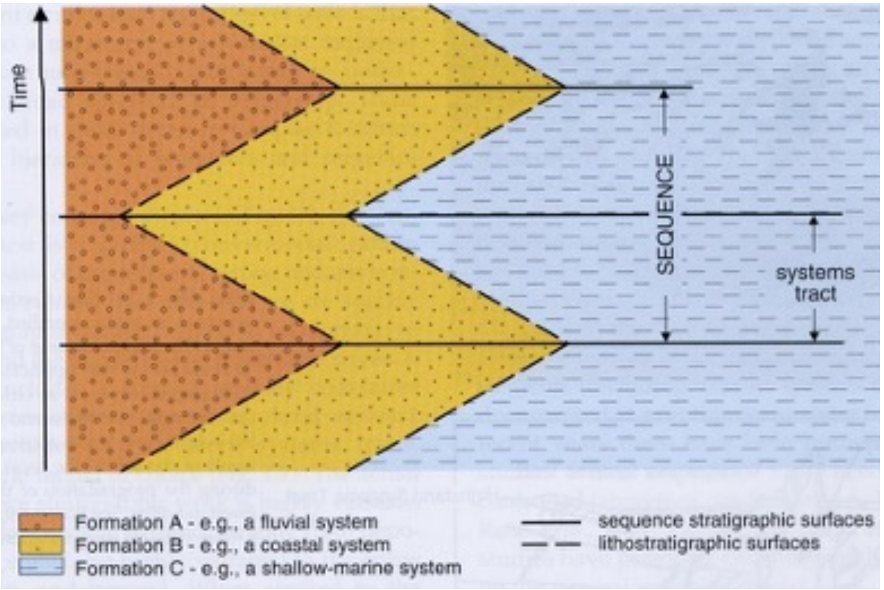


http://www.sepmstrata.org/Terminology.aspx?id=sedimentary%20architecture

Anna Del Ben, Corso di Interpretaione Sismica

Seismostratigraphy

The fundamental principle of Seismic Stratigraphy (or Seismostratigraphy) is that, within the resolution of the method, the seismic reflections follow the main stratifications approximating the time lines.

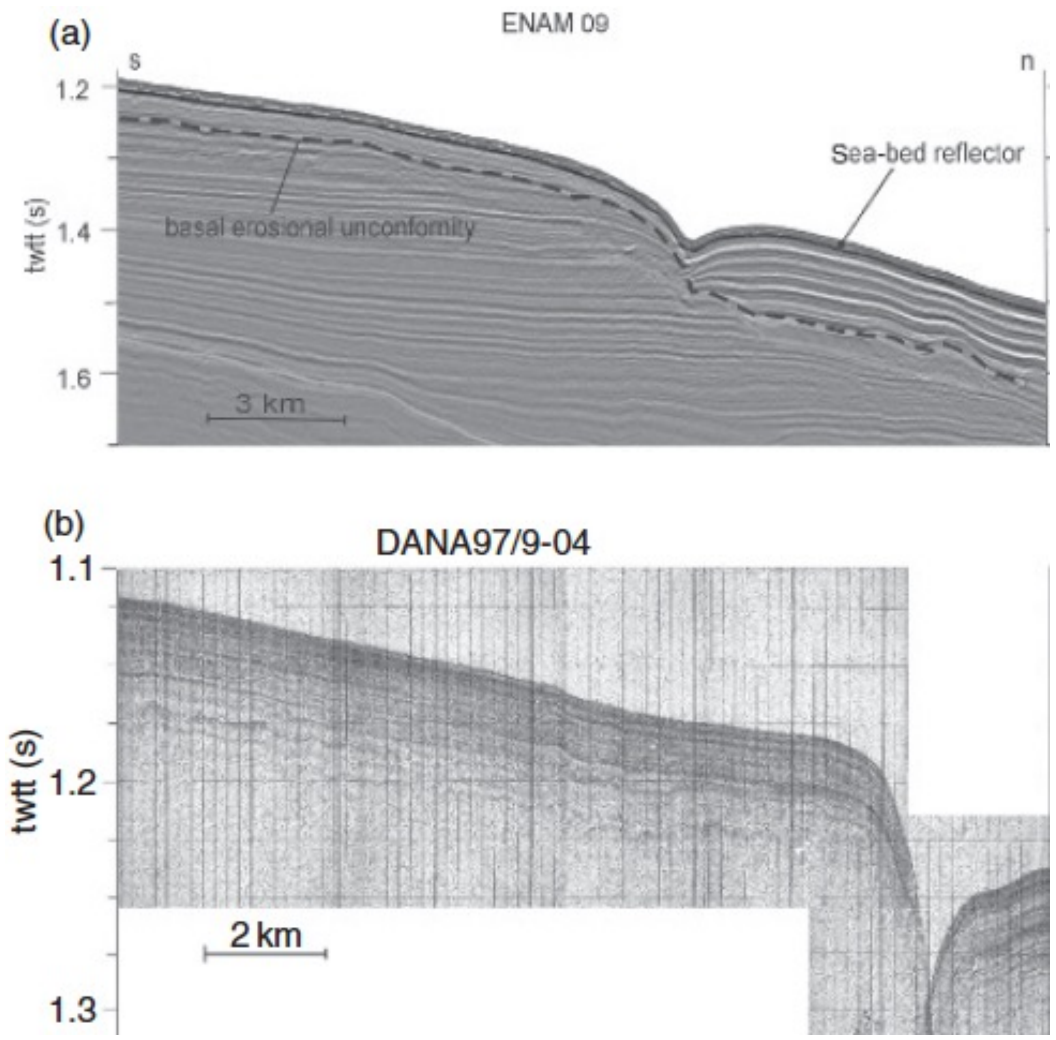


The impedance contrast represented on the seismic section is produced by the interfaces between the layers and not by the lateral facies variations.
At the scale of the seismic resolution, it can be assumed that the facies changes within time-equivalent layers in a gradual manner, without generating seismic reflections.
Thus, the reflections represent time surfaces in 3 dimensions, and separate older rocks from younger ones.
Some exceptions: contacts between different fluids, diagenetic variations, bottom simulating reflector, tuning phenomena, etc.
We can therefore say that seismic reflections provide information of chronostratigraphic type, while lithological information can be interpreted on the basis of the characteristics of the signal and of the geometries.

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.



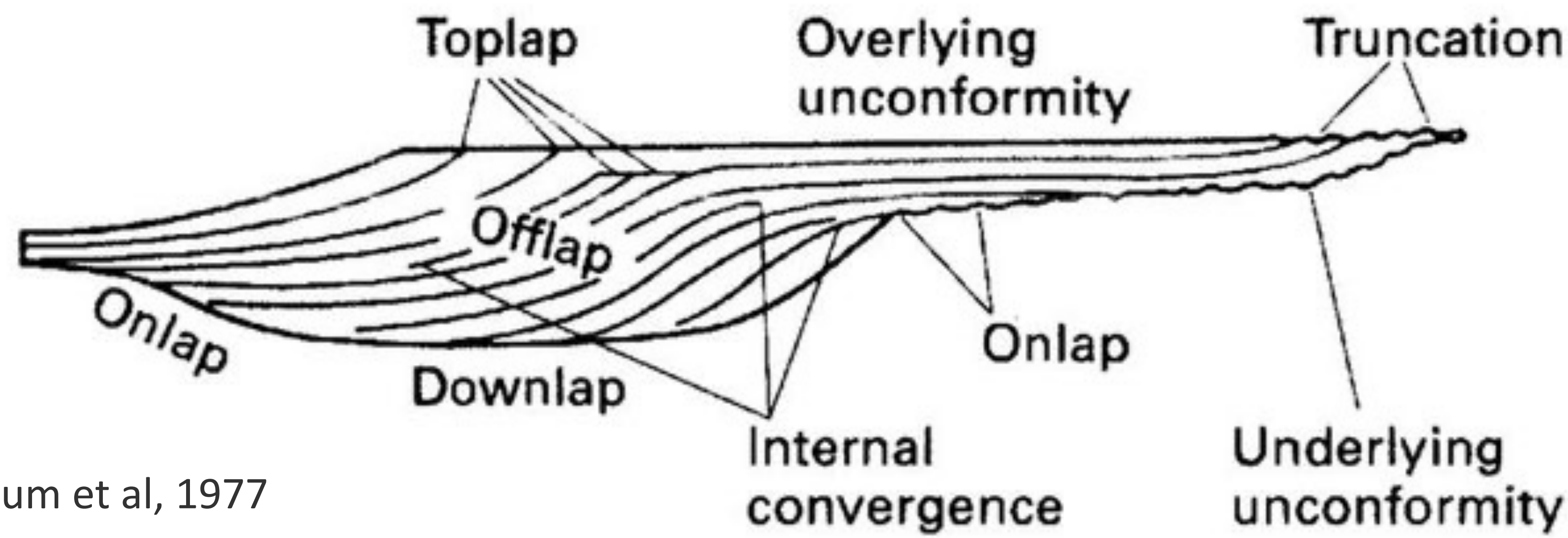
Nielsen, Knutz, Kuijpers, 2008. Seismic Expression of Contourite Depositional Systems. *Developments in Sedimentology*, 60, 301–321

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.

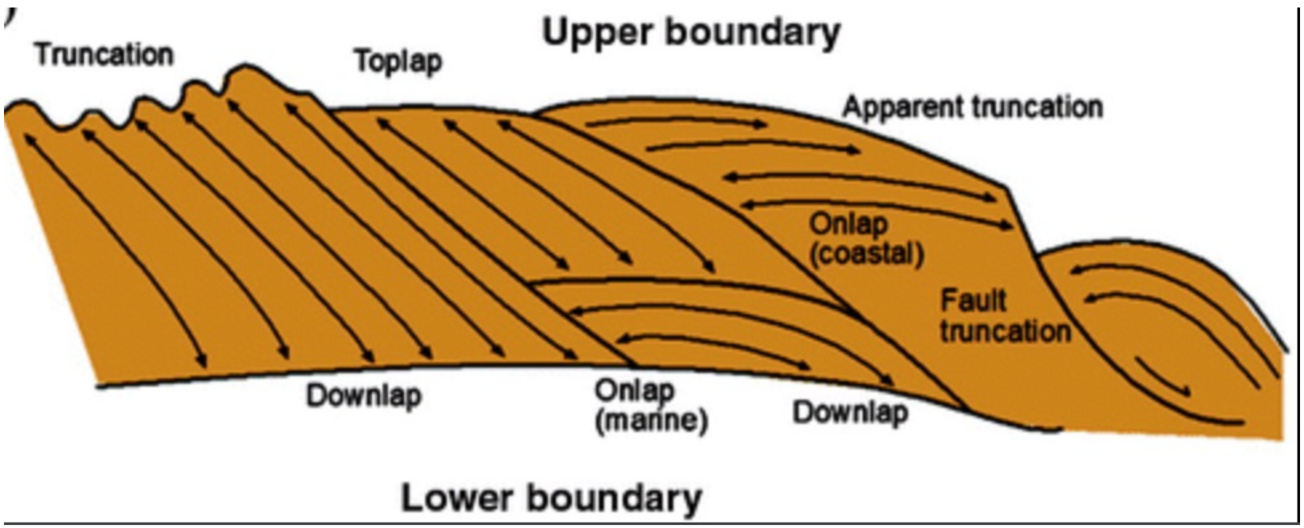
Their limits are often discontinuous due to either a depositional hiatus or an erosional unconformity and could represent anywhere from thousands to millions of years. The identification of seismic sequences is based on the geometry of the termination, at top and bottom, of a group of reflectors, and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



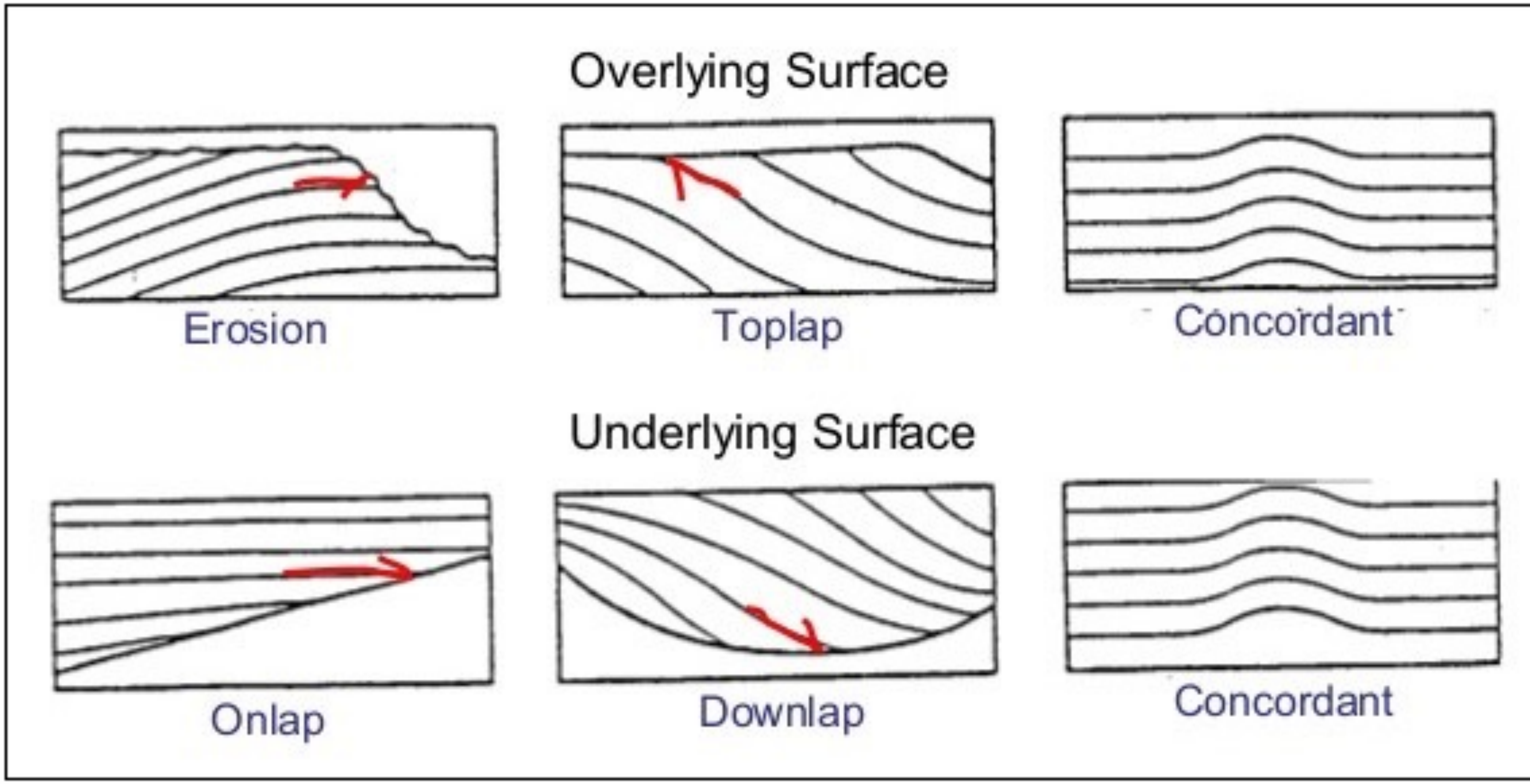
Mitchum et al, 1977

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.

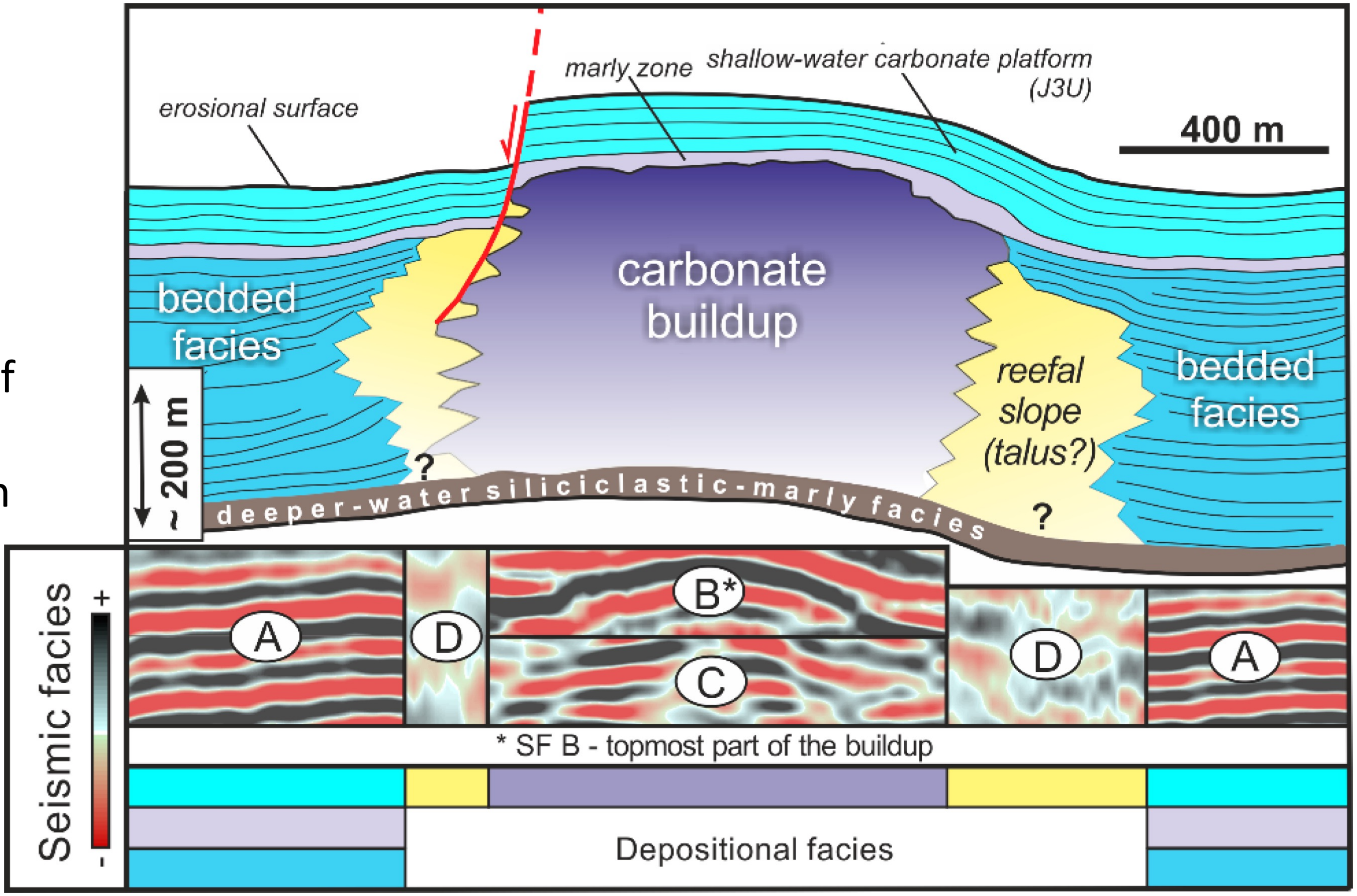
Since the concepts of ''seismic stratigraphy'' and ''seismic sequence stratigraphy'' were introduced in the 1970–1980s (Vail et al., 1977a; van Wagoner et al., 1988), a whole set of terms has developed for seismic interpretation that are now widely used. However, the conventional concept of seismic sequence 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.

Nielsen, Knutz, Kuijpers, 2008.

Seismic facies analysis

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

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).



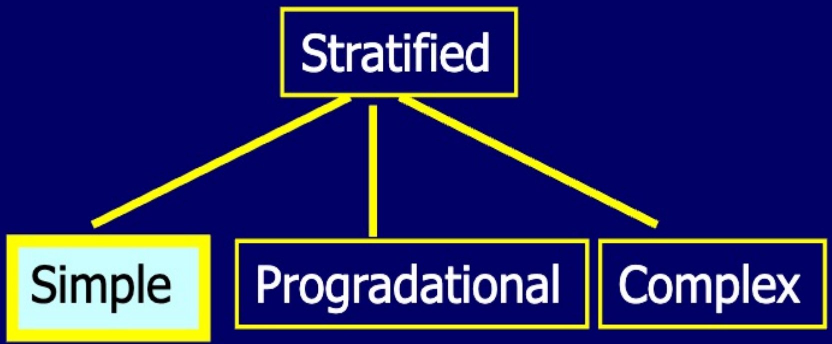
Seismic facies

Analysis 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.

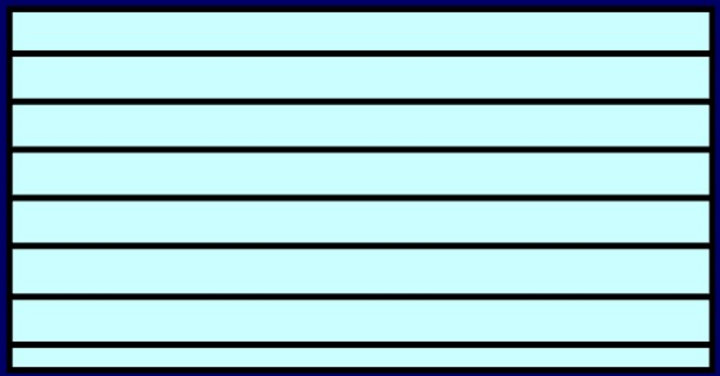
Basically there are two categories of seismic attributes: those that quantify the geometric aspects and those that quantify the reflectivity components of the seismic data. The geometric attributes reveal information on dip, azimuth and termination of a reflector or horizon, which can in turn be related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

Nielsen, Knutz, Kuijpers, 2008.

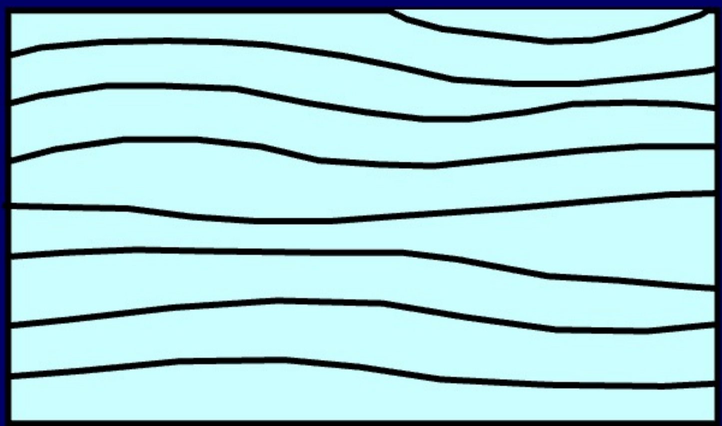
Simple Stratified Internal Configurations



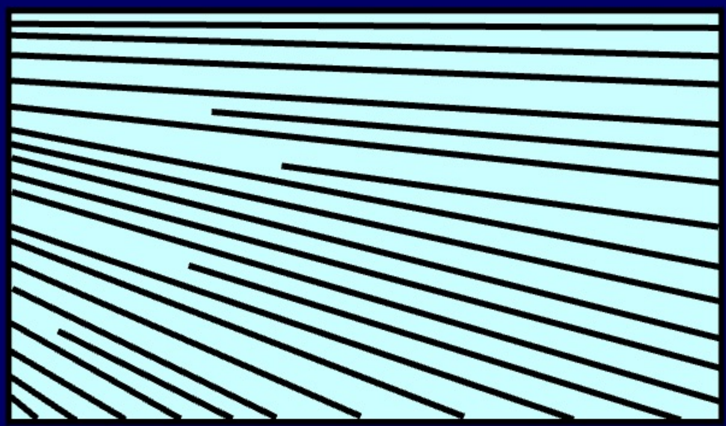
Parallel - Even



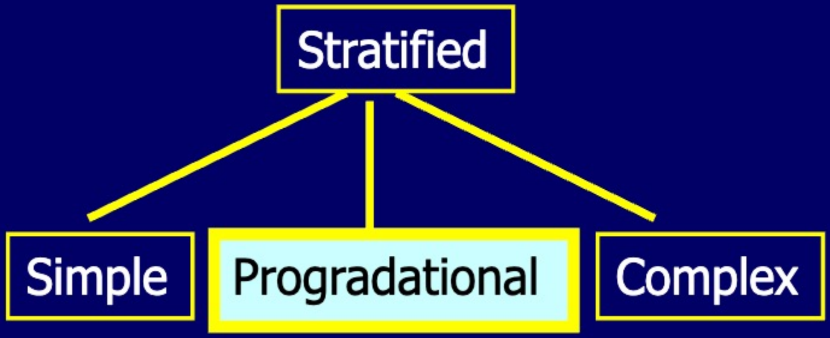
Subparallel

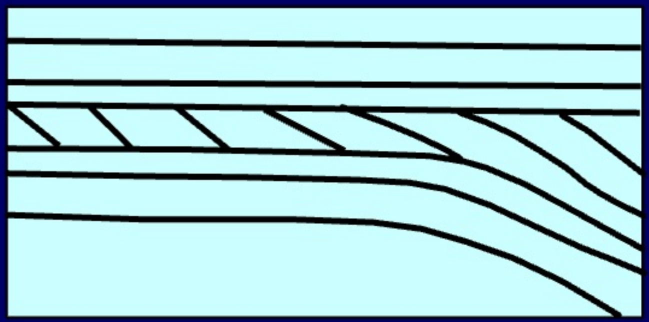


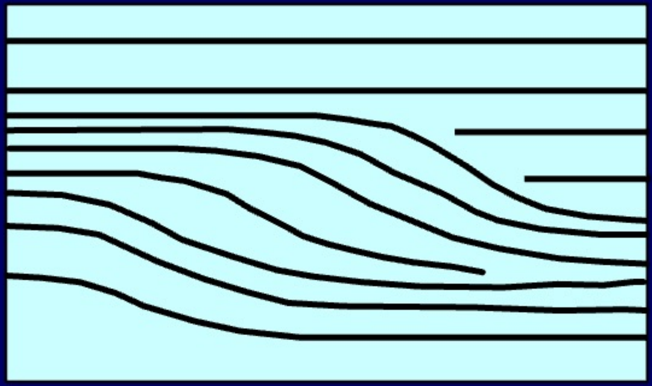
Divergent

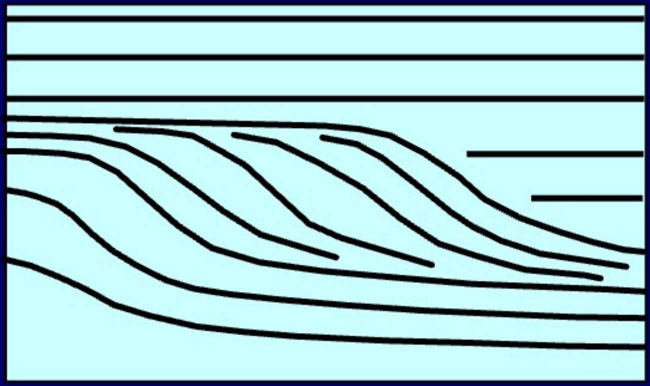


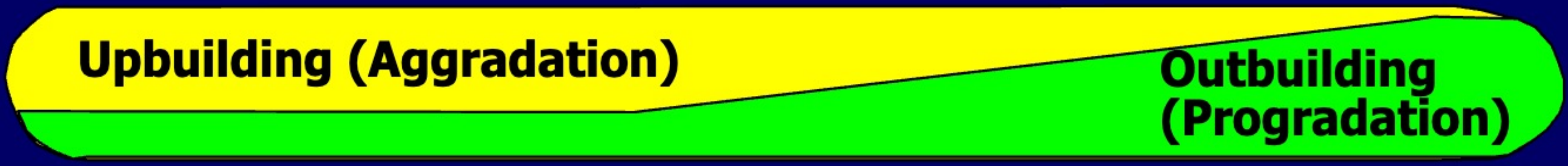
Progradational Internal Configurations











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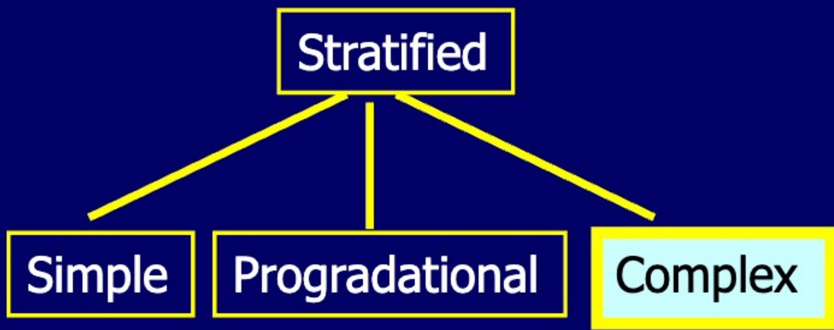
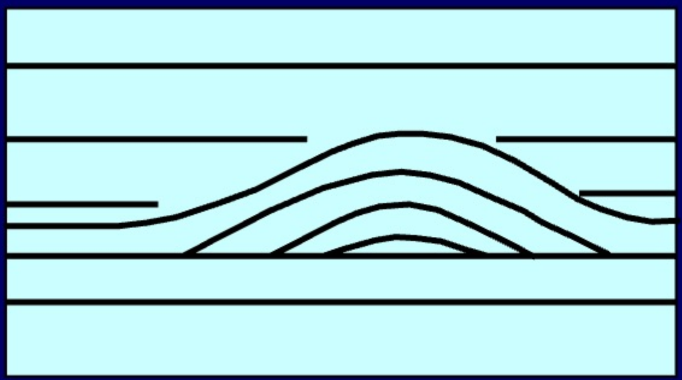
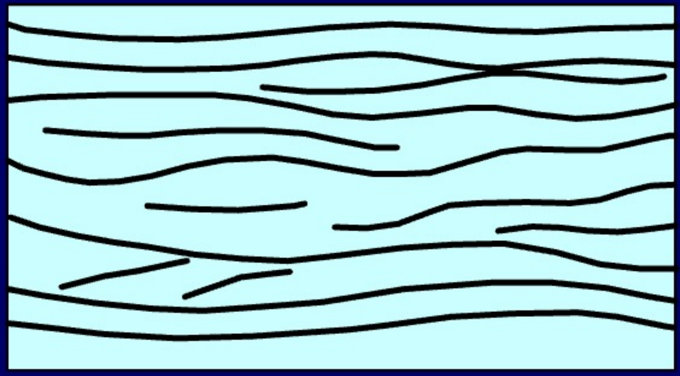
Complex Internal Configurations



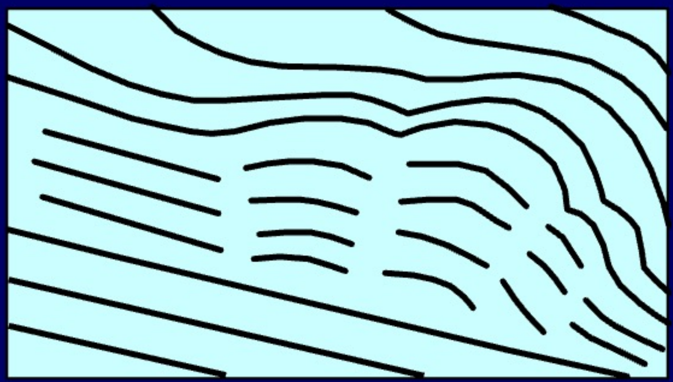
Mounded



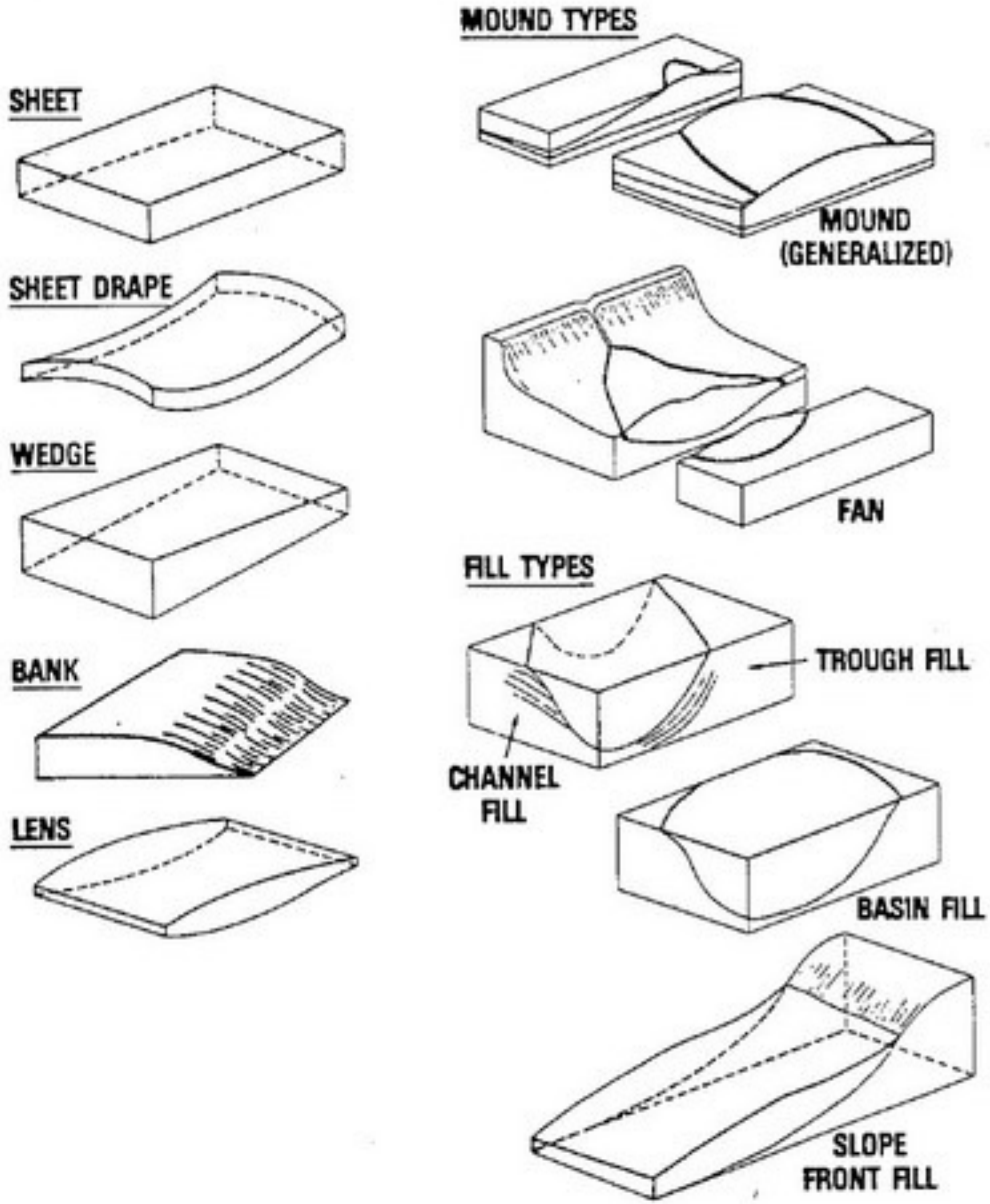
Hummocky



Deformed



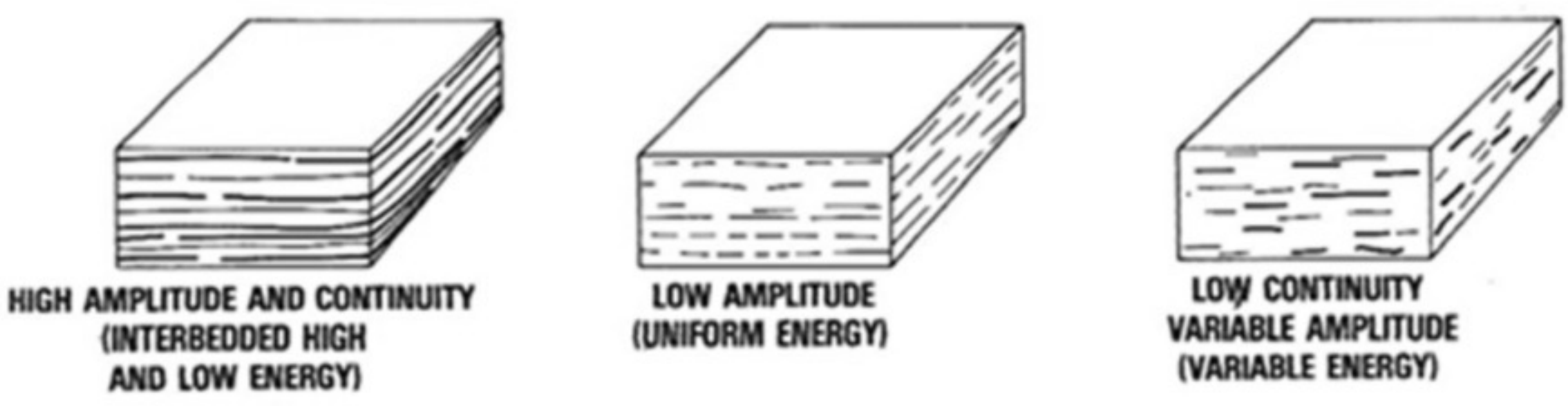
Manin types of external forms of seismic units



Seismic attributes (reflection parameters)

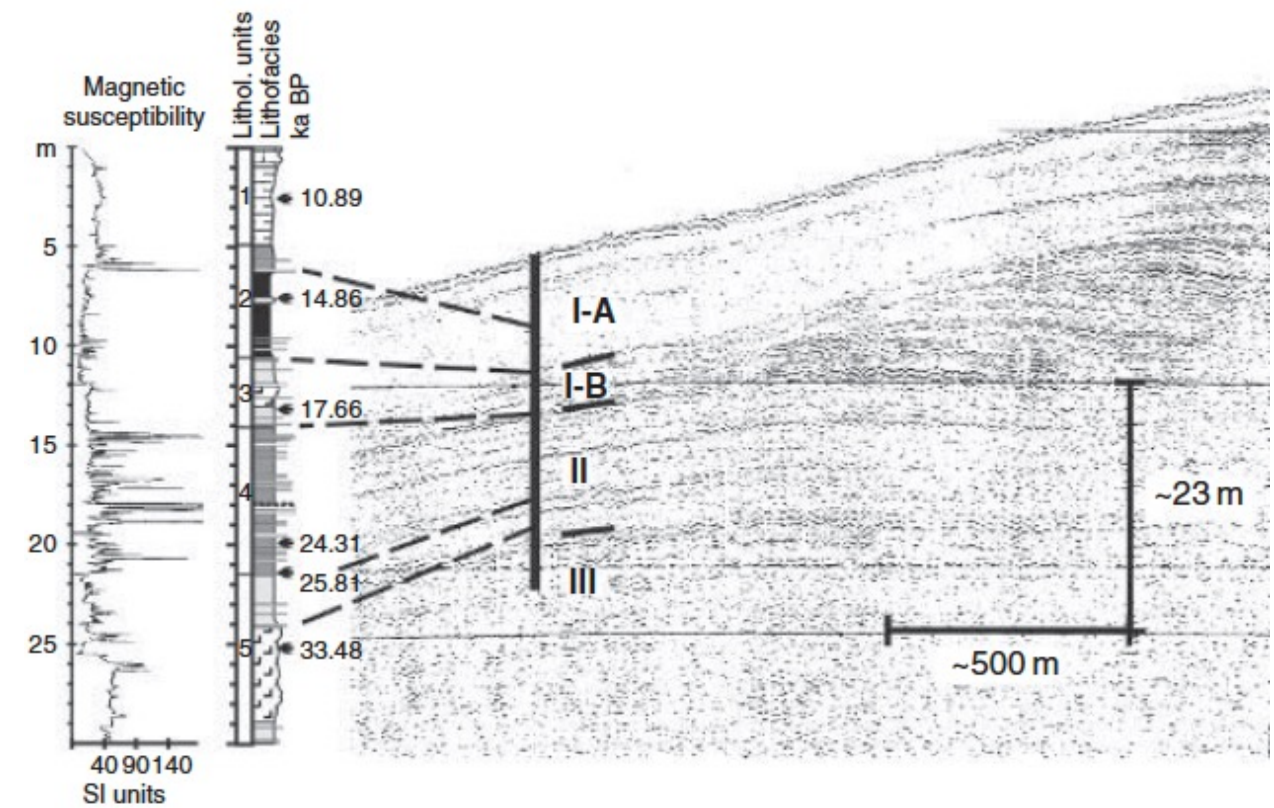
Amplitude
Lateral continuity
Frequency
Phase
Polarity

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



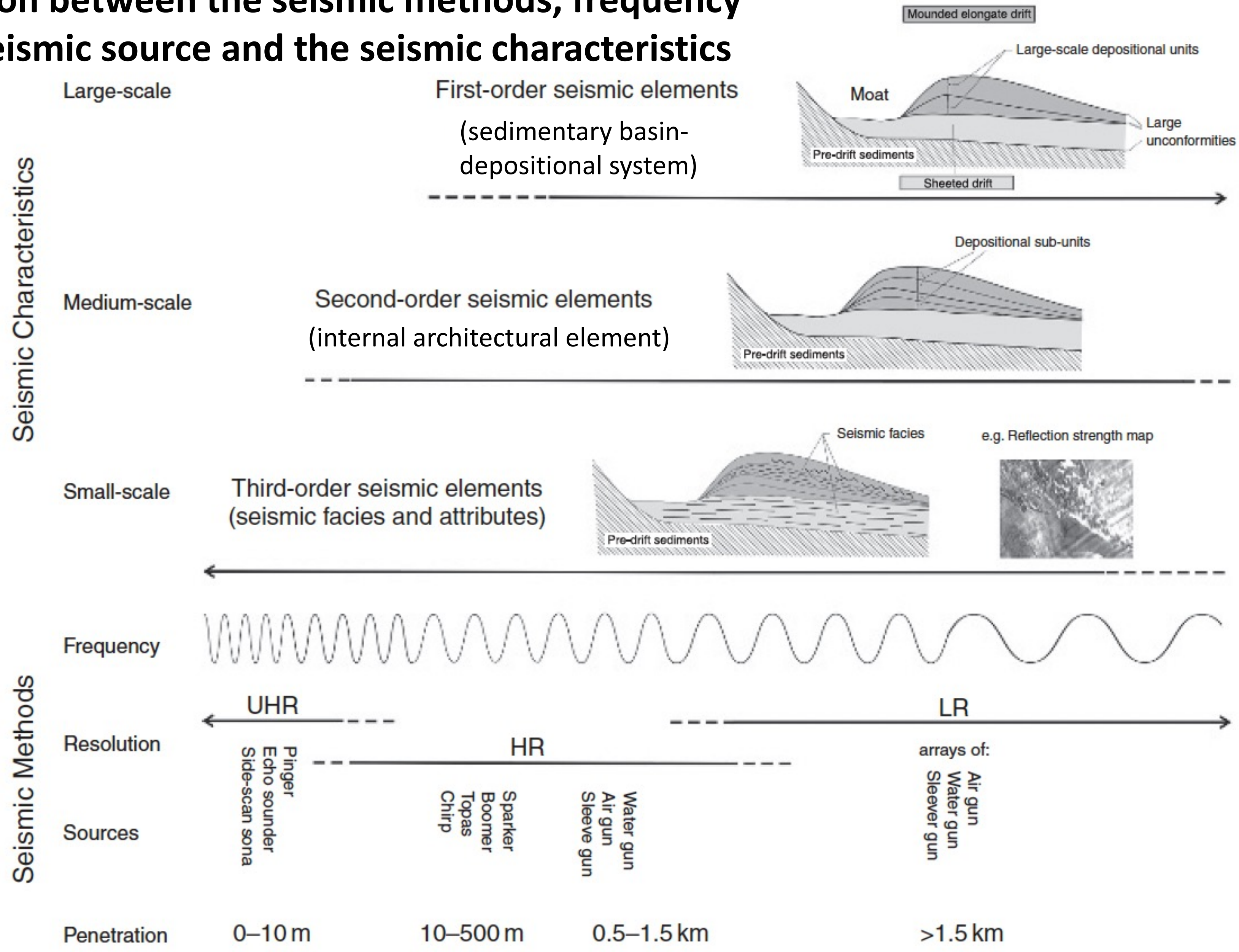
Seismic inversion: converting seismics into geology

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.



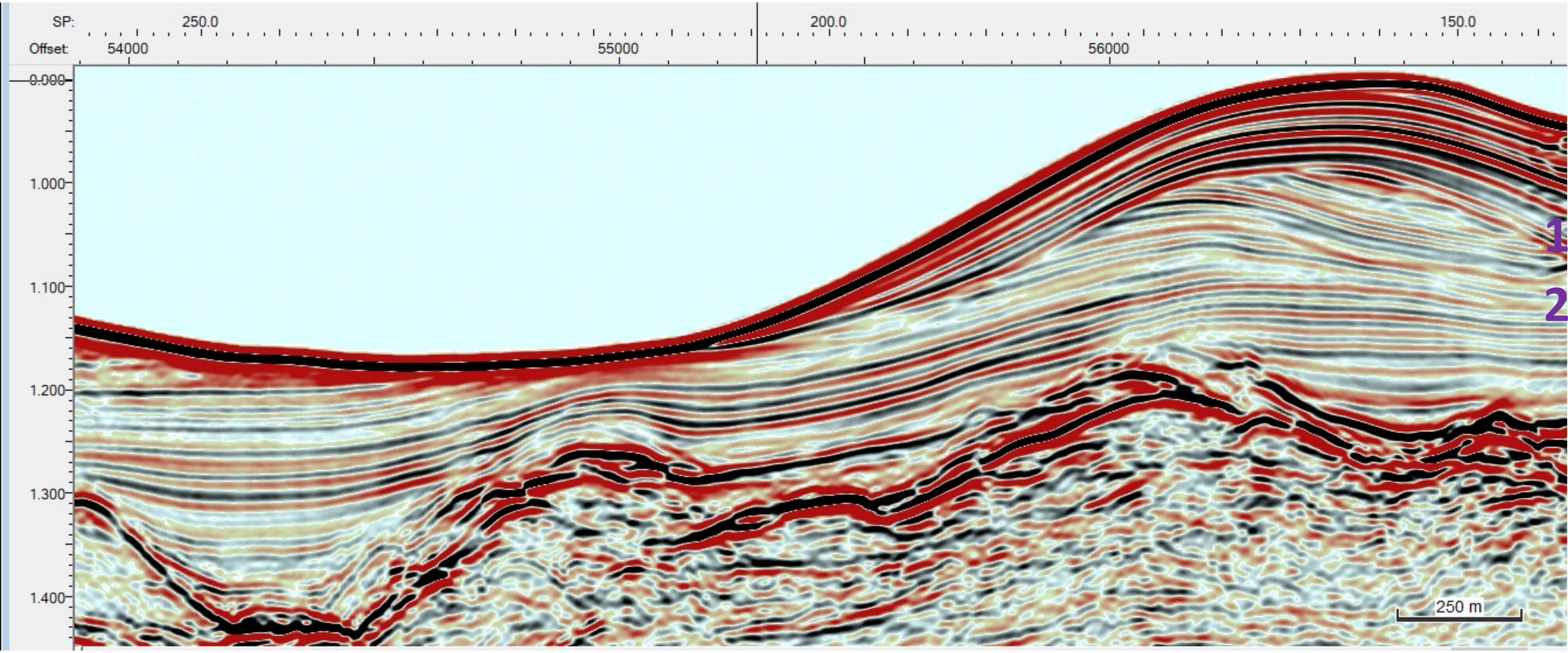
In seismic depth conversion, the twtt is converted to depth. This process requires estimation of the seismic velocity, which in fact is the most uncertain link between seismics and geology. Therefore, the use of core and borehole information in combination with seismics requires information on the seismic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

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



Excercise:

- Trace horizons 1, 2 and the basement
- Mark: onlap ➔ downlap ➔ erosion



Rob Butler, University of Aberdeen
YouTube "the Shear Zone"
Seismic interpretation
The geological interpretation of seismic reflection profiles

Interpreting a seismic reflection profile: Inner Moray Firth