So Different, Yet So Similar: Comparing and Contrasting Siliciclastic and Carbonate Slopes*

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Abstract

Carbonate slopes have a tendency to be steeper than their clastic counterparts. Commonly the stabilization potential by binding of slope sediment and early cementation of carbonates is evoked to explain this difference. However, differences and similarities between clastic and carbonate slope systems with respect to their gross development, curvature, and angle of dip are only expressed if one evaluates slope settings that are affected by comparable extrinsic and intrinsic processes. The likeness of clastic continental slopes and cool-water carbonate platforms is great where deep shelves, low-slope angles and usually sigmoidal-slope profiles are typical. Coarse-grained deltas compare with tropical carbonate platforms. Both have steep depositional slopes, exponential and linear slope profiles, and coarse sediments originating from shallow-water depths. Exponential profiles are common on rimmed platforms because reefs are resistant to erosion and the platform edge therefore relatively stationary vertically. This also accounts for ice-covered margins because the grounding level of the ice limits vertical fluctuations. A special case for carbonates is the in situ accretionary slope factory with abiotic and biotically induced precipitates stabilizing and building carbonate slopes. However, in situ slope accretion and stabilization in itself do not necessarily explain the large-scale geometry of the platform flanks. It is more reasonable that the slope factory is insensitive to light and can therefore accrete during both low- and highstands. Thus, when a relative sea-level fall exposes the platform top and shallow-water carbonate production stops, in situ carbonate production continues in the slope realm. The combined effort of both types of sediment production and hence surplus allow the system to build-up to the angle of shear and constantly prograde. A direct comparison is coarse-grained fjord and lake deltas, where the inherent fast-prograding system, which is dominated by a mixture of coarse sand and rubble, obtains steep, planar slopes. Clearly, while sediment properties vary greatly, stark similarities in gross development, curvature, and angle are observed in comparable settings.

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AAPG 2012, Long Beach, California

Statoil

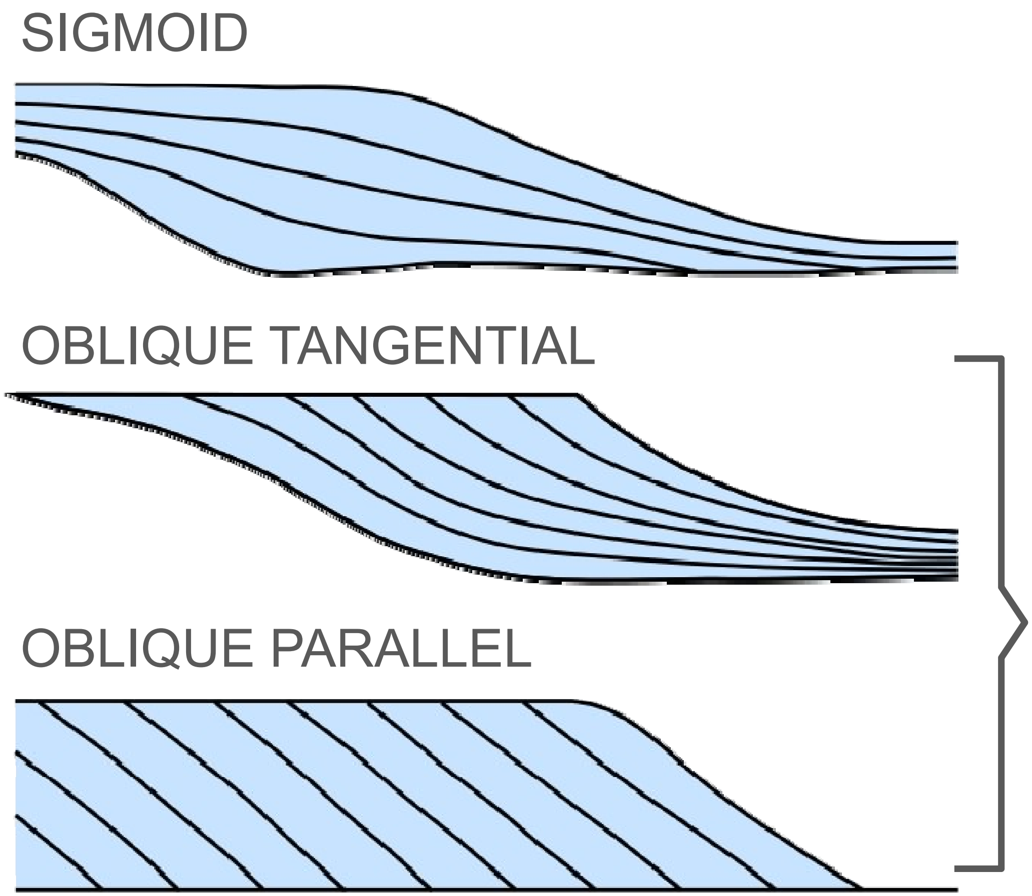
In memory of Lorenz Keim

- Lorenz Keim, outstanding Dolomites geologist, perished in a snow avalanche on February 4 and only 43 years old, leaving behind a wife and three children and a big hole in South Tyrolean geology.

Summary and take-away message

- Carbonates versus siliciclastic slopes:
  - Production near platform top (mostly during highstand shedding), or in situ on the upper slope (during all systems tracts) versus source-to-sink
  - Early lithification of carbonates
  - Petrophysical properties, i.e., shear-strength, pore systems, heterogeneity, acoustic properties
- The established view:
  - Carbonate slopes tend to be steeper than their clastic counterparts
  - The stabilization potential by binding of slope sediment, early cementation, and in situ growth of carbonates is evoked to explain this difference
- This talk:
  - Stark similarities in gross development, curvature, and angle are observed if similar settings, situations or processes prevail

Classification of prograding clinoforms based on seismic



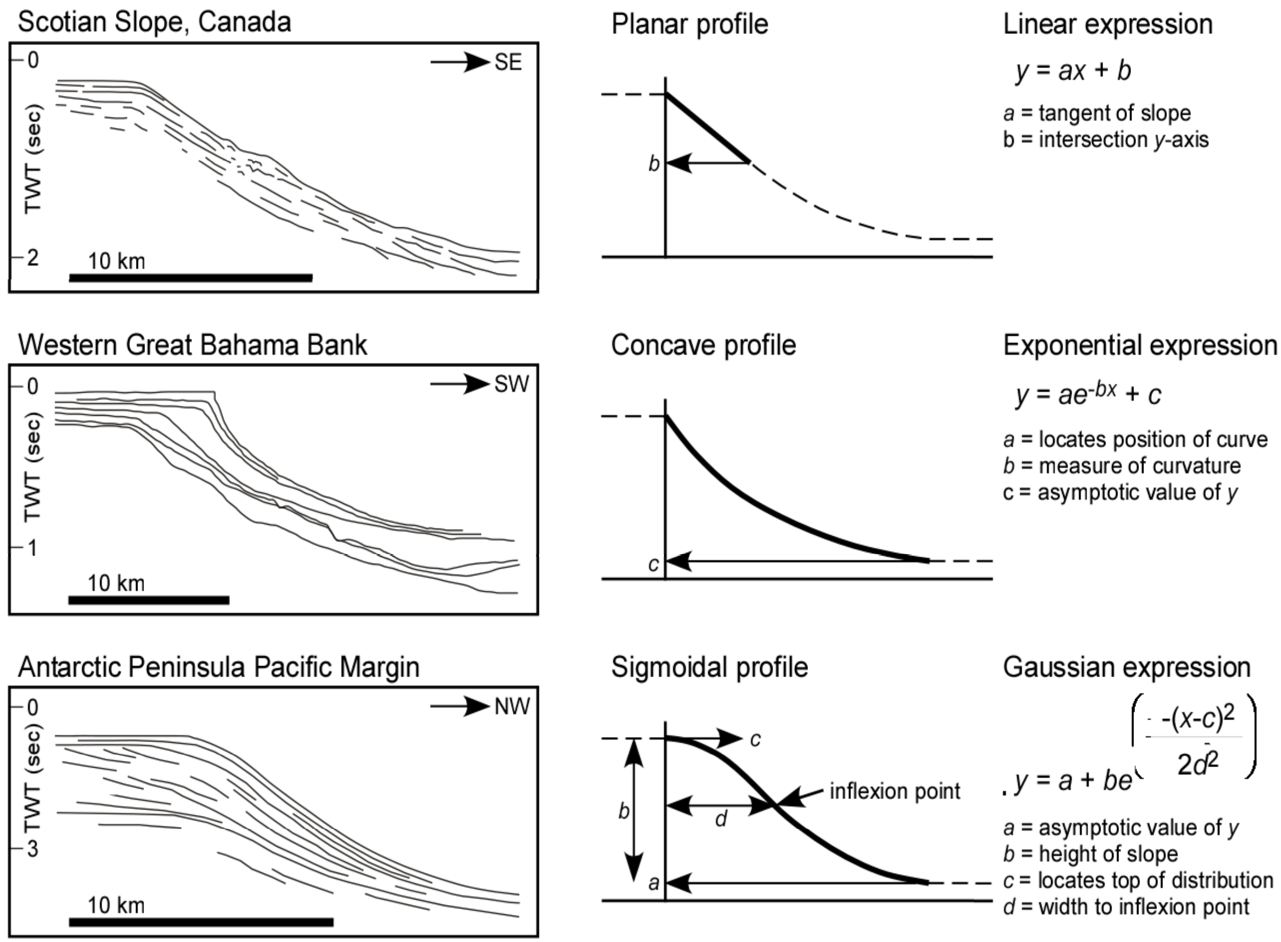
Modified after Vail et al., 1977

Low-sediment supply and rapid rise in relative sea level

High-sediment supply and stable relative sea level

Quantifying slope curvature

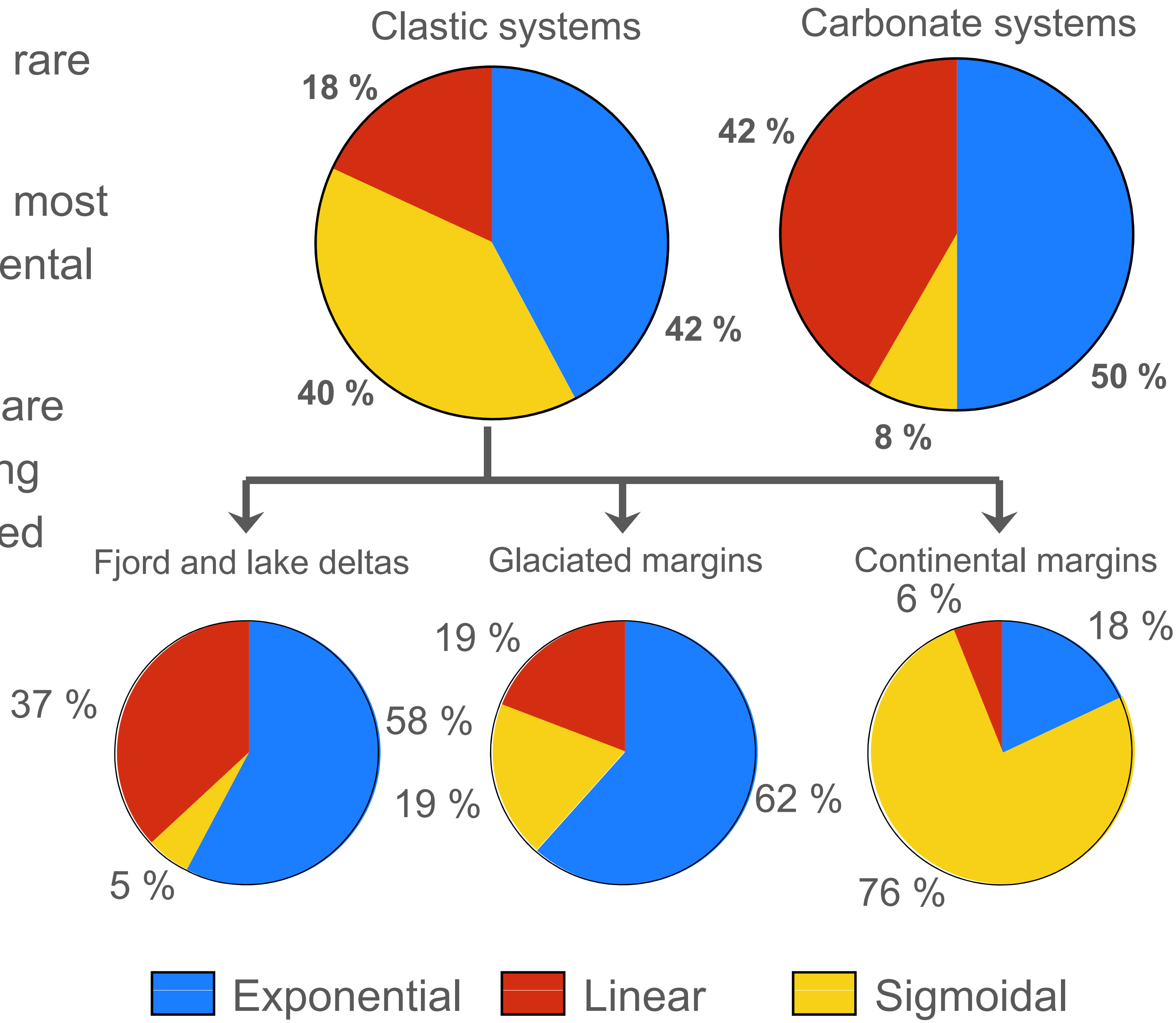
- Database comprising 150 modern slopes
- Curve fitting on first-order morphology
- Three equations quantify 90% of database
- Three basic types of slope curvature
  - Planar→ Linear
  - Concave→ Exponential
  - Sigmoidal→ Gaussian



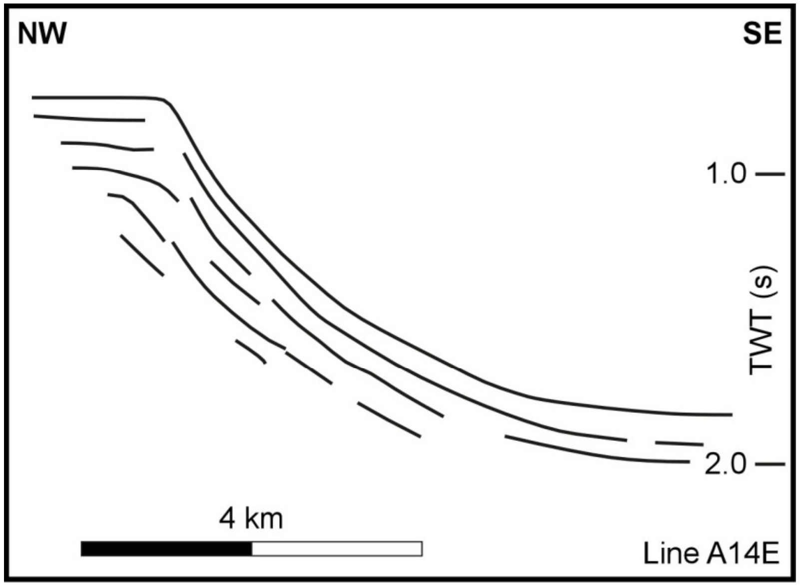
Modified from Adams and Schlager, 2001

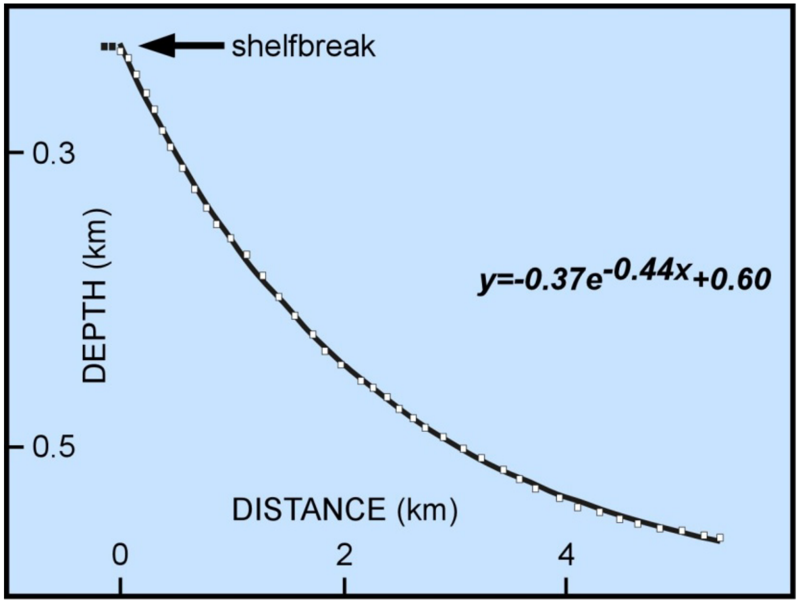
Distribution of slope curvature

- Sigmoidal profiles rare in carbonates
- Sigmoidal profiles most common in continental margins
- Carbonates compare with fast-prograding deltas and glaciated margins

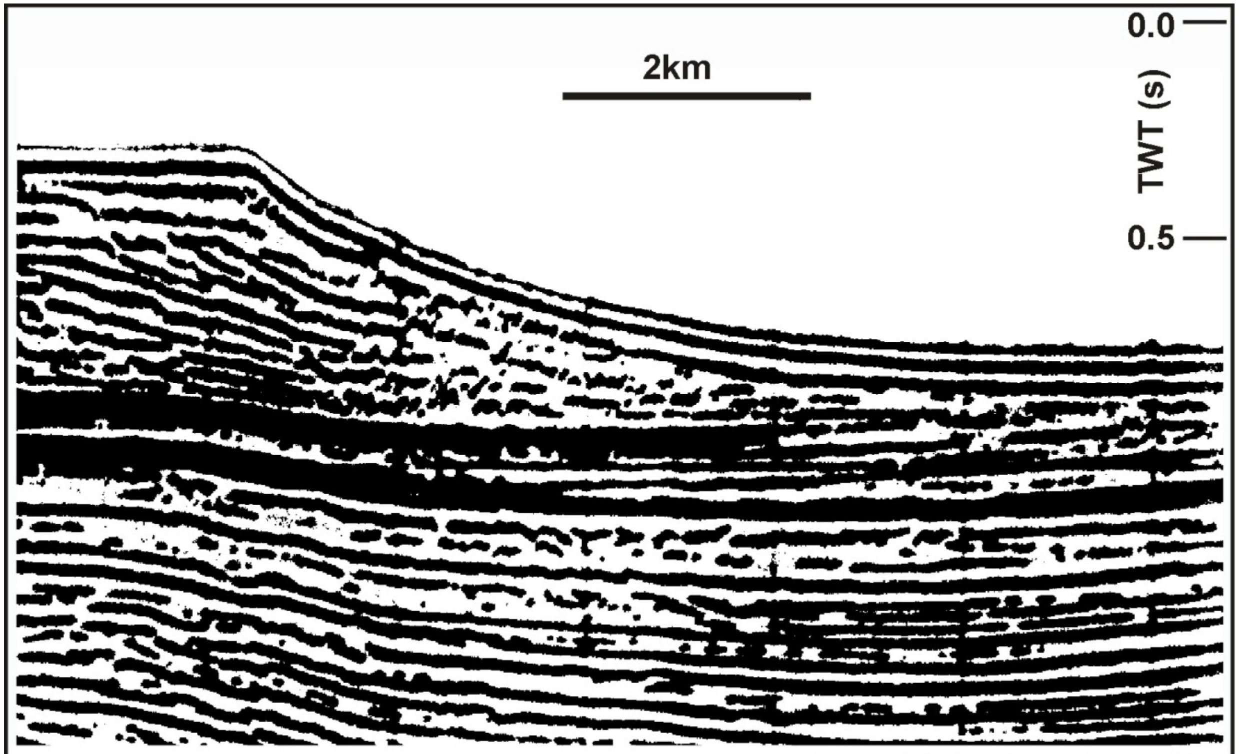


Exponential profile - Southeast South Island, New Zealand



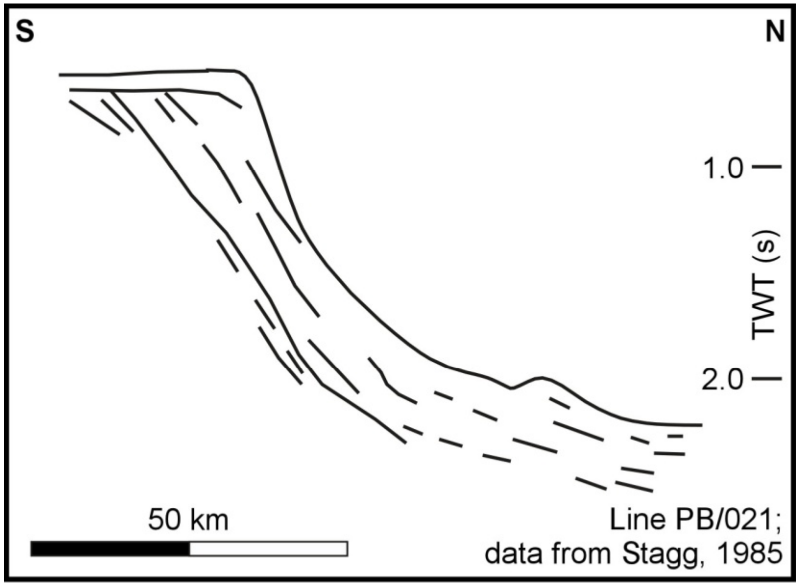


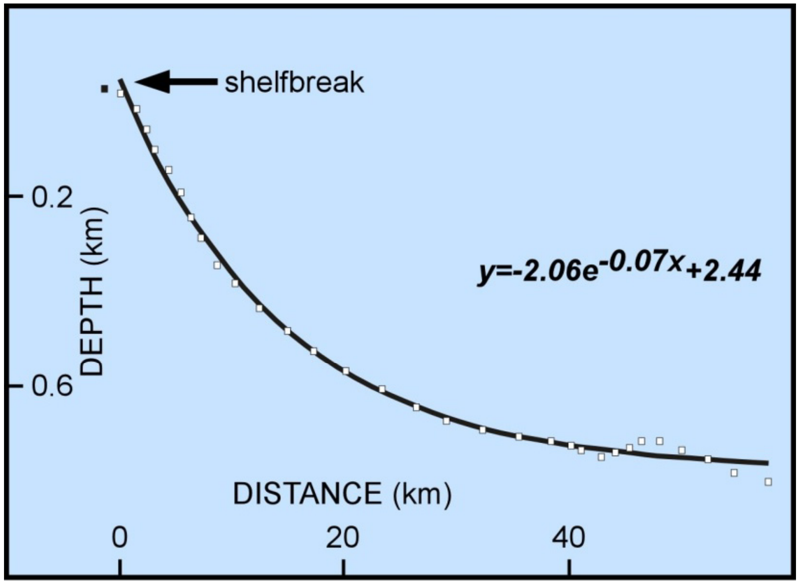
- Rapidly prograding, continental-shelf delta
- Terrigenous sand and silt
- Maximum inclination 10º



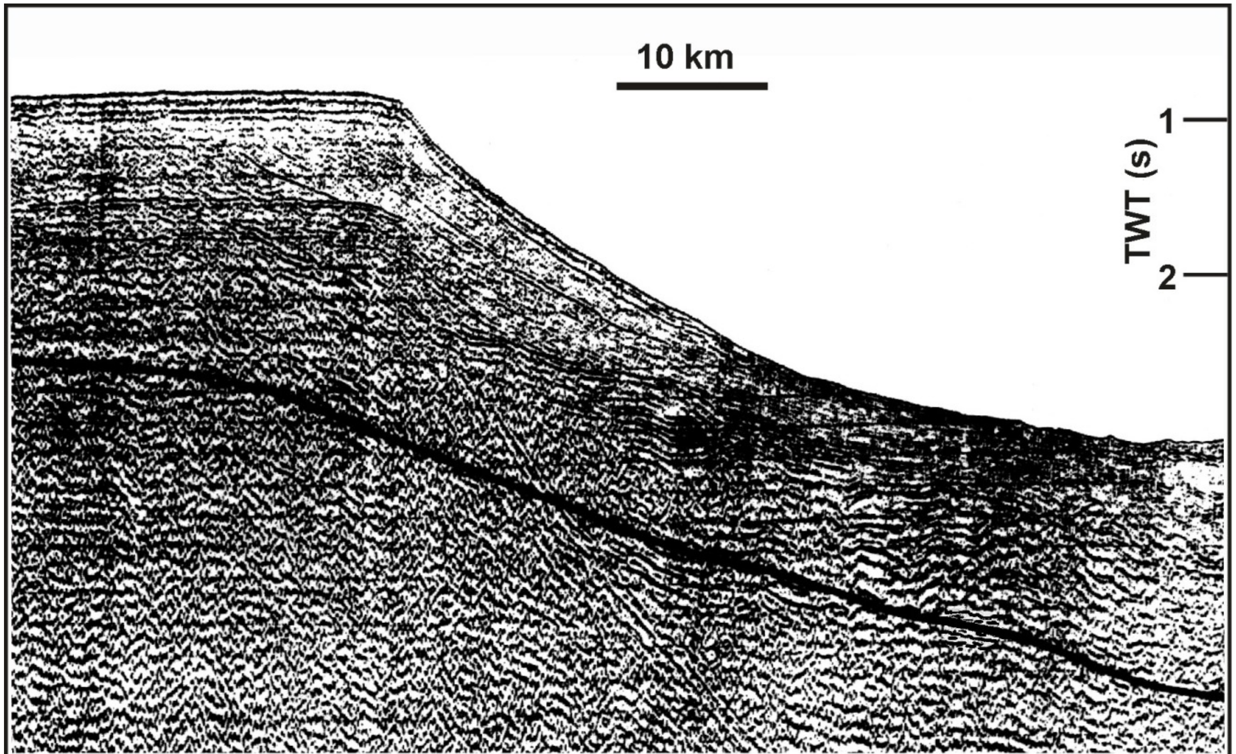
Line A14E, data from Carter, 1988

Exponential profile - Prydz Bay, Antarctica





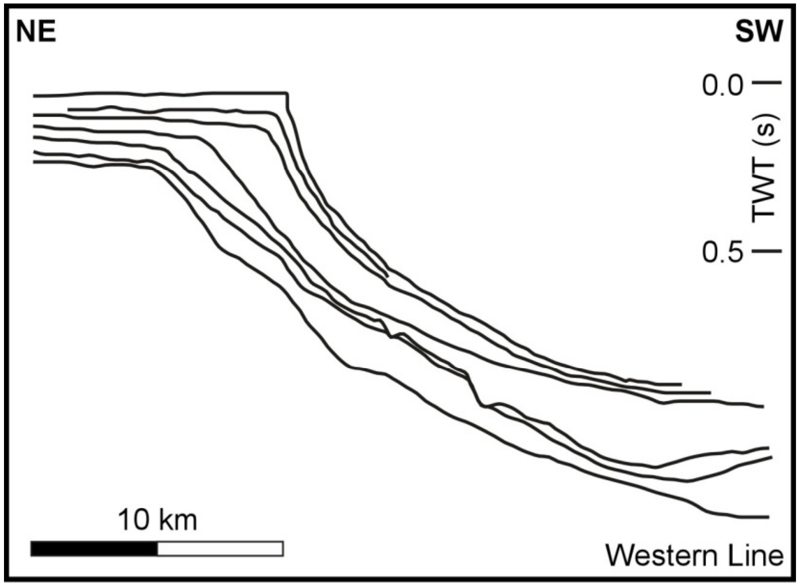
- Glaciated, continental margin
- Poorly sorted terrigenous diamictite
- Maximum inclination 8°

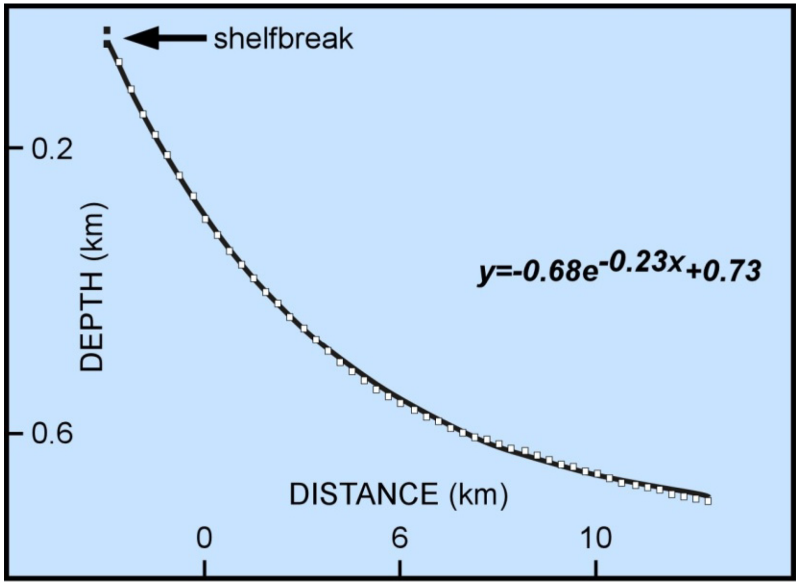


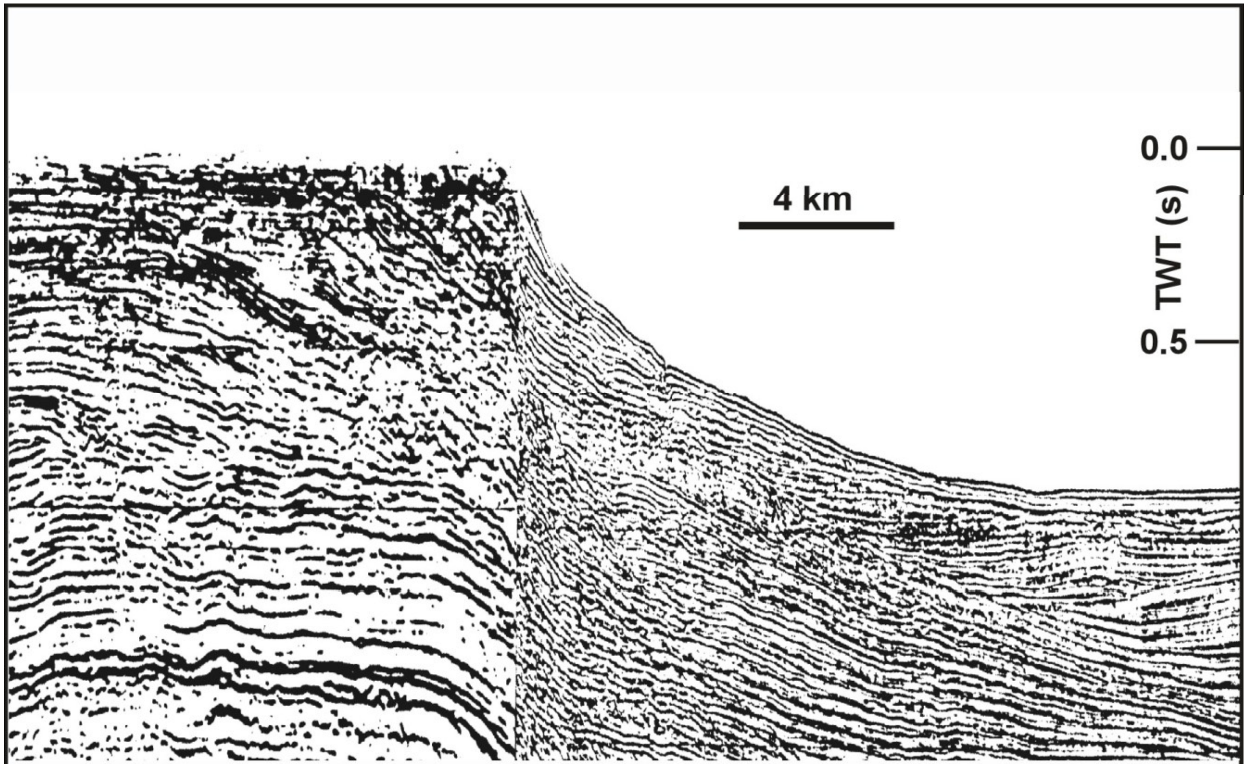
Line 33006, data from Kuvaas and Leitchenkov, 1992

Exponential profile - Western Great Bahama Bank

- Tropical, carbonate platform
- Carbonate mud and fine sand
- Maximum inclination 8º





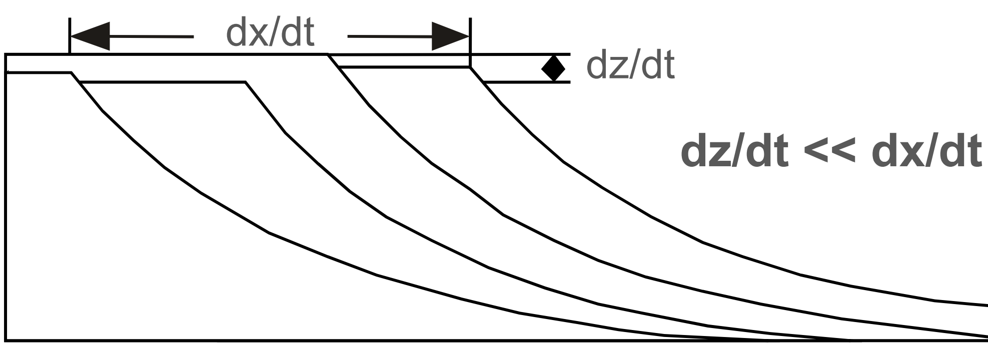


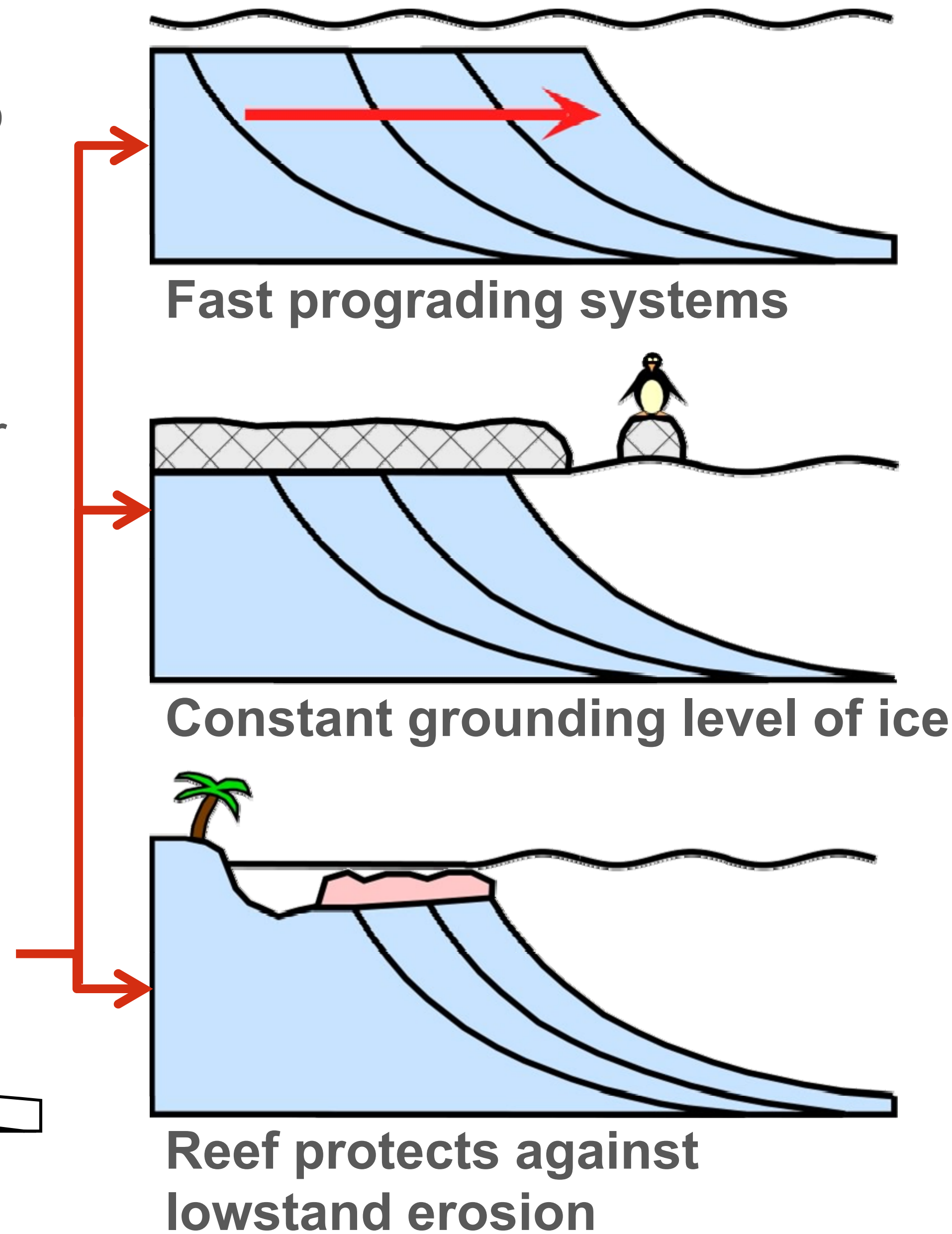
Western Line, data from Eberli et al., 1997

Exponential profiles

- Exponential curvatures and abrupt shelf breaks develop when the ratio between rate of vertical fluctuations of base level to rate of horizontal progradation is small

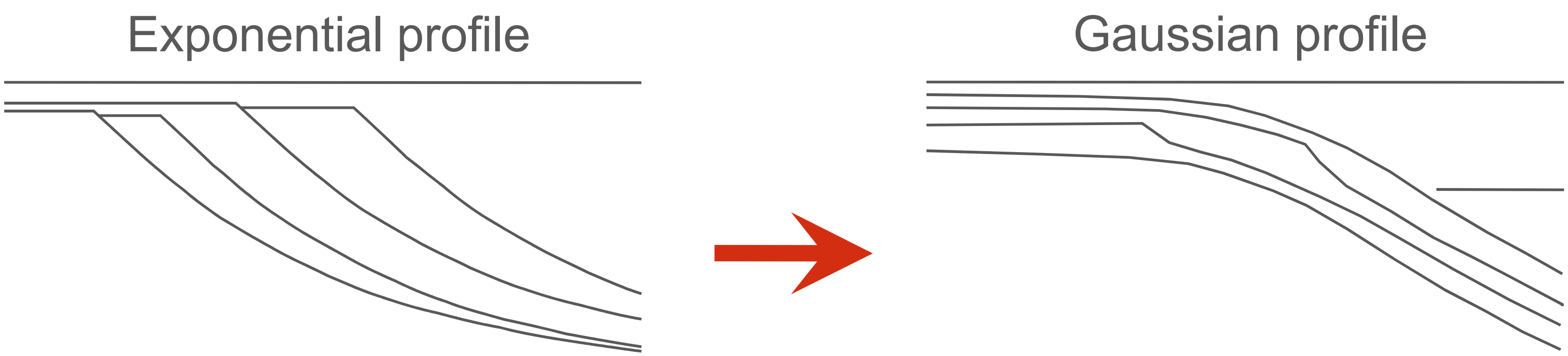
1. Fast prograding systems with minor base-level fluctuations
2. Grounding ice sheets
3. Reef protection





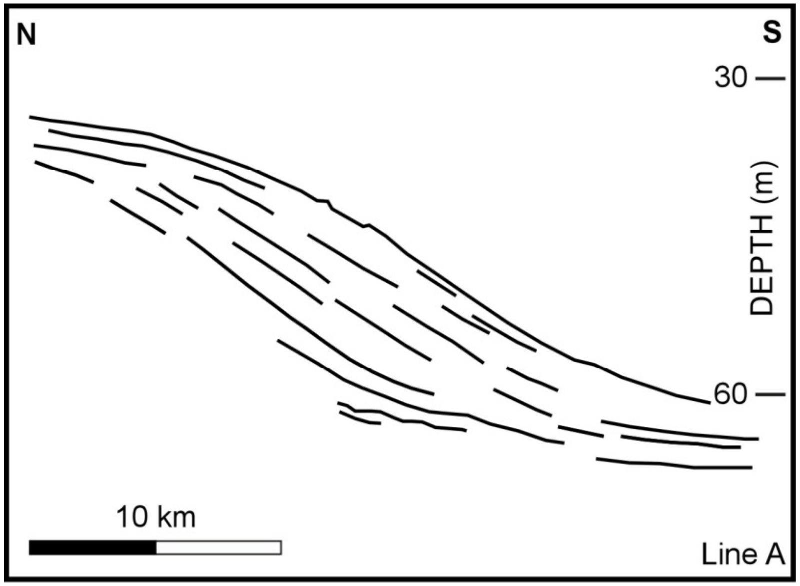
Exponential profiles and their modification to Gaussian

- Sigmoidal curvatures develop if base-level fluctuations round-off the shelfbreak

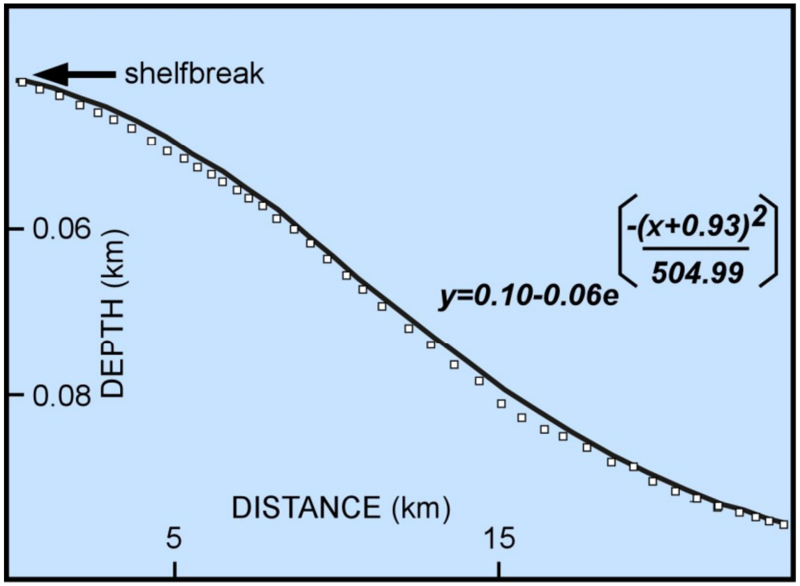


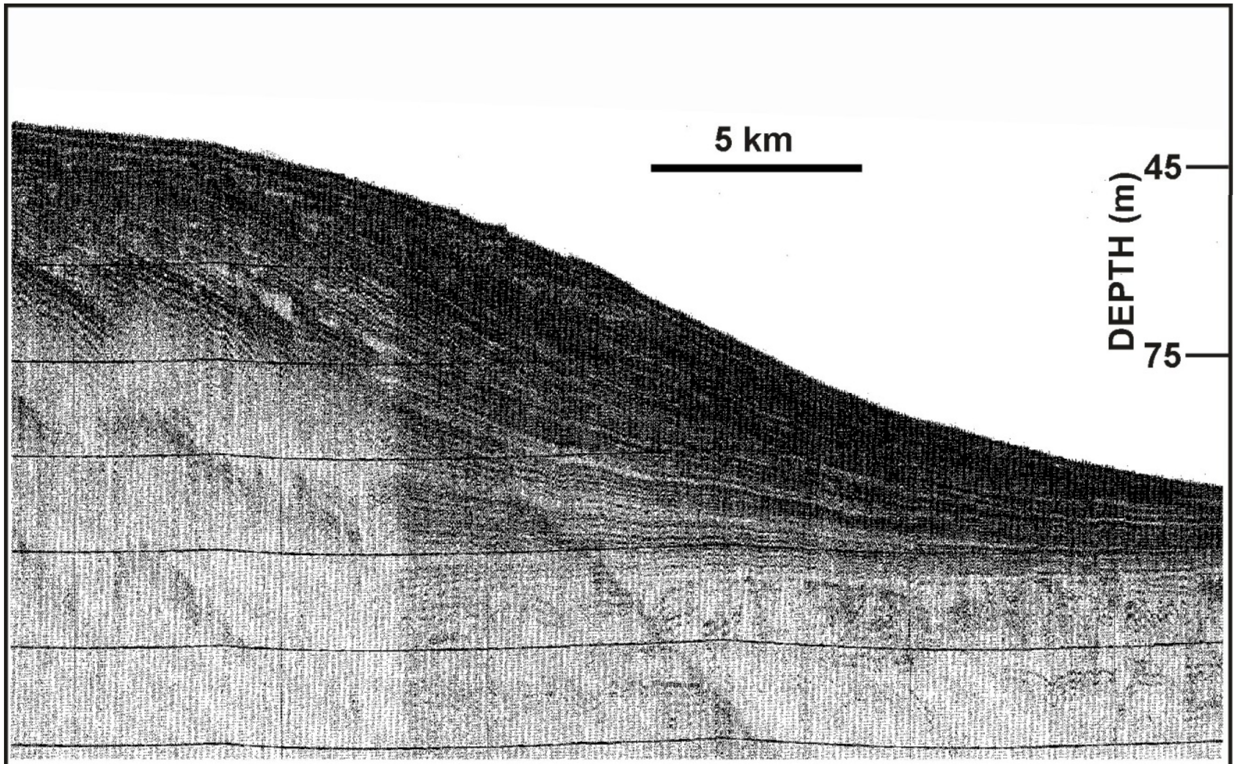
base-level fluctuations round-off the shelfbreak

Gaussian profile - Ganges-Brahmaputra delta



- Storm-dominated, continental-shelf delta
- Terrigenous silt and fine sand
- Maximum inclination 0.2°

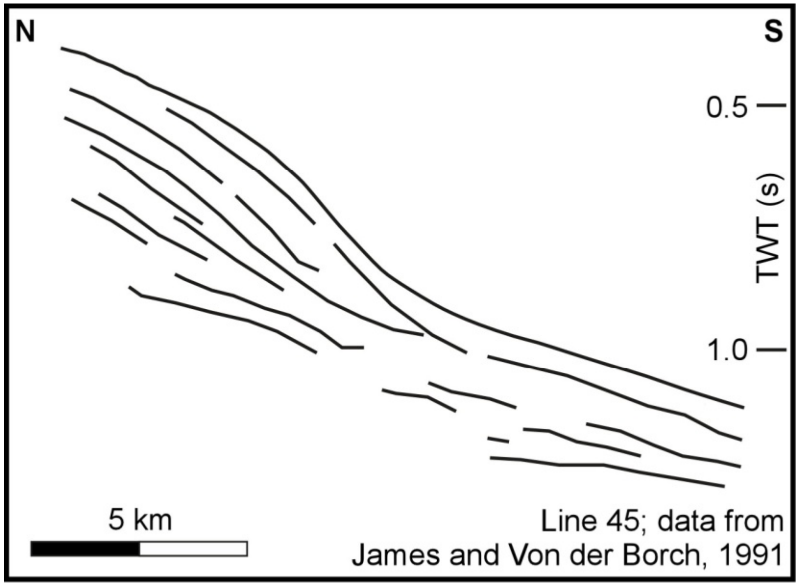


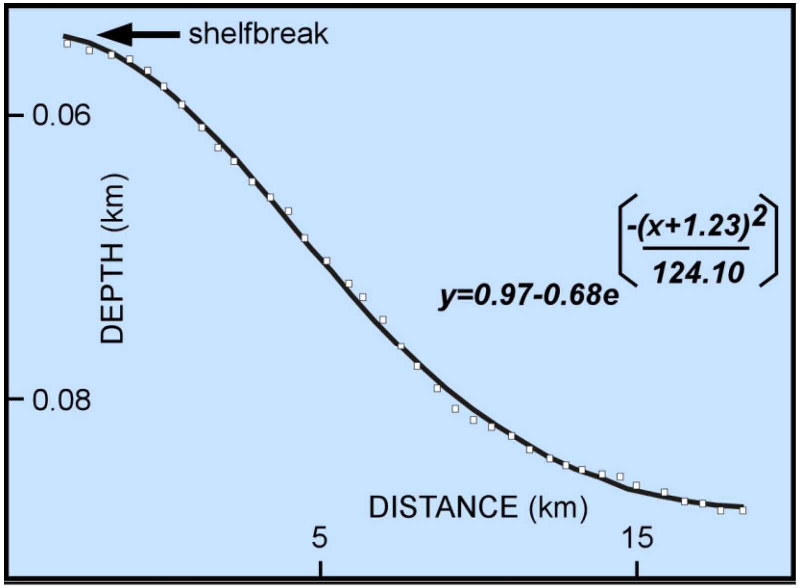


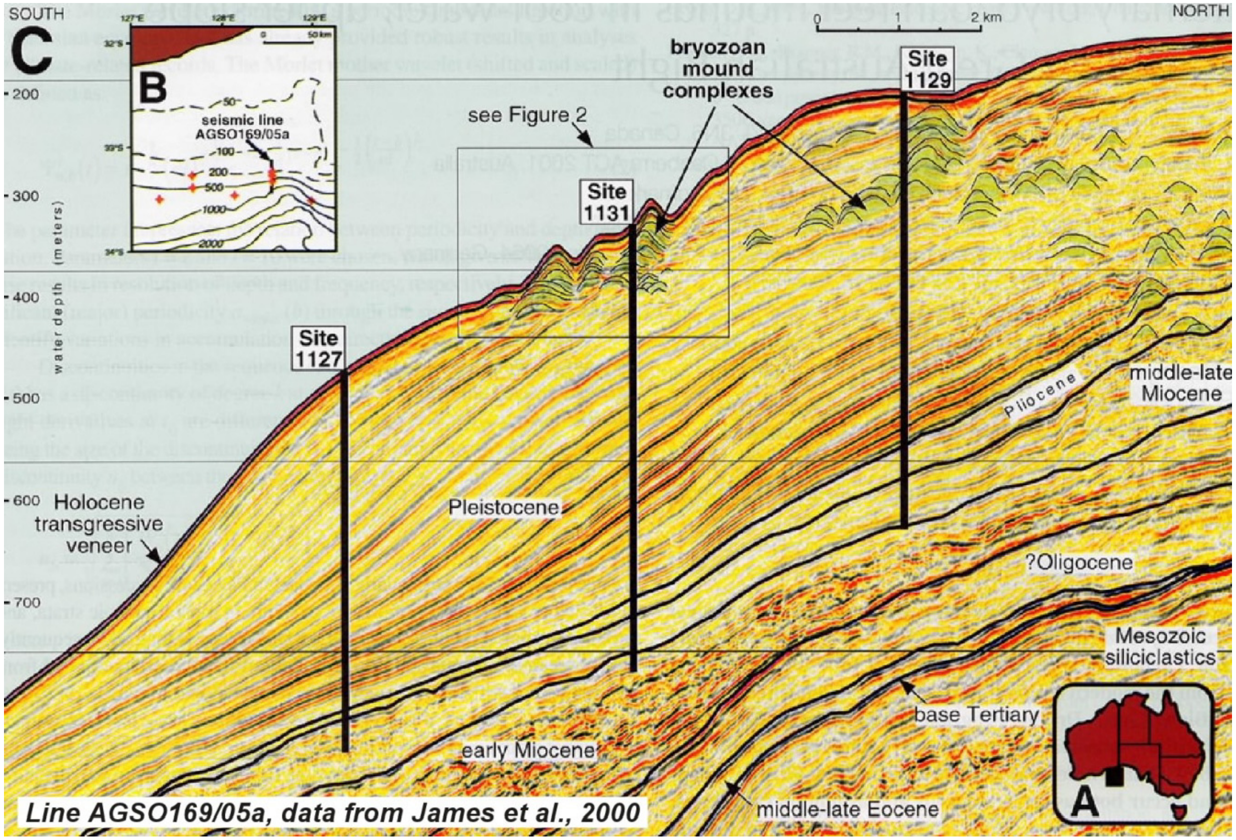
Line A, data from Kuehl et al., 1997

Gaussian profile - Great Australian Bight

- Open shelf, cool-water carbonate
- Fine-grained skeletal carbonates
- Maximum inclination 3.0^o

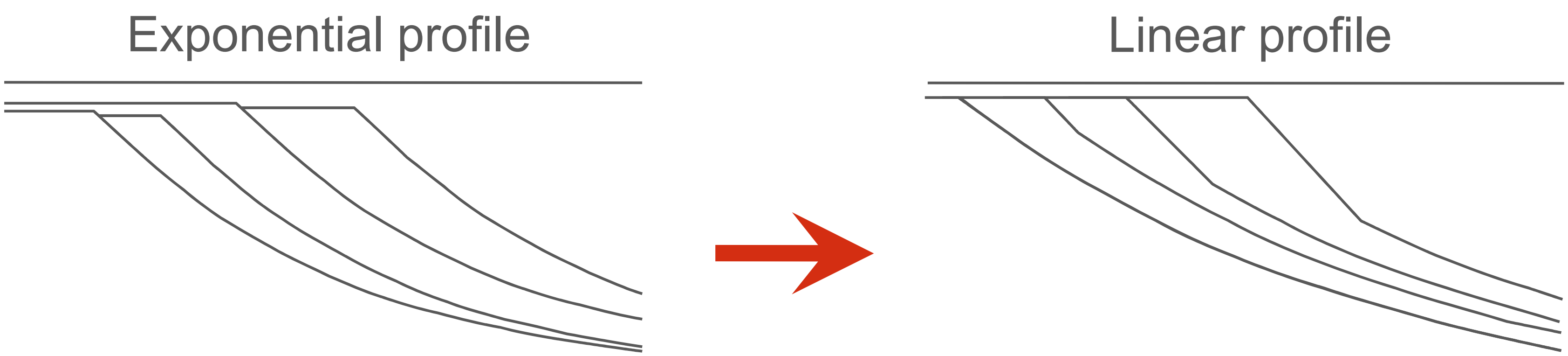






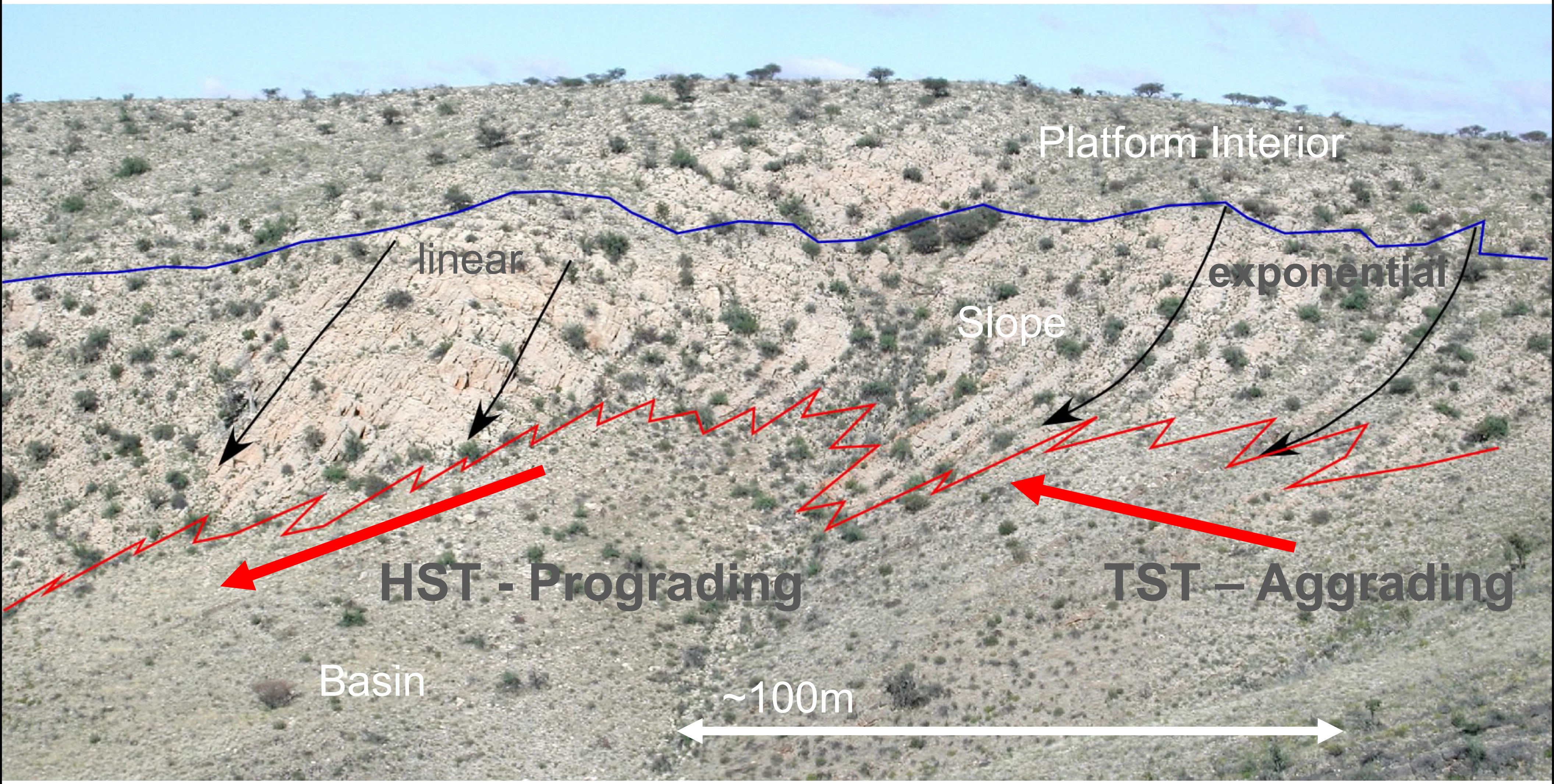
Exponential profiles and their modification to Linear

- If a surplus of sediment is provided, the sediment fabric limits the slope inclination, and linear profiles develop.



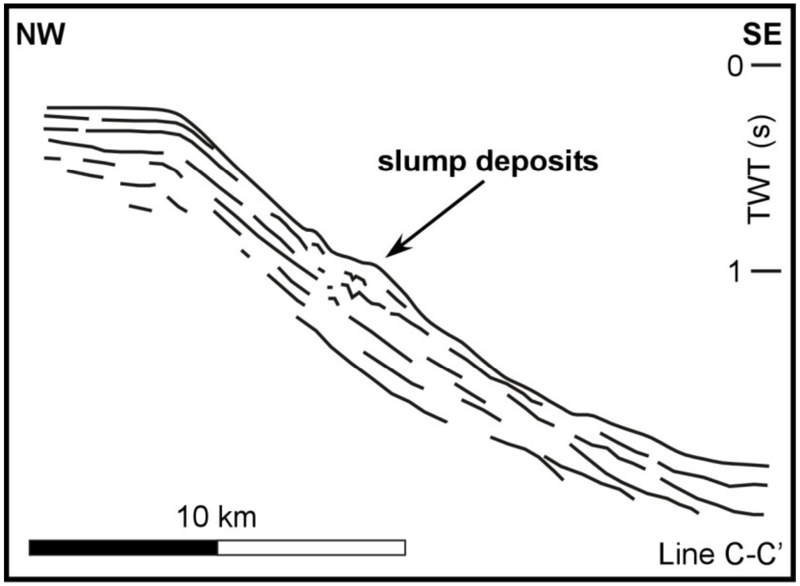
Increasing progradation rate steepens slope until sediment fabric limits the angle of dip and linear profile develops.

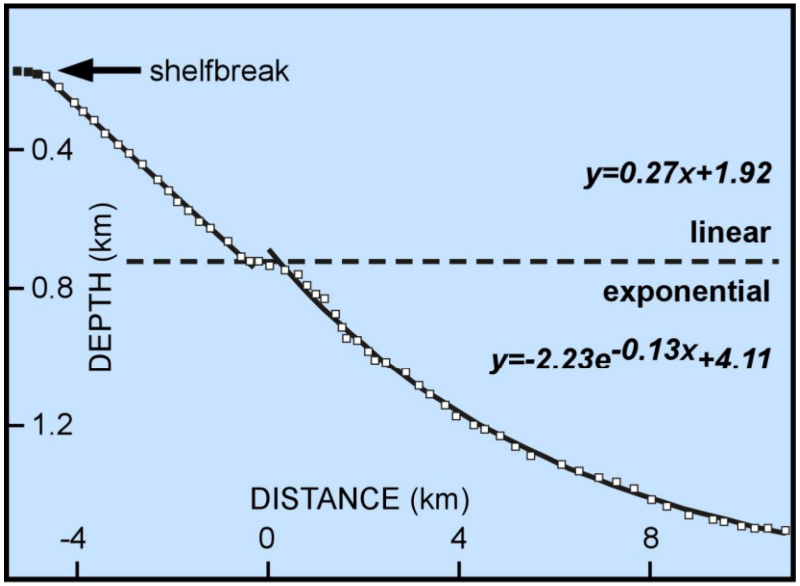
From TST exponential to HST planar profiles



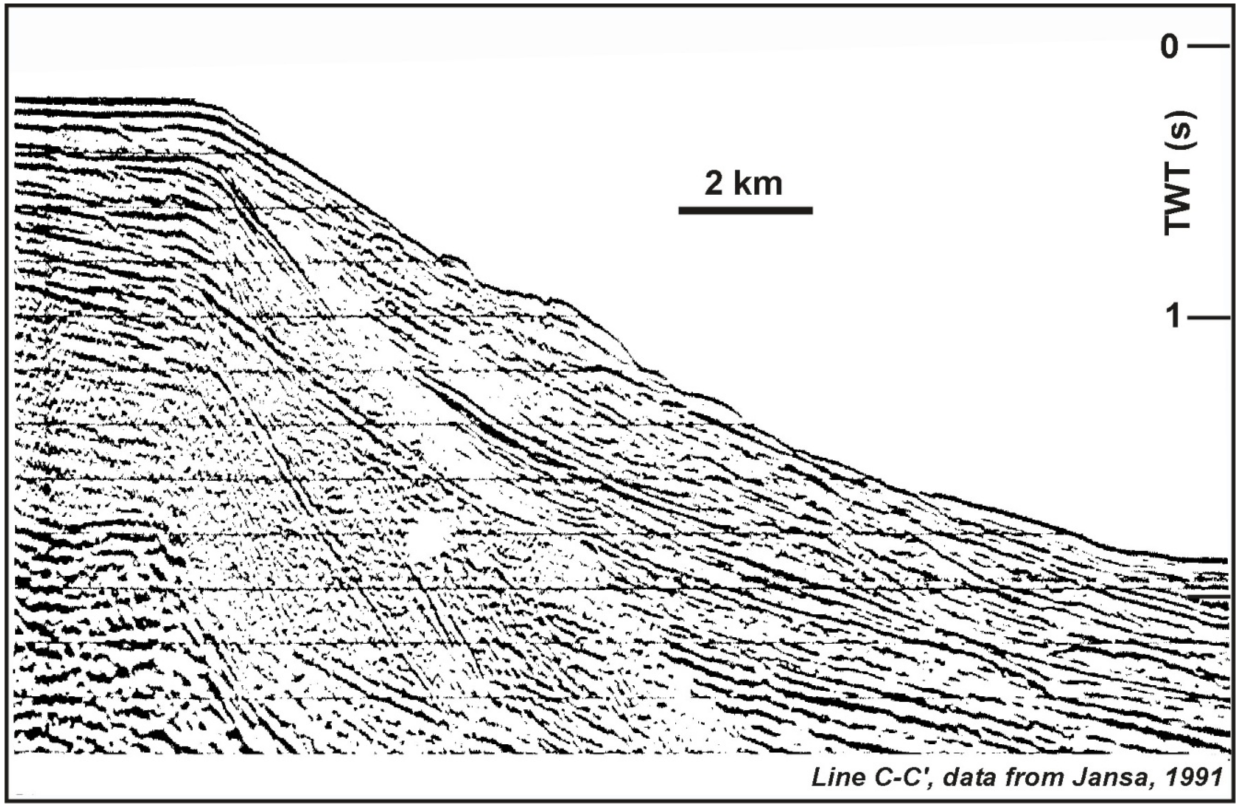
- Terminal Proterozoic carbonate platform, interbedded grainstone and mudstone, maximum inclination 20-25 degrees

Linear profile - Scotian Slope, Canada

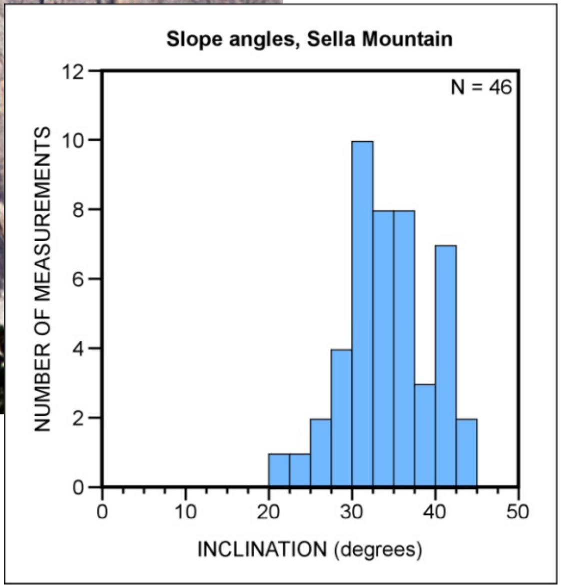




- Continental margin
- Very fine-grained terrigenous sediments
- Maximum inclination 7°

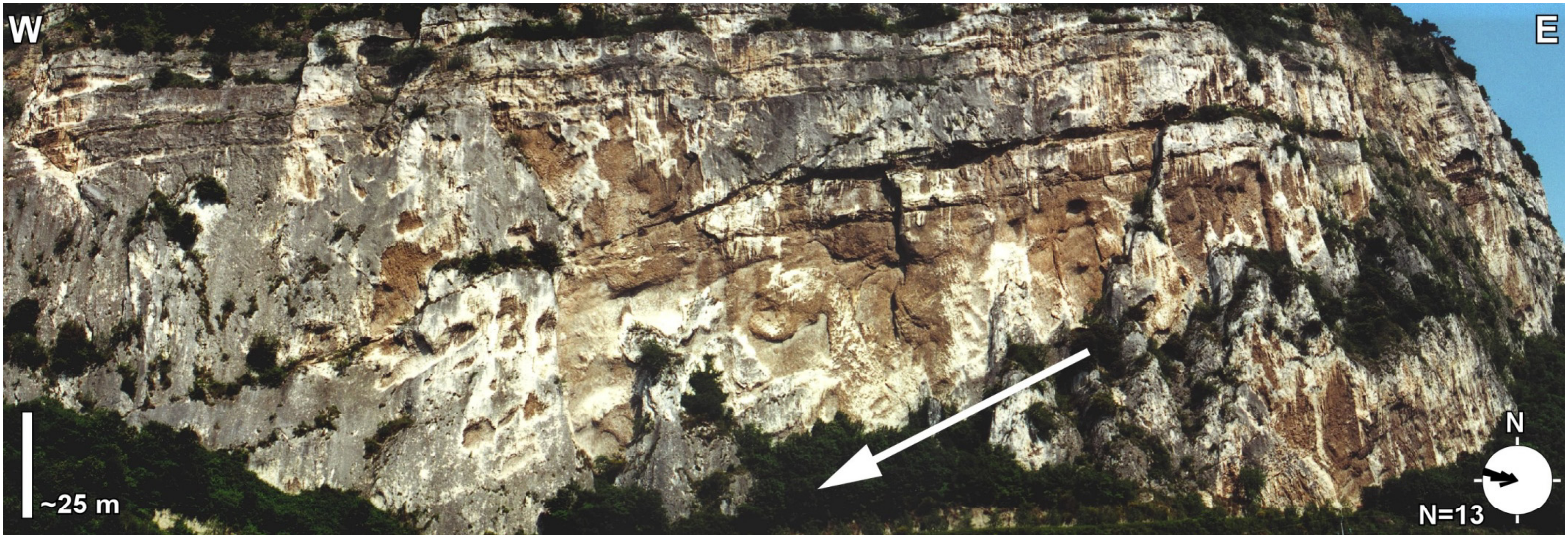


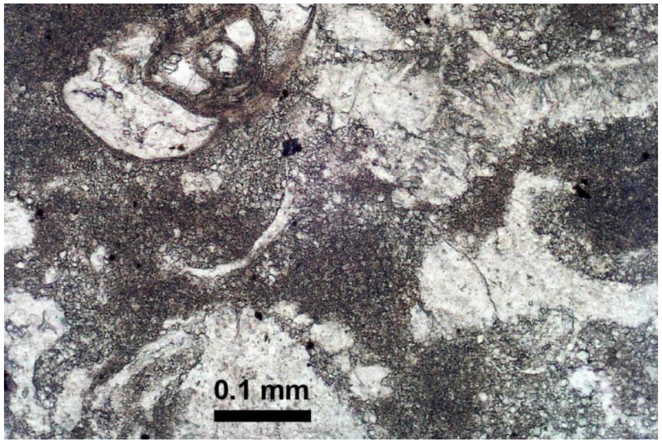
Linear profile – Sella Mountain, Dolomites, Italy

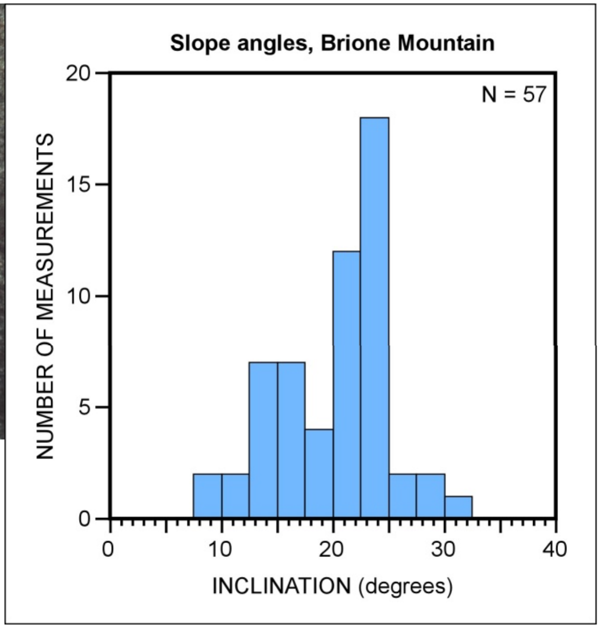


- Triassic carbonate platform, rudstone and breccias with microbial micrite, maximum inclination 35-40 degrees

Linear profile – Brione Mountain, Italy

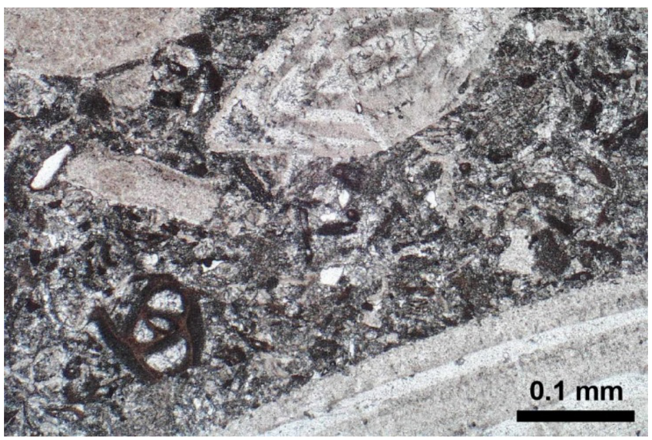


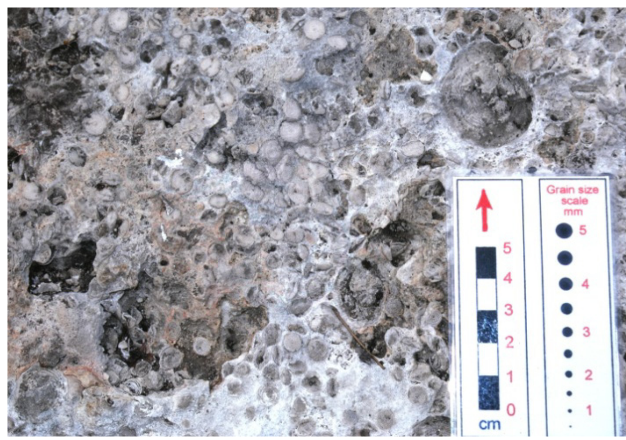


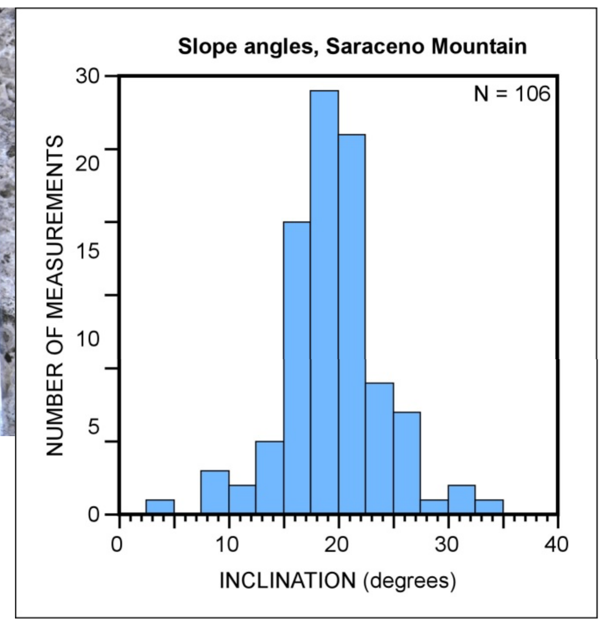


- Oligocene carbonate platform, bioclastic packstone, maximum inclination 20-25 degrees

Linear profile – Saraceno Mountain, Italy

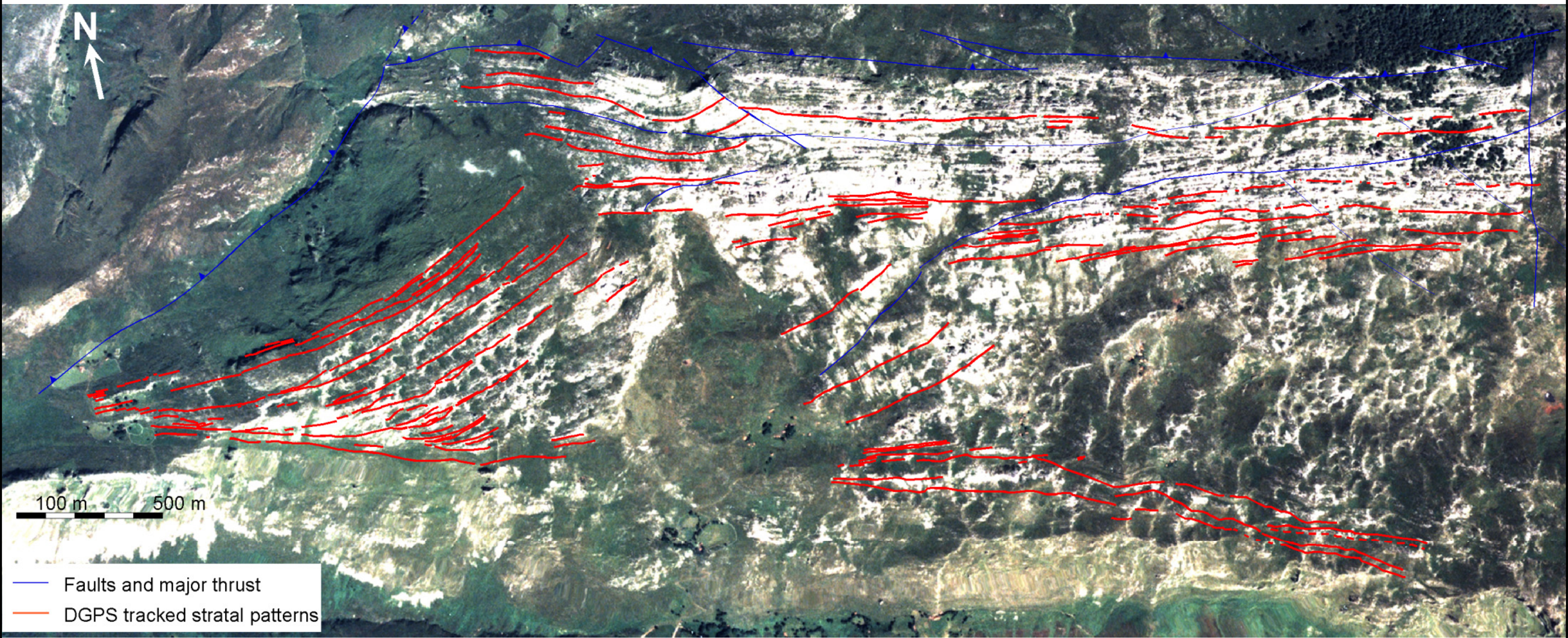






- Eocene carbonate platform, bioclastic pack- to-rudstone, maximum inclination 20-25 degrees

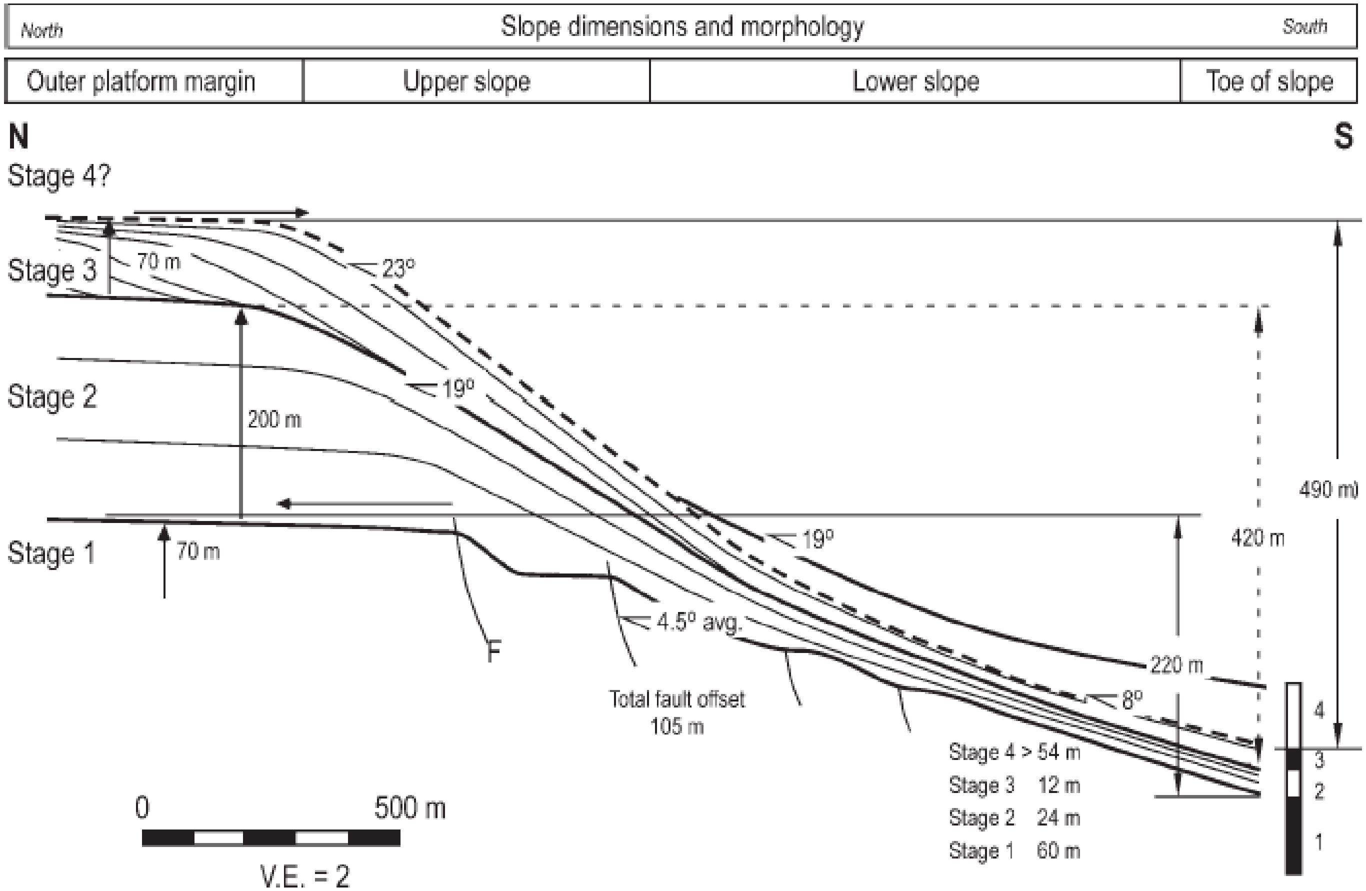
Linear profile – Sierra de Cuera, Spain



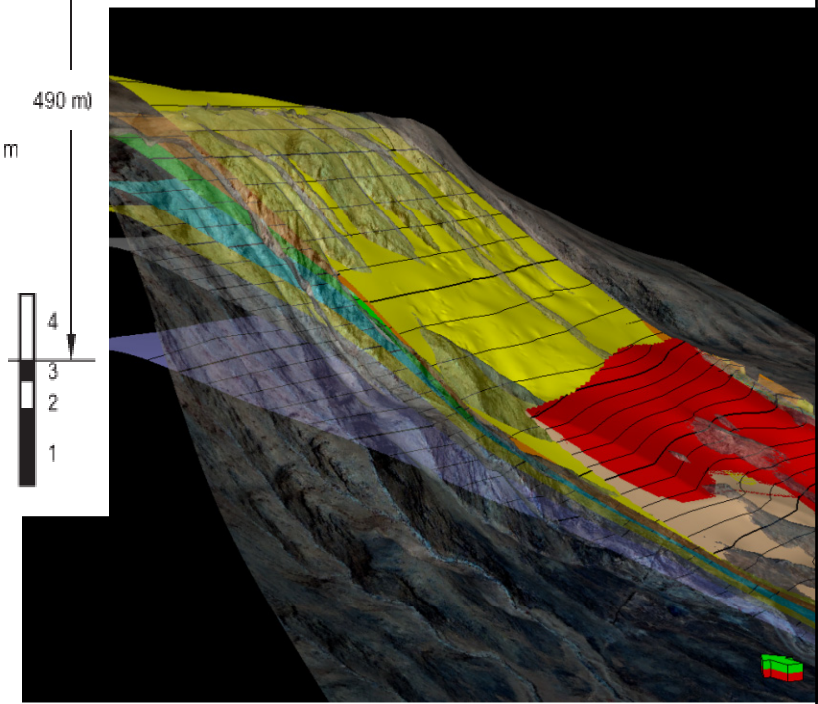
From Verwer et al., 2004

- Pennsylvanian carbonate platform, in situ microbial boundstone and breccia linear upper slope 30-35 degrees and exponential lower slope picking up mud

Linear profile – Djebel Bou Dahar, Morocco



Slope model with surfaces fit through tracked bedding intersections in DEM (lower right) and interpreted cross section (left)



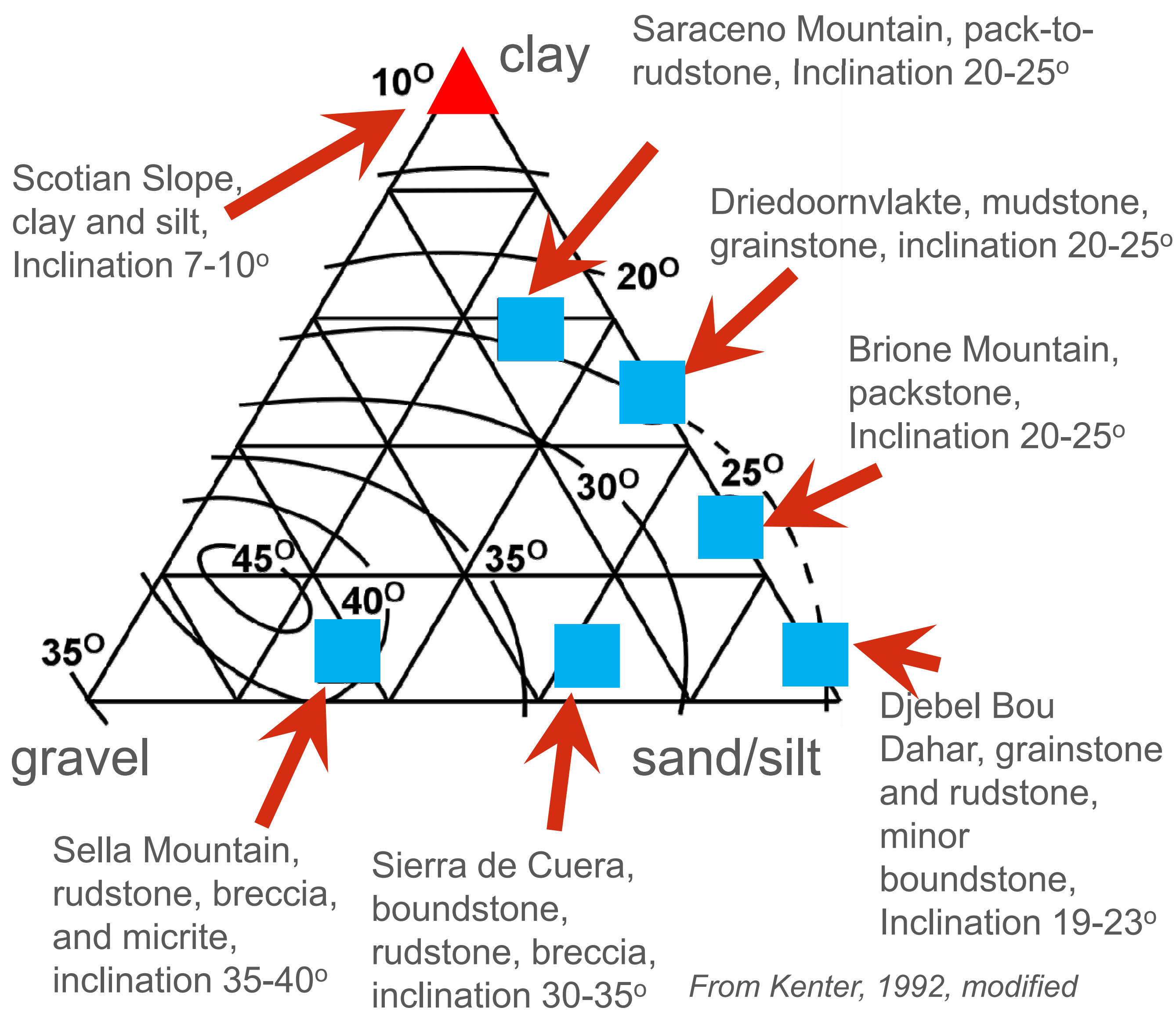
- Lower Jurassic carbonate platform, grainstone and rudstone stablilized by microbial micrite linear upper slope 19-23 degrees

From Verwer et al., 2009 and Della Porta pers comm (2012)

Planar clinoforms rest at the angle-of-repose

- In systems built to the angle of repose, slope inclination is directly correlated with grain size (Kenter, 1990) and the curvature is linear (Adams, 2001)

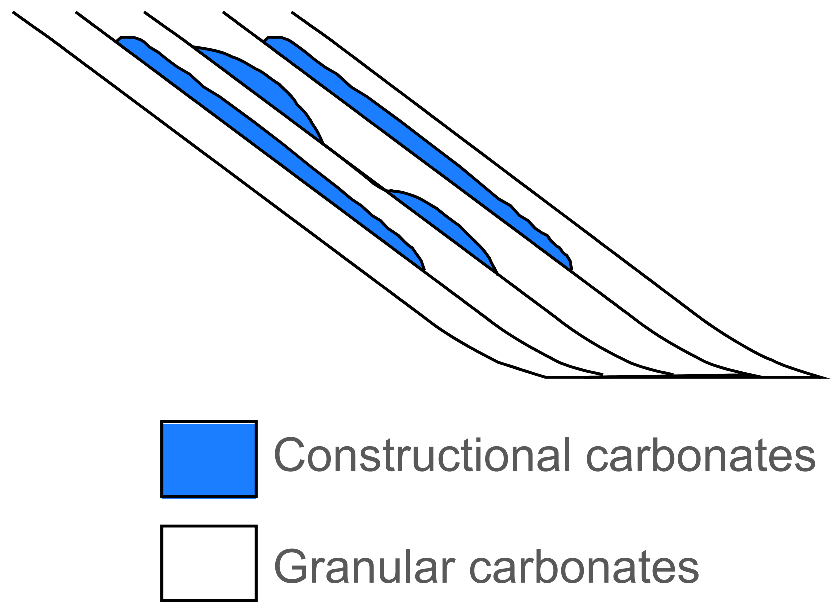
1. Non-cohesive sediments have straight planar foresets
2. Cohesive sediments have irregular surfaces due to creep and slumping

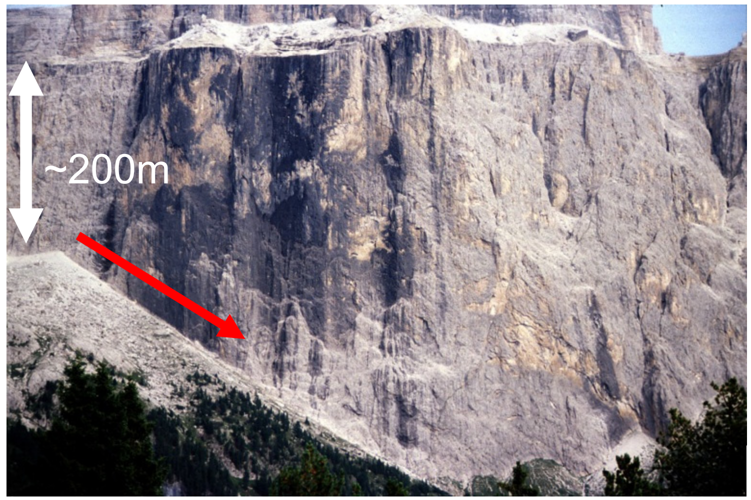


From Kenter, 1992, modified after Kirkby, 1987

Steeply-inclined carbonates rest at the angle of repose

- Inclinations of linear carbonate slopes are in agreement with the angles of repose
- Supports assumption that linear slopes are normally inclined at the angle of repose, or the angle of shear approximates angle of repose for loose material
- Angle of repose is determined by non-cohesive layers in alternating systems (i.e., Sella) or angle of shear in massive boundstone (i.e., Sierra de Cuera): carbonates fail, disintegrate and slide, resulting in similar declivities
- Critical is independence of light and "all time" shedding by large production area providing high accretion/production rates

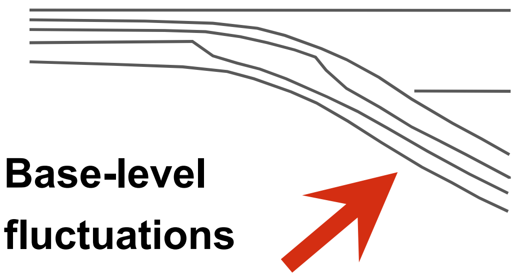




Unraveling Slope Origin and Composition

Gaussian

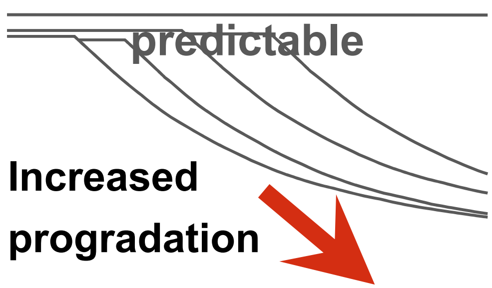
sediment type independent of dip NOT predictable



Base-level fluctuations

Exponential

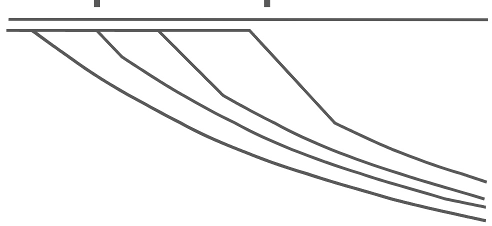
sediment type impacts curvature POSSIBLY predictable



Increased progradation

Linear

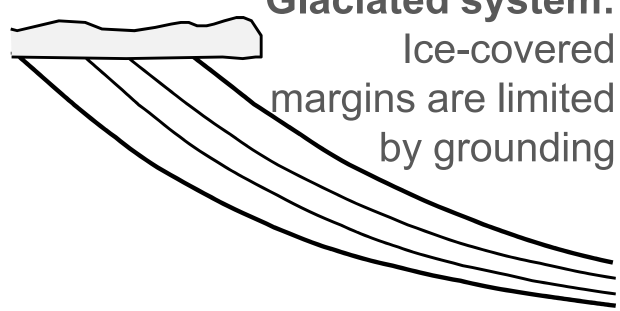
sediment type limits angle of dip THUS predictable



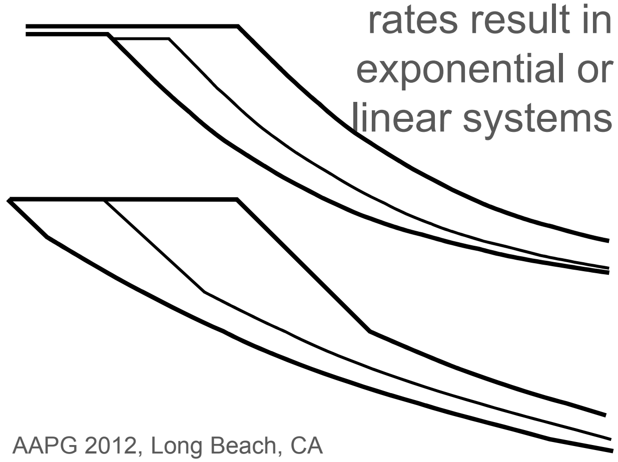
Siliciclastics

Open-shelf system:
Storms and sea-level cycles induce significant fluctuations of base level

Glaciated system:
Ice-covered margins are limited by grounding

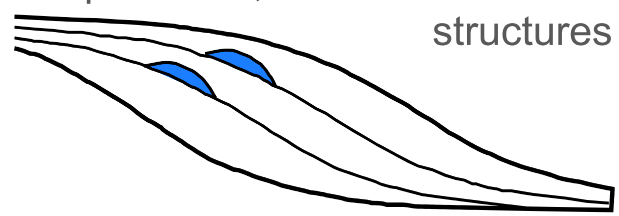


Fast prograding system:
High progradation rates result in exponential or linear systems

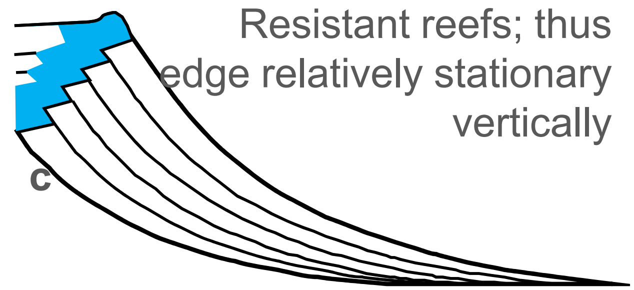


Carbonates

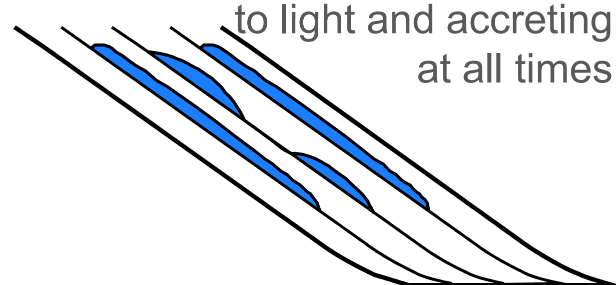
Cool-water system:
Non-rimmed carbonate platforms, with individual reef structures



Tropical system:
Resistant reefs; thus edge relatively stationary vertically

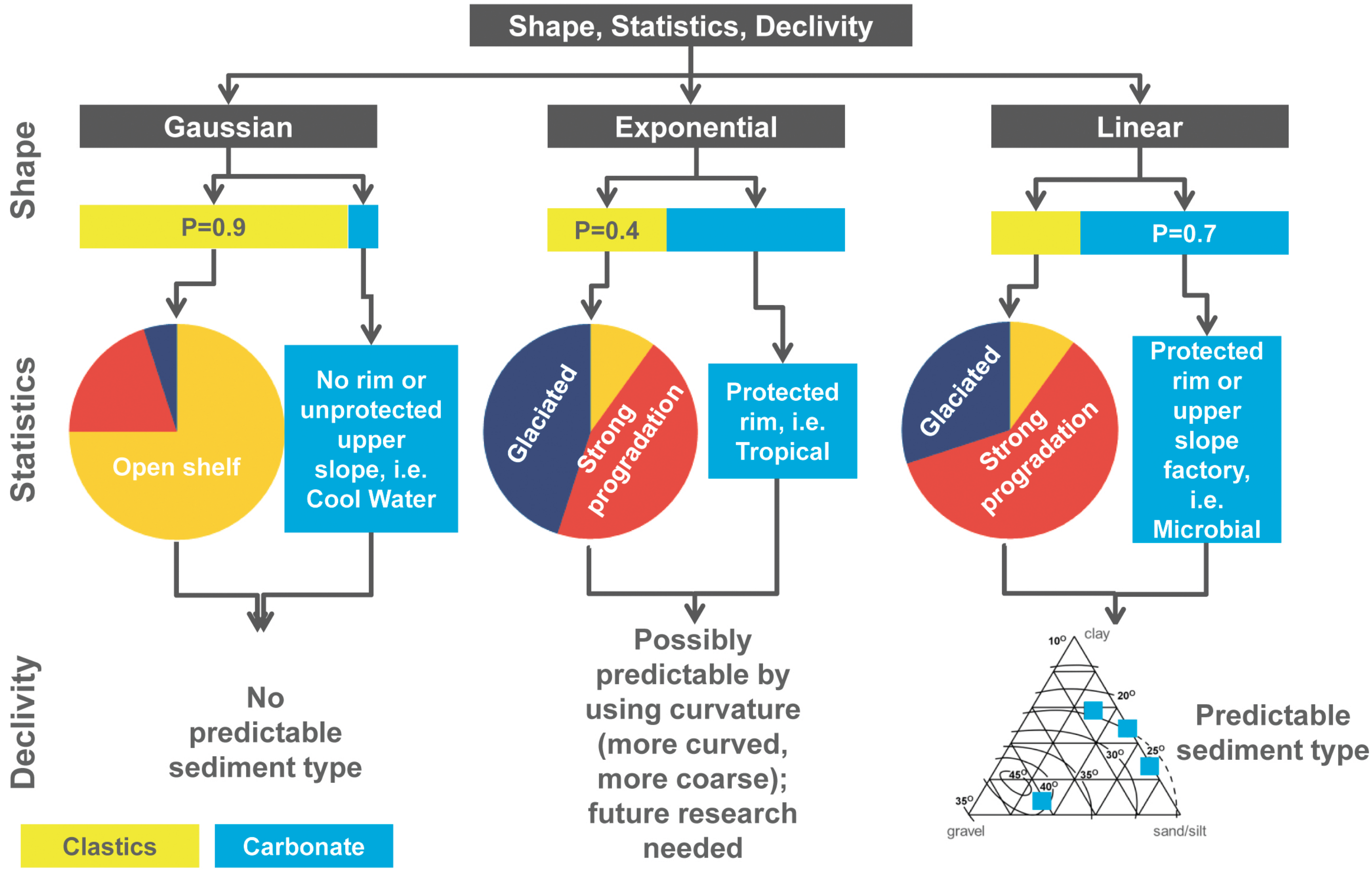


Mud-mound system:
Factory is insensitive to light and accreting at all times



in situ carbonates

Or “Find My Slope Ahead of Drill”



Conclusions

- The established but biased view: carbonate slopes tend to be steeper than their clastic counterparts; in part because of stabilization through early cementation and microbial activity
- However, an unbiased dataset suggests similarities in gross development, curvature, and angle if similar settings, situations, or processes prevail
- The shelf edge is sharp and the profile exponential if sedimentary base level remains stationary during progradation
  - Sigmoidal: base-level fluctuations round-off the shelfbreak
  - Linear: excess sediment is piled up to the angle-of-repose
- Microbial slopes are insensitive to light and can therefore accrete during both low- and highstands, i.e., high accretion/production rates allowing systems to build-up to higher declivities
- Combining such rules may give a better handle on prediction of slope system, processes and type of sediment but needs additional refinement and validation