Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

Curriculum: Esplorazione Geologica

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Analisi di Bacino e Stratigrafia Sequenziale (426SM)

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Modulo 3.1
Rivers, lakes and deserts

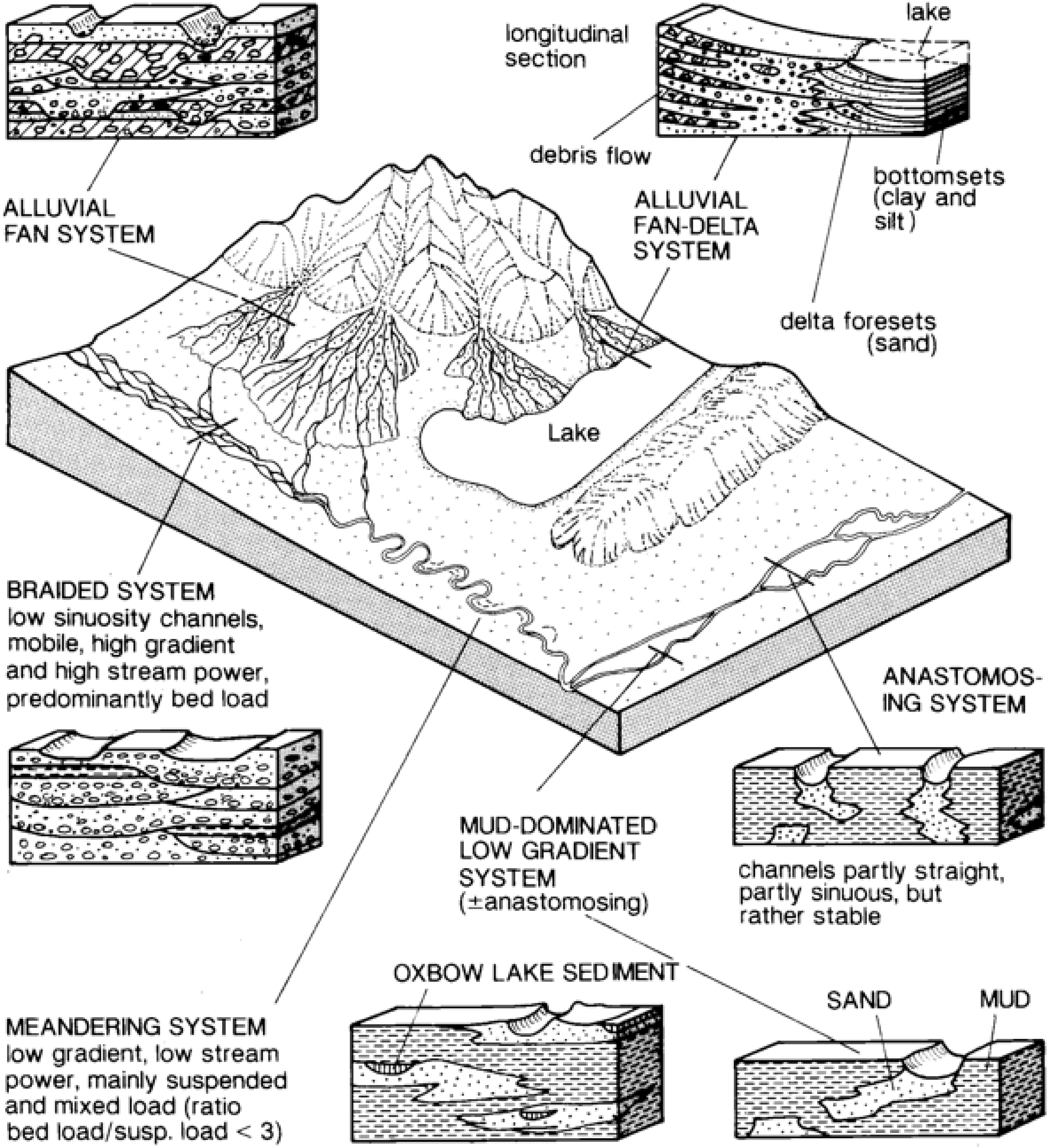
Outline:

- Introduction to alluvial deposits
- Alluvial fans
- Braided rivers
- Meandering rivers
- Channel belt sandstone packages
- Seismic examples

- Lacuatrine sediments
- Seismic example

- Aeolian sediments
- Seismic example

Principal types of fluvial systems and generalized characteristics of their cross sections (vertical scale exaggerated)



Several types of fluvial systems, although there are no sharp boundaries between these depositional environments

Einsele. Sedimentary Basins, 1992

Glossary

alluvial deposit = Material deposited by rivers

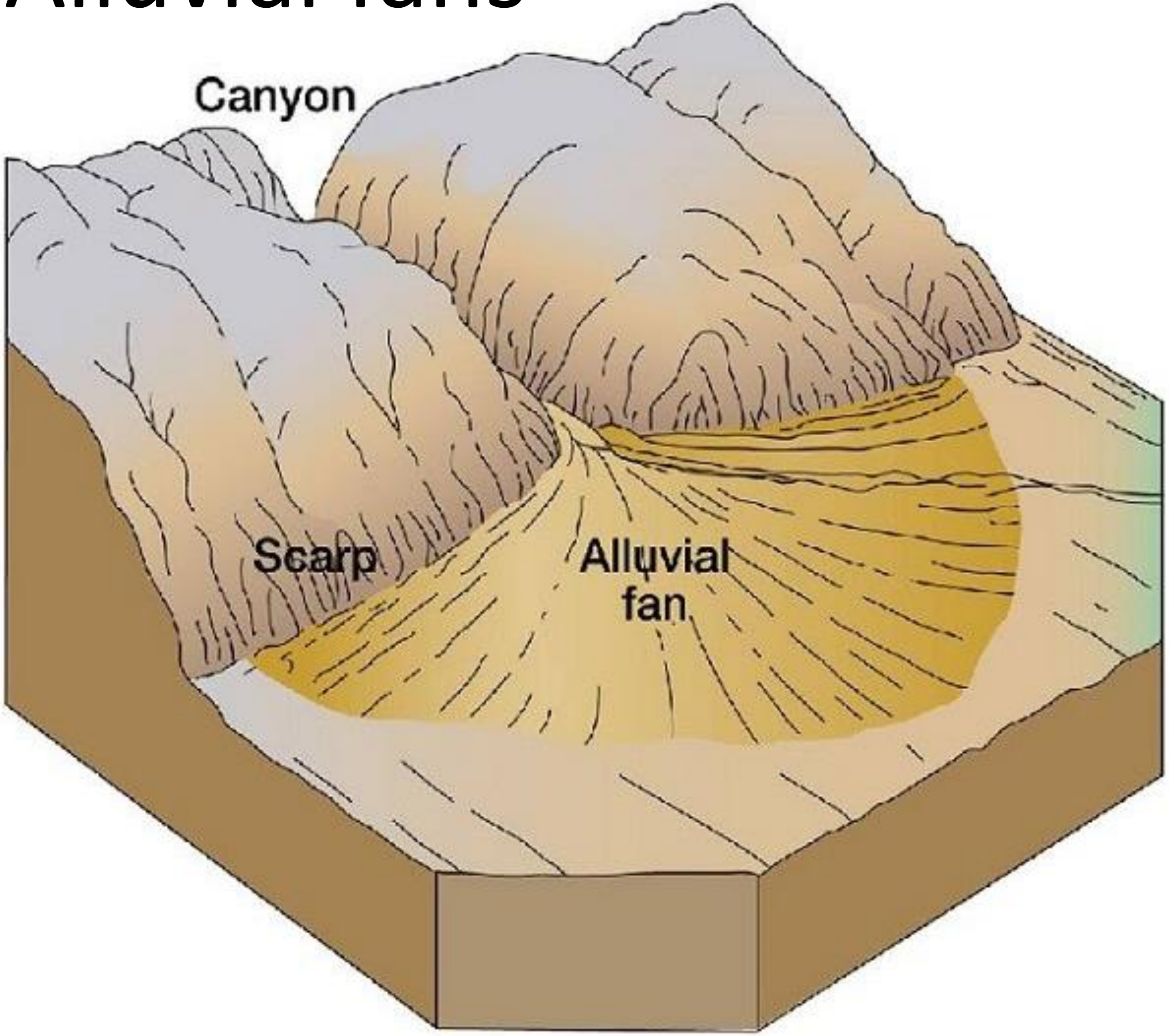
Alluvium= A general term for clay, silt, sand, gravel or similar unconsolidated detrital material, deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semi-sorted sediment

A point bar is a depositional feature made of alluvium that accumulates on the inside bend of streams and rivers.

A crevasse splay is a sedimentary fluvial deposit which forms when a stream breaks its natural or artificial levees and deposits sediment on a floodplain

Alluvial fans

A low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or a segment of a cone, deposited at the base of mountains where fast-flowing streams from a narrow mountain valley meet relatively-flat surfaces of basin floors or broad valleys. At this juncture, the gradients of streams abruptly decrease and gravel, sand, and other sediments are deposited.



Graded profile

Non-marine environments are poorly preserved because they sit above the base level (usually sea level) of streams flowing across them and often above their graded longitudinal profile, the level on Earth's surface above which sediments must eventually erode, and below which they are deposited.

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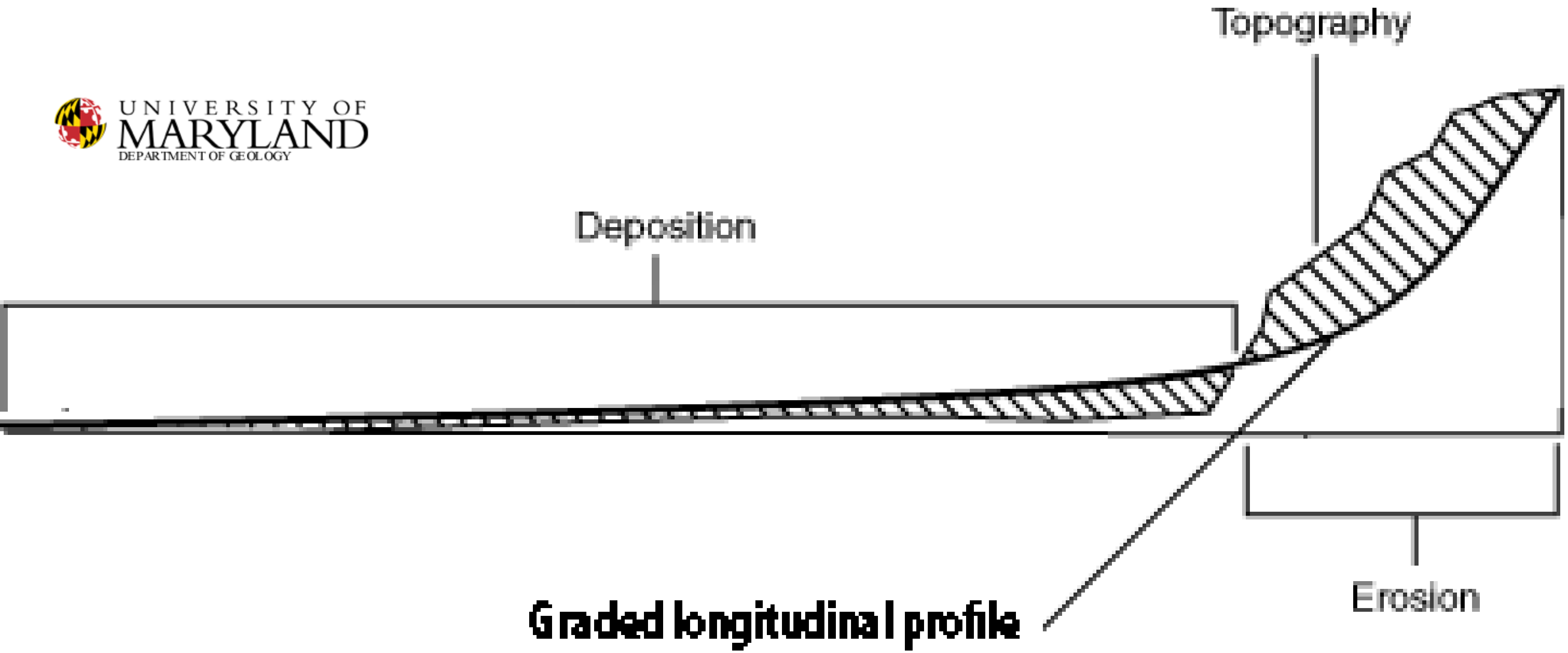

The alluvial fan is the most proximal (close to sediment source) and coarse grained of water-transported sedimentary environments. They typically form at the point where streams lose the competence to transport framework clasts. Consequently, the sediment alluvial fans contain is recently derived from local sources. Alluvial fans are generally restricted in area, typically being no more than 1-10 km from their sediment's source rock.

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Alluviual fans are the products of two main depositional processes:

Debris flows: channelized slurry flows consisting of sediment-water mixtures incorporating fine material (sand, silt and clay), coarse material (gravel and boulders) and a variable quantity of water.

Sheet-flow: Shallow water that is not confined to a stream bed, moving across a shallow incline.

Debris flow deposits

A debris flow deposit occurs when the masse of all sizes of sediment (ranging from boulders to clay) saturated with water is rapidly deposited on the proximal (upper) to middle fan as paraconglomerates with little to no stratification.

They form bodies that are:
lobate in map view (above)
tabular and of uniform thickness in cross section (left).
Debris flows deposits occasionally preserve reverse grading (coarsening upward), especially near their bases.

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Sheet flows

Shallow water that is not confined to a stream bed, moving across a shallow incline.

Recall that in arid environments, rain tends to come as large intermittent cloudbursts. Thus, although braided stream channels may cross the fan surface, these are usually dry. When flow occurs during flash floods, it soon overtops the channels and floods the fan surface as sheet flow. Sheet flow deposits (right) are usual stratified and well sorted with sand ripples and cross beds, and basal conglomerates

Secondary processes include:

Mudflow: Dominated by matrix particles saturated with water that move en masse and rapidly deposited.

Stream flow: Across the surface, usually as braided streams.

Flow regime

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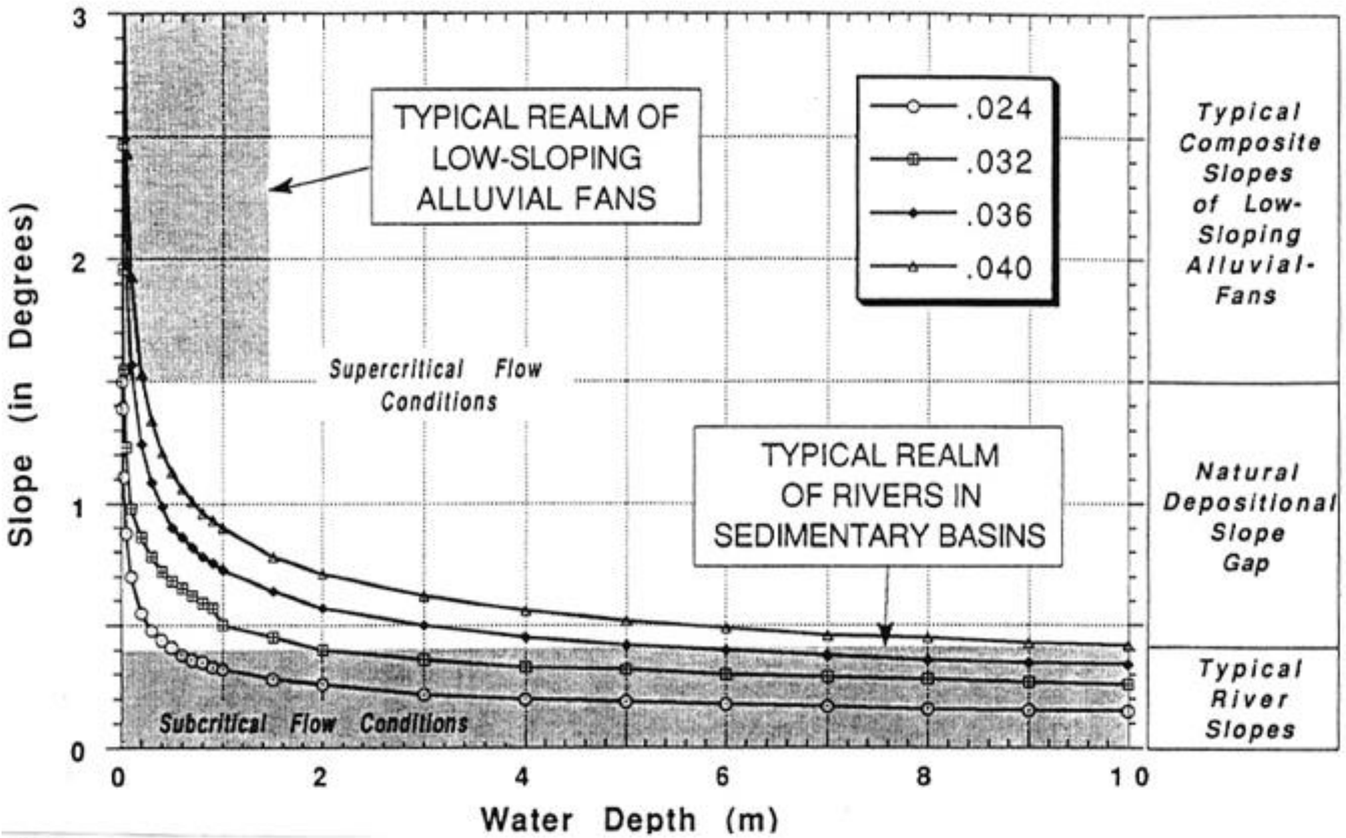
Slope angle increases with sediment size. Thus, the slope magnitude depends on the fan's source material (with coarser clasts yielding steeper slopes) and tectonic setting.

Due to this steep slope, alluvial fans are always upper flow regime (i.e. turbulent - Re > 2000) and commonly supercritical (i.e. rapid - Fr > 1). In contrast, river (fluvial) environments have gradients of 0.5 - 0.01 degree.

In the modern world, alluvial fans are bodies of very course grained sediment. They have steep upper surfaces, ranging from 16 -1.5 degrees, with the slope decreasing towards the basin.



Sieve deposits

Sediment laden water flowing down the steep gradient of the fan surface doesn't deposit fine sediment.
Indeed, this tends to wash through the pore space between large clasts. Instead only other large clasts are captured in orthoconglomerates termed sieve deposits.

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Braided stream deposits

The upper surface of an alluvial fan is dominated by braided streams, which typically have wide and shallow anastomosing channels that form in the upper reaches of streams where slope is greater and where flowing water is often choked with more sediment than the fluid can carry. During the highpoint in a flood water escapes the main channel and creates a sheet flood of well-sorted sand or fine gravel with little or no silt or clay (midfan sheets are typically well-sorted, well stratified, and cross-bedded). During low flow or the waning stages of flash floods when water is confined to stream channels, braided stream deposits are laid down.

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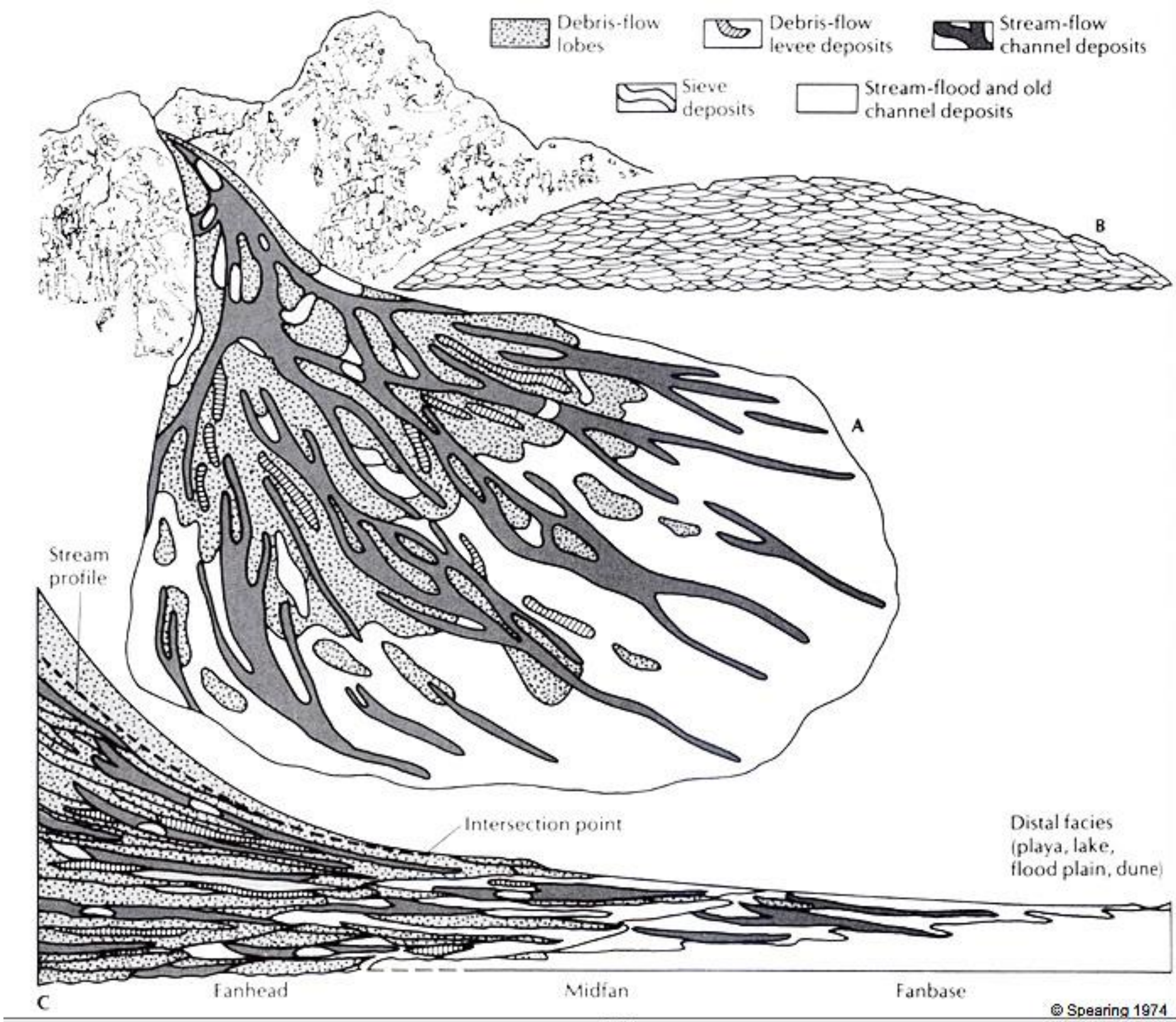
distribution of the four fan deposits

the fan tends to aggrade upward, becoming steeper as it does so and prograde outward into the basin.
As a result, at any given locality, there is a general coarsening upward trend.



© Spearing 1974

The sequence of coarsening upward cross-bedded sandstones, conglomerates, and unsorted debris flow deposits occurs due to progradation of the fan out into the distal valley.
Fan deposits are generally limited in lateral extent, but their thickness can be considerable (up to 1000s of m in some basins if subsidence is persistent).
Sediments can be very immature and angular with abundant coarse rock fragments and feldspars.
Sheet flood deposits are typically oxidized, so redbeds are common.
Fossils are not generally preserved in the coarse-grained facies of an alluvial fan.
Regardless of grain size, current flow is indicated through sedimentary structures and/or imbrication, with sand being the smallest clast size.

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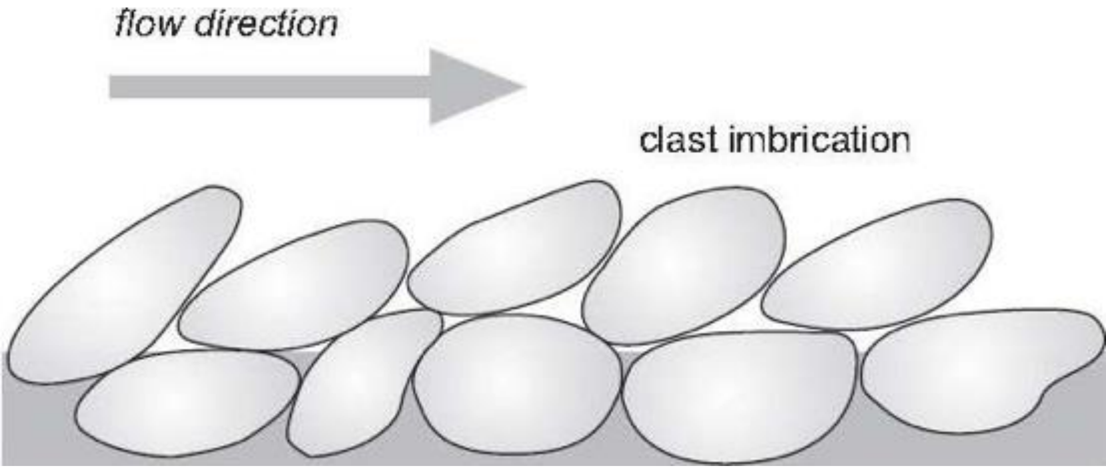
Imbrication

In sedimentology, imbrication is a primary depositional fabric consisting of a preferred orientation (**in the direction of flow**) of clasts such that they overlap one another in a consistent fashion, rather like a run of toppled dominoes. Imbricated sediments are deposited in relatively high energy, unidirectional flow. Imbrication along the long-axes observed in conglomerates is formed through deposition of clasts carried in suspension in a rapidly waning flow (for example flash floods)



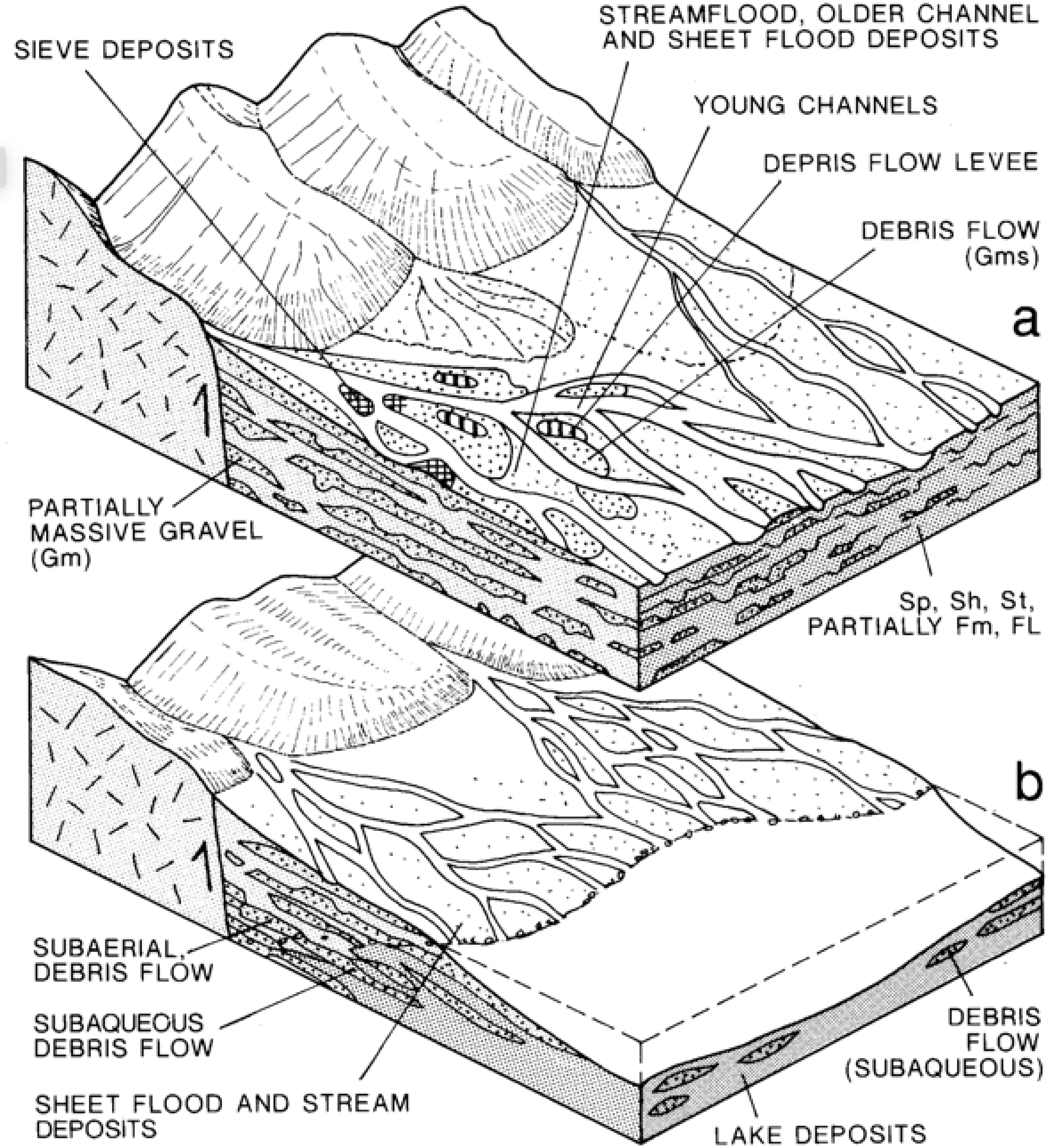
Do not confuse alluvial fan deposits with:

Laminated conglomeratic mudrock: These have a bimodal distribution of gravel and larger clasts interspersed in laminated mudrocks - typically as dropstones are deposited in fine deep marine or lacustrine sediment. They typically don't record indications of current flow (stream, debris flow).

Tillite: Unsorted sediments of all sizes with no indication of current flow.

Stream deposits: Although basal channel conglomerates and current flow sed structures may be present, conglomerates are a minor portion of the sediment volume and deposits show a fining upward pattern.

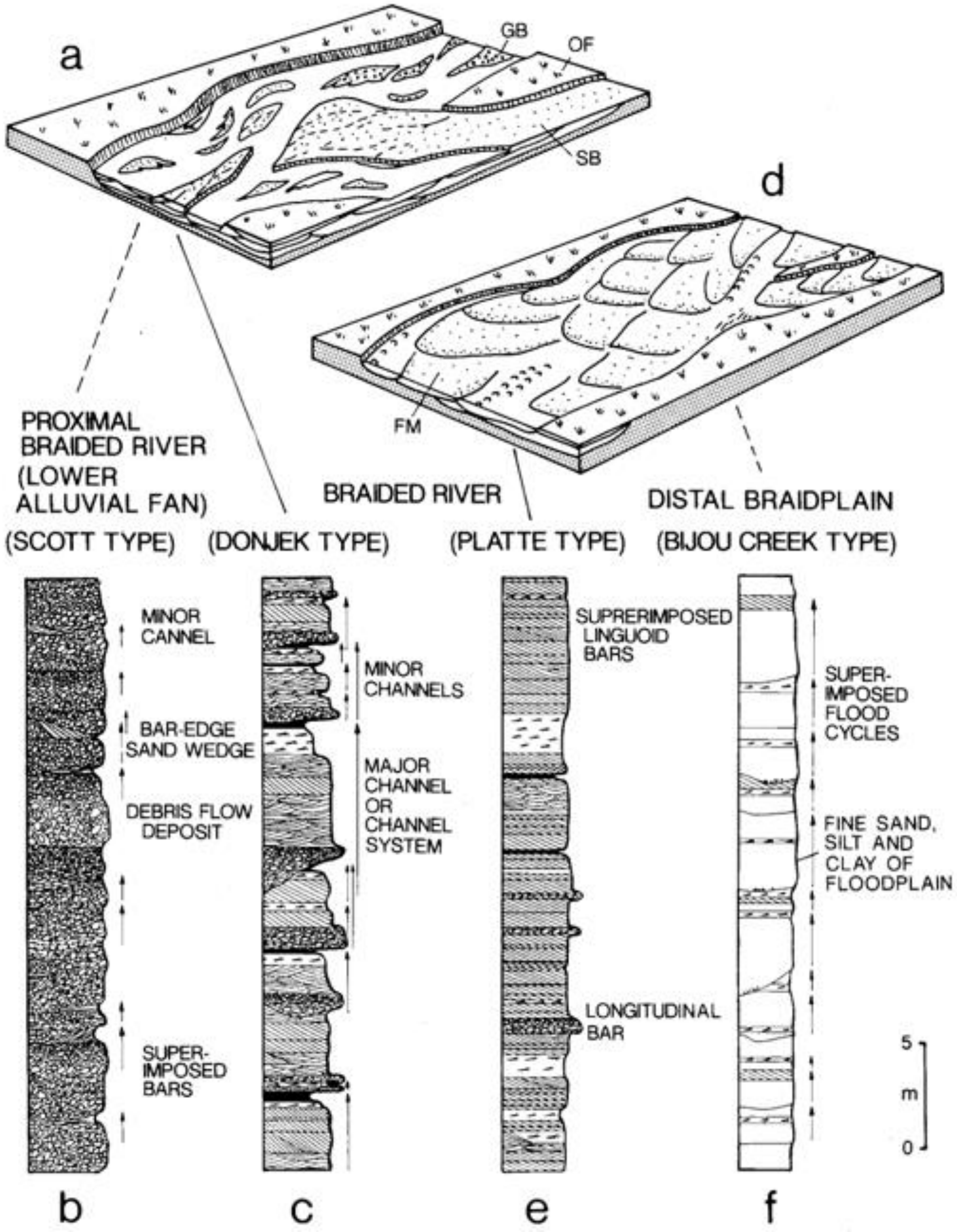
Simplified facies model of (a) alluvial fan (proximal to mid fan region) and (b) fan delta



Einsele. Sedimentary Basins, 1992

Braided river systems

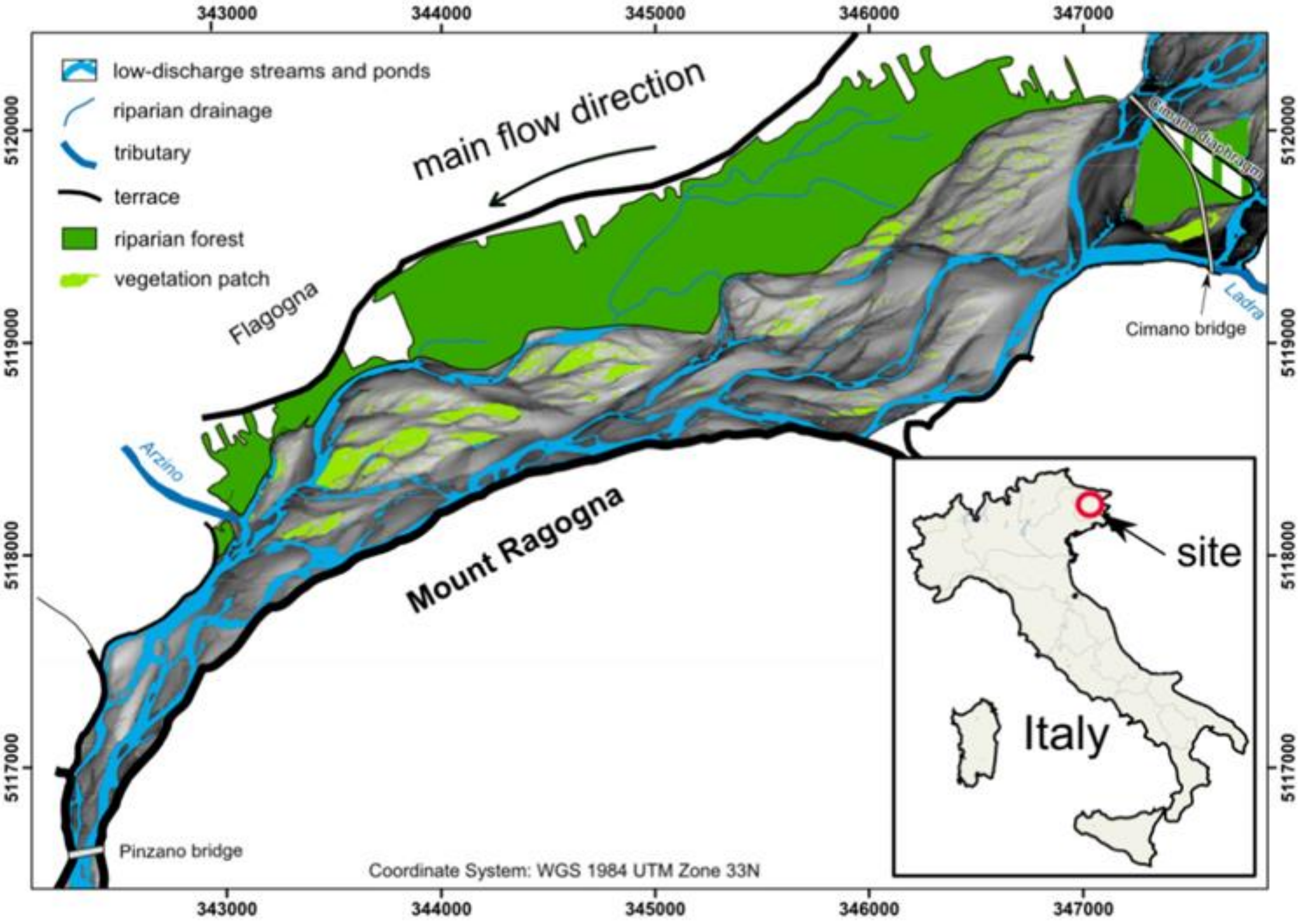
(a-c) Proximal to middle reaches, gravel-dominated (b), or sand-dominated (c) with minor proportion of gravel. (d-f) Distal, sand-dominated system with wide channels and flat, linguoid sand bars (d and e), or wide floodplain rarely inundated by flash floods (f)

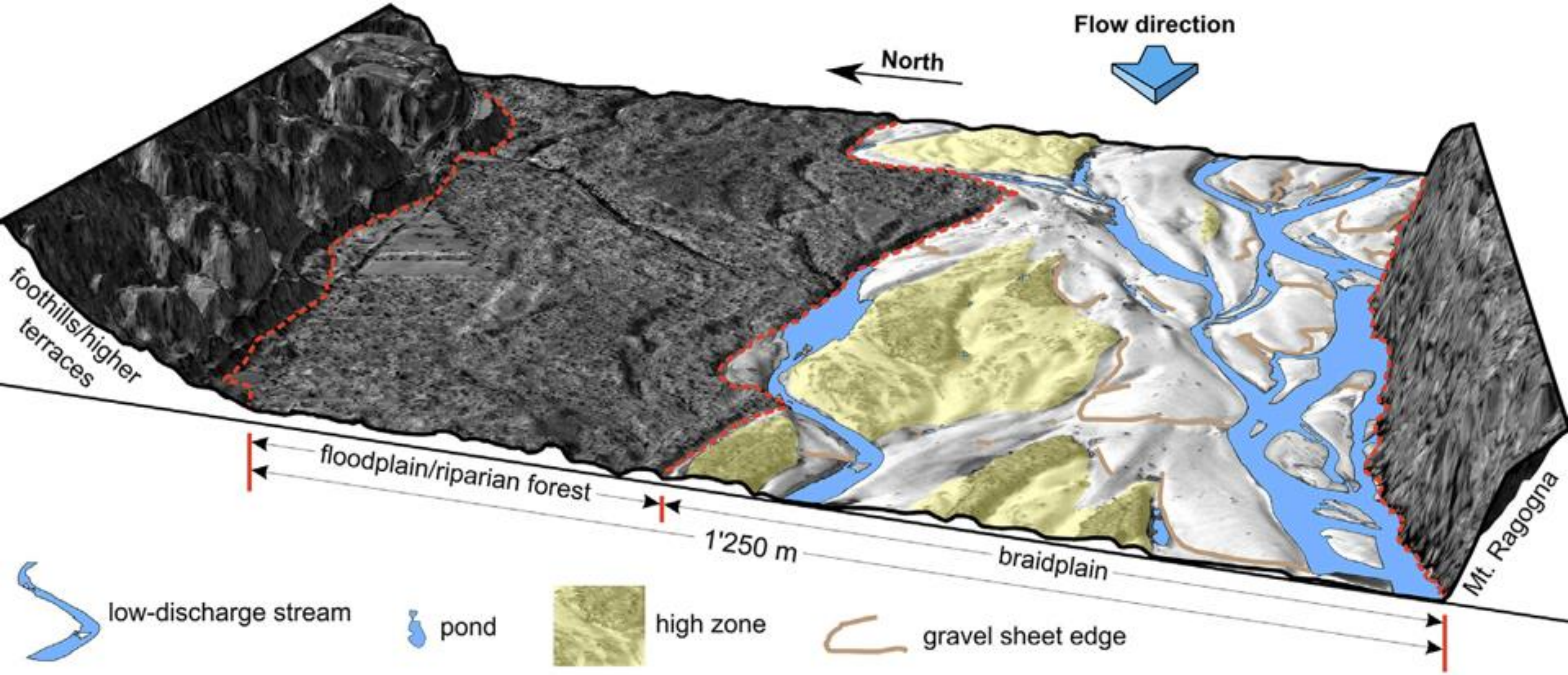


Einsele. Sedimentary Basins, 1992

Tagliamento River

Huber & Huggenberger (2015), Morphological perspective on the sedimentary characteristics of a coarse, braided reach. Geomorphology 248, 111–124



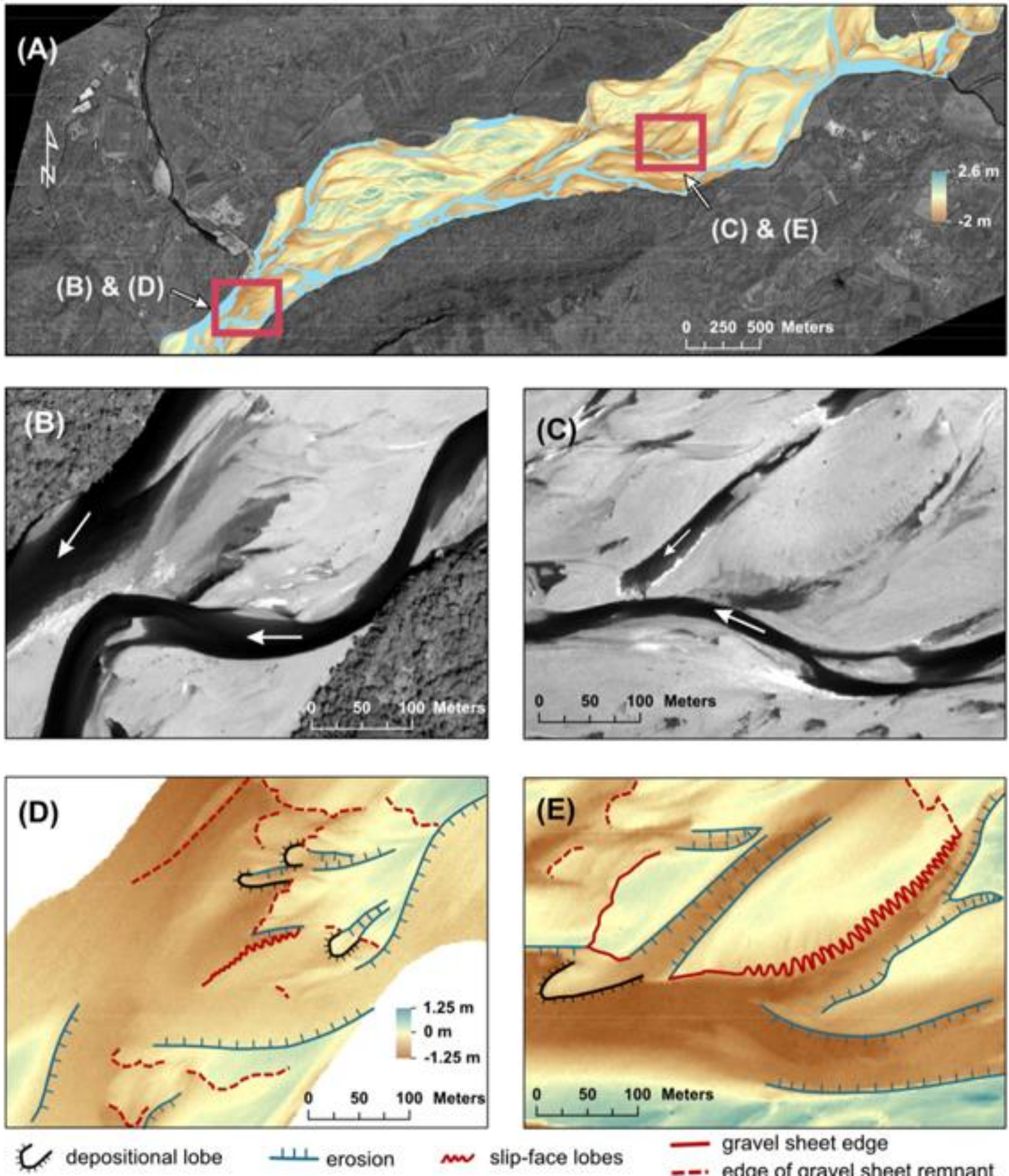


The braided river plain (or braidplain) is defined as the area that has been subjected to recent morphological changes by the river

Huber & Huggenberger (2015),

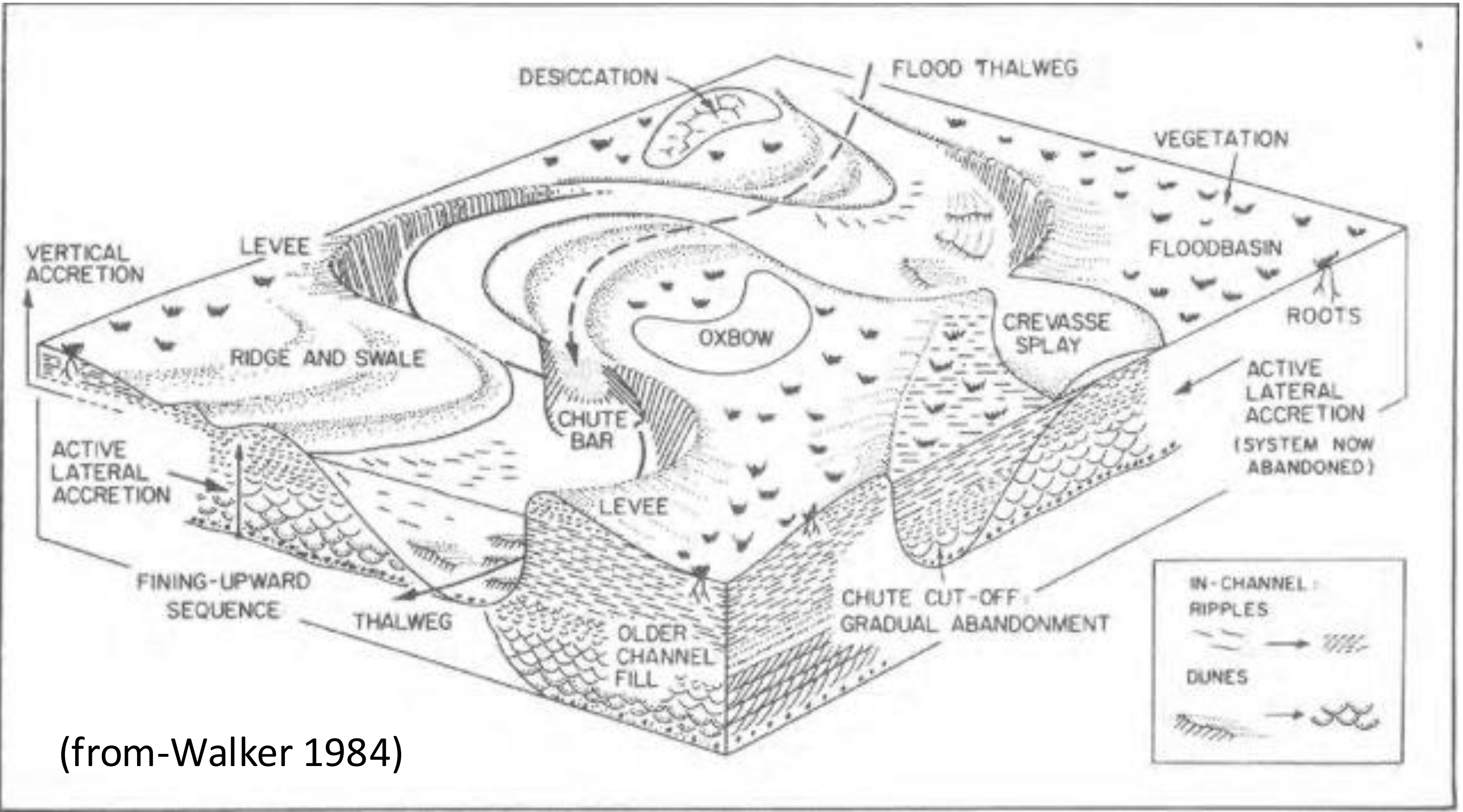
Two examples of gravel sheet reworking andoverlapping.(A) Position of the two locations in the. (B) and (C) panchromatic photographs. (D) and (E) LiDAR-derived DEM with superposed interpretations.

Interpretation: B) and D) = a complex overlapping of remnants of gravel sheets; C) and E) = well preserved gravel sheet dissected in its middle by a low-discharge incision.



Block diagram showing morphological elements of a meandering river system

Erosion on the outside bend of a meander loop leads to lateral accretion on the opposite point bar.



(from-Walker 1984)

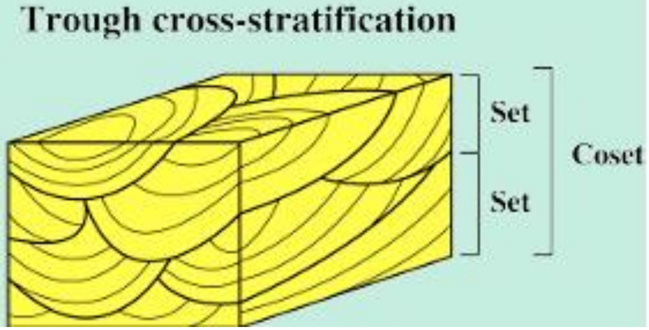
The dunes and ripples in the channel give rise to trough cross bedding and ripple cross lamination respectively (inset, lower right), which are preserved in a fining-upward sequence.

What is the most disgnostic sedimentary feature of (meandering) rivers?

What kind of stratification?

Trough cross-stratificaton:

Bounding surfaces are curved or trough shaped.



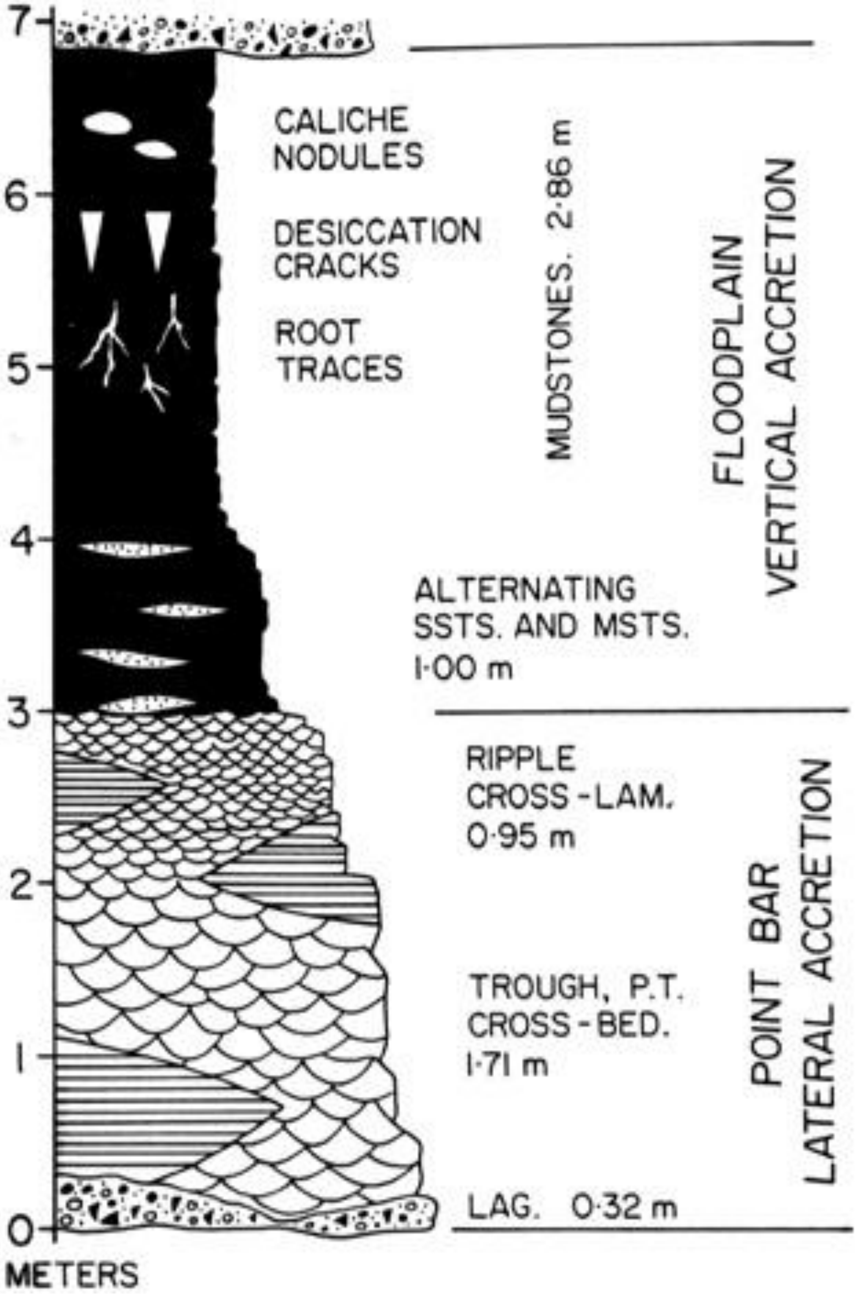
During average discharge, the typical bedform on the channel floor consists of sinuous-crested dunes ranging in height from about 30 cm to one metre. Preservation of these dunes results in trough cross-stratification

Cross-Bedding, Bedforms, and Paleocurrents
by David M. Rubin and Carissa L. Carter

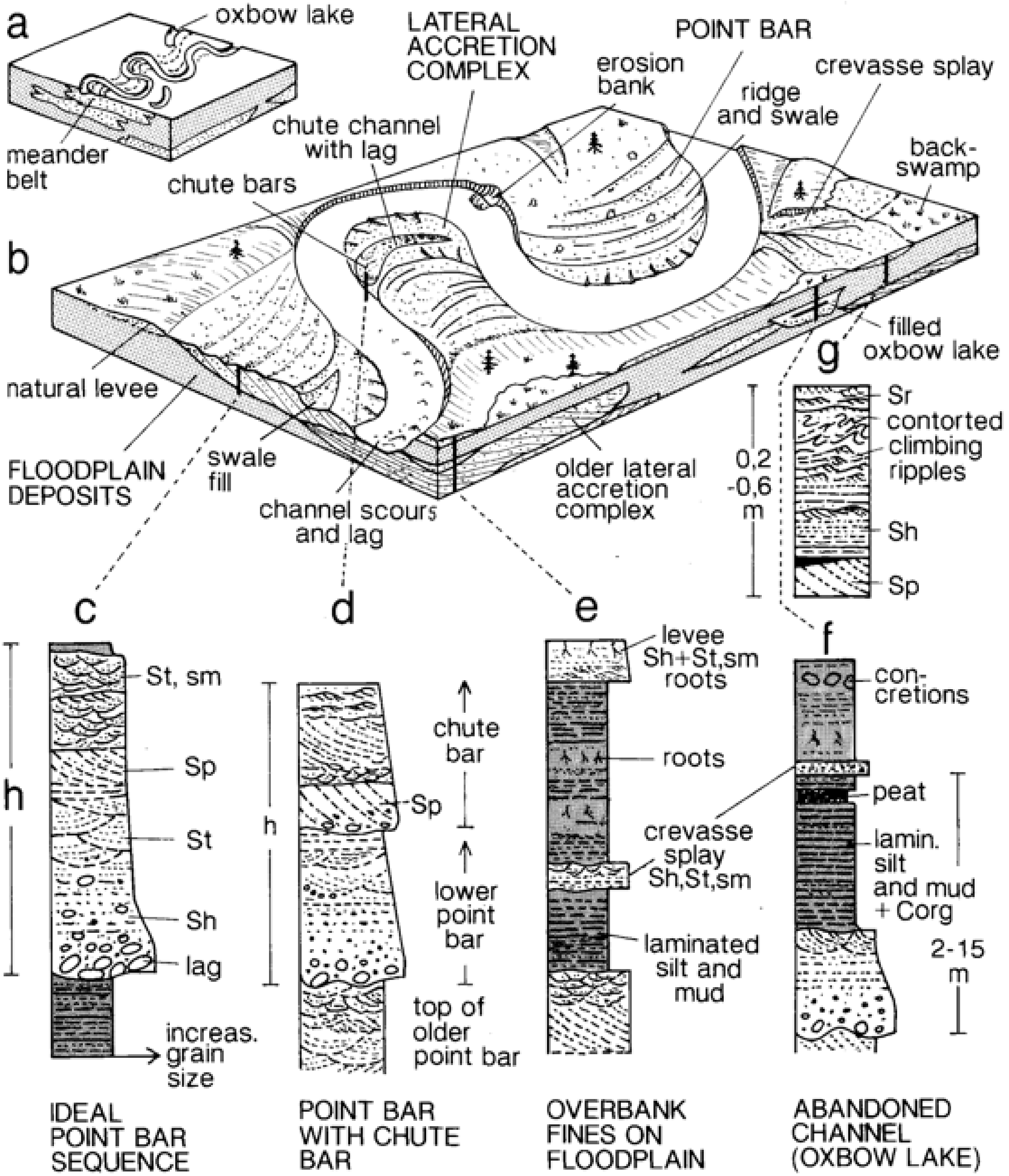
typical stratigraphic column for a meandering river system

Typically: the lag deposits on the bottom, followed by trough cross stratification and ripple cross lamination, overlain by a floodplain facies composed of mud cracks and root traces in a fine grained sediment.
In shallower parts of the flow, higher on the point bar, the bedform is commonly ripples. As a broad generalization, the preserved deposits will pass from trough cross-bedded coarser sands to small scale, trough cross- laminated finer sands upward. The development of a plane bed (without ripples or dunes, resulting in horizontal lamination) can occur at various river stages, and hence parallel lamination can be preserved interbedded with trough cross-bedding, or small scale trough cross-lamination

(from-Walker 1984)



Meandering river system

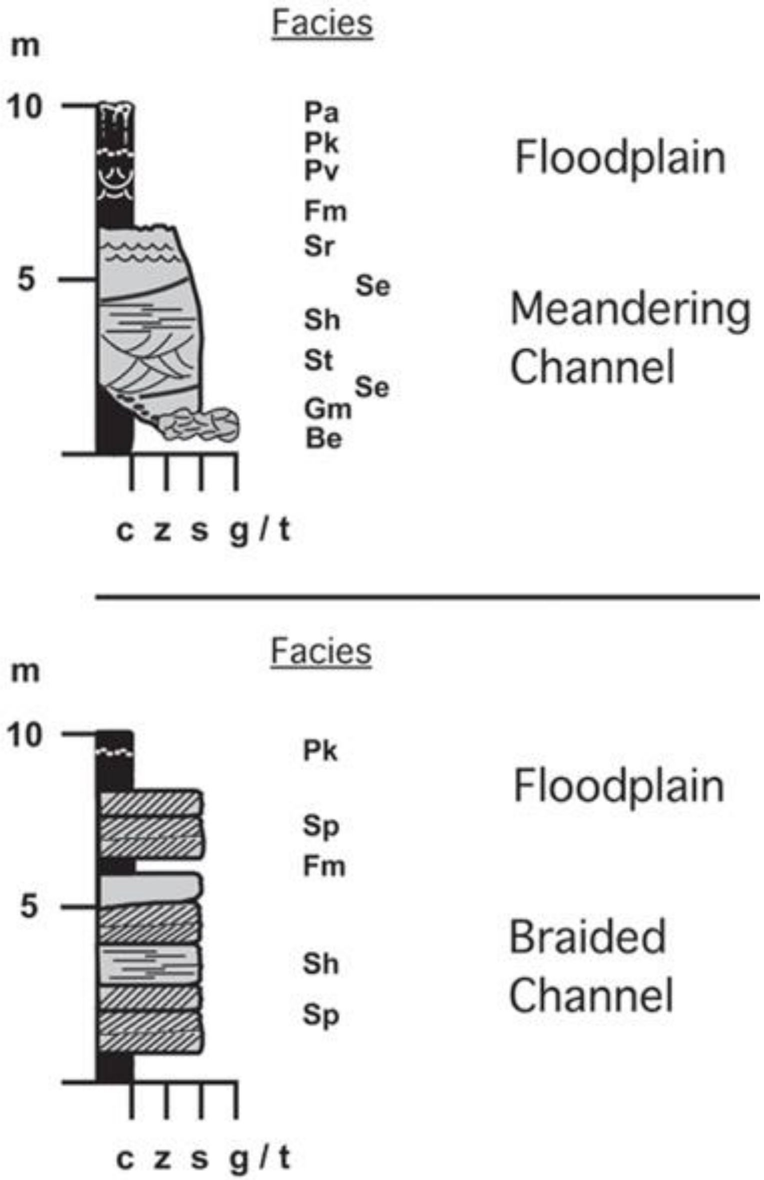


(a) Formation of sandy meander belt within a flood basin. (b) Different sub-environments of meandering channel. (c-g) Characteristic vertical sections of the youngest sediments of the flood basin. (h) One fluvial cycle (autocyclic).

Einsele. Sedimentary Basins, 1992

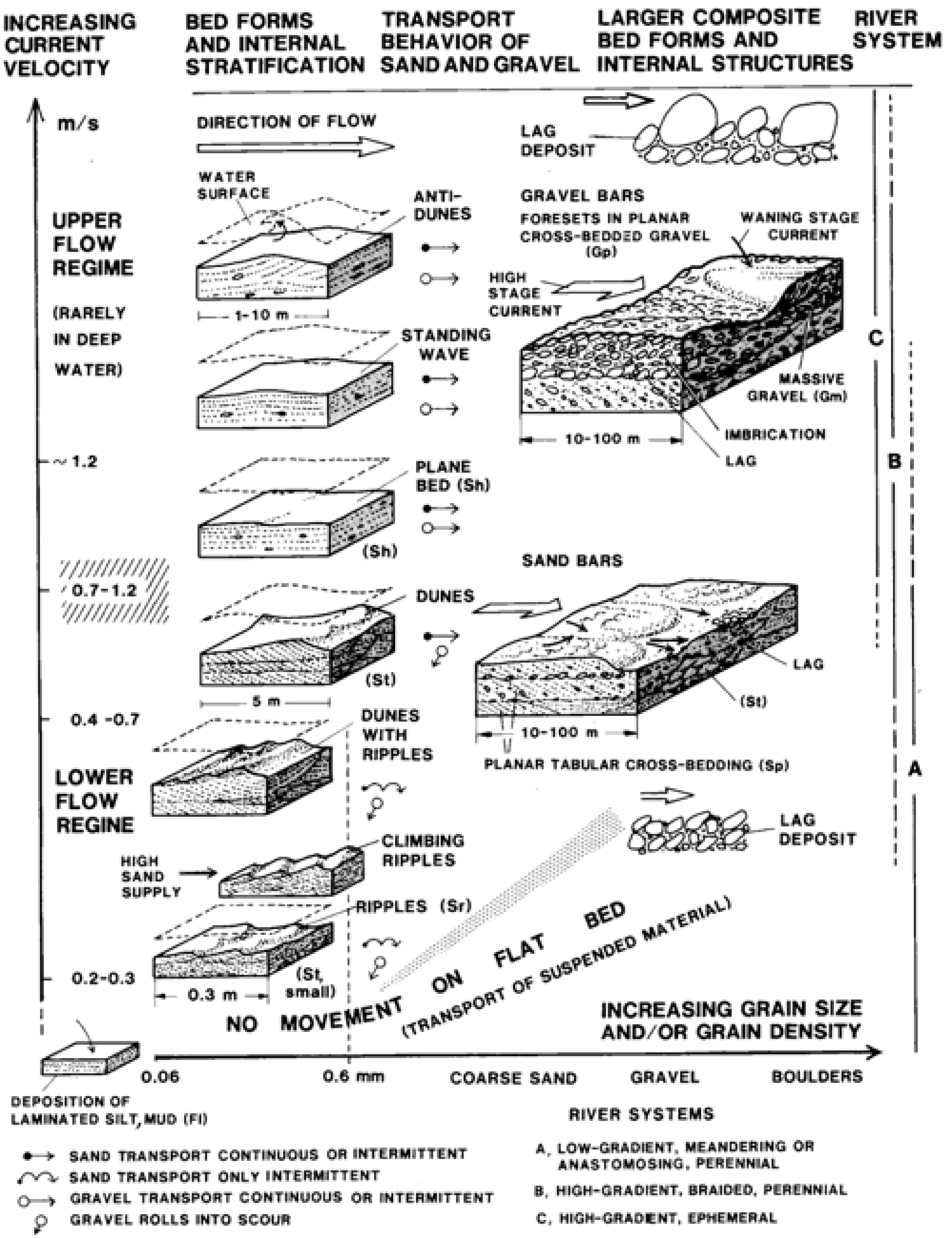
meandering versus braided river channel

There are also key differences in the facies for a meandering river channel and a braided river channel. Braided river channels will have coarser grain sizes due to their faster flow speeds. Meandering rivers carry lots of sediment within suspension that will be deposited in the structures associated with this environment, including point bars and oxbow lakes. Lastly, the migration of meandering rivers is more uniform in direction than a braided river because it will always migrate towards the eroding bank. A braided channel will migrate in many directions at the same time.



Characteristic features and sequences of the alluvial facies associations. Idealized stratigraphic columns are depicted, showing thickness and dominant lithology (c ,clay; z, silt; s, sand; g, gravel; t, tu).

Relationship between current velocity (hydraulic regime), grain size, minor and medium-sized bed forms, and internal sedimentary structures of fluvial deposits. The larger bed forms and their internal structures result from fluctuating water stages and current velocities, and therefore cannot be attributed to certain flow conditions. Small ripple forms develop only in fine to medium sands (< 0.6 mm). For transport of sand and gravel, current velocities higher than 70 to 120 cm/s (upper flow regime) are needed. The resulting beds are either horizontally stratified sands with some matrix-supported gravel, or planar cross-bedded gravelly sands. Gravel exposed to currents which are only capable of eroding and transporting sand roll into developing scours. If all sandy material is eroded, gravel may form lag deposits, which protect underlying finer material from further reworking.



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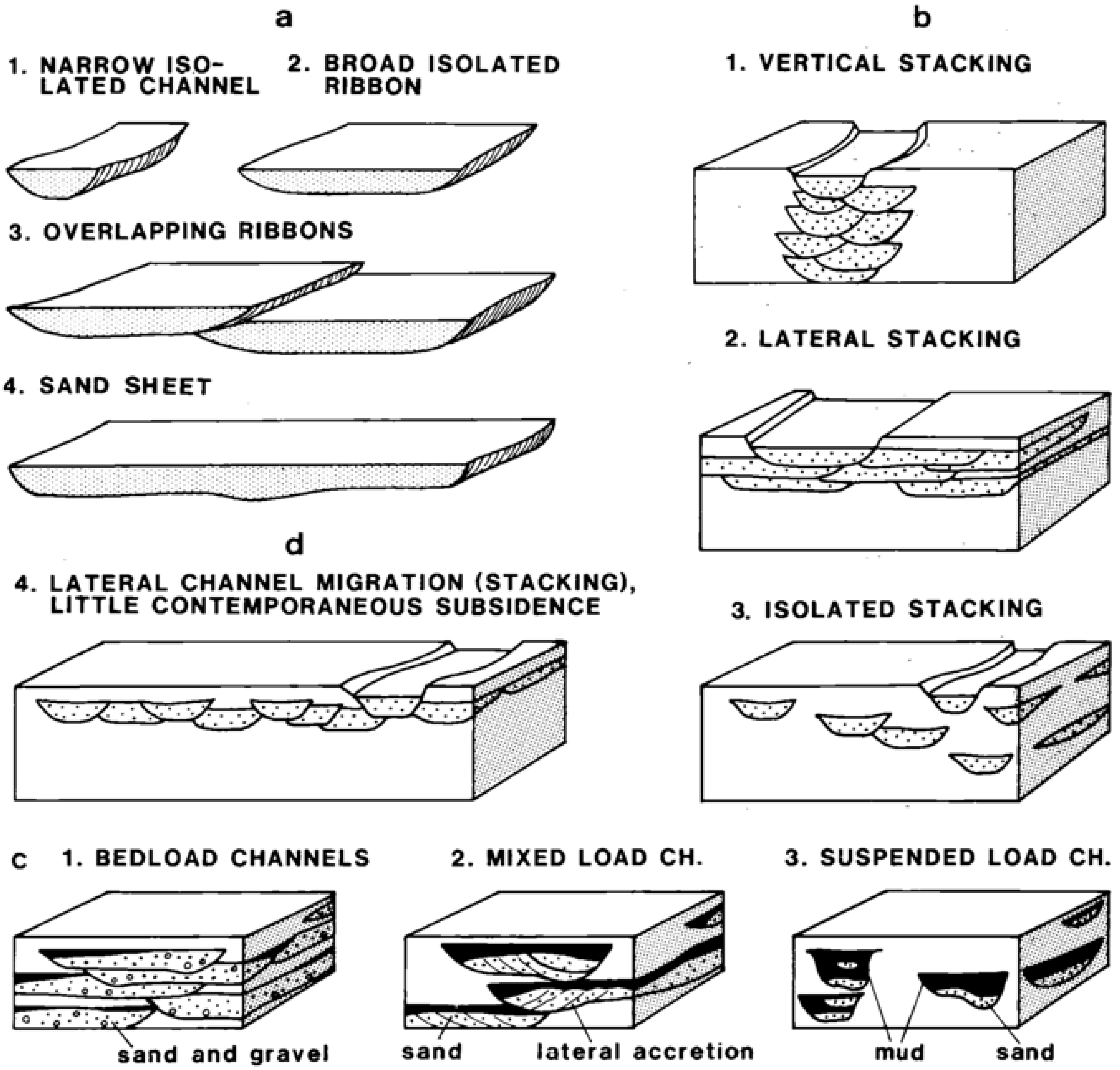
Principal types of sand and sandstone reservoir geometries generated by channel fills in fluvial systems



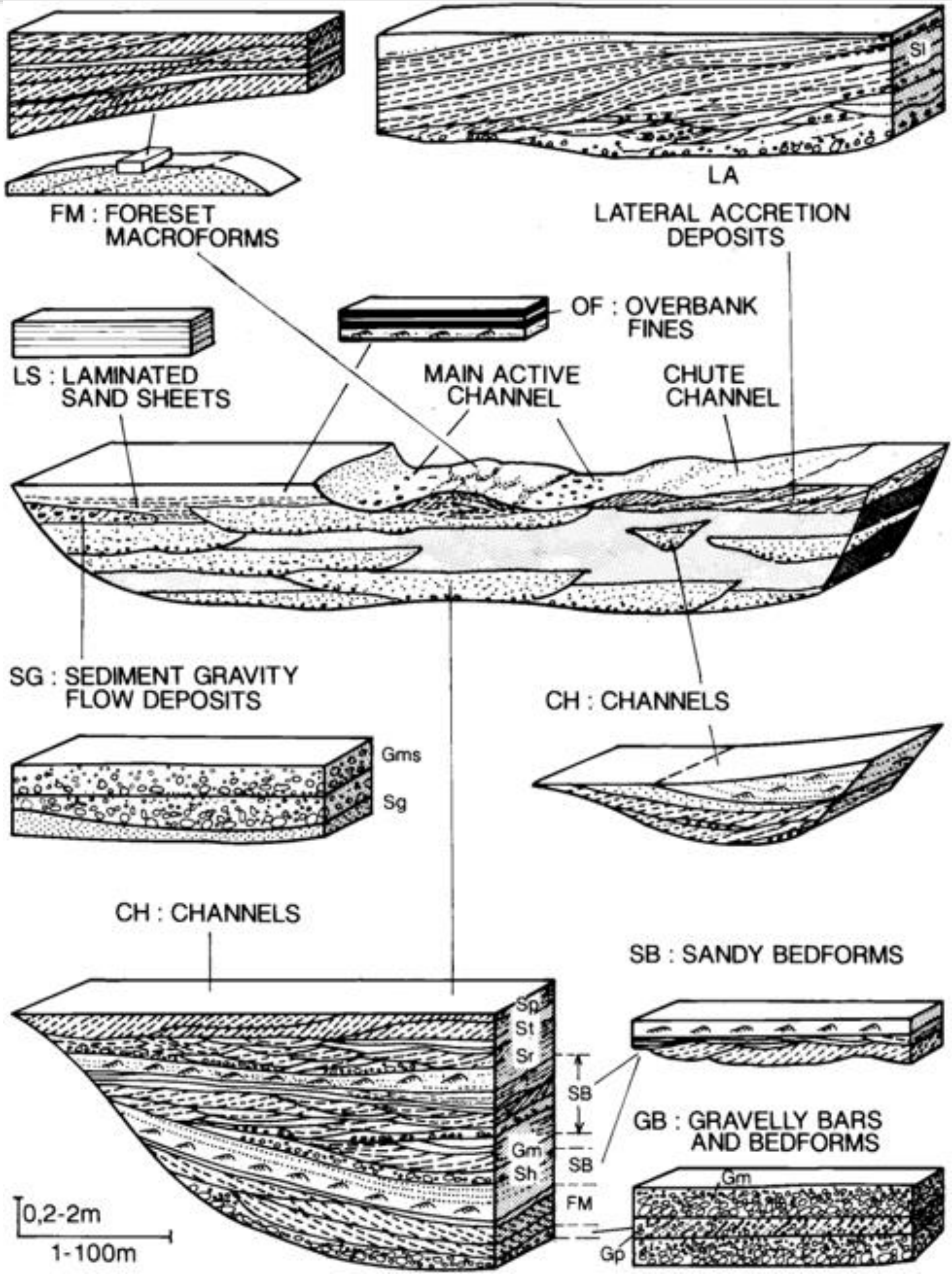
a) Single sandstone bodies. B) Different types of stacked channel sands. B1) is associated with rapid subsidence, b4) with little subsidence. c) Channel fills of bed-load, mixed-load, and suspended-load rivers.

Einsele. Sedimentary Basins, 1992

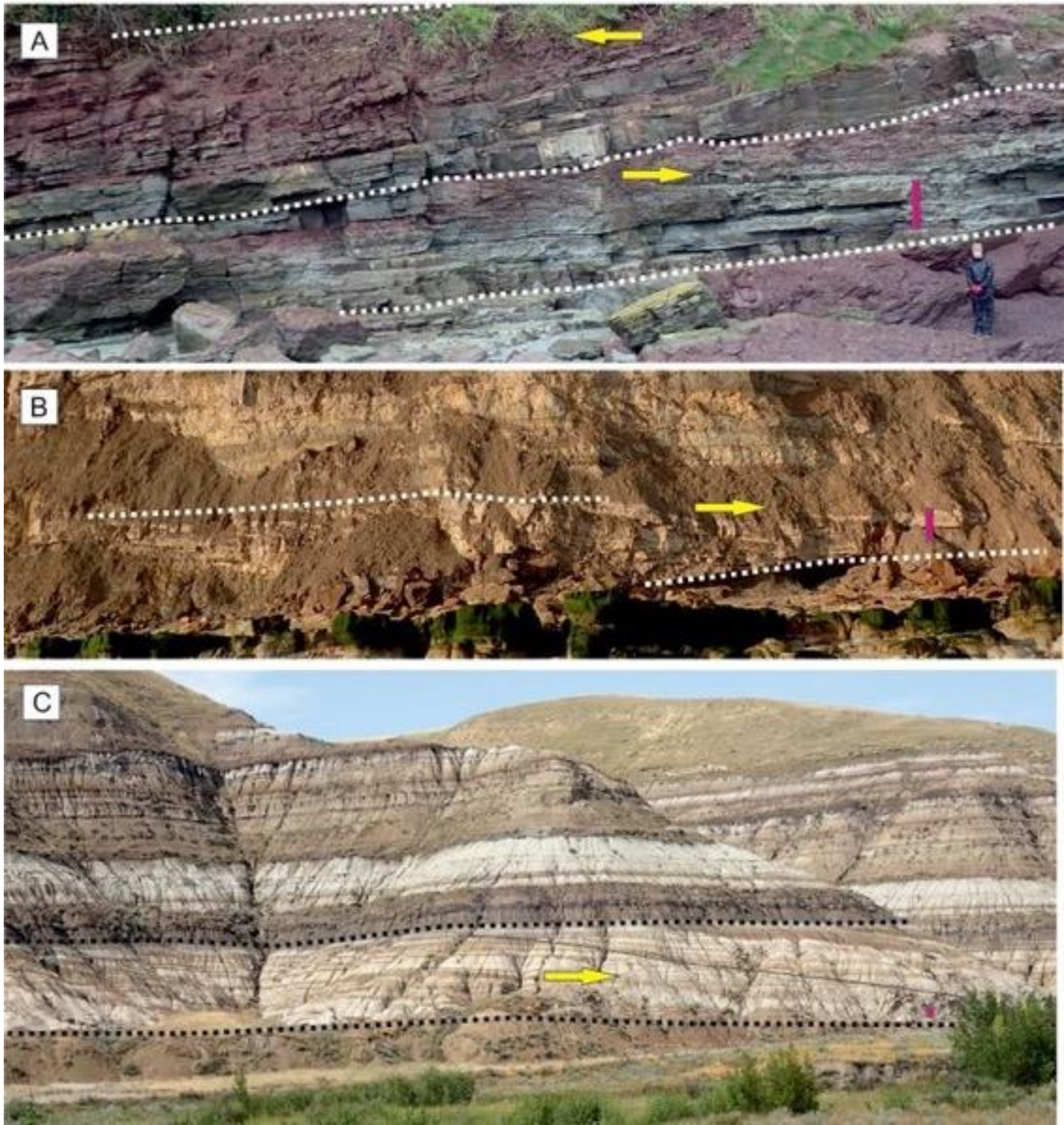
Basic architectural elements of fluvial deposits

Einsele. Sedimentary Basins, 1992

OF Overbank fines, sheet-like geometry, predominantly vertical aggradation of lithofacies Fl, mud or silt with thin lenses or laminae of silt to fine sand, commonly showing ripple cross- lamination; LS Laminated sand sheets, up to several meters thick, produced by flash floods, Sh lithofacies, and other sandy bedforms. SB Sand bedforms, including Sh, St, Sp, and Sr lithofacies. GB Gravelly bars and bedforms comprising lithofacies Gm and Gp, frequently alternating with SB and MF (in proximal regions); FM foreset macroforms of the active main channels, i.e., large compound bar forms, consisting of several co-sets of presumably upper flow regime bed forms; predominantly smaller-scale element in SB. LA Lateral accretion deposits (including point bar deposits), with variable internal geometry and lithofacies, consisting of different smaller-scale elements, for example GB (at the base) and SB, gently dipping surfaces toward the main channel. CH Channel fills of different size and geometry. MF Mass flow deposits, mainly Gms lithofacies, frequently associated with GB.



laterally-accreting inclined heterolithic stratification

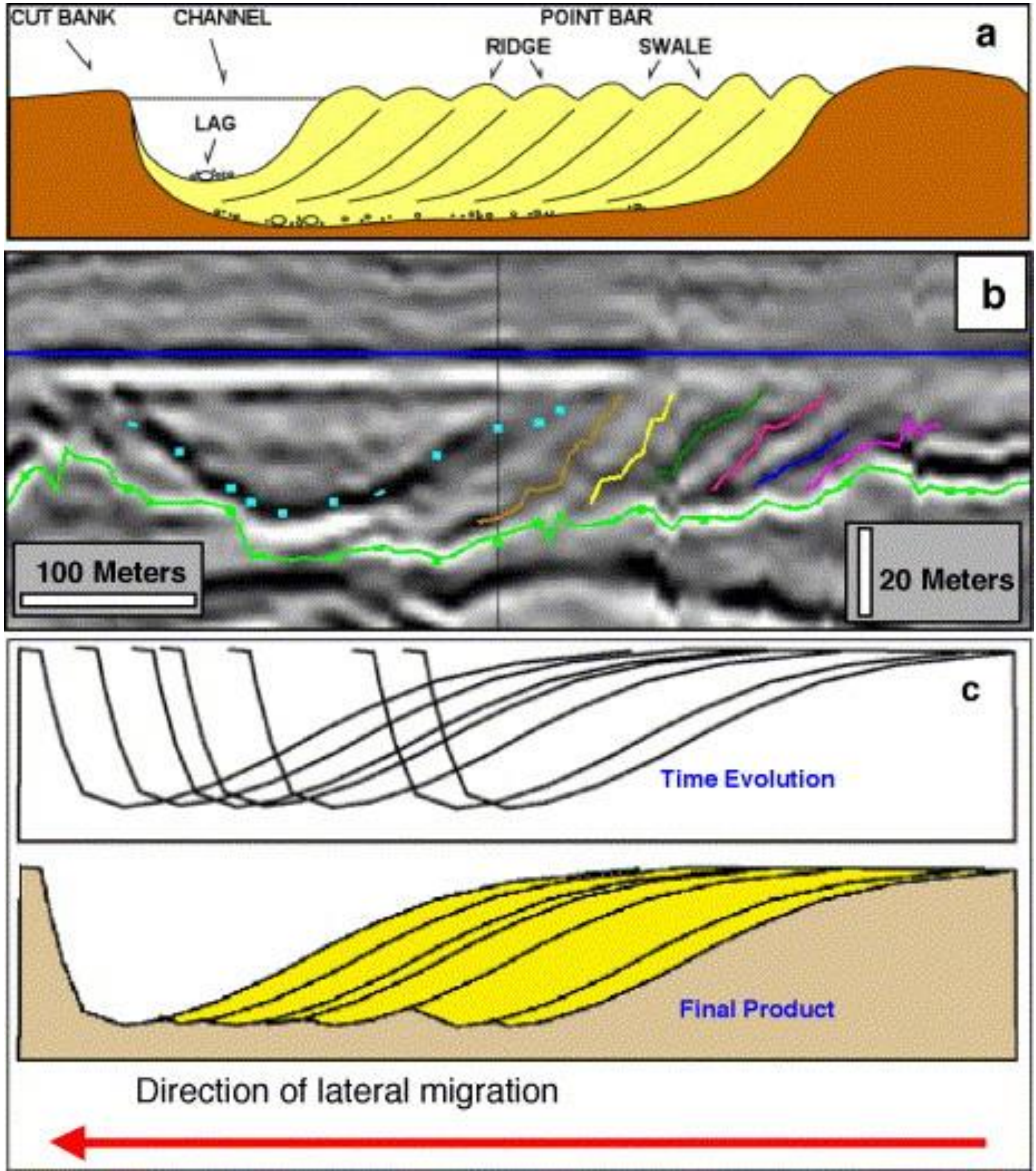


Outcrop expressions of LA-IHS recording point bar deposits of various scales.
In each image, dashed line shows bounding surfaces of the LA-IHS element, yellow arrow shows general direction of migration and pink bar represents one metre vertically: (A) Two superimposed LA-IHS packages in broadly opposed directions; strata deposited in a fluvial floodplain environment. Milford Haven Group, Wales; (B) Isolated LA-IHS within estuarine facies. Ashdown Formation, England; (C) Large scale LA-IHS with internal erosion surface, recording deposition within a tidally-influenced meandering point bar. Horseshoe Canyon Formation, Canada.

Lateral accretion packages

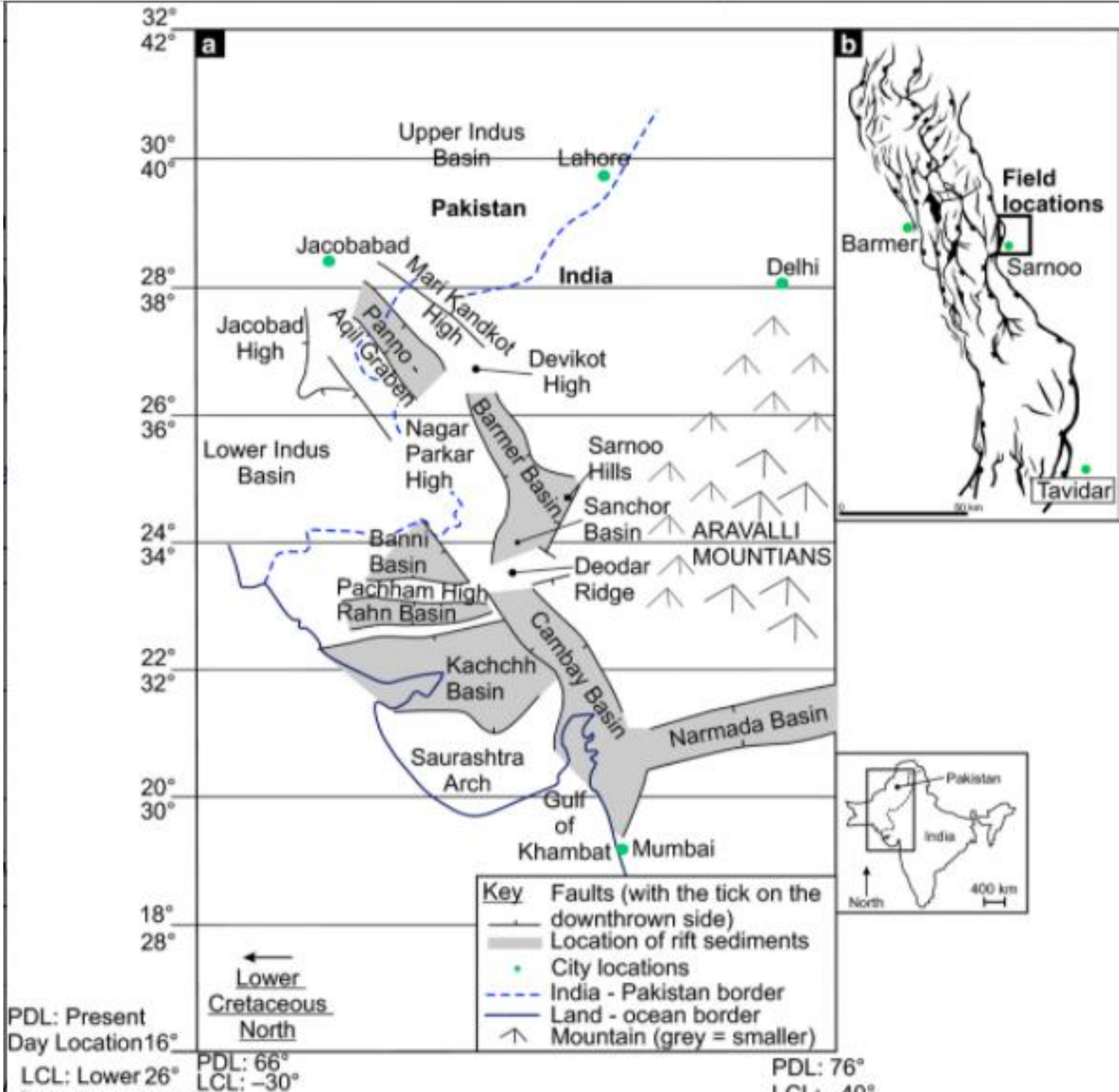
(a) Fluvial point-bar model. (b) The cross-section view of a LAP in a deepwater, sinuous, erosionally confined channel resembles the geometry of a fluvial point-bar. (c) Depositional model proposed for the LAPs. The accretion surfaces would be formed by relatively continuous lateral sweep of channel bends by systematic erosion of the outer banks and deposition along inner banks (the classic point-bar model).

Abreu et al., 2003, Lateral accretion packages (LAPs): an important reservoir element in deep water sinuous channels. Marine and Petroleum Geology 20, 631-648



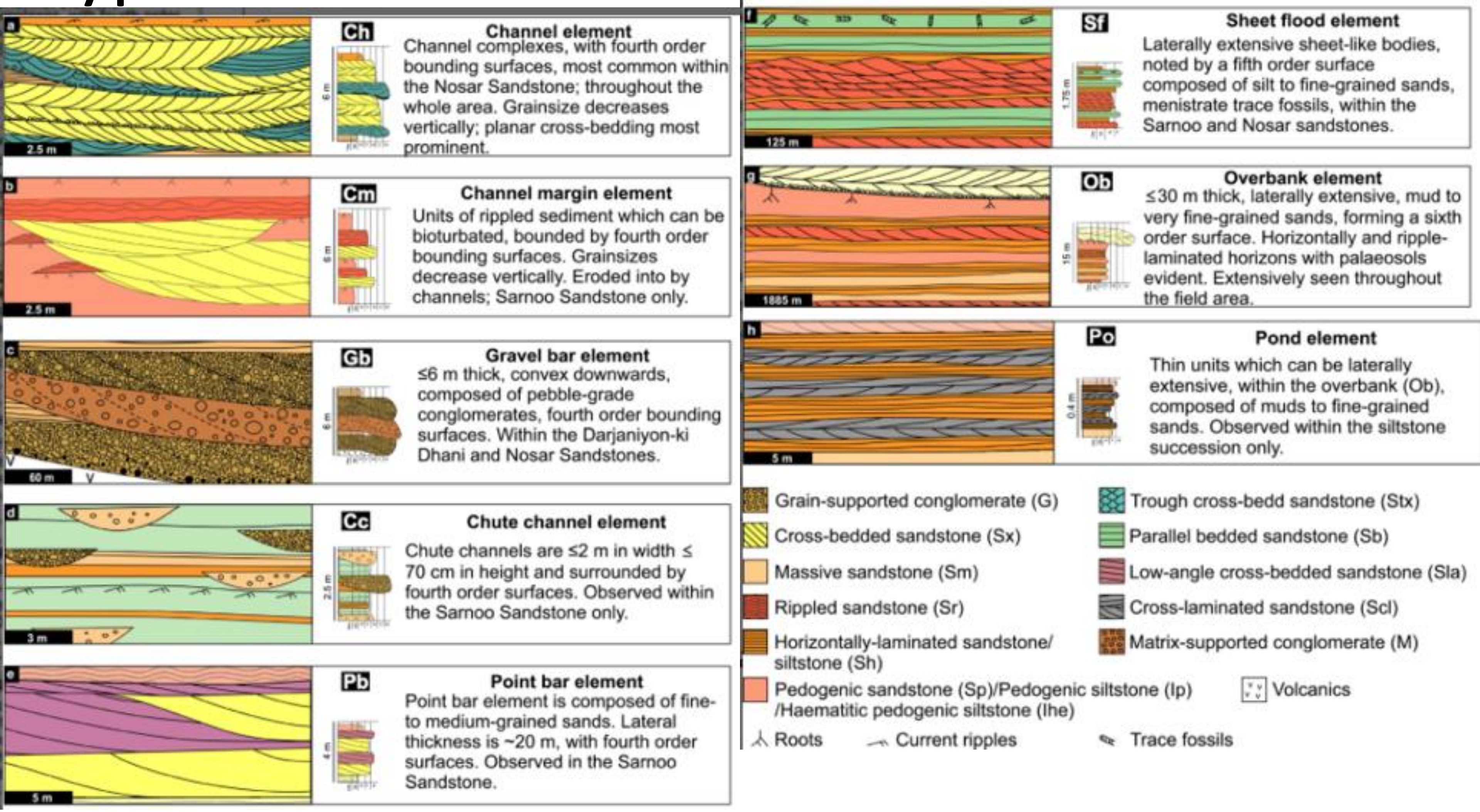
channel belt sandstone packages

Beaumont et al. (2018) The Depositional Record Sedimentology and the facies architecture of the Ghaggar-Hakra Formation, Barmer Basin, India



Key
- Faults (with the tick on the downthrown side)
- Location of rift sediments
- City locations
- India - Pakistan border
- Land - ocean border
- Mountain (grey = smaller)

Typical two-dimensional sketches and logs



Ch **Channel element**
Channel complexes, with fourth order bounding surfaces, most common within the Nosar Sandstone; throughout the whole area. Grainsize decreases vertically; planar cross-bedding most prominent.

Cm **Channel margin element**
Units of rippled sediment which can be bioturbated, bounded by fourth order bounding surfaces. Grainsizes decrease vertically. Eroded into by channels; Sarnoo Sandstone only.

Gb **Gravel bar element**
≤6 m thick, convex downwards, composed of pebble-grade conglomerates, fourth order bounding surfaces. Within the Darjaniyon-ki Dhani and Nosar Sandstones.

Cc **Chute channel element**
Chute channels are ≤2 m in width ≤ 70 cm in height and surrounded by fourth order surfaces. Observed within the Sarnoo Sandstone only.

Pb **Point bar element**
Point bar element is composed of fine- to medium-grained sands. Lateral thickness is ~20 m, with fourth order surfaces. Observed in the Sarnoo Sandstone.

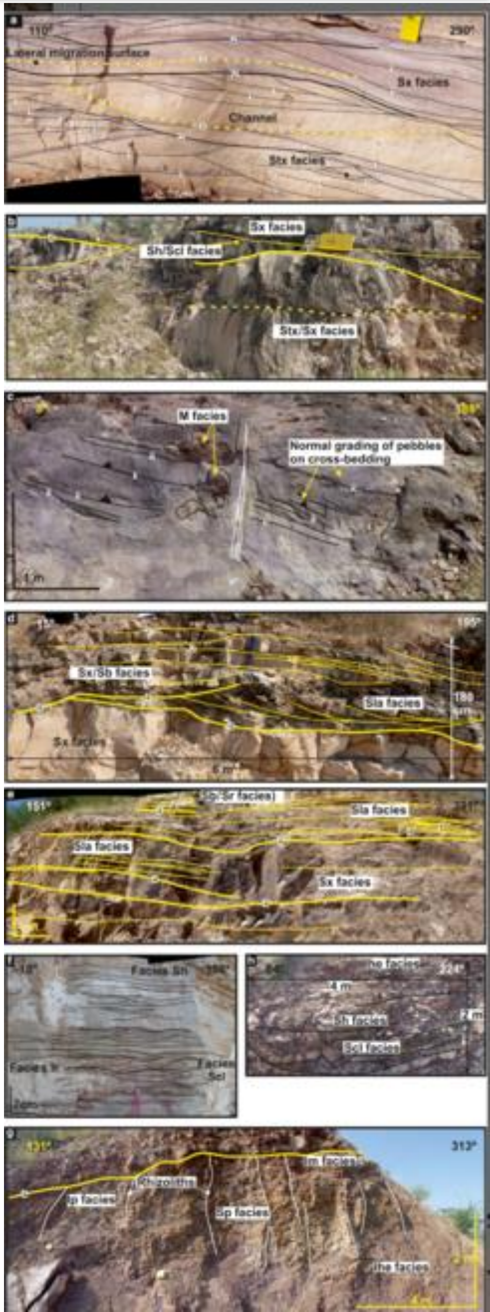
Sf **Sheet flood element**
Laterally extensive sheet-like bodies, noted by a fifth order surface composed of silt to fine-grained sands, menistrate trace fossils, within the Sarnoo and Nosar sandstones.

Ob **Overbank element**
≤30 m thick, laterally extensive, mud to very fine-grained sands, forming a sixth order surface. Horizontally and ripple-laminated horizons with palaeosols evident. Extensively seen throughout the field area.

Po **Pond element**
Thin units which can be laterally extensive, within the overbank (Ob), composed of muds to fine-grained sands. Observed within the siltstone succession only.

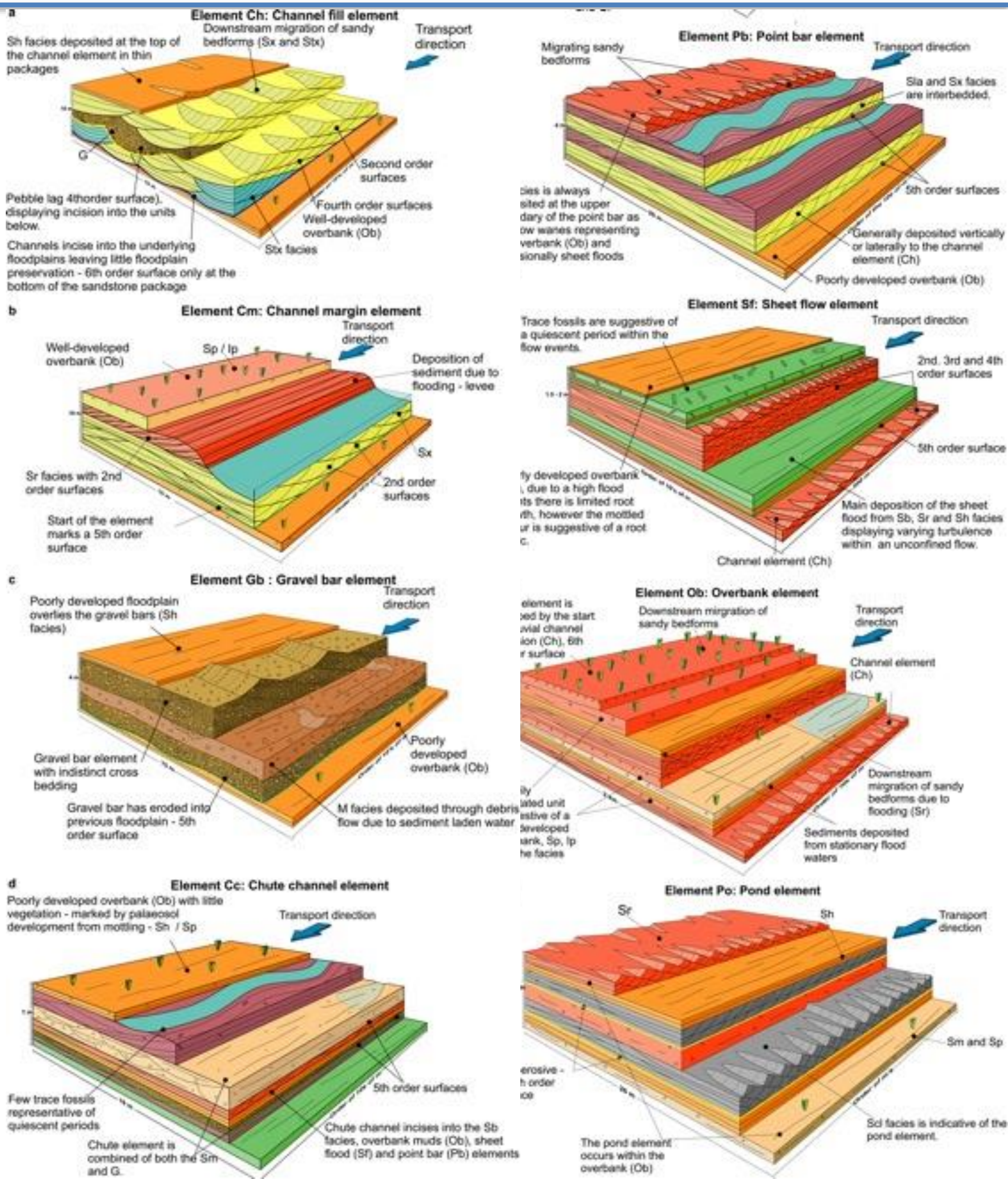
(a) Channel, Ch; (b) Channel margin, Cm; (c) Gravel bar, Gb; (d) Chute channel, Cc; (e) Point bar, Pb; (f) Sheet flow, Sf; (g) Overbank, Ob, and; (h) Pond, Po

Interpreted photographs of the architectural elements (a) Channel element (Ch) displaying first- to third-order bounding surfaces with the trough and planar cross-bedded sandstone facies; (b) Channel margin element (Cm) displaying the gradational change from the cross-bedded facies (Stx/Sx) into the cross/horizonal-lamination facies (Sh/Scl) overlain by an erosional surface and the planar cross-bedded facies; (c) Gravel bar element (Gb) displaying the conglomerate facies (M & G) with indistinct cross-bedding and upon some of the cross-beds there are graded clasts; (d) Chute channel element (Cc) this image depicts the channel element indicated by the planar cross-bedded facies (Sx), the Point bar element indicated by the low-angle cross-bedded facies (Sla) and the chute channel indicated by the thick, thin solid lines and the planar cross-bedded and planar horizontally bedded facies (Sx/Sb); (e) Point bar element (Pb) with low-angle cross-bedded facies (Sla) with second- and fourth-order bounding surfaces laterally migrating into the channel element (Ch); (f) Sheet flow element (Sf), here the element displays the horizonal-laminated and cross-lamination facies (Sh/Scl) with various types of ripples; (g) Overbank element (Ob) indicated by the rhizoliths and the pedogenic facies (Sp/Ip/Ihe), and; (h) Pond element (Po) indicated by the horizonal-laminated and cross-lamination facies (Sh/Scl)



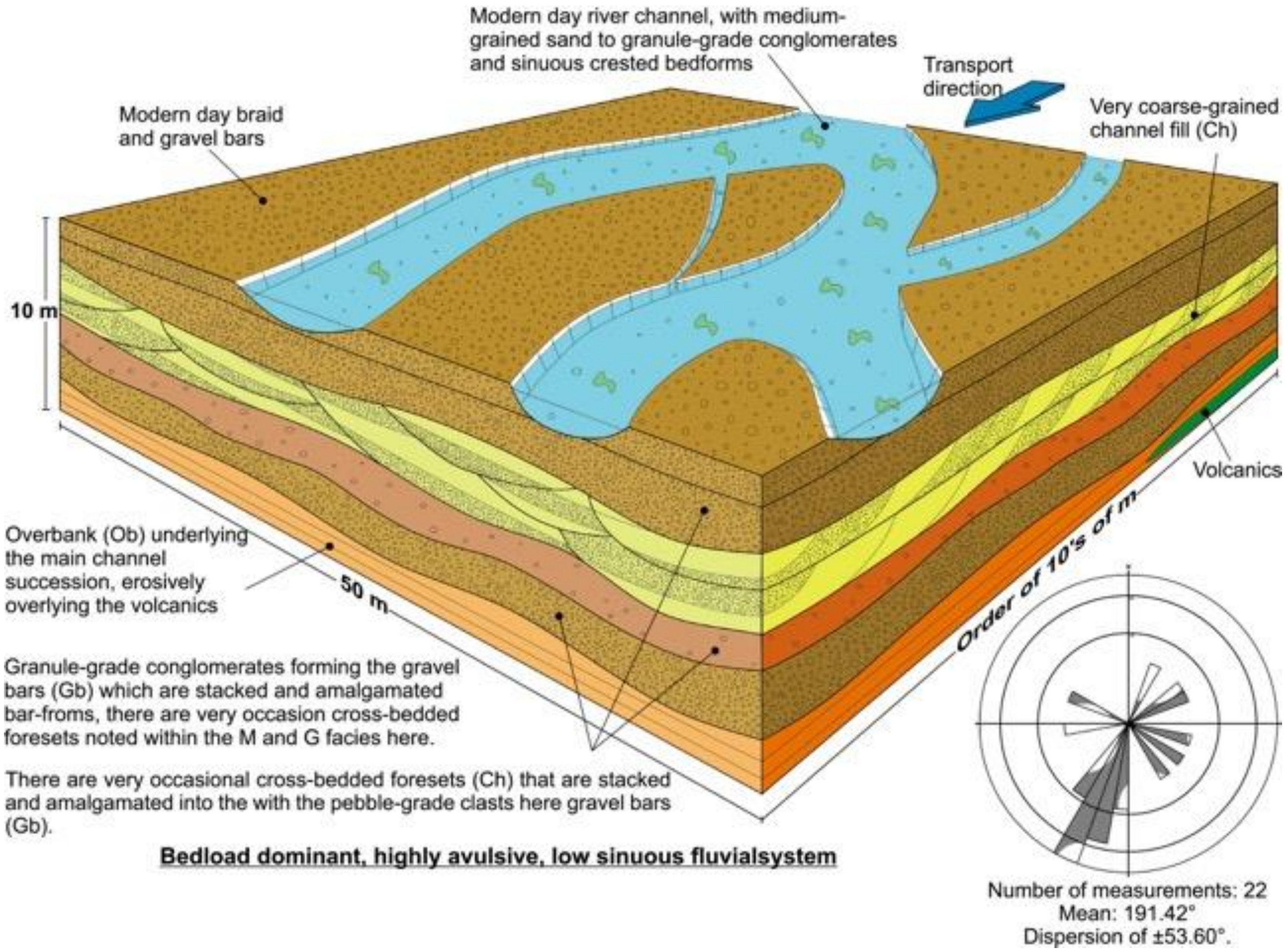
Three-dimensional facies models of the architectural elements

(a) The channel element (Ch) with an erosive lower base contains first- to third-order surfaces internally. (b) The channel margin (Cm) element with an erosive lower base and first- to third-order surfaces internally, the succession grades into the overbank. (c) The gravel bar (Gb) element with an erosive lower boundary and first- to second-order surfaces within. (d) The chute channel (Cc) element with an erosive lower boundary and occasional first order boundaries within. (e) The point bar (Pb) element with an erosive fourth order boundary with first- to third-order surfaces internally. This succession grades into the overbank. (f) The sheet flow (Sf) element starting with a lower fourth order bounding surface with first- to third-order surfaces within. There are quiescent periods here evidenced by trace fossils. (g) The overbank (Ob) element with first, second, and fourth-order surfaces within. (h) The pond (Po) element has a fourth order base and first- to second-order surfaces internally



Facies model of the gravel bedload dominant low sinuosity fluvial system

The Darjaniyon-ki Dhani Sandstone contains the channel (Ch), gravel bar (Gb) and the overbank (Ob) architectural elements. There are 4th to 6th order bounding surfaces within. The sets and cosets within are inconsistent suggesting the gravel bars are transient, suggesting fluvial immaturity. The proportion of channels to floodplain is 90% to 10%, respectively



Modern day river channel, with medium-grained sand to granule-grade conglomerates and sinuous crested bedforms

Overbank (Ob) underlying the main channel succession, erosively overlying the volcanics

Granule-grade conglomerates forming the gravel bars (Gb) which are stacked and amalgamated bar-froms, there are very occasion cross-bedded foresets noted within the M and G facies here.

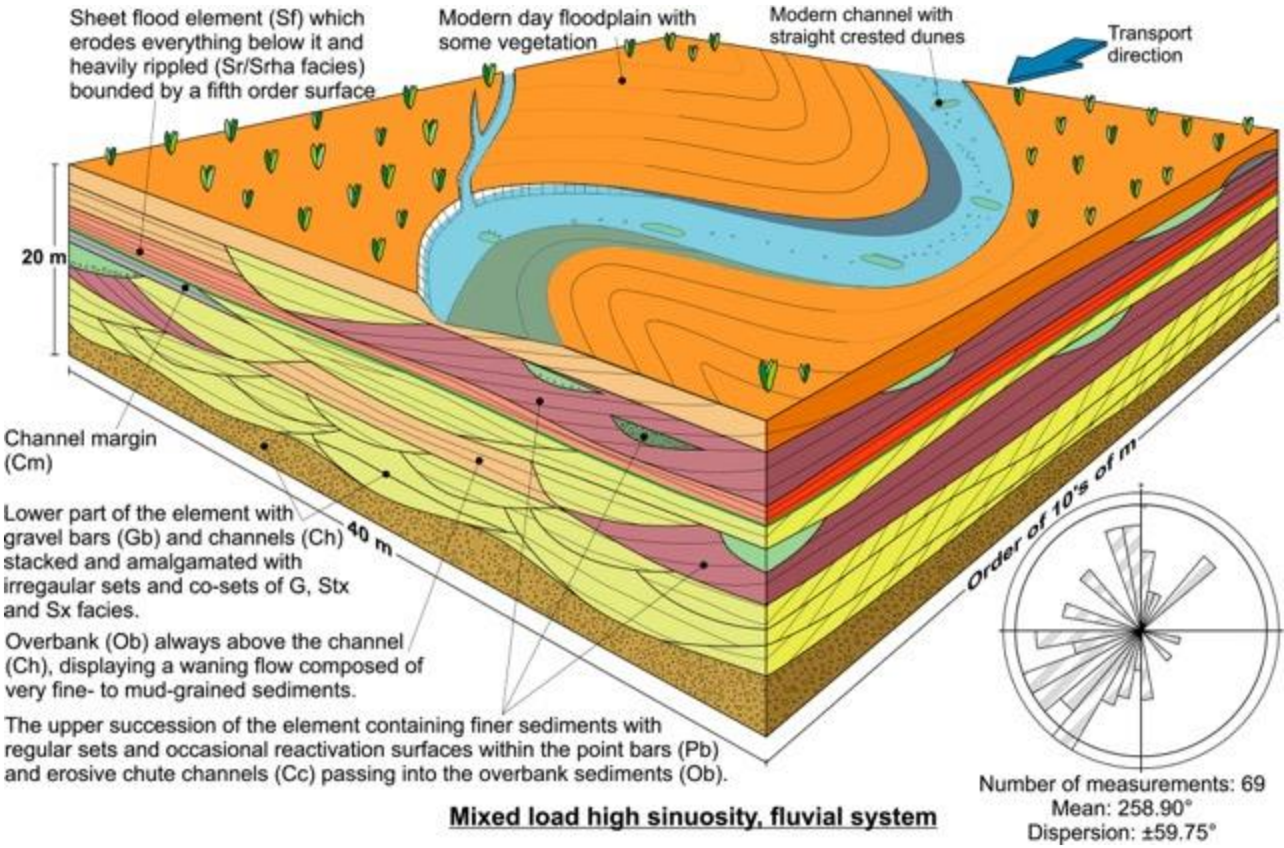
There are very occasional cross-bedded foresets (Ch) that are stacked and amalgamated into the with the pebble-grade clasts here gravel bars (Gb).

Bedload dominant, highly avulsive, low sinuous fluvialsystem

Number of measurements: 22
Mean: 191.42°
Dispersion of ±53.60°.

Facies model of the mixed load high sinuosity fluvial system

The Sarnoo Sandstone contains the channels (Ch), channel margin (Cm), gravel bars (Gb), chute channels (Cc) sheet flows (Sf), and overbank (Ob) elements. The consistency of sets and cosets representing the migration of in-channel bedforms suggests discharge stability. The proportion of sand to mud increases from 80% sand and 20% mud to 60% sand and 40% mud vertically throughout the facies model.



Sheet flood element (Sf) which erodes everything below it and heavily rippled (Sr/Srha facies) bounded by a fifth order surface

Modern day floodplain with some vegetation

Modern channel with straight crested dunes

Transport direction

Channel margin (Cm)

Lower part of the element with gravel bars (Gb) and channels (Ch) stacked and amalgamated with irregaular sets and co-sets of G, Stx and Sx facies.

Overbank (Ob) always above the channel (Ch), displaying a waning flow composed of very fine- to mud-grained sediments.

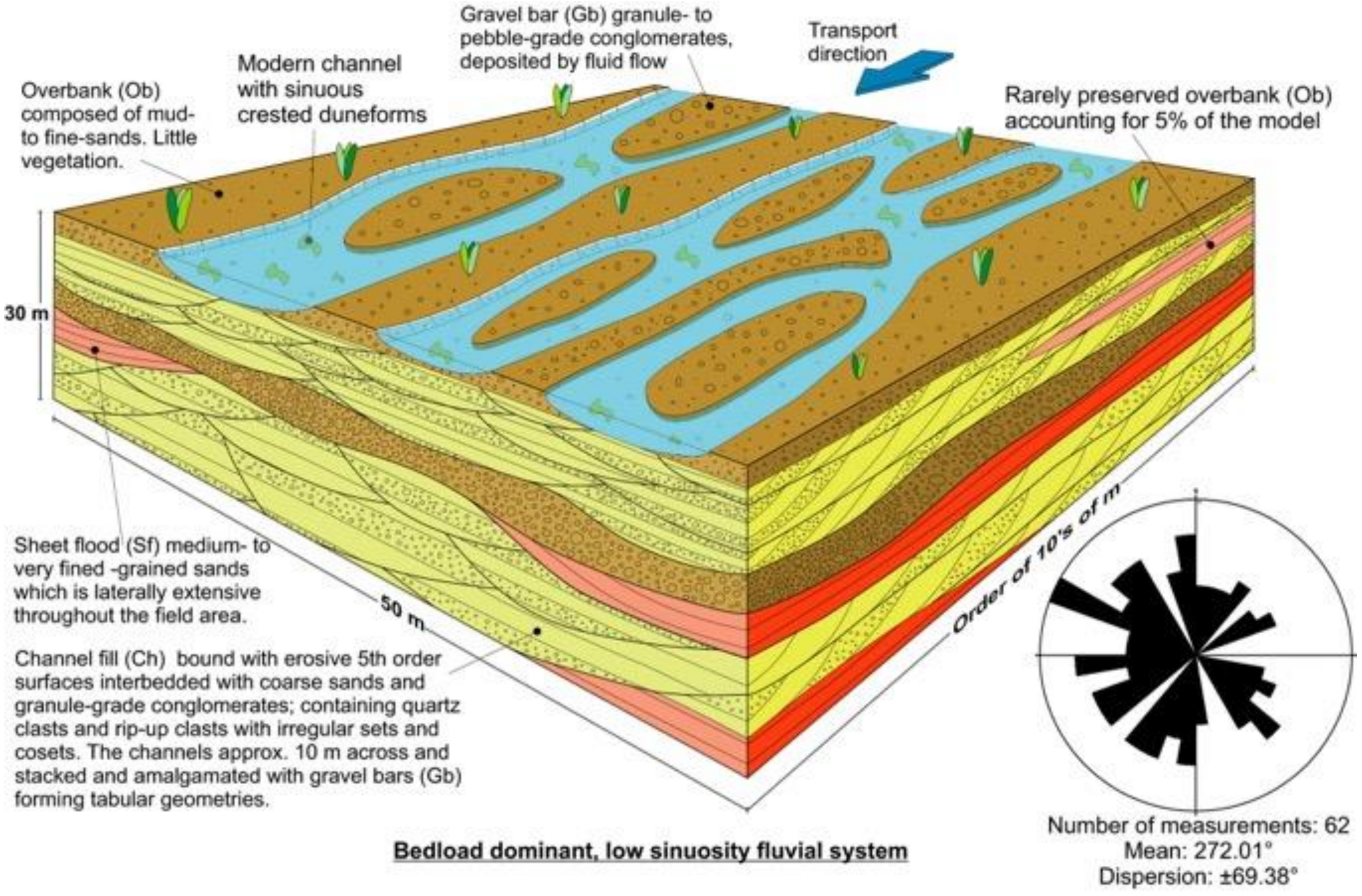
The upper succession of the element containing finer sediments with regular sets and occasional reactivation surfaces within the point bars (Pb) and erosive chute channels (Cc) passing into the overbank sediments (Ob).

Mixed load high sinuosity, fluvial system

Number of measurements: 69
Mean: 258.90°
Dispersion: ±59.75°

Facies model of a well-developed, bedload dominant, low sinuosity fluvial system

The Nosar Sandstone displays channel (Ch), floodplain (Ob), gravel bars (Gb) and sheetflow (F6) elements. There are all six types of bounding surfaces within indicating erratic surfaces and multiple truncations. This suggests discharge irregularity and a high level of channel migration. The proportion of sand to mud is at 90:10



Overbank (Ob) composed of mud- to fine-sands. Little vegetation.

Modern channel with sinuous crested duneforms

Gravel bar (Gb) granule- to pebble-grade conglomerates, deposited by fluid flow

Rarely preserved overbank (Ob) accounting for 5% of the model

Sheet flood (Sf) medium- to very fined -grained sands which is laterally extensive throughout the field area.

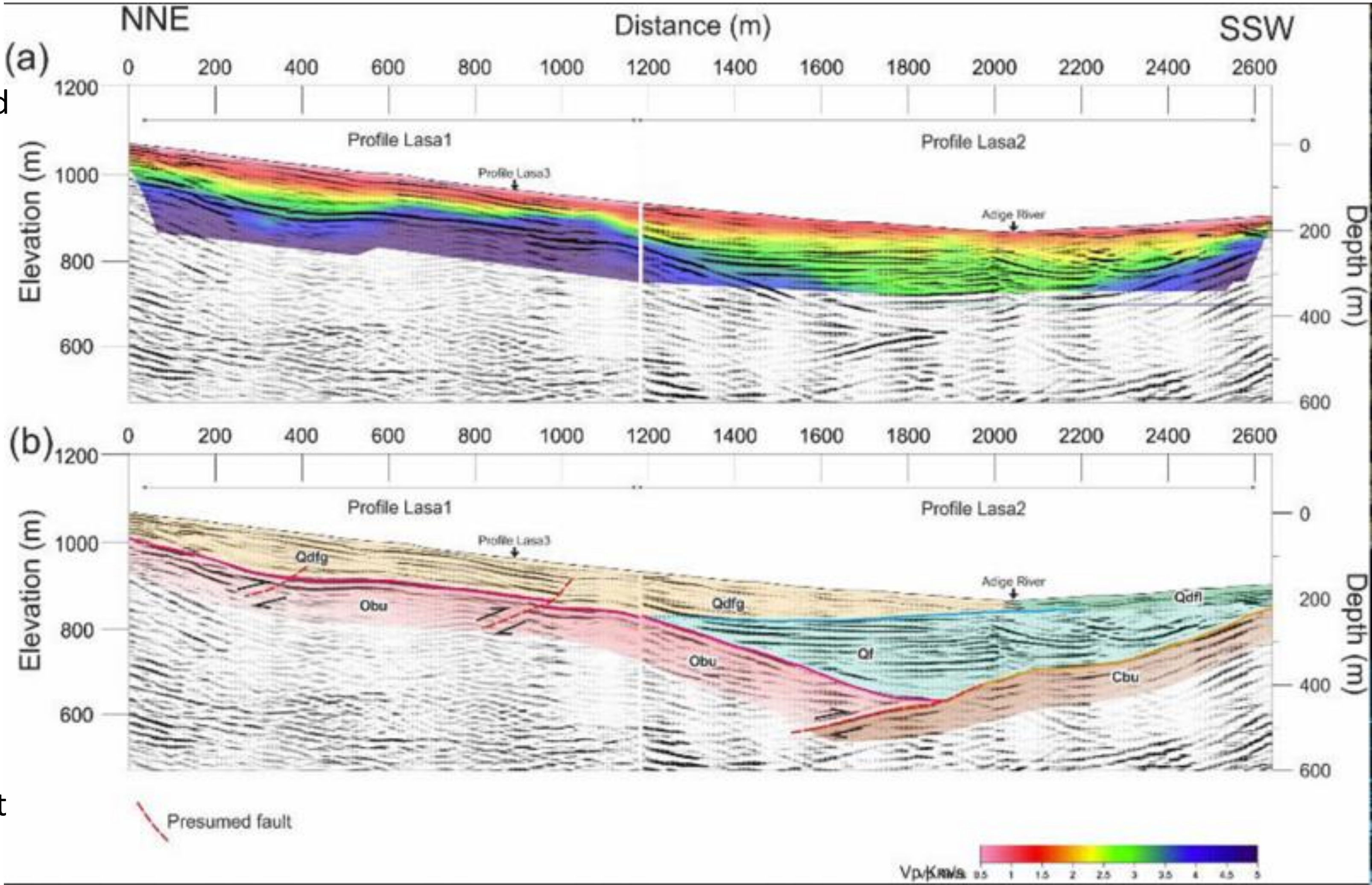
Channel fill (Ch) bound with erosive 5th order surfaces interbedded with coarse sands and granule-grade conglomerates; containing quartz clasts and rip-up clasts with irregular sets and cosets. The channels approx. 10 m across and stacked and amalgamated with gravel bars (Gb) forming tabular geometries.

Number of measurements: 62
Mean: 272.01°
Dispersion: ±69.38°

Bedload dominant, low sinuosity fluvial system

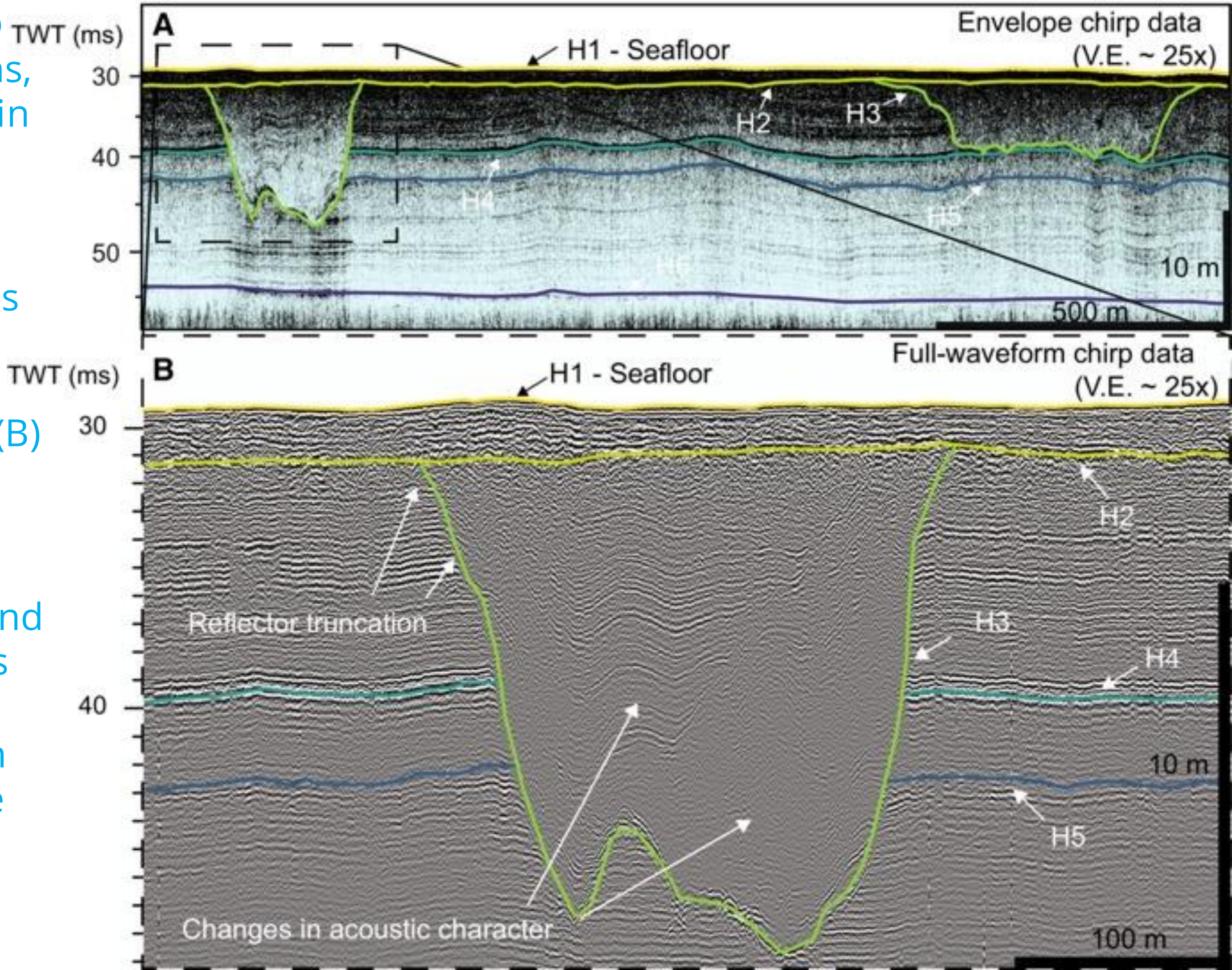
Maraio et al., 2018. High-resolution seismic imaging of debris-flow fans, Val Venosta,Journal of Applied Geophysics

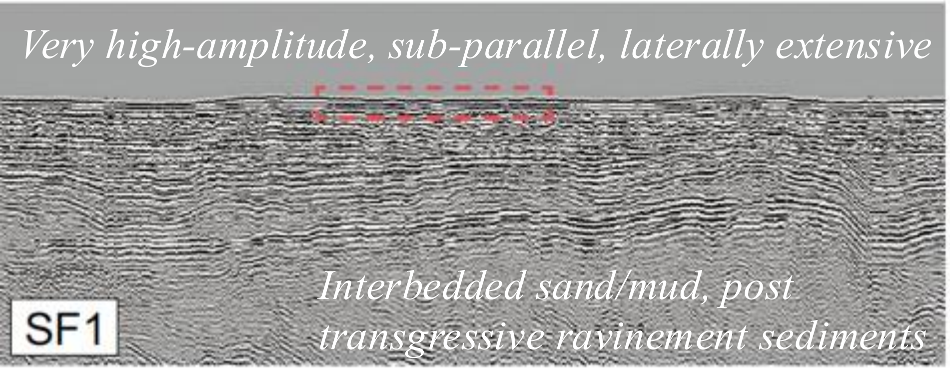
(a) uninterpreted (overlaid with the results of refraction tomography) and (b) interpreted seismic profiles. Qdfg: Quaternary debris-flow fan deposits (Gadria); Qdfl: Quaternary debris-flow fan deposits (Lasa); Qf: Quaternary fluvial deposits; Obu: Ötztal basement unit; Cbu: Campo Nappe basement unit.



Speed, C.M., Swartz, J.M., Gulick, S.P.S., Goff, J.A. (2022) **Seismic expression and stratigraphic preservation of a coastal plain fluvial channel belt and floodplain channels on the Gulf of Mexico inner continental shelf.** Sedimentology, in press. DOI: 10.1111/sed.13044

Examples of the 2D chirp data, interpreted horizons, and observed variations in acoustic character. (A) Envelope chirp data exemplify regional stratigraphic relationships and large-scale erosional features such as channel forms and ravinements. (B) Decimetre-scale vertical resolution full-waveform chirp data enable near outcrop-scale mapping and interpretation of changes in reflector character (amplitude, configuration and continuity) indicative of unconformities and lithological variations within channel fills.

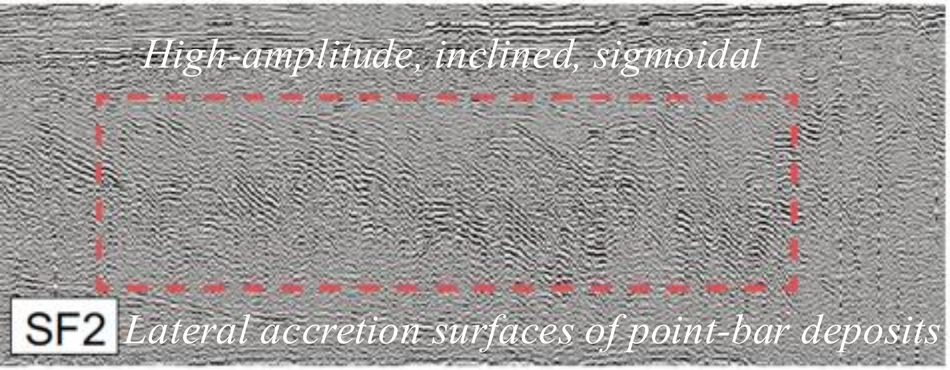




SF1

Very high-amplitude, sub-parallel, laterally extensive

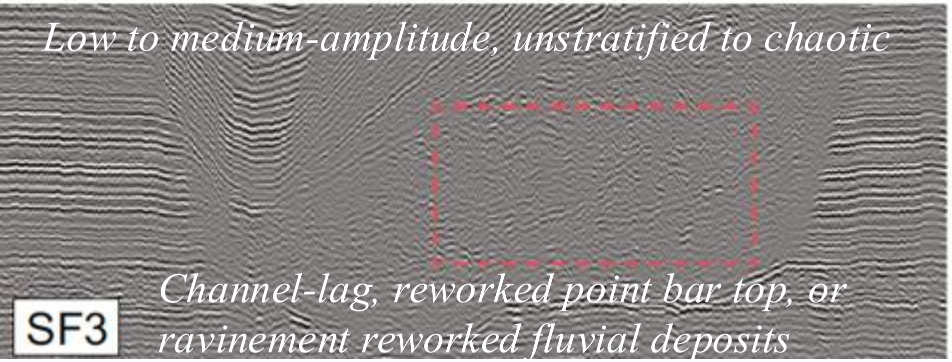
Interbedded sand/mud, post transgressive ravinement sediments



SF2

High-amplitude, inclined, sigmoidal

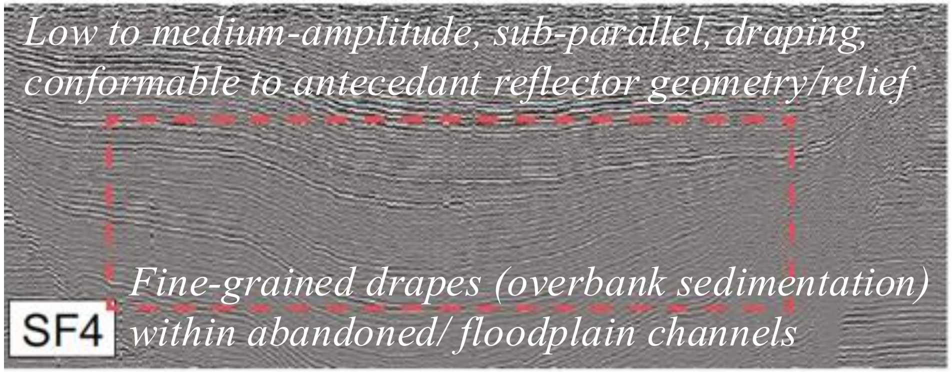
Lateral accretion surfaces of point-bar deposits



SF3

Low to medium-amplitude, unstratified to chaotic

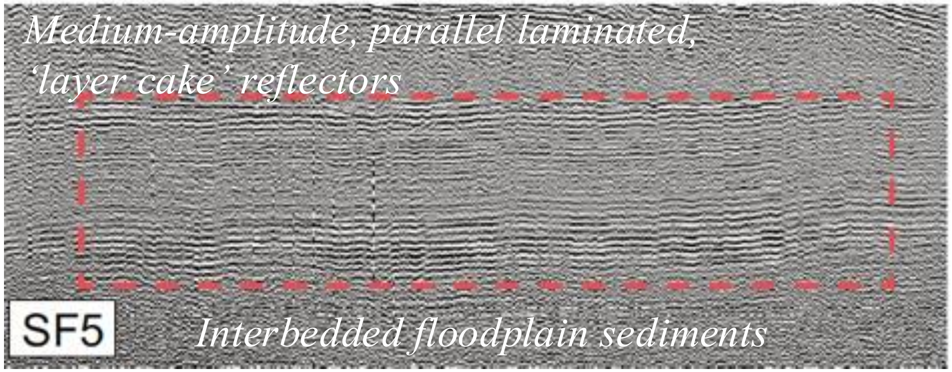
Channel-lag, reworked point bar top, or ravinement reworked fluvial deposits



SF4

Low to medium-amplitude, sub-parallel, draping, conformable to antecedant reflector geometry/relief

Fine-grained drapes (overbank sedimentation) within abandoned/ floodplain channels



SF5

Medium-amplitude, parallel laminated, 'layer cake' reflectors

Interbedded floodplain sediments

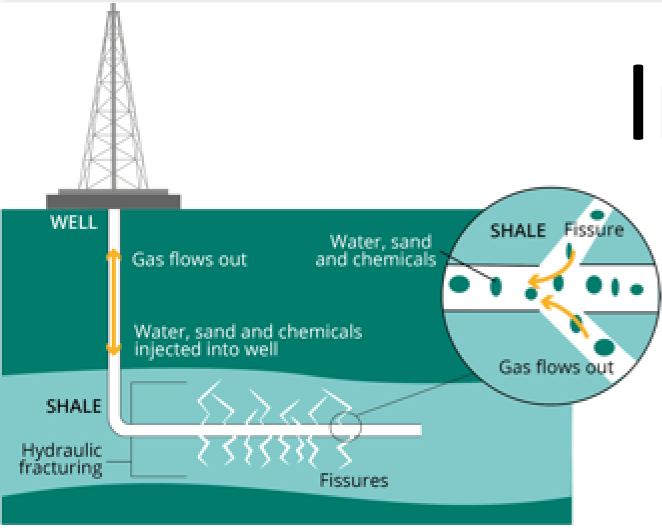
Examples and descriptions of seismic (sub-bottom) facies differentiated by unique acoustic characteristics including **reflector amplitude, geometric configuration and continuity**.

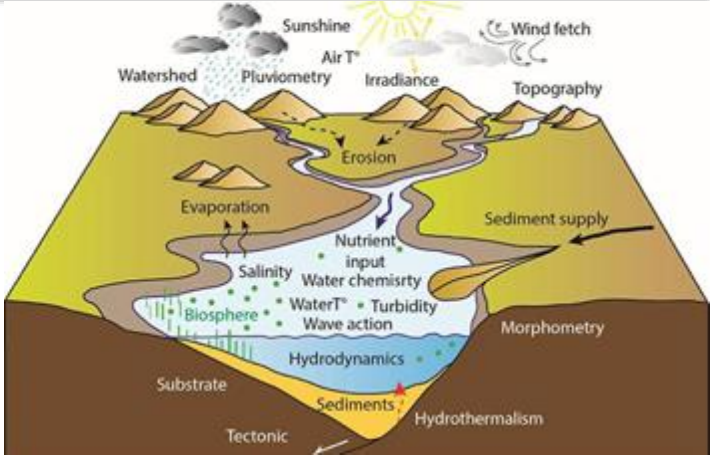
Red dashed boxes indicate diagnostic reflector character for each seismic facies.

Lacustrine sediments

https://sites.google.com/site/wvugeol616advancedsed/home/kory?tmpl=%2Fsystem%2Fapp%2Ftemplates%2Fprint%2F&showPrintDialog=1

Introduction





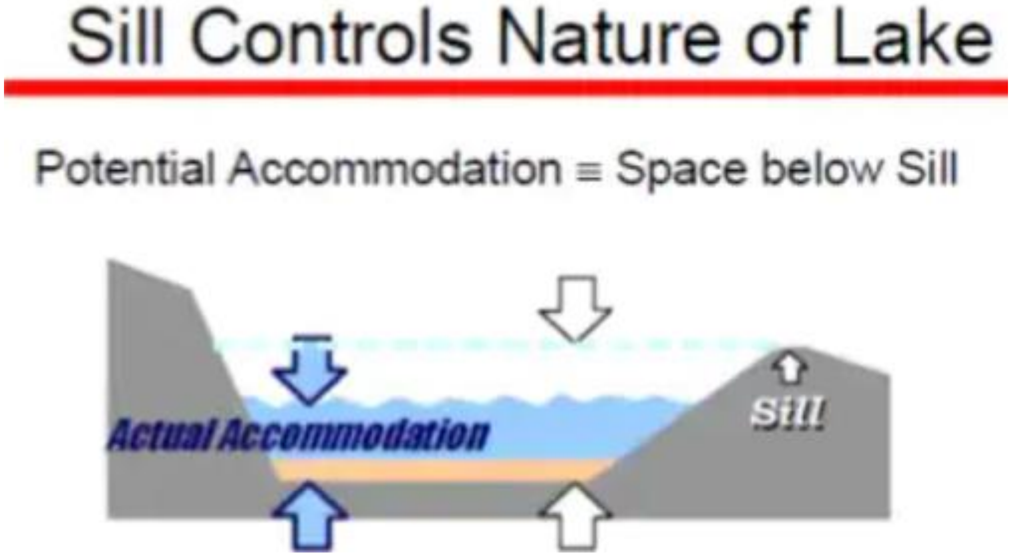
Lacustrine deposits are important, but relatively understudied terrestrial depositional environments. The discovery of large shale gas reservoirs in lacustrine systems and the development of hydraulic fracturing (fracking) has led to a renewed interest in exploring the lacustrine systems. Oxygen depleted waters near the base of lakes can preserve and breakdown organic material, creating oil shale's that serve as common source rocks in reservoirs.

Lacustrine deposits are often confused with marine deposits due to similar lithologies. The main distinguishing feature between lacustrine and marine systems is differences in sedimentary structures. Lakes have little wave/storm action, so lacustrine deposits are typically laminated shale/ mudstones deposited with limited sedimentary structures.
Because lakes are typically not influenced by eustatic sea level rise, lakes tend to shallow and coarsen upward with time. Lake systems also experience seasonal alterations in sediment infill. Lacustrine and marine systems can also be separated based on fossil assemblages.

Geomorphology and Modern Analog

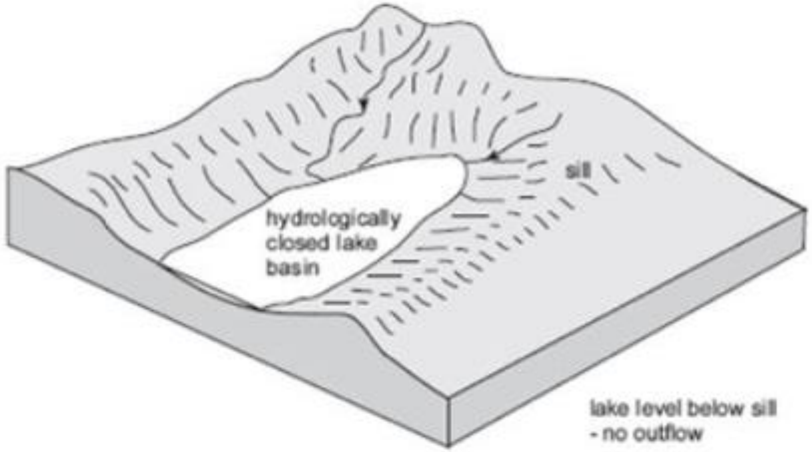
Lacustrine systems can form in a variety of settings. Large lakes may form in areas with sufficient accommodation space and inflow of water. Accommodation space is required in a closed system to trap water and sediment. Accommodation spaces typically include tectonic depressions, glacial depression, calderas, and karst sinkholes.

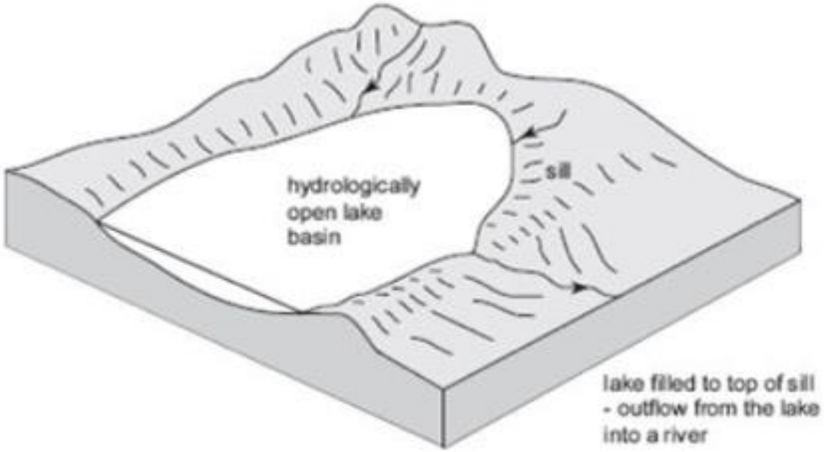
The barrier are called sills. If the lake level is above the sill, the lake is called open and overflow will be common. If the lake level is below the sill, water and sediment will be trapped behind the sill, and evaporation/dessication will occur if more water is not introduced into the system. Common features of a lake system include a fluvial system bringing water into the lake, a delta where sediment is deposited, and a deep lacustrine system where fine muds are deposited.


Sill Controls Nature of Lake

Potential Accommodation = Space below Sill

Lake Classification





Lacustrine systems can be classified as open or closed lakes.

Open lake systems input and output water and sediment from rivers, ground water, or other lakes. Open lake systems are freshwater and typically form stratified, organic rich shales. Clast dominated lakes often form in open systems due to influx of sediment and water from rivers. Clast dominated lakes are mud dominated in the center, and sand/cobble dominated near the beach.

Closed lake systems do not recieve, or output sediment and water. Water can be either fresh or saline with lithologies including organic-rich shales, carbonates, and evaporites. Closed lake systems can often form saline lake systems. Closed lake systems tend to be evaporate and carbonate rich due to precipitation and little influx of water sedimentation.

Modern Example: Crater Lake

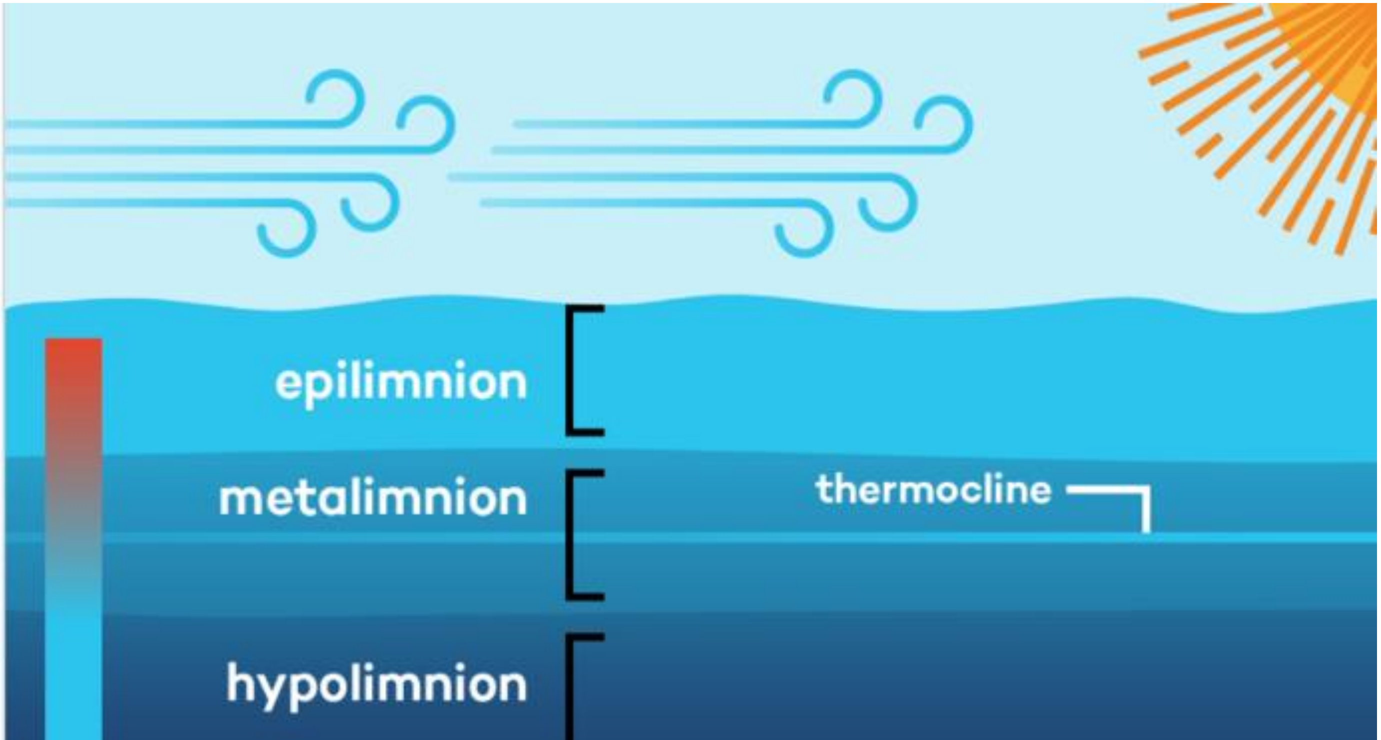
Crater Lake, Oregon, formed in the collapsed cadera after the Mazama eruption 7,700 years ago. Following the eruption, the magma chamber was drained and the mountain collapsed. The caldera is over 5 miles in diameter, and the caldera is 600 m deep, making it one of the deepest lakes in North America. The Caldera infilled with rain water and snow melt. The Lake is a closed system, with no inflow from other rivers. Water enters the lake through precipitation and flow through rocks, and leaves through evaporation.

© FRANCOIS GOHIER/ARDEA/CATERS NEWS

Due to the lack of river channels entering the basin, sedimentation is limited. Sedimentation is mainly derived from mass wasting deposits of volcanic rocks on the side. Pelagic sediments can also ooze out. Fine grained deposits of mud and sand can be transported by wind, or eroded by the edges. The bottom of the basin is composed of small volcanoes, while the sides are composed of colluvial deposits near the edge of the crater.

Stratification

Temperature stratification forms due to the higher density of hot fluids. The Epilimnion is the top of the lake, which is oxygenated. The middle layer is the Metalimnion, which contains the thermocline. The bottom is the Hypolimnion, which is anoxoic, cold water. The colder water will typically be trapped on the bottom, while hotter water will be trapped above the thermocline. Very fine sediment can be trapped above the thermocline boundary. Stratification can also occur due to salinity, with more saline water trapped under less saline water (hylocine).



Oxygen-rich water will be trapped on the upper surfaces of water, while oxygen-depleted water will be closer to the bottom. The anoxic conditions at the bottom of lakes will preserve organic matter and create kerogen rich shales that are common source rocks.

Streamflow and Waves/shore processes

Inflowing streams will disrupt pre-exisiting stratification. In overflow, water will float above the thermocline. If the water is cold and dense enough, it can sink to the bottom in underflows. Cold water will also drag sediment down with it, creating small scale turbitide deposits. Stream flow varies seasonably. Melting of snow melt will introduce high discharge of cold water into lacustrine systems. Stream flow will often deposit the coarsest sediment near the margin in deltatic deposits, with finer material deposited offshore.

Waves are low intensity compared to oceans. There are no tides in lakes, although lake level can transgressive/regressive as water level changes. Wave action will rework sediment, creating small climbing ripplies. Hummocky cross stratification is common in storm influenced settings.

An example of stratified mud deposits that are the most common features in lacustrine systems

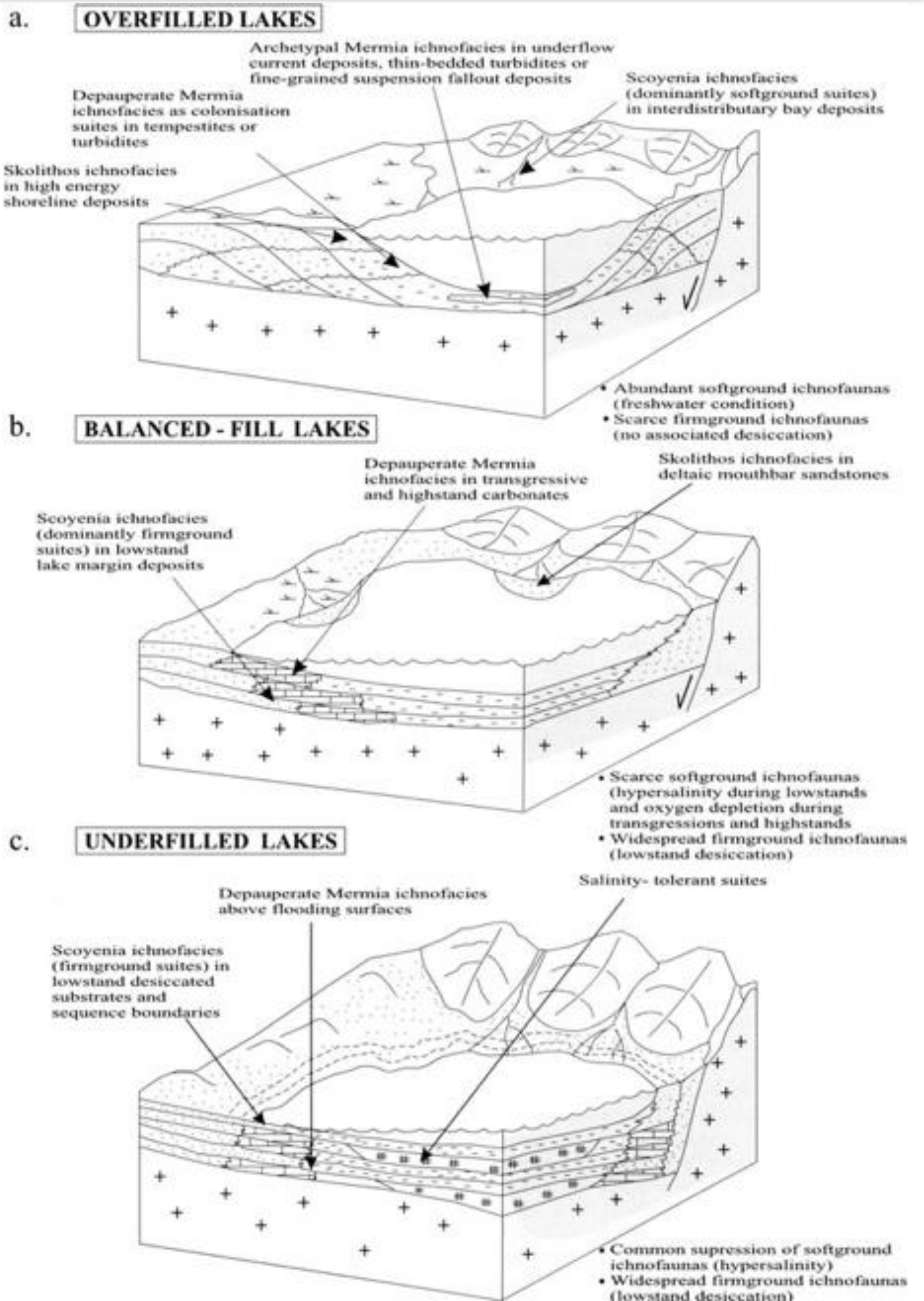
Groundwater and Chemistry

Groundwater is discharged into lacustrine systems through springs. In arid regions, influx of water may be entirely through ground water. Ground water influx into lakes occurs mainly on the sandier margins. Ground water cannot penetrate through the deeper, muddier shale on the bottom due to its low permeability. Evaporate and carbonate minerals will precipitate on the margin where ground water inflows/outflows from lakes, and these are often distinguishing features of arid lakes in the rock record.

Chemical sediment can predominate in lacustrine systems, producing carbonate and evaporate deposits with salinities higher then oceans (see acid-saline lakes). Precipitation of lacustrine carbonates can also occur due to fluctuations in pH. Carbonate ions are derived from surrounding limestones. Typical carbonate lacustrine sediments are called oncolites.

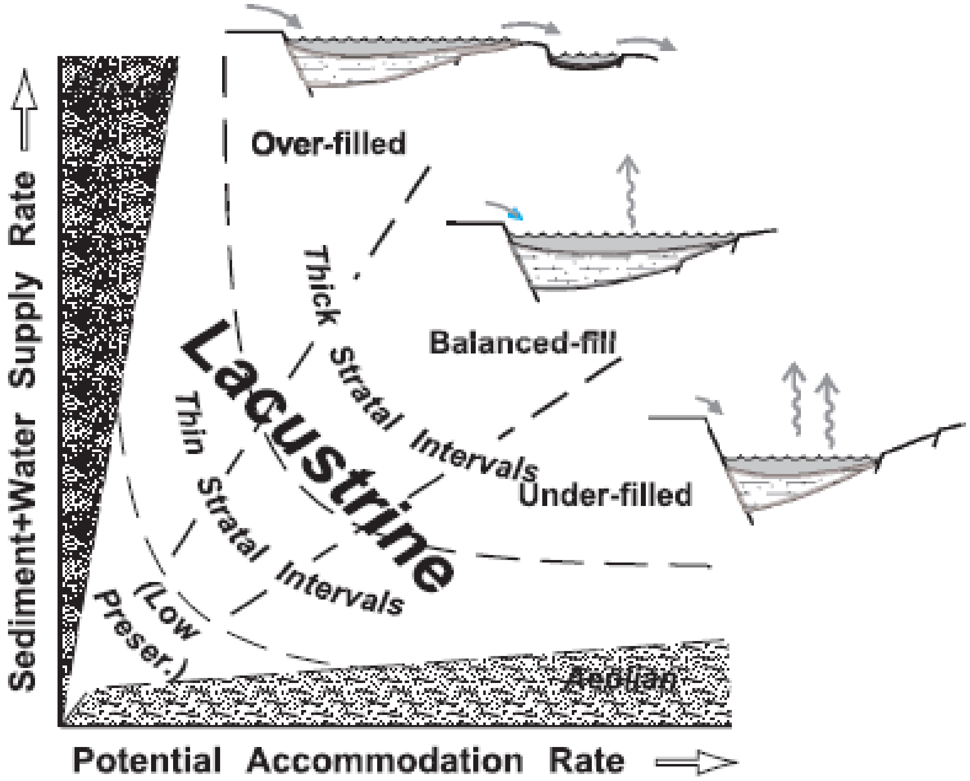
Accomodation space

If accommodation space increases faster then water-sediment infill rate, the basin will be **underfilled** and will typically contain evaporate and lacustrine carbonate precipitated minerals. In **balanced** basins, sediment water inflow into and out of the the basin matches the accommodation space. With high sediment-water influx into the basin vs little accommodation space, the basin will **overflow**.



Controls on Depositional System Evolution

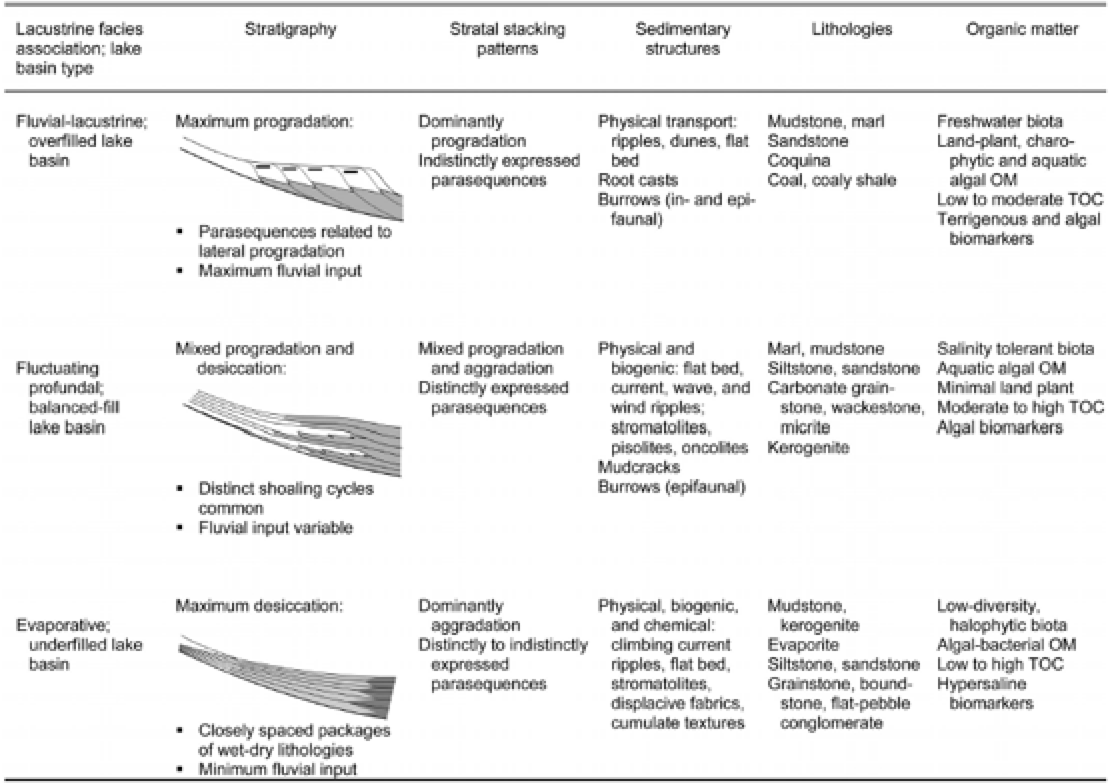
Accommodation space is typically created through **tectonic** processes. Rift basins commonly result in graben or half graben structures. Collision can also create create accommodation space by flexure. The foreland basin can often fill with sediment and the forebuldge will serve as the sill. Cratonic sag can occur in old dense, crust forming intracratonic basins.



Changes in **climate** will influence the amount of material that enters or leaves a lake basin. If climate is arid, the influx of water into the basin will decrease, causing lake level to drop and mineral formation will dominate. If the climate is wet, increased volumes of sediment and water may enter the basin, overfilling it. High discharge sedimentary structures can also form, such as ripple marks. Storms may create hummocky cross stratification in the beach deposits.

Facies related to inflow and outflow of water

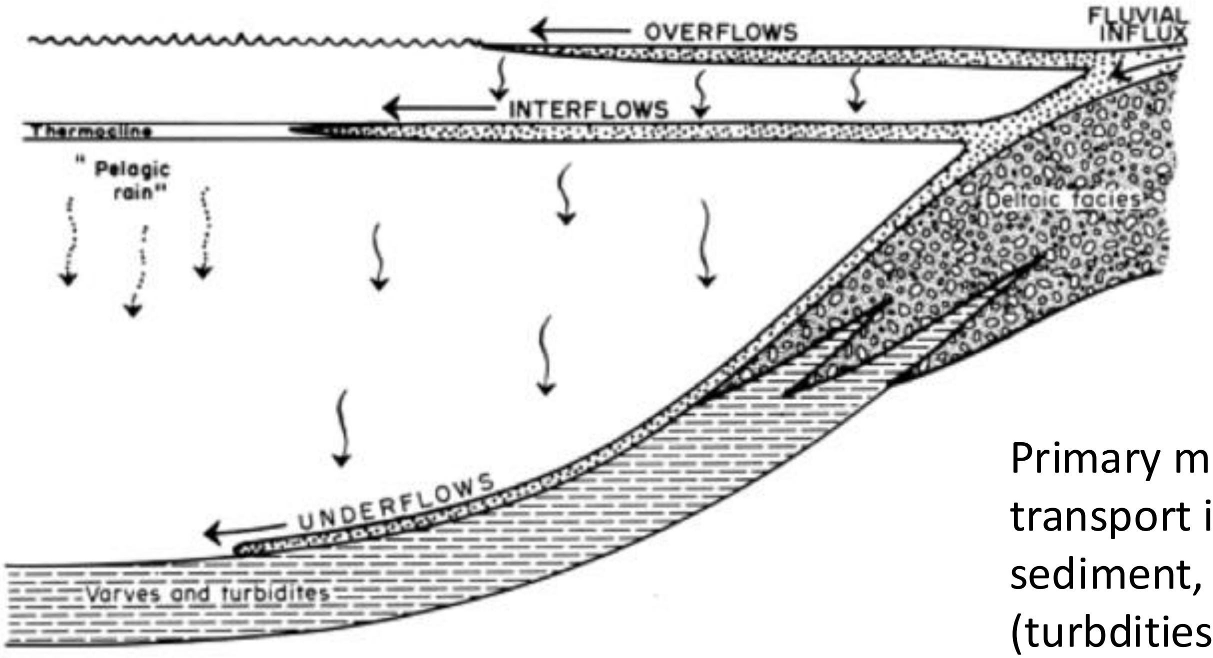
In a **overfilled lake**, there is progradation away from river to the lake margins. Parasequences develop related to alterations in fluvial input and water level. Sedimentary structures include ripples, dunes, and flat beds. Lithology can include sandstone, mudstone, coal, and limestone. In a system **where fluvial input is variable**, there are mixed episodes of progradation and dessiciation. These are expressed as distinct parasequences. Sedimentary structures are similar to the over filled lake basin, but include mudcracks, stromatolites, pisolites, and oncolites. Carbonates are more common.



Lacustrine facies association; lake basin type	Stratigraphy	Stratal stacking patterns	Sedimentary structures	Lithologies	Organic matter
Fluvial-lacustrine; overfilled lake basin	Maximum progradation: • Parasequences related to lateral progradation • Maximum fluvial input	Dominantly progradation Indistinctly expressed parasequences	Physical transport: ripples, dunes, flat bed Root casts Burrows (in- and epi-faunal)	Mudstone, marl Sandstone Coquina Coal, coaly shale	Freshwater biota Land-plant, charophytic and aquatic algal OM Low to moderate TOC Terrigenous and algal biomarkers
Fluctuating profundal; balanced-fill lake basin	Mixed progradation and desiccation: • Distinct shoaling cycles common • Fluvial input variable	Mixed progradation and aggradation Distinctly expressed parasequences	Physical and biogenic: flat bed, current, wave, and wind ripples; stromatolites, pisolites, oncolites Mudcracks Burrows (epifaunal)	Marl, mudstone Siltstone, sandstone Carbonate grain-stone, wackestone, micrite Kerogenite	Salinity tolerant biota Aquatic algal OM Minimal land plant Moderate to high TOC Algal biomarkers
Evaporative; underfilled lake basin	Maximum desiccation: • Closely spaced packages of wet-dry lithologies • Minimum fluvial input	Dominantly aggradation Distinctly to indistinctly expressed parasequences	Physical, biogenic, and chemical: climbing current ripples, flat bed, stromatolites, displacive fabrics, cumulate textures	Mudstone, kerogenite Evaporite Siltstone, sandstone Grainstone, bound-stone, flat-pebble conglomerate	Low-diversity, halophytic biota Algal-bacterial OM Low to high TOC Hypersaline biomarkers

The third facies associated in the **evaporative underfilled lake** basin, which is a closed lake basin dominated by evaporation. Sedimentary structures include climbing current ripples, and dessiciation cracks. Lithology can include mudstone, evaporate, siltstone, sandstone, and carbonate minerals.

Depositional Processes and Depositional Facies



Water infills lacustrine systems through rivers, rain, and groundwater, and will leave through similar methods or evaporation.

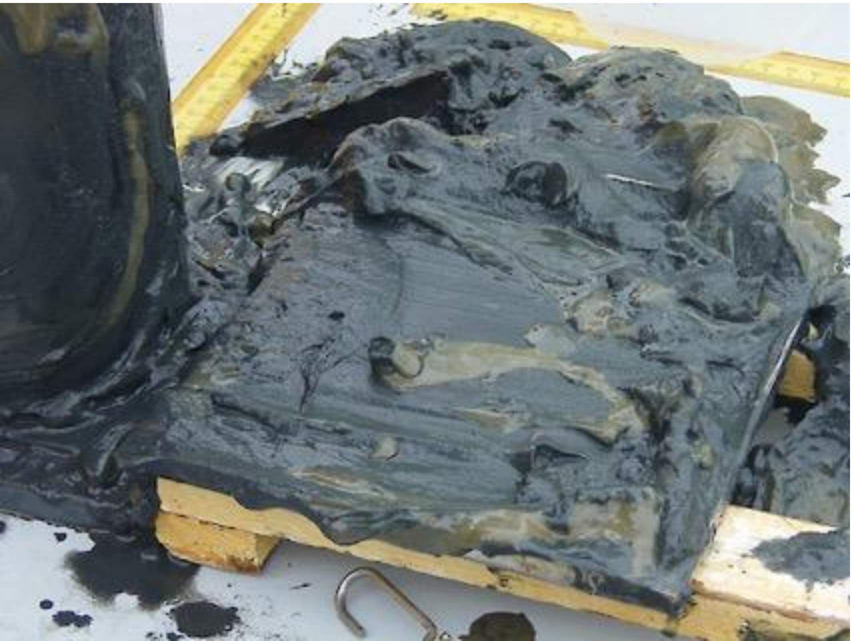
Model showing the main settings and sediment deposition patterns in a lacustrine system (Galloway and Hobday, 1993). Sediment originates from the fluvial channel, and is deposited in the fluvial delta, or in overflows/underflows. Overflows occur over the thermocline, while underflows occur under it.

Primary mechanisms of sediment transport include wind blown sediment, gravity processes (turbdities), and river infow. The supply, ratio of water to sediment, influences lake fill. The facies of a lake changes with time, with evaporites in under filled lakes, fluctuating profundal in balanced fill lakes, and fluvial-lacustrine in over filled lakes.

Depositional Facies

Facies associations with lacustrine systems are related to the main depositional processes. Lacustrine Delta facies consist of delta deposits immediately adjacent to river inflow into the river. They typically contain a coarsening upward sequence, gilbertian foresets, and climbing ripples. Gilbert deltas consist of coarse grained, well bedded deposits. Turbitide sequences can be present down fan.

Wind tidal flat facies: Although lacustrine systems do not have tides, shoreline deposits do bear similarities to tidal shoreline deposits. Lake shorelines contain small diverse, small scale structures, including lenticular, wavy bedding, flasar bedding, mud drapes, and dessiciation cracks. There can also be bioturbation, including root and burrowing structures.



Deepwater facies: Typically flat, laminated shale and mudstone. High organic content due to anoxoic conditions.

climbing ripples

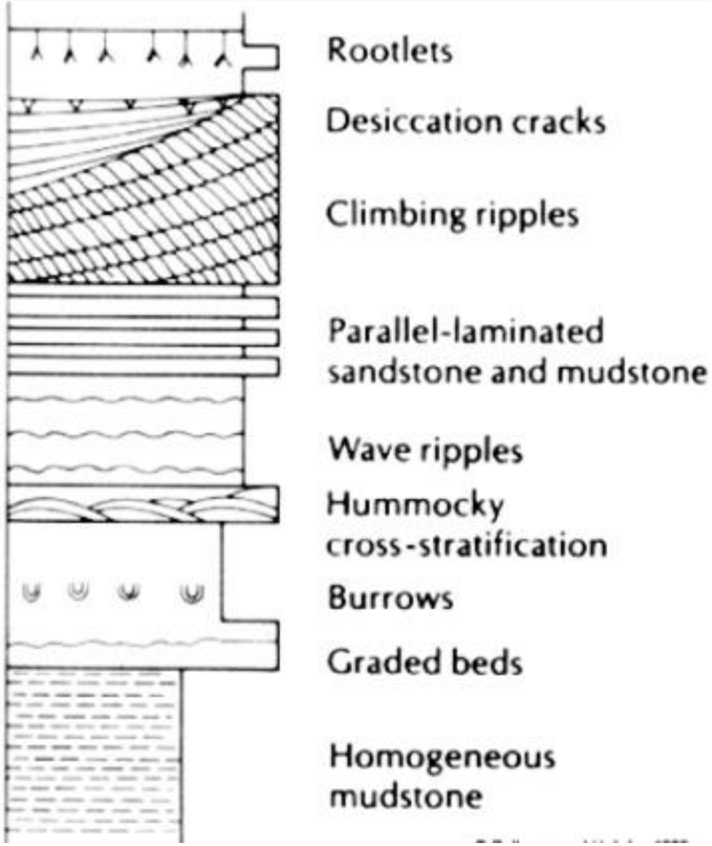
What they generally have that oceans lack:

Seasonal alternation of turnover and stagnation.
Because lakes tend, geologically speaking, to be ephemeral, their deposits are often sandwiched between adjacent continental deposits.
Because they are comparatively deficient in critters with CaCO3 skeletons, carbonate deposits are likely to occur as direct precipitates.

As such, laminated fine-grained deposits dominate all but the margins of ancient lake deposits. If the laminations show alternating seasonal variation, they are called varves. They are commonly characterized by a low abundance, low diversity fauna.

http://hays.outcrop.org/images/glaciers/press4e/figure-16-21-5.jpg

Facies Models



coarsening up lacustrine sequence, Karoo Basin, South Africa (Galloway and Hobday, 1983)

The deepest part of the lacustrine system contains homogeneous, horizontally laminated mudstone. The deepwater deposits contain anoxoic conditions with potential for black shale deposits. Above the mudstone are graded bed deposits. Graded bed deposits are found on the slope of lacustrine systems, and are coarsening up .

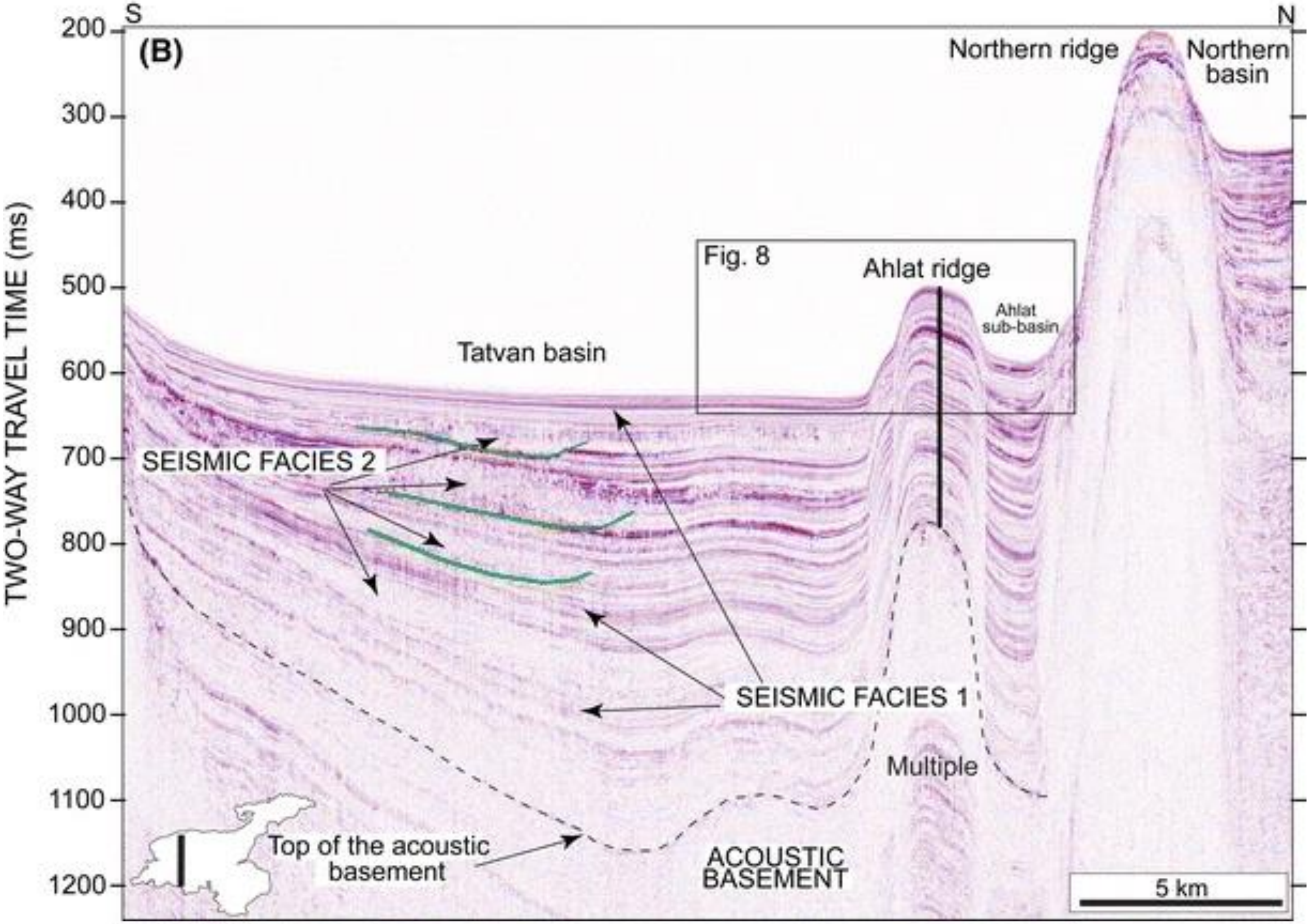
Burrows are also found close to the shelf and lacustrine shore. Hummocky cross-stratification forms in shallow waters due to storm events. Wave ripplies occur in a shallow water beach setting due to the gentle wave action of water. Parallel laminated sandstone and mudstone are deposited during periods of fine and coarse deposition from river influx. Climbing ripples represent the vertical and horizontal aggradation of sediment from unidirectional flow, often from rivers. Desiccation cracks are found in settings with occasional influx of water, probably along the side of a river or up on a beach.

Lake Van

Sedimentary evolution of Lake Van (Eastern Turkey) reconstructed from high-resolution seismic investigations.

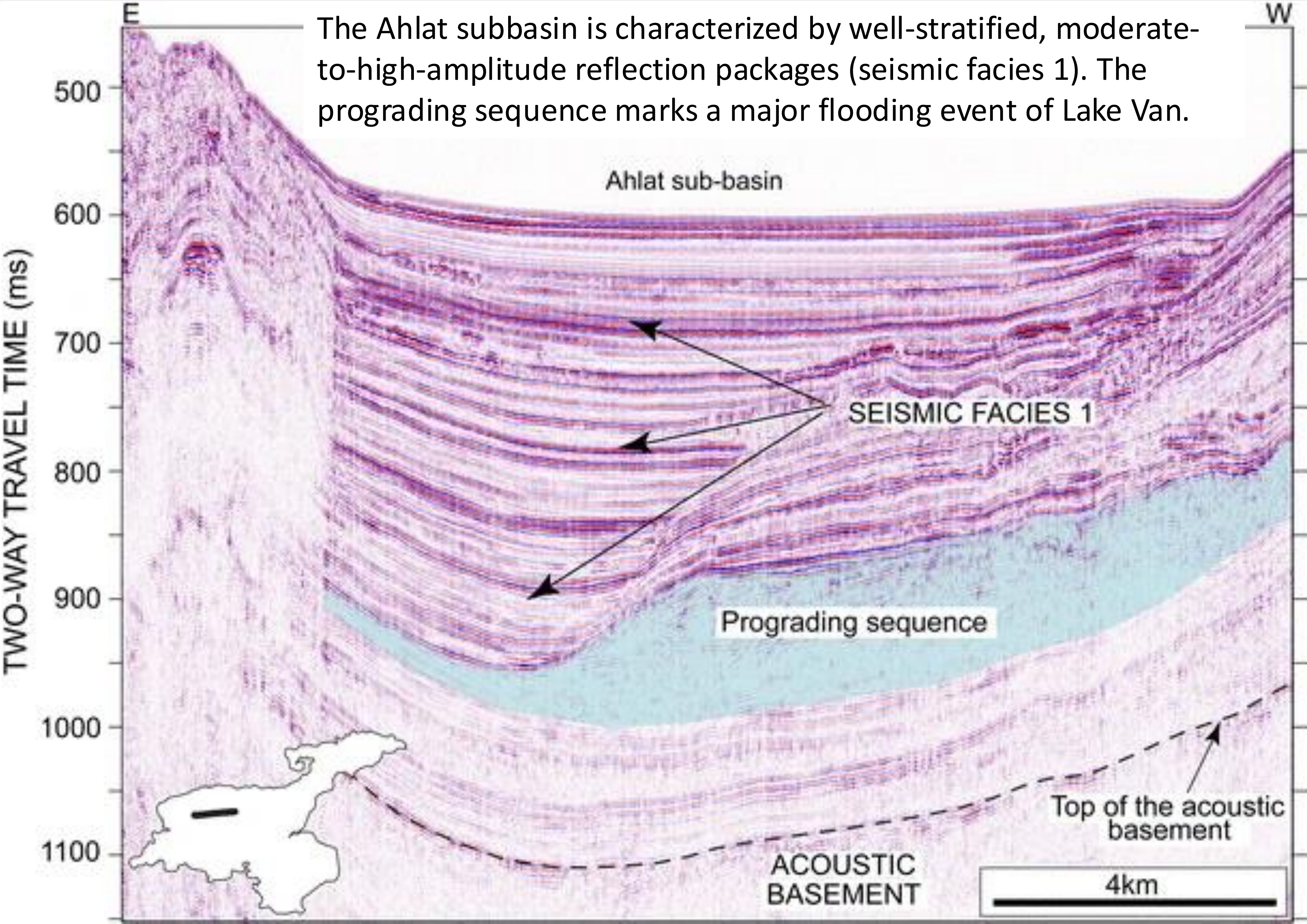
Cukur et al. (2013) Int J Earth Sci 102, 571–585

seismic reflection profile crossing the Tatvan basin.



The sub-surface section in the Tatvan basin is largely characterized by well-stratified, moderate-to-high-amplitude, continuous reflections (seismic facies 1) that are interpreted as lacustrine sediments and tephra layers. Transparent-to-chaotic seismic facies (seismic facies = 2) are seen locally and are interpreted as mass-flow deposits.

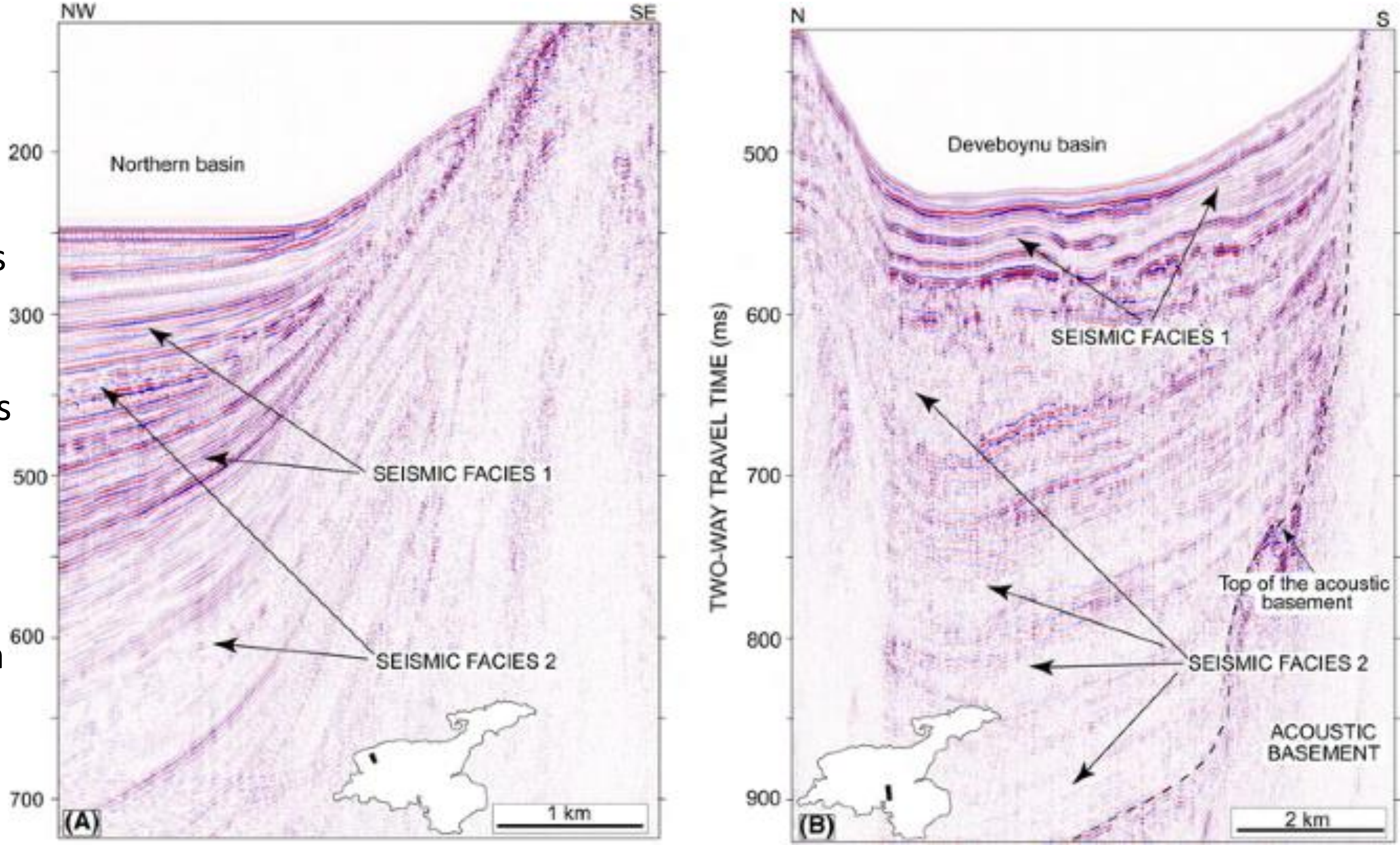
The Ahlat subbasin is characterized by well-stratified, moderate-to-high-amplitude reflection packages (seismic facies 1). The prograding sequence marks a major flooding event of Lake Van.



Seismic reflection profiles from the Northern basin (a) and the Deveboynu basin (b).

The sedimentary section in the Deveboynu basin is dominantly characterized by low-to-variable-amplitude, discontinuous or chaotic reflections (seismic facies 2). Seismic facies 1 (lacustrine and tephra layers) is seen in the upper part of the basin

The Northern basin is dominated by seismic facies 1.
Seismic facies 2 (mass-flow deposits) are also seen locally.



Aeolian sediments

The work on both modern and ancient desert sediments has been stimulated by economic pressures.

Aeolian dune sandstones, which commonly have high initial porosities, may be important aquifers and hydrocarbon reservoirs, as, for example, the gas fields of the North Sea. Ancient playa lake deposits are a rich source of evaporite minerals and desert alluvium may provide hosts for mineralization.

Aeolian deposits

Aeolian deposits are sediments transported by the wind.

The most important environments of aeolian transport and deposition are deserts, beaches and glacial outwash plains.

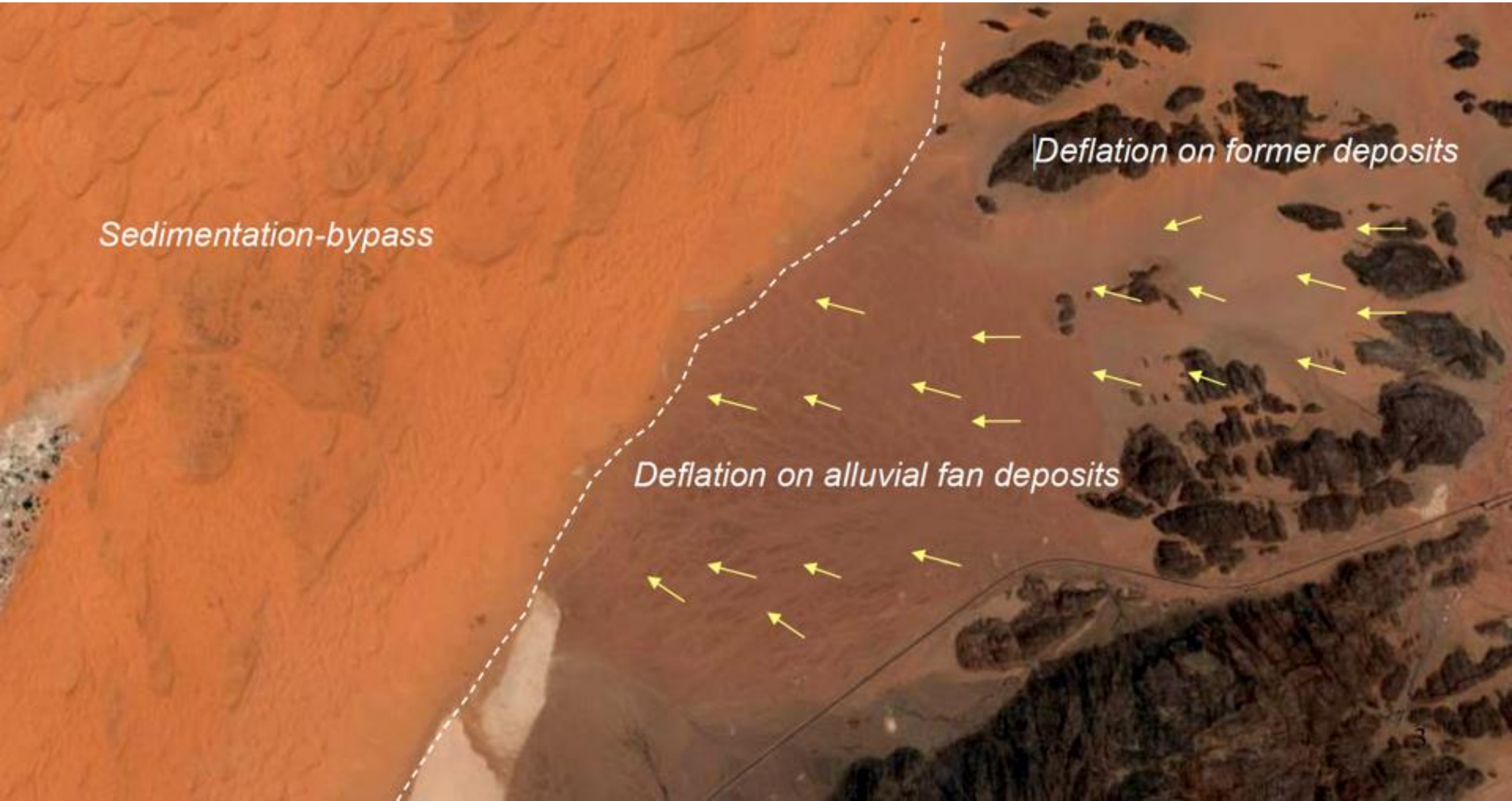
Mechanical weathering supplies large quantities of sand for transport.

Desert regions are subject to strong winds capable of moving large quantities of material.

Deserts cover 30% of present day land surface.

Deflation/accumulation areas

A deflation area (i.e. where sediment is picked up by winds) and a by-pass/accumulation area (where sediment is incorporated in the geological record) can be generally distinguished

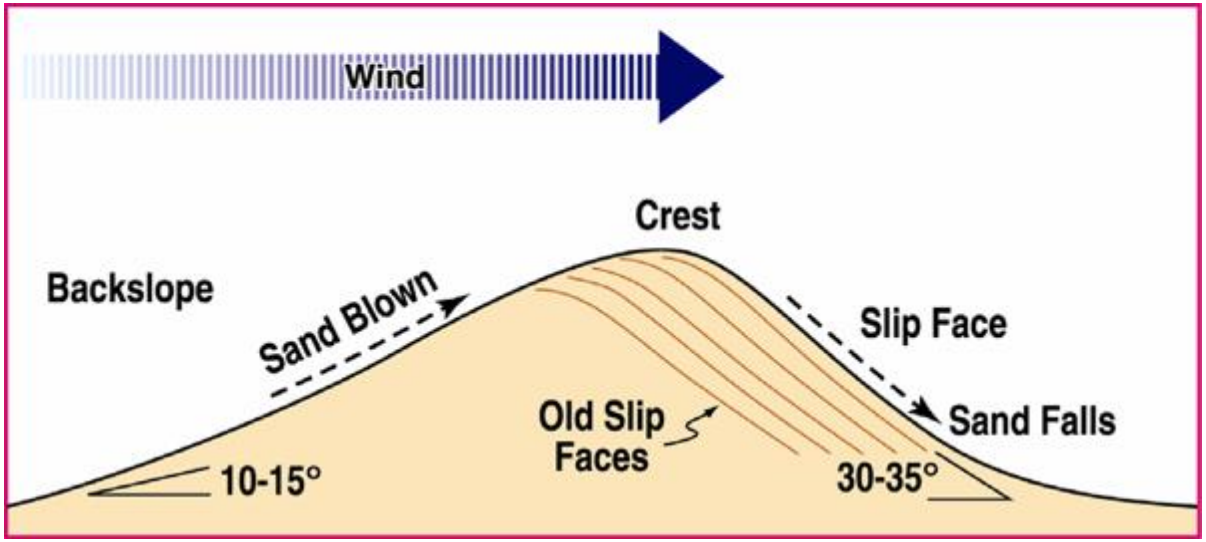


deposition

sand which can be accumulated in the shadow zones close to obstacles (gravels or bushes)

sedimentary structures

The main eolian sedimentary structures are dunes and ripples.



Bedforms

Ripples – 6 cm to 1+ m wavelength - rapid migration (>1 km/yr). Ripples occur on dune stoss slopes and (<20°).

Dunes - 10 to 100 m wavelength - moderate to slow migration (10-100 m/yr).

Draa - a very large eolian landform, with a length of several kilometers and a height of tens to hundreds of meters, and which may have superimposed dunes. - very slow migration(<10 m/yr).

In addition, aeolian processes may deposit plane beds, adhesion ripples, wavy lamination, crinkly lamination and brecciated lamination

A draa in Sossusvlei, Namibia.

Distribution of sedimentary structures

The main eolian sedimentary structures are dunes and ripples. The distribution of sedimentary structures within eolian systems is not uniform, since it reflects the amount of available sediment and the interplay between eolian and other depositional systems.

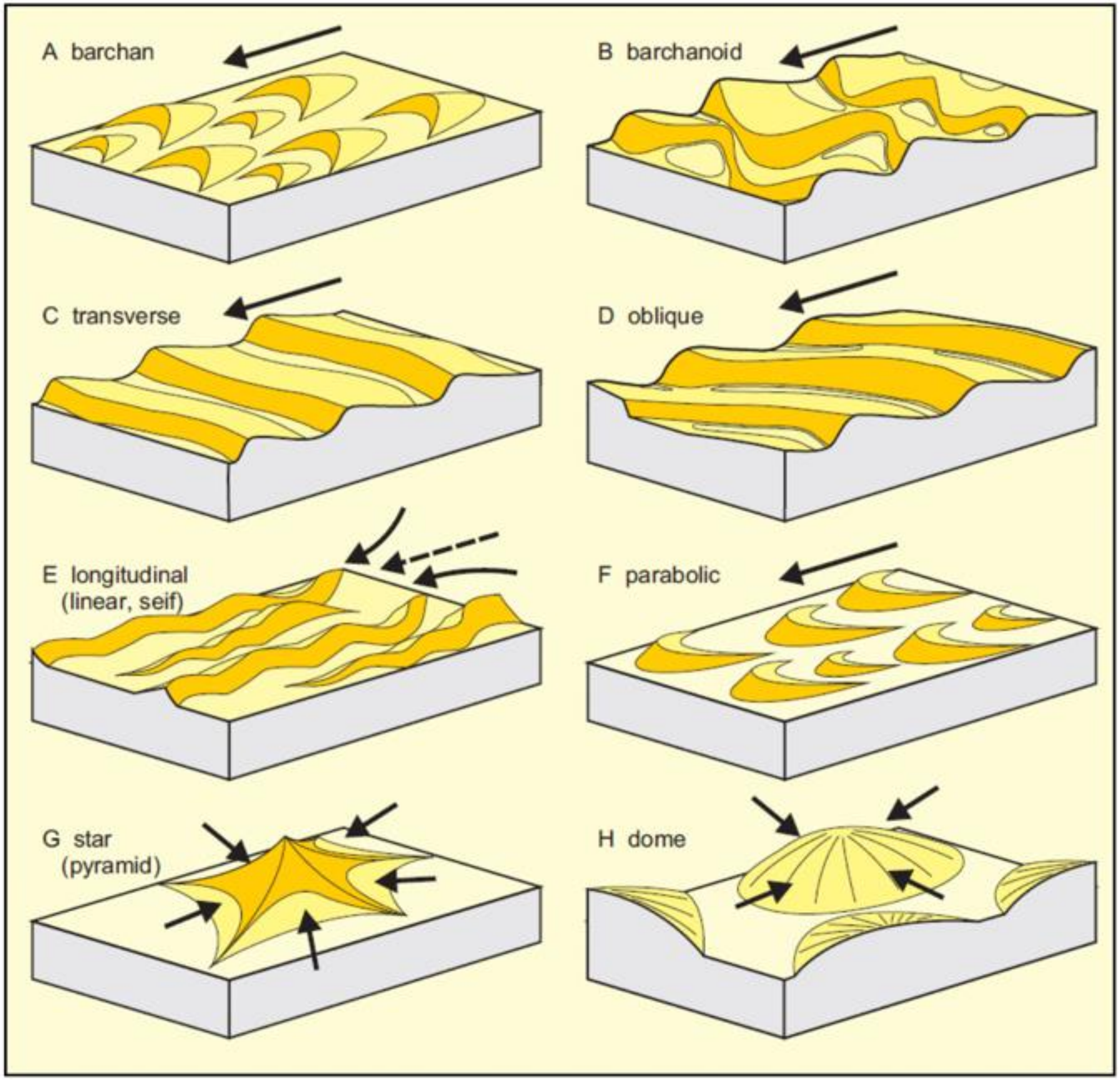
Alternation of depositional systems

Dune fields characterize desertic or coastal areas (i.e. non-deltaic coasts), thus being the depositional sites of thick eolian deposits. Dunes are the most prominent bedforms in terms of sediment volume, although ripples are also common. Eolian deposits often alternate vertically with deposits of nearby depositional systems (e.g. fluvial deposits). Such an alternation may result from alternating different climatic regimes.

Cross stratification

Analogously to subacqueous dunes, eolian dunes originate cross-stratified sets, up to few decameters thick.

Dune shaes



Opposite to subacqueous dunes,eolian dunes shows a variety of shapes, due to the fact that wind can blow from different directions during different time span. Dome and star shapes are indicative of higly variable winds. Dunes with well-defined crests, either transversal orparallel to wind directionare a typical feature ofareas with nearly steady winds.

Characteristics of aeolian deposits

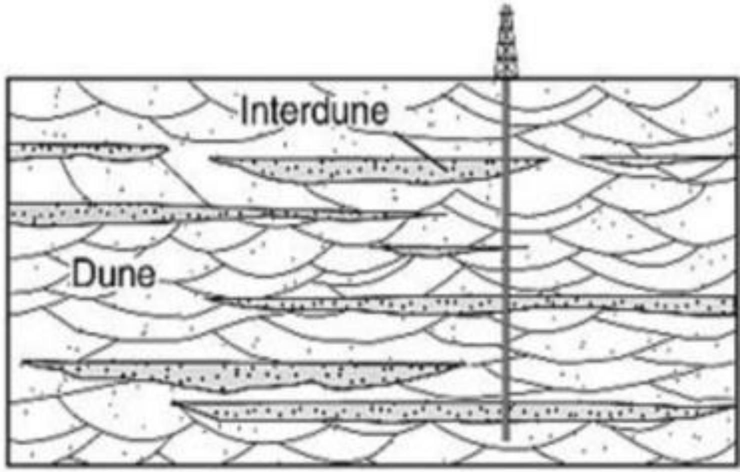
- lithologies –mainly sand and silt
- mineralogy – mainly quartz, with rare examples of carbonate or other grains
- texture – well- to very well-sorted fine to medium sand
- fossils – rare in desert dune deposits, occasional vertebrate bones
- bed geometry – tabular or large scale lenses of sand
- sedimentary structures – large-scale dune crossbedding and parallel stratification in sands (2D /3D cross bedding)
- palaeocurrents – dune orientations reconstructed from cross-bedding indicate wind direction .
- colour – yellow to red due to iron hydroxides and oxides
- facies associations – occur with alluvial fans, ephemeral river and lake facies in deserts, also with beach deposits or glacial outwash facies

Key Criteria for recognizing dune deposits:

- well sorted
- pitted, frosted grains
- thick cross bed sets
- high angle foresets

Implication for petroleum geology

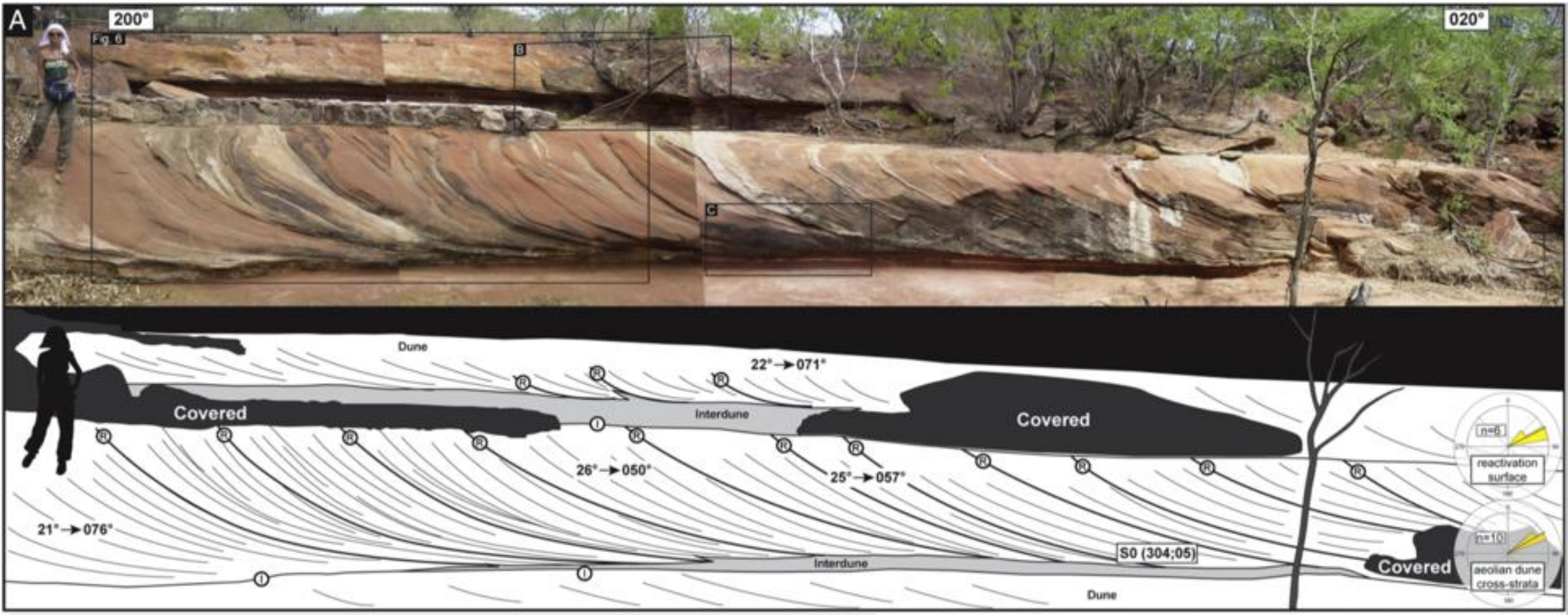
Given the overall lack of fine grained sediments, eolian deposits are commonly prone to be good reservoirs, although characterized by an high complexity.
Complexities of eoilan reservoirs arise from:
i) fine-scale cross-stratification at various angles;
ii) occurrence of related fluvial, playa and marine facies;
iii) existence of differential diagenesis.
All these features contribute to a compartimentalization and an high degree of permeability anisotropy



In eolian successions, reservoir compartimentalization or permeability anisotropy are strictly linked with major bounding surfaces. As a consequence a detailed knowledge of internal architeture and facies distribution is required during exploration of eolian deposits. Further changes in local porosity/ permeability are linked with changes in cementation within laminae, which is commonly controlled by sedimentary and diagenetic processes and interaction between different depositional environments. A exhaustive knowledge of sedimentary processes and their products is therefore required in the frame of a detailed reservoir characterization

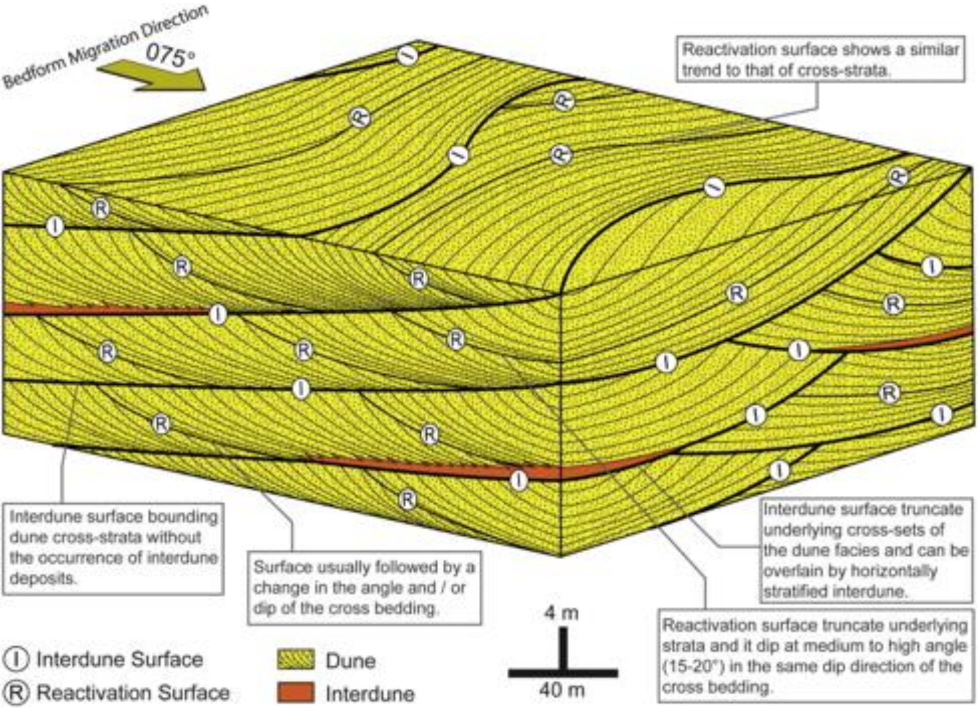
Facies architecture and stratigraphic evolution of aeolian dune and interdune deposits, Permian Caldeirão Member (Santa Brígida Formation), Brazil

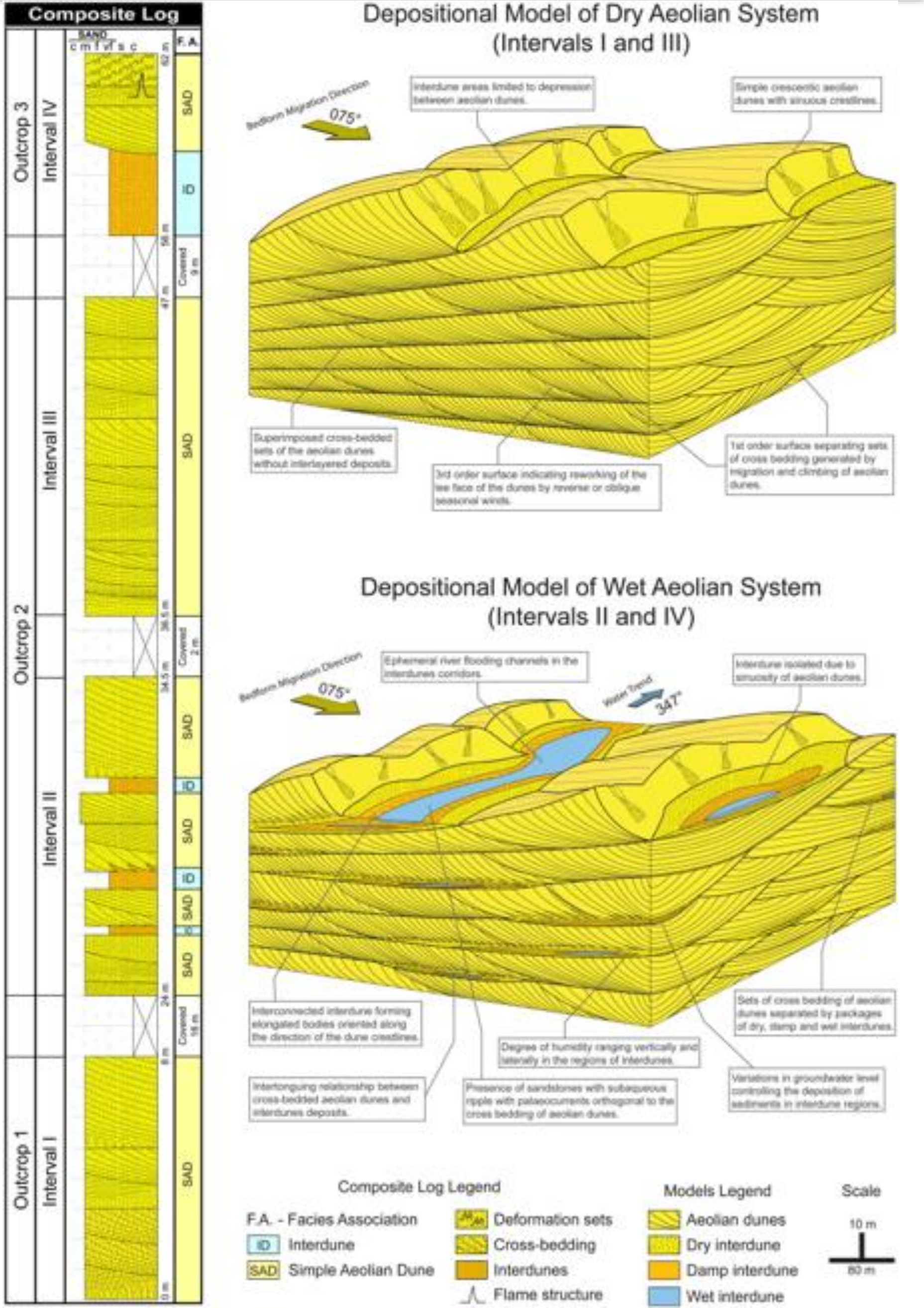
Herbert et al., 2016, Sedimentary Geology 337, 133-150



Photomosaic and interpretative outcrop panel showing the geometry and relationships between dune and interdune sandstones.

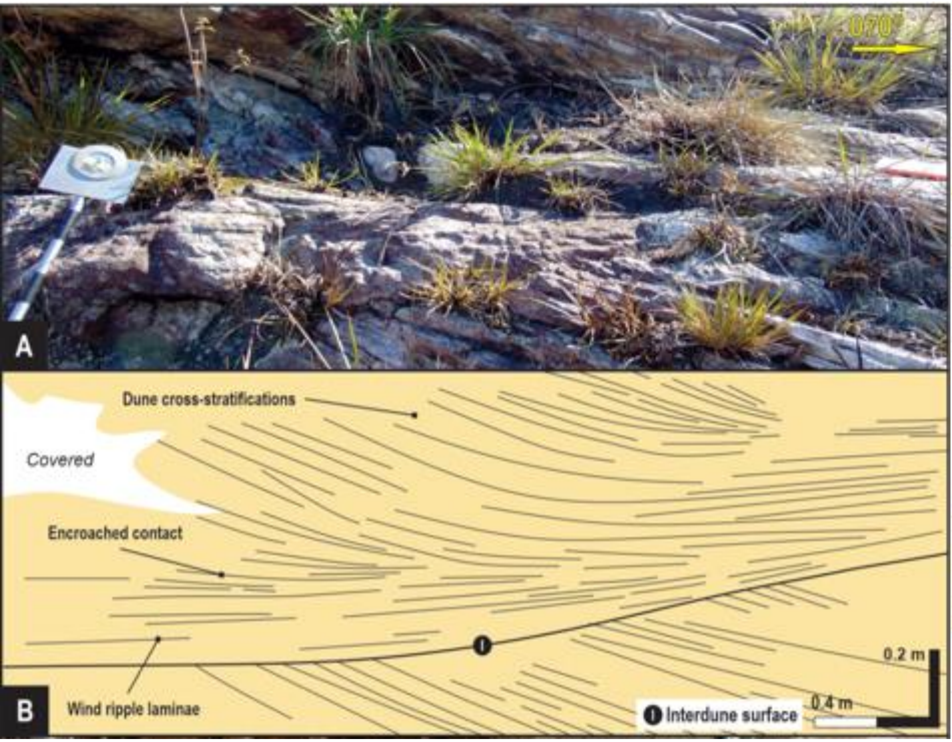
Diagram block showing the bounding surface hierarchy to the aeolian dunes of the Caldeirão Member.



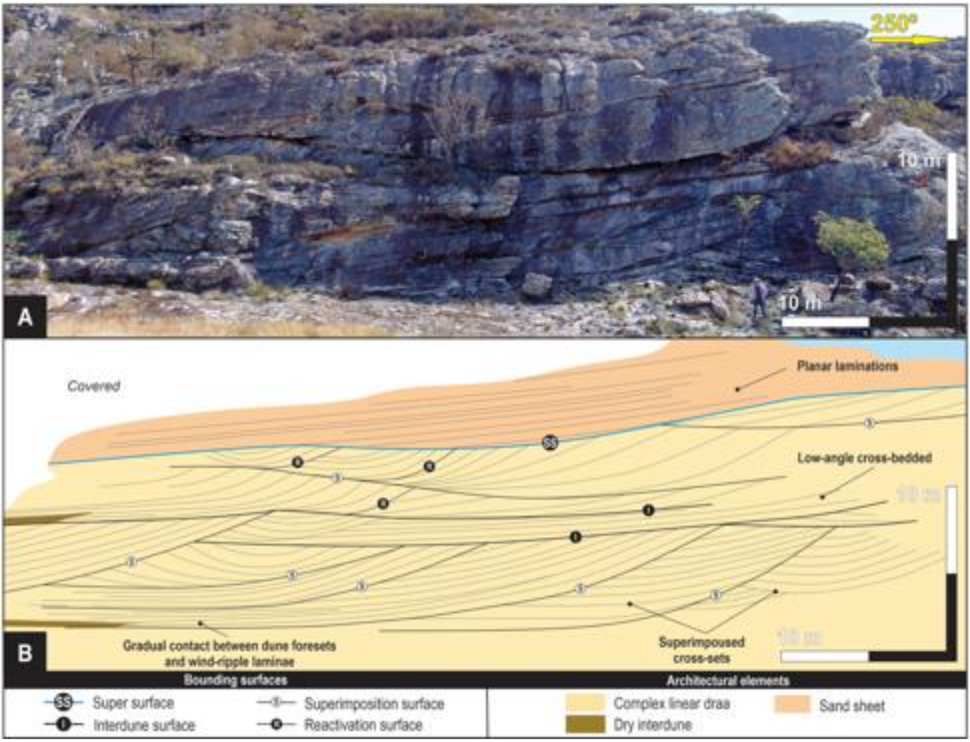


Composite log and summary three-dimensional architectural models for dry aeolian system (Intervals I and III) and the wet aeolian system (Intervals II and IV) to studied outcrop section of the Caldeirão Member.

Morphology, accumulation and preservation of draa systems in a Precambrian erg (Galho do Miguel Formation, SE Brazil). Ferreira Mesquita et al., 2021, Sedimentary Geology 412, 105807



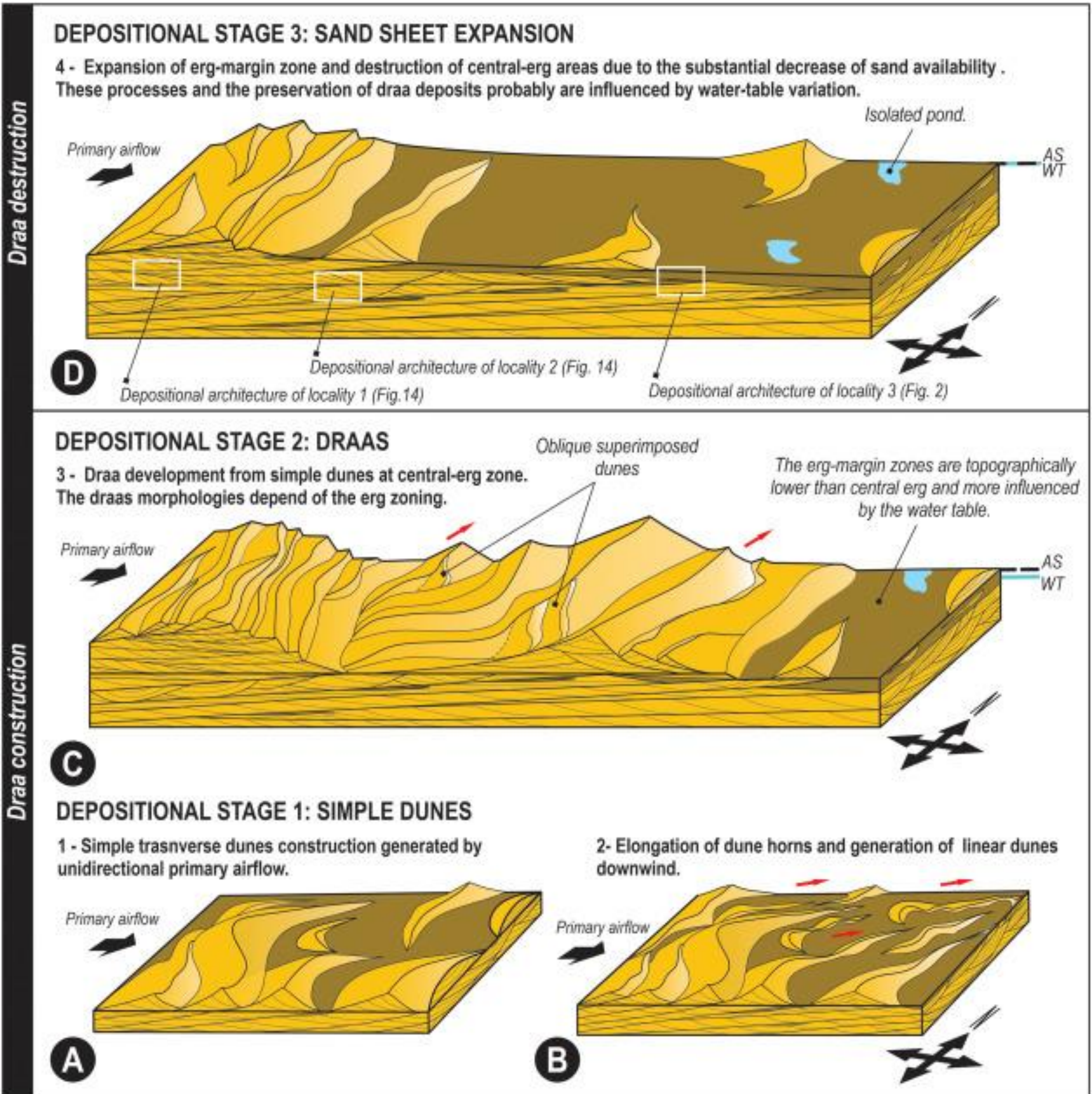
(A) overview and (B) sketch of lens-shaped sets bounded at the bottom by planar and near-horizontal erosive surface (interdune surface) and by aeolian dune deposits.



(A) overview and (B) interpretation in palaeowind transverse-section. This succession is interpreted as residual deposits of complex linear draa with important lateral migration.

Depositional model

(A) and (B) Depositional stage 1: simple dune construction. (C) Depositional stage 2: draa development. (D) Depositional stage 3: sand sheet expansion. The red arrows represent secondary airflows probably originated by the interference of primary airflow with the draa/dune topography, as identified in current aeolian models. Legend: [AS] accumulation surface; [WT] water table level.



DEPOSITIONAL STAGE 3: SAND SHEET EXPANSION

4 - Expansion of erg-margin zone and destruction of central-erg areas due to the substantial decrease of sand availability . These processes and the preservation of draa deposits probably are influenced by water-table variation.

DEPOSITIONAL STAGE 2: DRAAS

3 - Draa development from simple dunes at central-erg zone. The draas morphologies depend of the erg zoning.

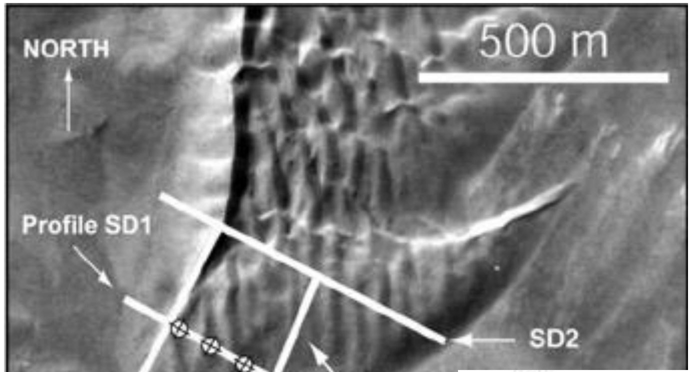
The erg-margin zones are topographically lower than central erg and more influenced by the water table.

DEPOSITIONAL STAGE 1: SIMPLE DUNES

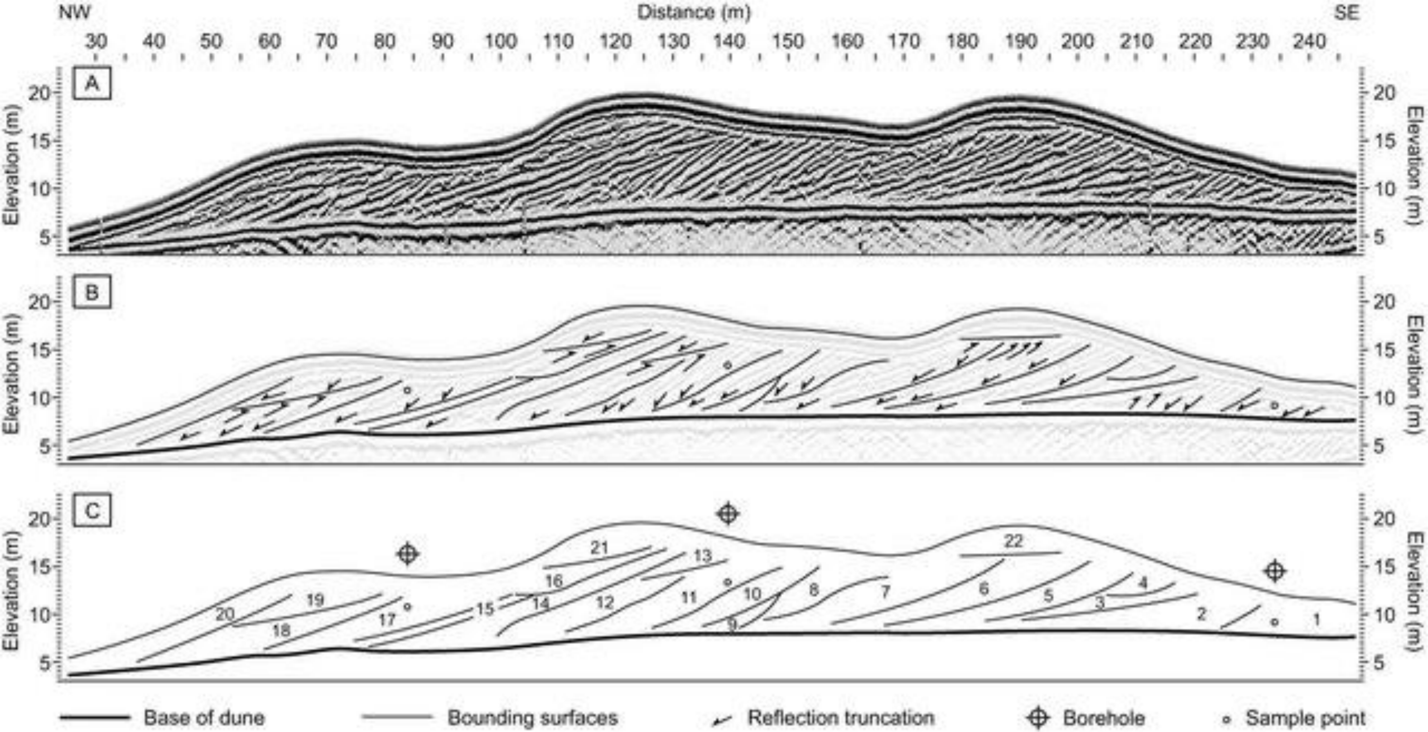
1 - Simple trasnverse dunes construction generated by unidirectional primary airflow.

2- Elongation of dune horns and generation of linear dunes downwind.

Combining ground penetrating radar surveys and optical dating to determine dune migration in Namibia



Thick sets of cross-stratification indicate when the dune was most active, whereas thin sets of cross-stratification are interpreted to indicate the increased prevalence of wind reversals and lower rates of dune migration, with bounding surfaces formed during periods of stabilization, non-deposition or erosion.



Bristow et al., 2005. Journal of the Geological Society