Reinterpreting the Paleosalinity and Water Depth of Peripheral Foreland Basin Flysch*

Roger Higgs[1]

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Abstract

Countering the idea that every peripheral foreland basin (PFB) has an early deep-water stage, recent articles and my observations show (1) Taiwan PFB (6.5-0 Ma) has never been deep, and (2) many 'external flysch' formations (e.g. Annot, Brushy, Bude, Hecho, Jackfork, Marnoso, Ross, Skoorsteenberg, Toro) have recurrent event beds with evidence for waves (e.g. HCS; near-symmetric ripples). The following non-actual model explains this and why PFB flysch basins inherently fluctuate from marine to fresh.

When a long (1,000s km) continent collides with another (e.g. Alpide, Gondwanide, Variscan orogens) or an island arc, collision occurs first at a salient. Thrust mountains (carrying "internal flysch" scraped off ocean crust) mount the incoming passive-margin shelf, initiating a PFB on it. The PFB and mountains lengthen by diachronous collision and advance until suturing occurs (progressively later strikewise). The initial PFB is a shelf-depth strait (e.g. Taiwan), merging axially with the passive shelf. The strait can deepen only if sedimentation < subsidence (cf. 2.5-0 Ma Timor Trough, >2 km deep due to scant supply from arid Australia). Eventual high supply from the growing mountains builds an alluvial neck (tombolo at first), splitting the strait into back-to-back gulfs (blind shelves). The forebulge runs down each gulf, crosses the adjacent shelf and slope obliquely (thus annexing a 'shelf triangle' to the PFB), and runs along the remnant ocean as a trench outer rise. Gradual along-shelf migration of the bulge and gulf forms an unconformity onlapped by gulf/triangle flysch (see below). Collision at a 2nd salient pinches off a remnant-ocean sector, forming an 'ocean lake', dammed by a 2nd tombolo (unless one collider is a gapped island arc).

If river inflow > evaporation, the lake freshens and overflows, carving a trans-dam spillway. Eustatic rises over the spillpoint (SP; in spillway) raise the lake and, if high enough to admit an ocean wedge, raise the salinity (to marine if wedge height and width suffice). Eustatic falls below SP leave the lake perched (at SP), freshening. This curtailment of falls ('sill-damped eustasy') means only the innermost gulf is forcibly exposed, so even at lowest lowstand (SP) the gulf remains long (>100 km); it cannot shorten by gulf-head-delta progradation as the lake is then freshest and distributaries incised deepest, both maximizing hyperpycnal delta bypass. Megaflood hyperpycnal events feed 'shallow flysch' to the gulf and triangle, mainly Bouma, Lowe and storm-wave-modified beds. 'False bathyal' foram assemblages reflect internal-flysch forams

reworked by rivers in flood and deposited in hypo/ meso/hyperpycnal mud; plus ‘slope mimicking’ by the gulf during highest highs (i.e. marine; mud floor; dysoxia by thermohaline stratification).

Many so-called hybrid beds, slurries and slumps are seismites, in situ or nearly. The forebulge may supply carbonate-rich tsunamites into the gulf. Shallow-flysch hitherto enigmatic alternation of thinner- and thicker-bedded (coarser) packets 1-30 m thick is eustatic T-R cyclicity; the inter-packet leap in average bed thickness (e.g. cm vs dm) shows that rises and falls are brief (inter-event) yet large enough to greatly alter proximality, i.e. they are very fast, e.g. 20 m rise or fall in 0.5 ka (like Quaternary glacioeustatic solar cycles) moves the delta mouth 20 km on a 1:1000 gulf gradient. Lack of inter-packet evidence for winnowing (erosion) or condensation (drowning) means the gulf axial gradient is near-linear (‘storm-graded’ equilibrium profile, intrinsic to tideless shelves free of forced exposure), so any rise or fall alters depth (wave power) and proximality equally (%), thus the grain-size arrays (background and event) simply shift in- or out. At stillstand (hi-, low), each megastorm shaves off a layer (cm-dm; swept over shelf edge), maintaining the equilibrium profile, preventing emergence. Shallow flysch interfingers upflow with highstand delta-slope muddy clinothems; and orogenward with olistostromes. Shallow-flysch sand bodies (point-fed hyperpycnite ovoids cut by hyperpycnitic slope-canyon tributaries) are bad ‘outcrop analogs' for fully marine, truly deep-sea, leveed-channel and fan oil reservoirs.

Reinterpreting the Salinity & Water Depth of Peripheral Foreland Basin Flysch

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AAPG European Regional Conference
Lisbon, Portugal, 18th-19th May 2015

MAIN CONCLUSIONS

Foreland flysch ...

- shelfal
- mainly megaflood hyperpycnites & wave-modified hyperpycnites
- poor ‘outcrop analog’ for passive-margin deep-sea reservoirs (Africa, Brazil, Gulf of Mexico, etc.)
- no modern analog

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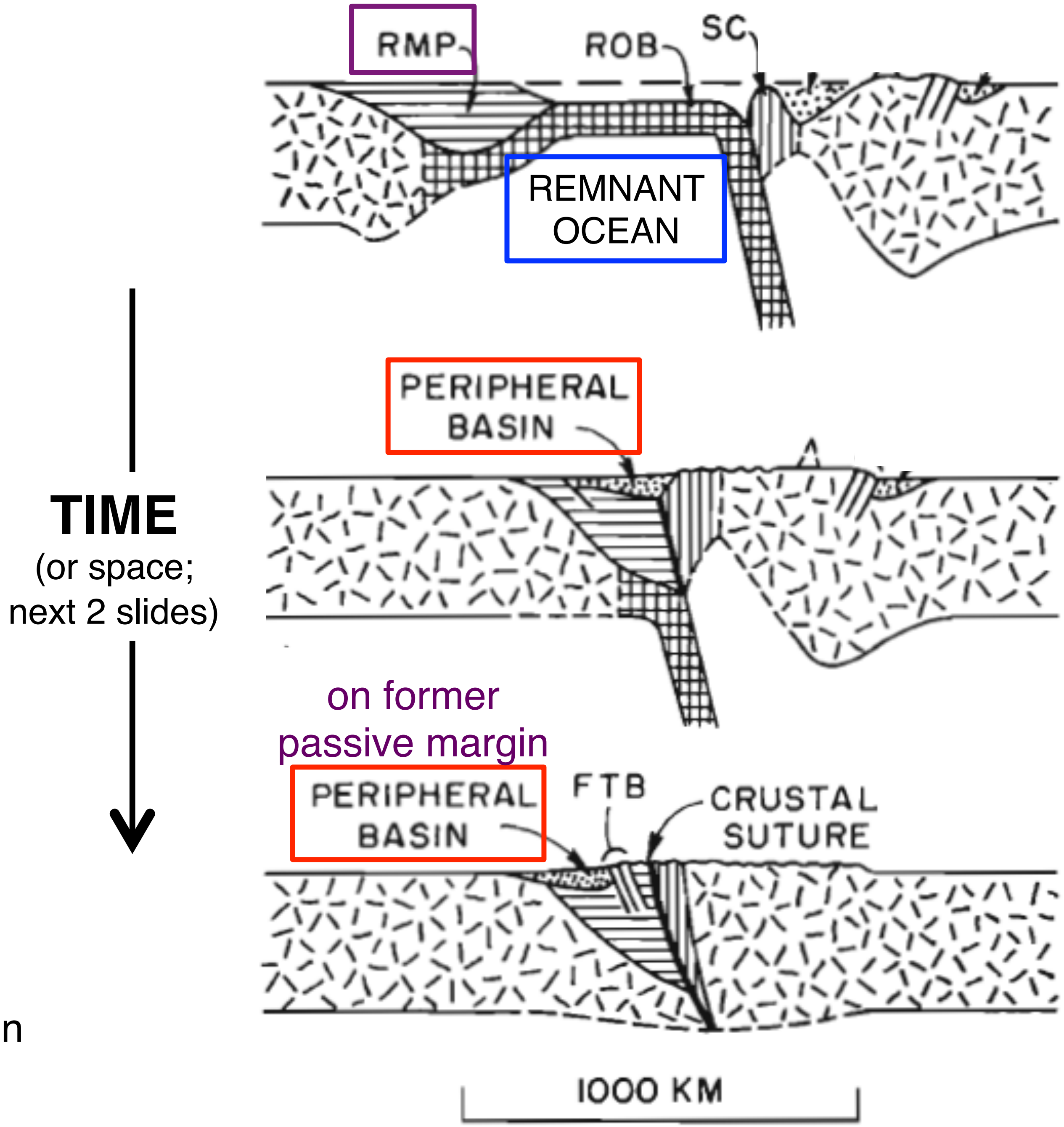
2. Definition of foreland flysch e.g. Annot, Hecho, Marnoso-arenacea
3. Foreland flysch water depth
4. Foreland flysch salinity
5. Remnant oceans inevitably become isolated ‘ocean lakes’
6. New depositional model: foreland ‘flysch shelf’
7. Poor ‘outcrop analog’
8. No modern analog
9. Conclusions & References

Peripheral foreland basin (PFB) development

(Dickinson 1974)



FTB = fold-thrust belt
RMP = rifted margin prism
ROB = remnant-ocean basin
SC = subduction complex

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Continental collisions are diachronous,

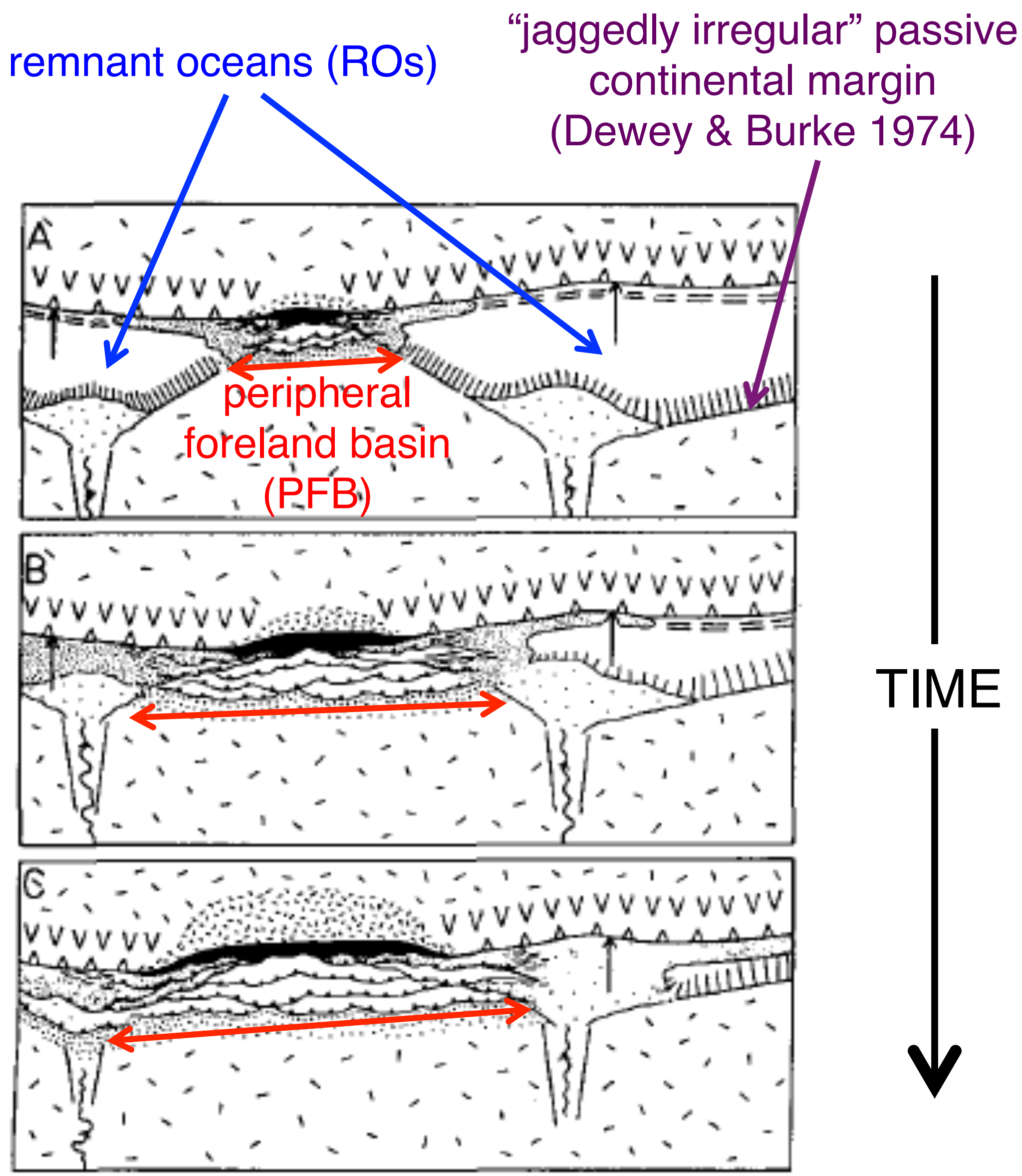
therefore ...

all PFBs adjoin subducting remnant oceans (ROs) alongstrike

&

with time PFBs lengthen, ROs shorten

& (next slide) ...



Dewey & Burke 1974

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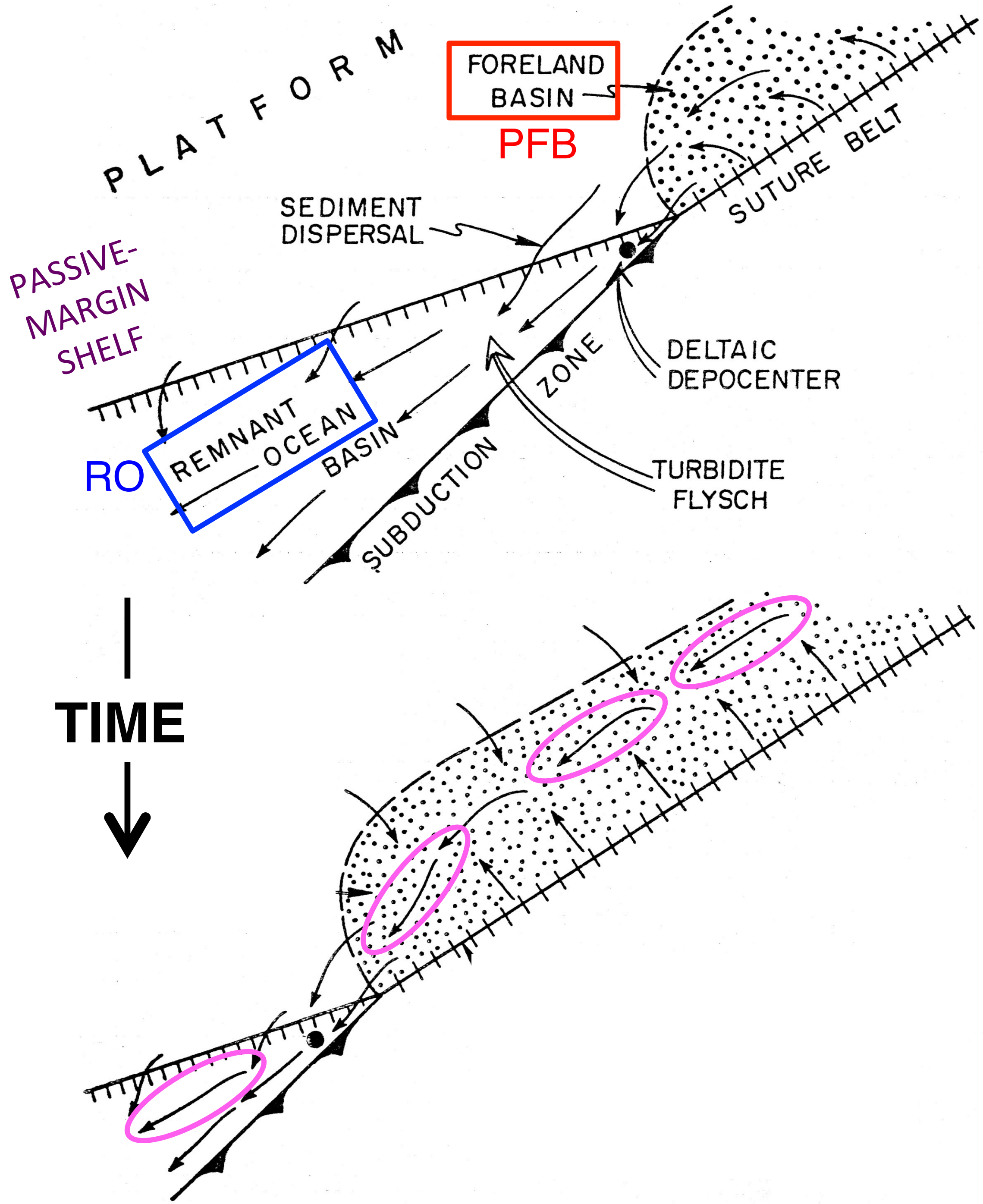
Dickinson 1978



Sediment transport is mainly axial in both the PFB & RO

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A definition of 'flysch' ...

- thick (100s-1000s m) turbiditic strata in & beside orogens

- usually interpreted as deep-sea

Abbate et al. 1970: two flysch settings in Italy

"Eugeosynclinal flysch": orogenically internal; rootless nappes scraped off subducted ocean; usually highly deformed

"Miogeosynclinal flysch" *: e.g. Marnoso-arenacea; external; on continental crust; autochthonous or para-; weak to strong deformation

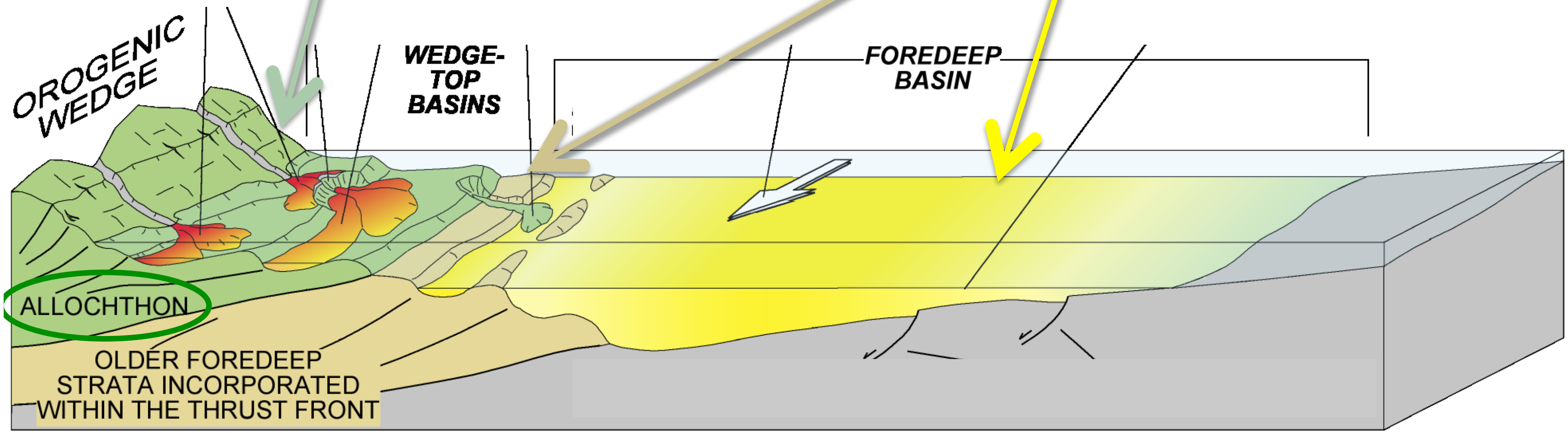

Fig. from Roveri et al. 2002, after Artoni et al. 2000, based on Marnoso-arenacea Formation (yellow color)

* "Exogeosynclinal flysch" of Dewey & Burke 1974

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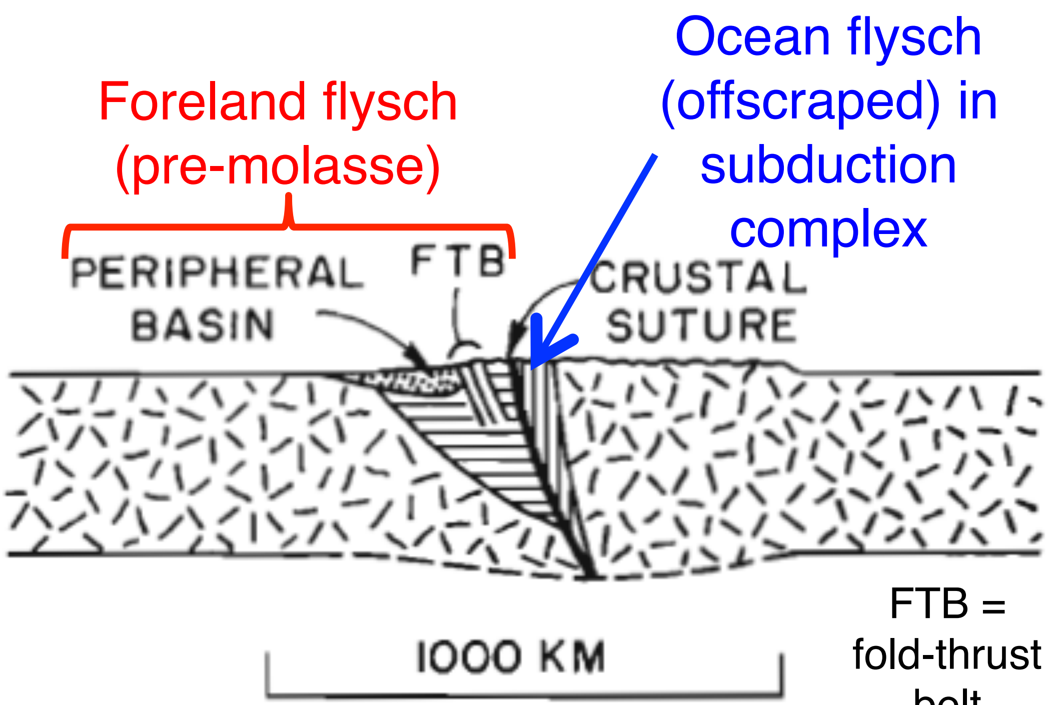
Terms preferred here:

Foreland flysch

vs

Subduction flysch

Same 2 settings reiterated by Dickinson 1974 ...



FTB = fold-thrust belt

Dickinson 1974: fluvio-deltaic molasse “may be preceded by turbidites deposited on ... continental or transitional crust ...”

“The turbidites of peripheral basins as well as the turbidites of oceanic basins ... may ... be termed flysch in many cases”

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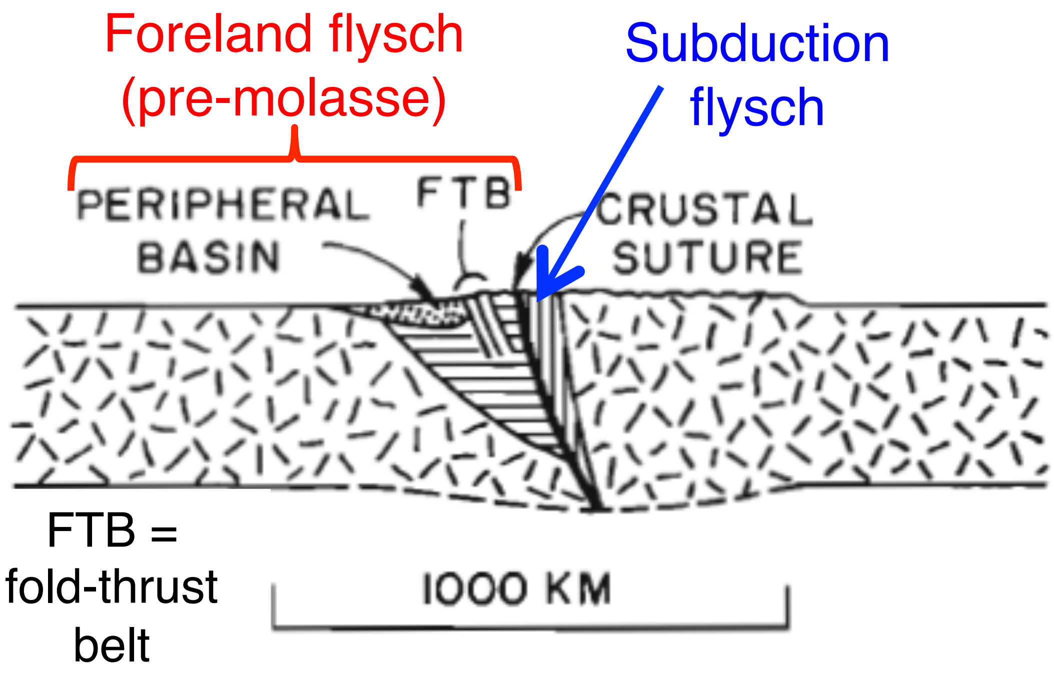
Subduction flysch is **much** less studied sedimentologically (usually highly deformed, in mountainous terrain)



Contrast exhaustive studies of well exposed, almost undeformed foreland flysch in agreeable locations,
e.g. Annot, Brushy, Hecho, Marnoso, Ross, Skoorsteenberg

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Terminology confusion

Einsele 2000 (this fig.):
"Molasse deposits tend to evolve from marine (possibly rather deep, **flyschoid**) to continental"

This follows Homewood & Lateltin (1988) who urged, in Switzerland, strictly geodynamic redefinition of:

Flysch (a, b): entirely pre-collisional (here called subduction flysch) &

Molasse (c, d): post-dates initial collision; turbidites (hitherto included with flysch; here called foreland flysch) followed by shallow marine, deltaic & fluvial

BUT (next slide) ...

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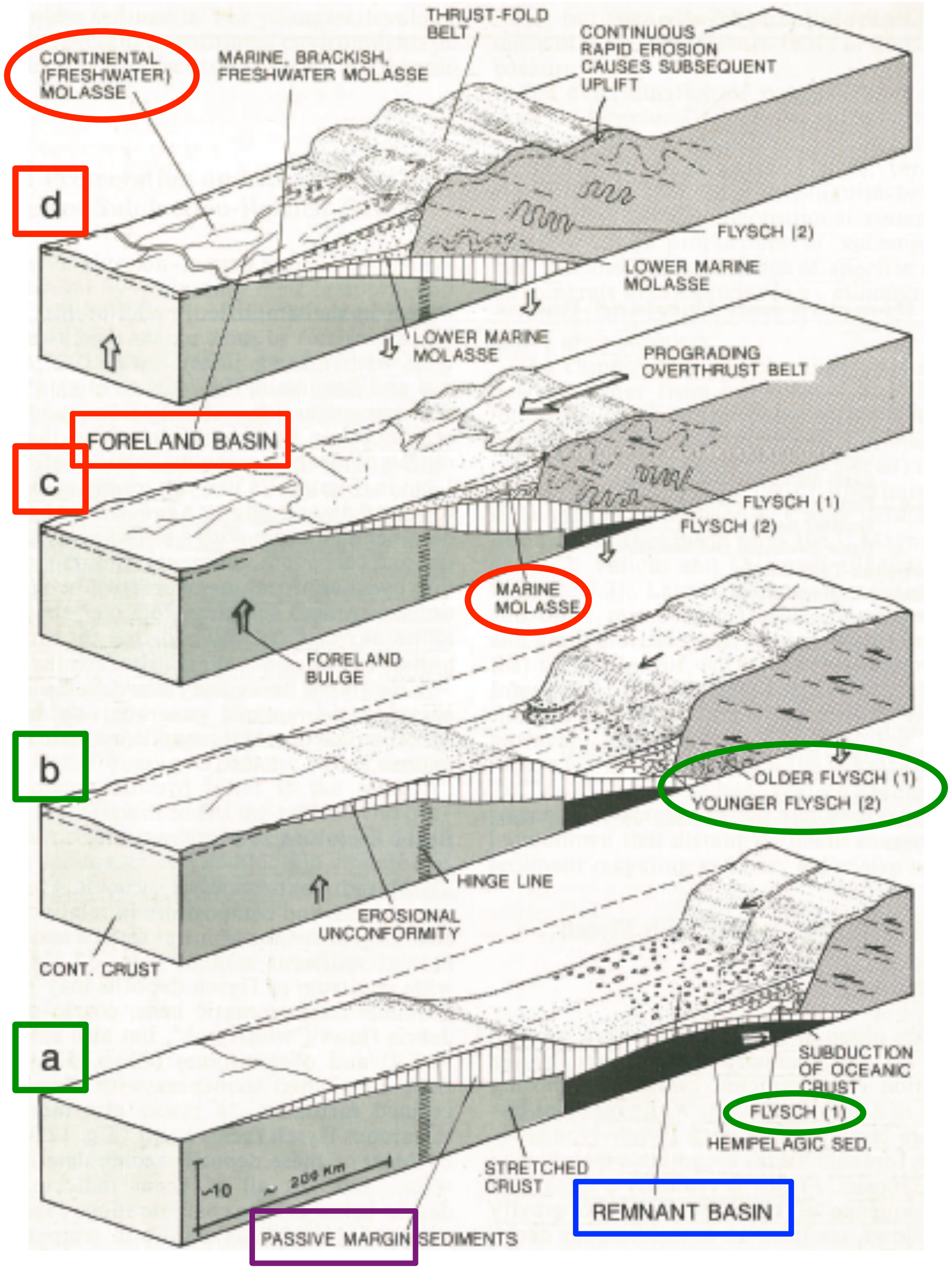


Problems with this approach

- Time of initial collision varies along strike
- Determining exact time of initial collision at any position is subjective
- Descriptive sedimentological differences between ‘flyschoid’ strata & subduction flysch are undefined

therefore ...

the term ‘foreland flysch’ must be retained

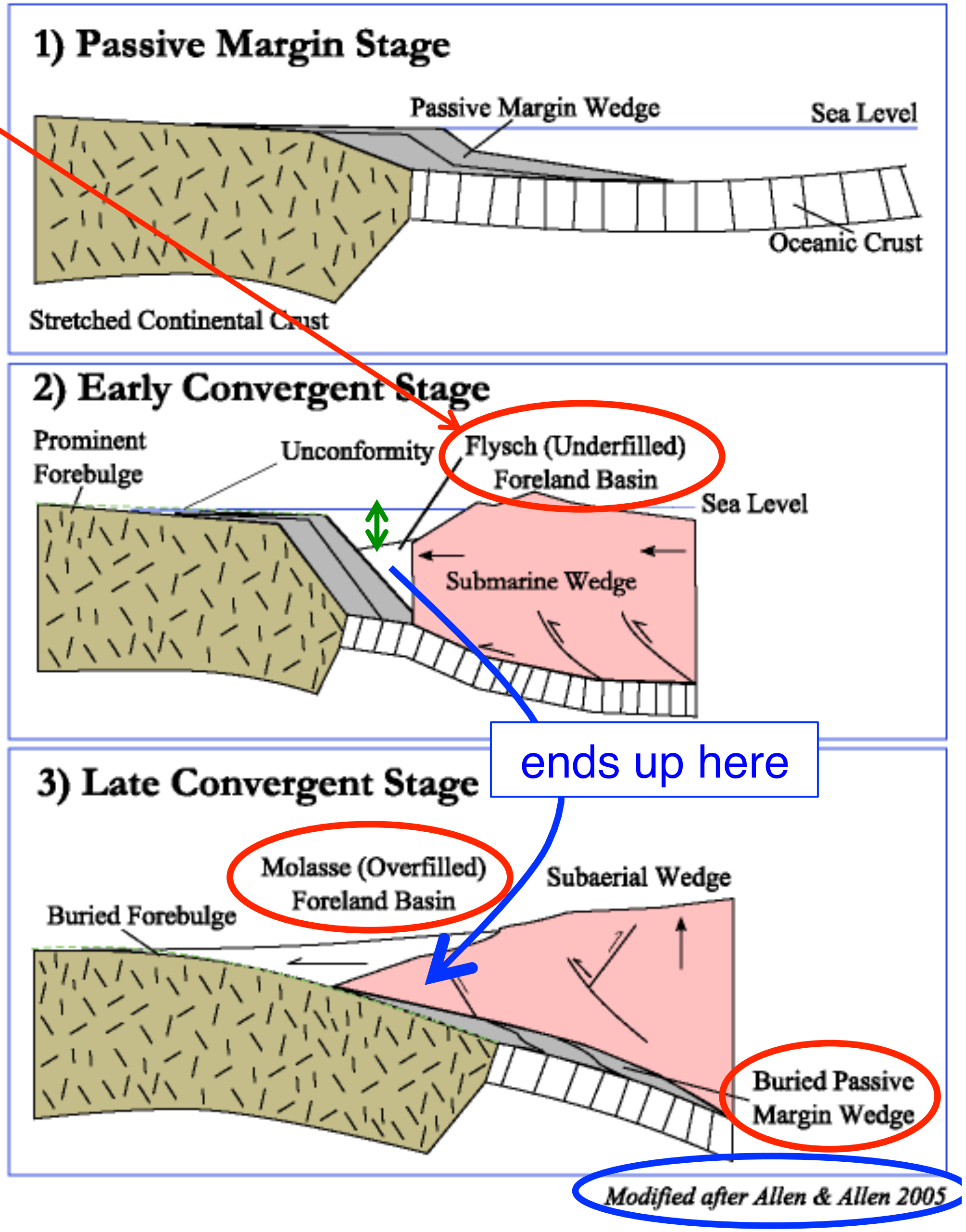
More confusion ...

Fig. wrongly implies foreland flysch was deposited above ocean crust (contrast Slides 7 ,8, 11, 13 above), then thrusted onto continental crust (my blue arrow), then overlain unconformably by molasse.

The original (Allen & Allen 2005 fig. 4.31) labeled this as *Trench ('flysch') basin* (see next slide), ascribing it to the early foreland-basin stage. In fact it is the final increment of subduction flysch.

Fig. also implies deep water (green double arrow); see "underfilled" (term of Allen et al. 1986) in Slide 40.

after Wikipedia, 'Foreland Basin', 14-5-2015



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The same misunderstanding persists ...

i.e. early foreland basin

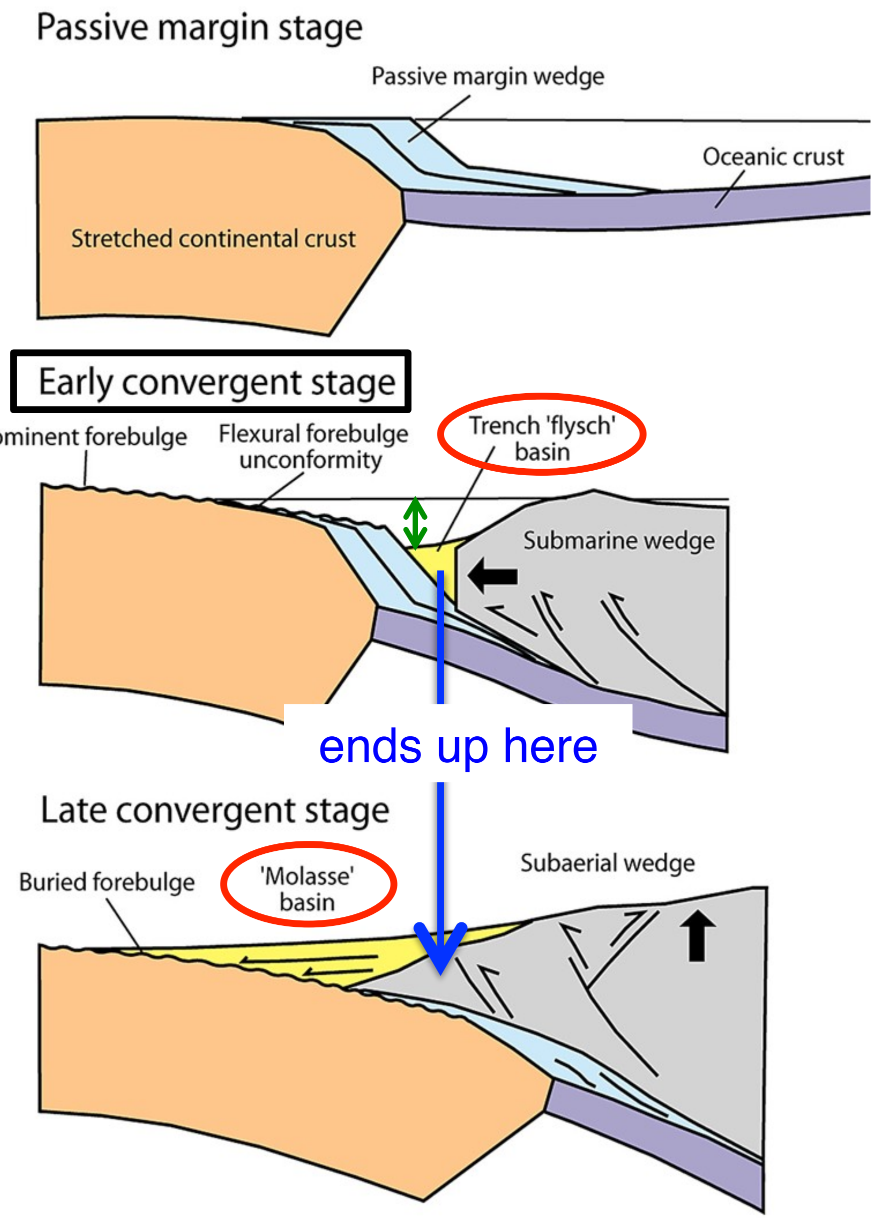

Fig. 4.49 Model involving orogenic loading of a previously stretched continental margin during the early stages of convergence (Stockmal *et al.* 1986 – AAPG © 1986 and reprinted by permission of the AAPG whose permissio use; Watts 1992), modified by Allen *et a*

after
Allen & Allen 2013,
redrawn from
Allen & Allen 2005

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Foreland flysch, usual depo-model ...

‘deep-sea fan’ & ‘basin plain’
confined in an orogen-parallel marine gulf ...

dating back to 1970s papers on Hecho & Marnoso-arenacea ...

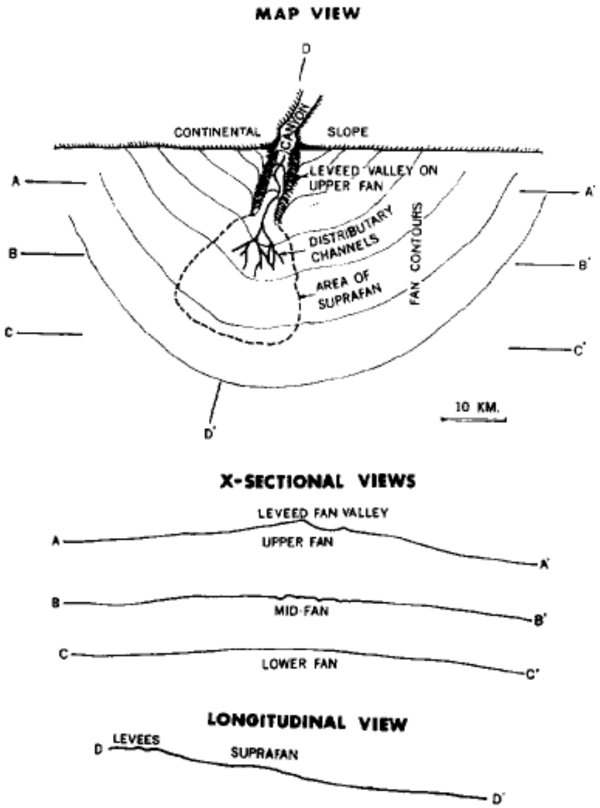
influenced by modern deep-sea fans off western North America
(unconfined & in different tectonic setting)

But review of the evidence (below) in foreland flysch suggests...

-shelf depths (wave-influenced sed. structures)

- hyposalinity at times

Normark 1970, deep-sea-fan model based on modern La Jolla & San Lucas fans



Mutti 1977, deep-sea-fan model for Hecho Group, Eocene, Spain

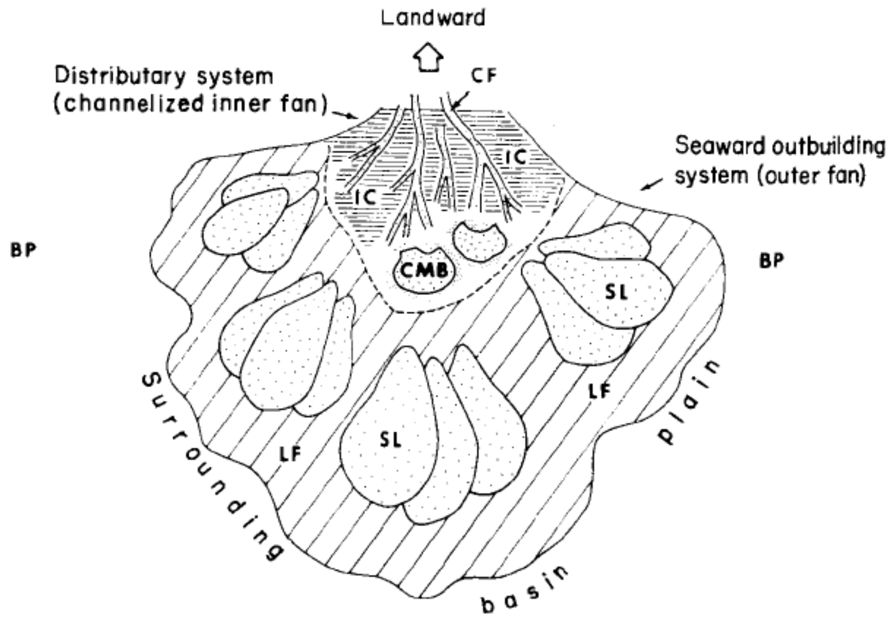


Fig. 2. Depositional model of the Hecho Group turbidite system as inferred from observed facies and facies association relationships. The model does not take into account the actual, elongate basin configuration and is not to scale. The distributary system depicted in the figure is highly diagrammatic and, as such, does not show the complex pattern of countless and relatively small channels observed in the Hecho Group deposits. Thin-bedded facies: IC inter-channel and levee; CMB Channel-mouth bar; LF Lobe fringe; BP Basin plain; Thick-bedded facies: CF Channel fill; CMB Channel-mouth bar; SL Outer fan sandstone lobe.

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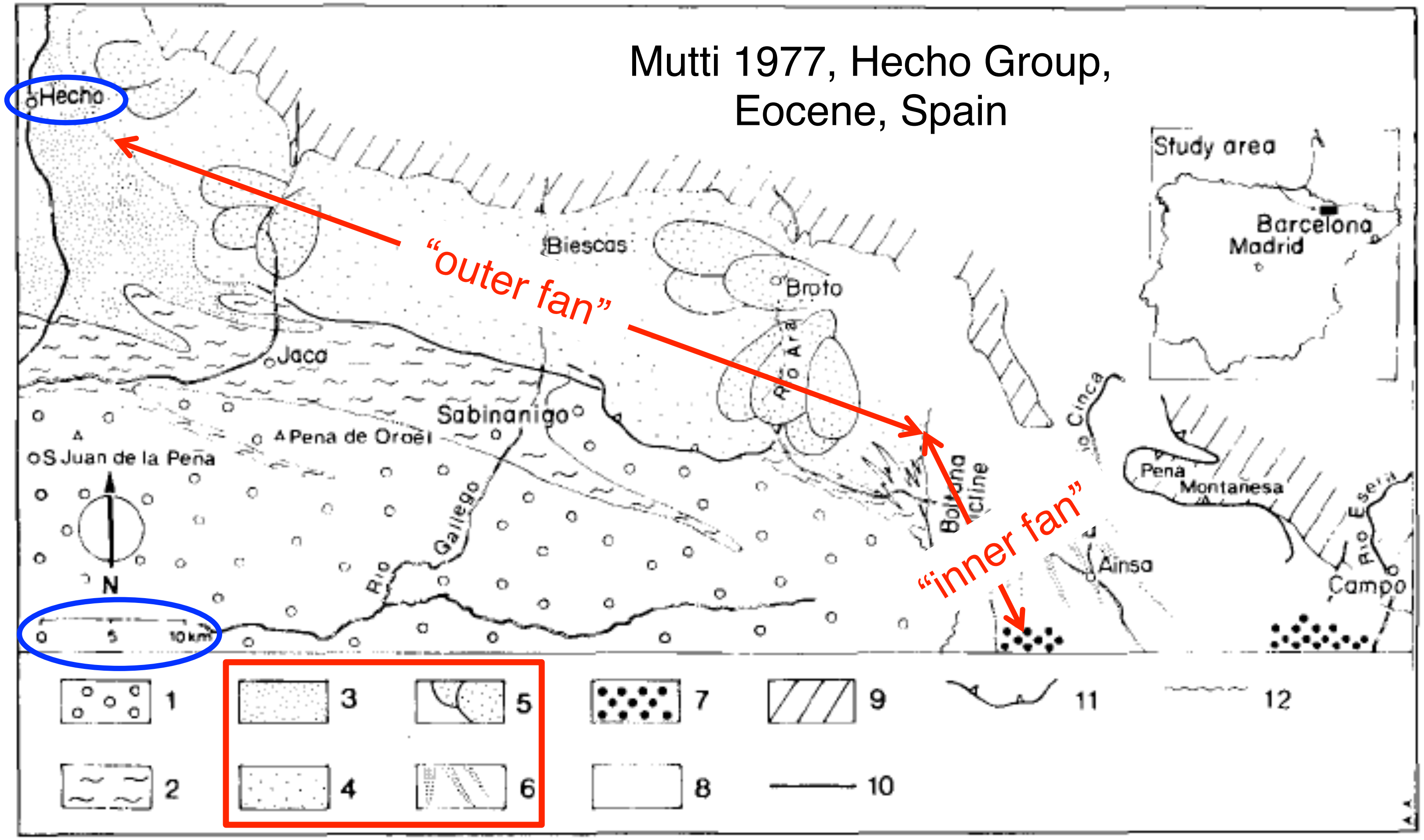

Fig. 1. Sketch map showing distribution of turbidite facies associations in the Eocene Hecho Group between the Esera and the Aragon valleys, south-central Pyrenees, Spain. Legend: 1—Fluvial and underlying deltaic and nearshore deposits (Upper Eocene to Oligocene); 2—Pamplona Marl, an offlapping mudstone sequence including from top to base shelfal and slope deposits (Middle to Upper Eocene); Hecho Group (Cuisian to Middle Eocene): 3—basin plain deposits; 4—fan-fringe and outer fan deposits; 5—outer fan deposits with an abundance of depositional sandstone lobes; 6—inner fan deposits; 7—Deltaic deposits; 8—Unnamed mudstone sequence linking the deltaic deposits (7) to the inner fan sediments (6) of the Hecho Group; 9—Pre-Cuisian rocks; 10—Fault; 11—Low-angle thrust;

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Ten famous foreland-flysch formations:

1. Annot, Eocene-Oligocene, France

2. Brushy, Permian, USA *

3. Bude, Carboniferous, UK *

4. Cerro Toro, Cretaceous, Chile

5. Hecho, Eocene, Spain

6. Jackfork, Carboniferous, USA

* studied by the author

... continued

7. Krosno, Oligo-Miocene, Poland

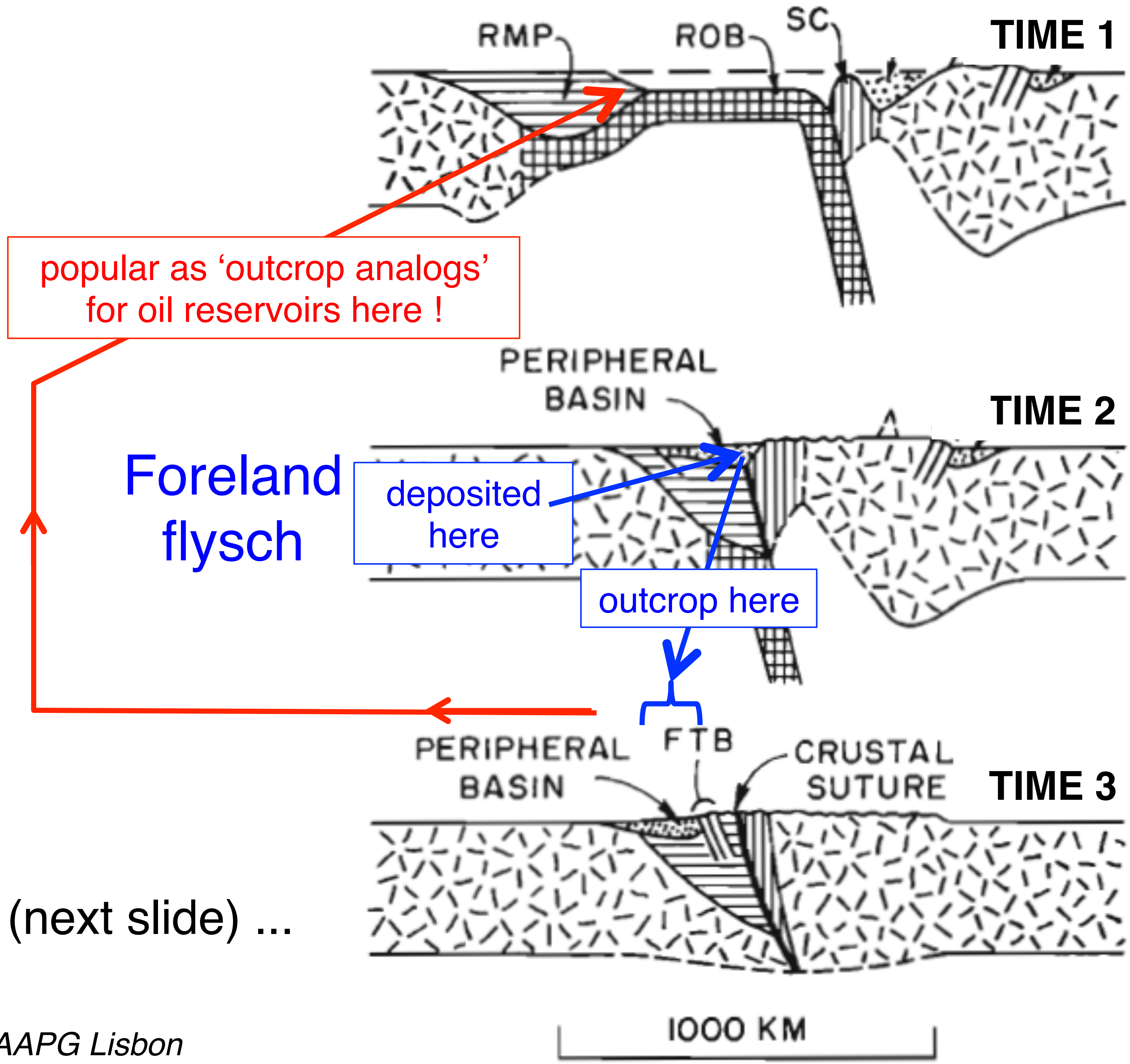
8. Marnoso-arenacea, Miocene, Italy

9. Ross, Carboniferous, Ireland *

10. Skoorsteenberg, Permian, S Africa *

* studied by the author

All except Bude & Krosno are popular as 'outcrop analogs' for *passive-margin* (sic) deep-sea-fan reservoirs, i.e. (next slide) ...



BUT (next slide) ...

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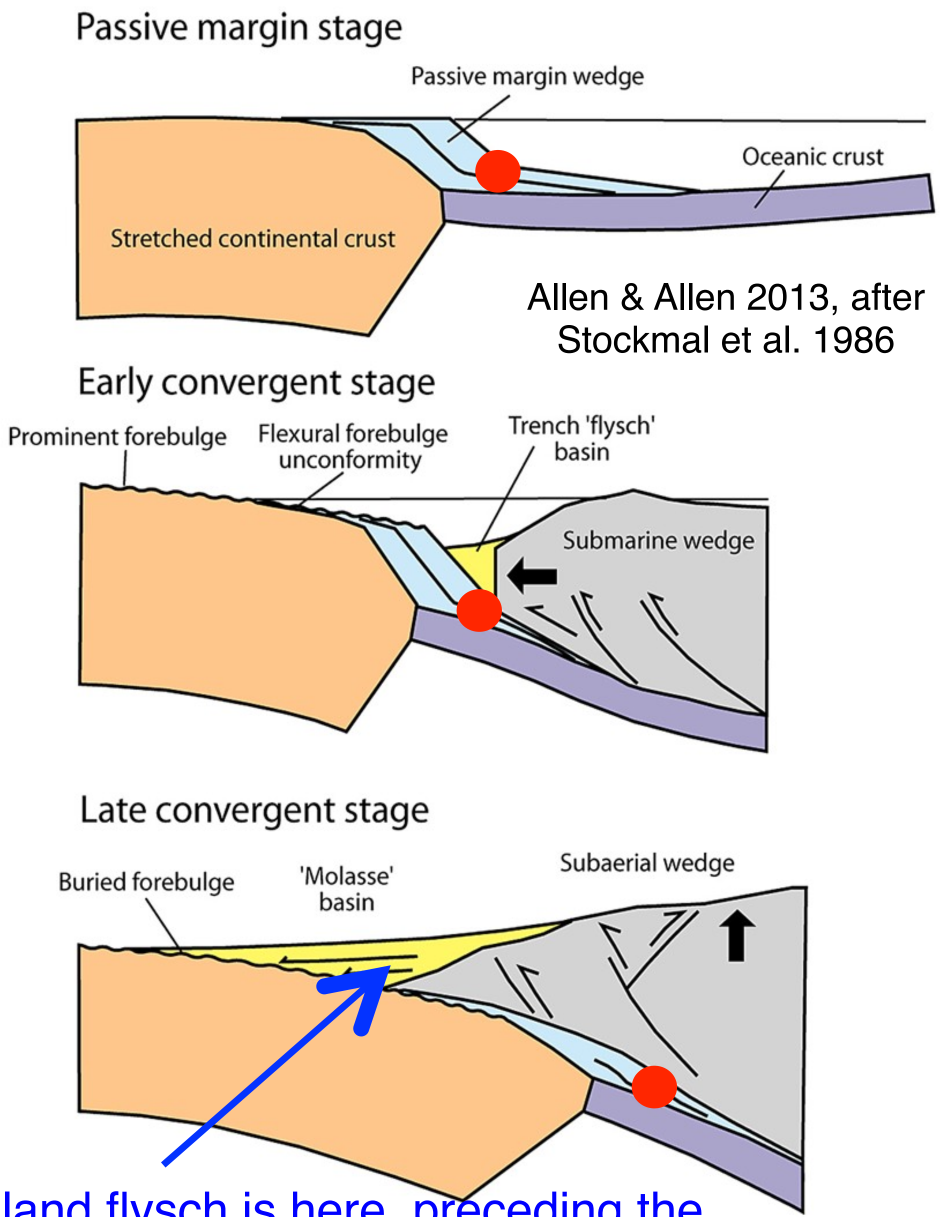
Passive slope & rise strata (red dot) are deposited on ocean crust &/or thinned continent, so are destined for subduction

They can feasibly be ‘jacked up’ to outcrop (Platt 1986 wedge model) but would be ...

highly deformed & metamorphosed !

Thus proper ‘outcrop analogs’ for passive-margin deep-sea oil reservoirs **do not exist**



Allen & Allen 2013, after Stockmal et al. 1986

Foreland flysch is here, preceding the molasse. Can be caught up in foreland thrust belt (cf. Slide 13) & deformed, e.g. Bude Fm, Slides 1, 28, 68, 82

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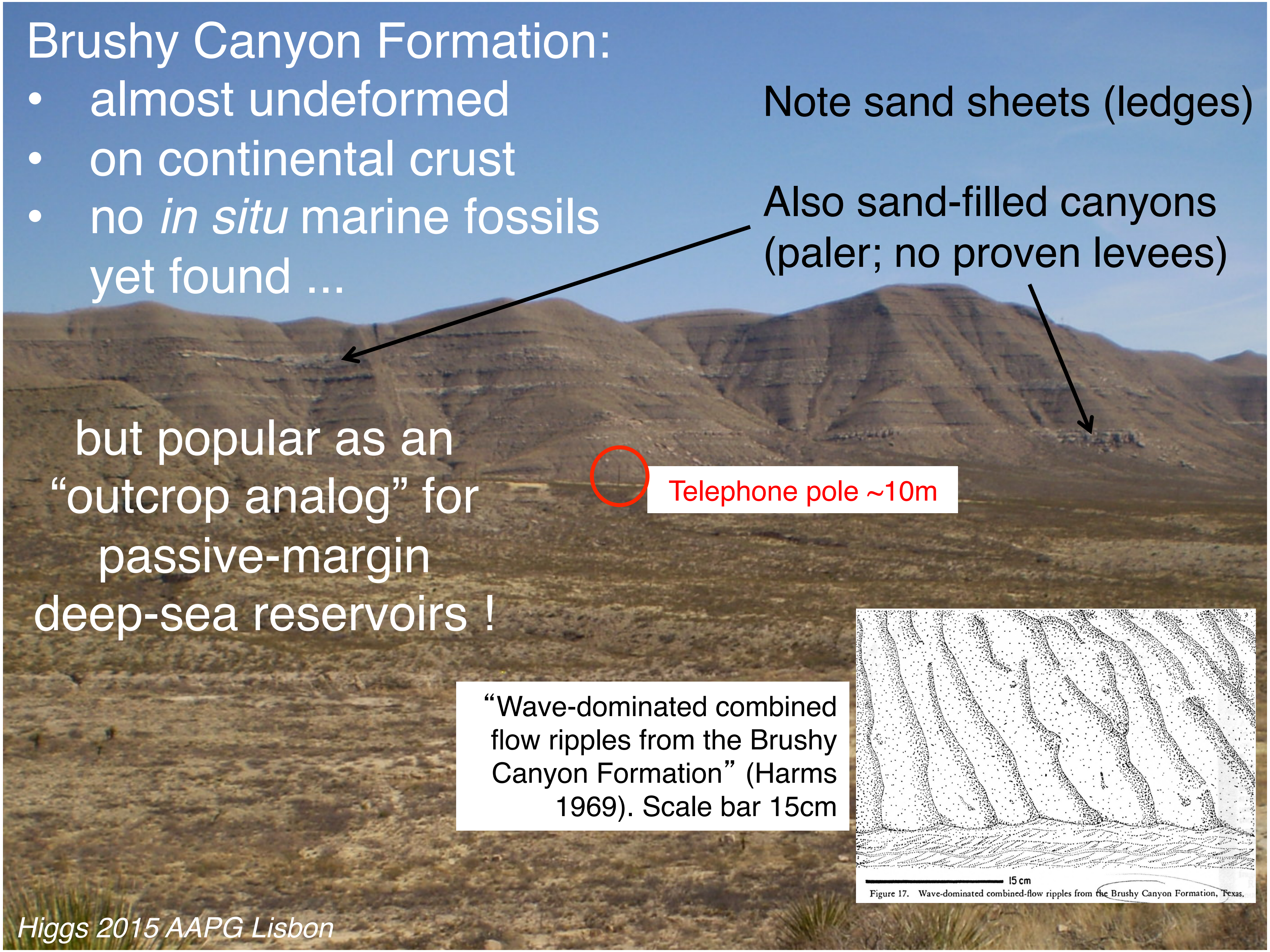
Brushy Canyon Formation:
• almost undeformed
• on continental crust
• no *in situ* marine fossils yet found ...
Note sand sheets (ledges)
Also sand-filled canyons (paler; no proven levees)
but popular as an "outcrop analog" for passive-margin deep-sea reservoirs !
Telephone pole ~10m
"Wave-dominated combined flow ripples from the Brushy Canyon Formation" (Harms 1969). Scale bar 15cm
15 cm
Figure 17. Wave-dominated combined-flow ripples from the Brushy Canyon Formation, Texas.
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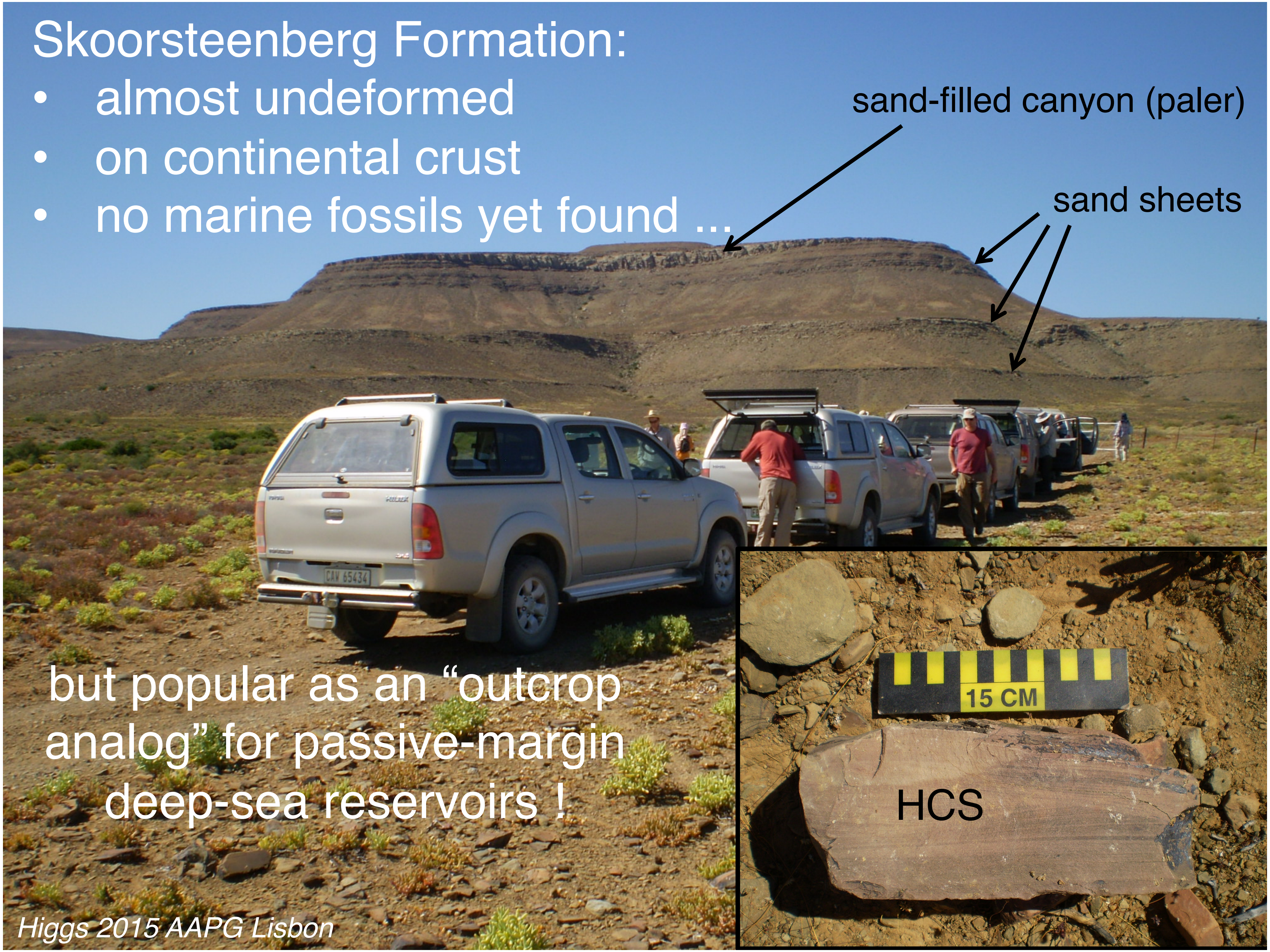
Skoorsteenberg Formation:
• almost undeformed
• on continental crust
• no marine fossils yet found ...
sand-filled canyon (paler)
sand sheets
but popular as an "outcrop analog" for passive-margin deep-sea reservoirs !
15 CM
HCS
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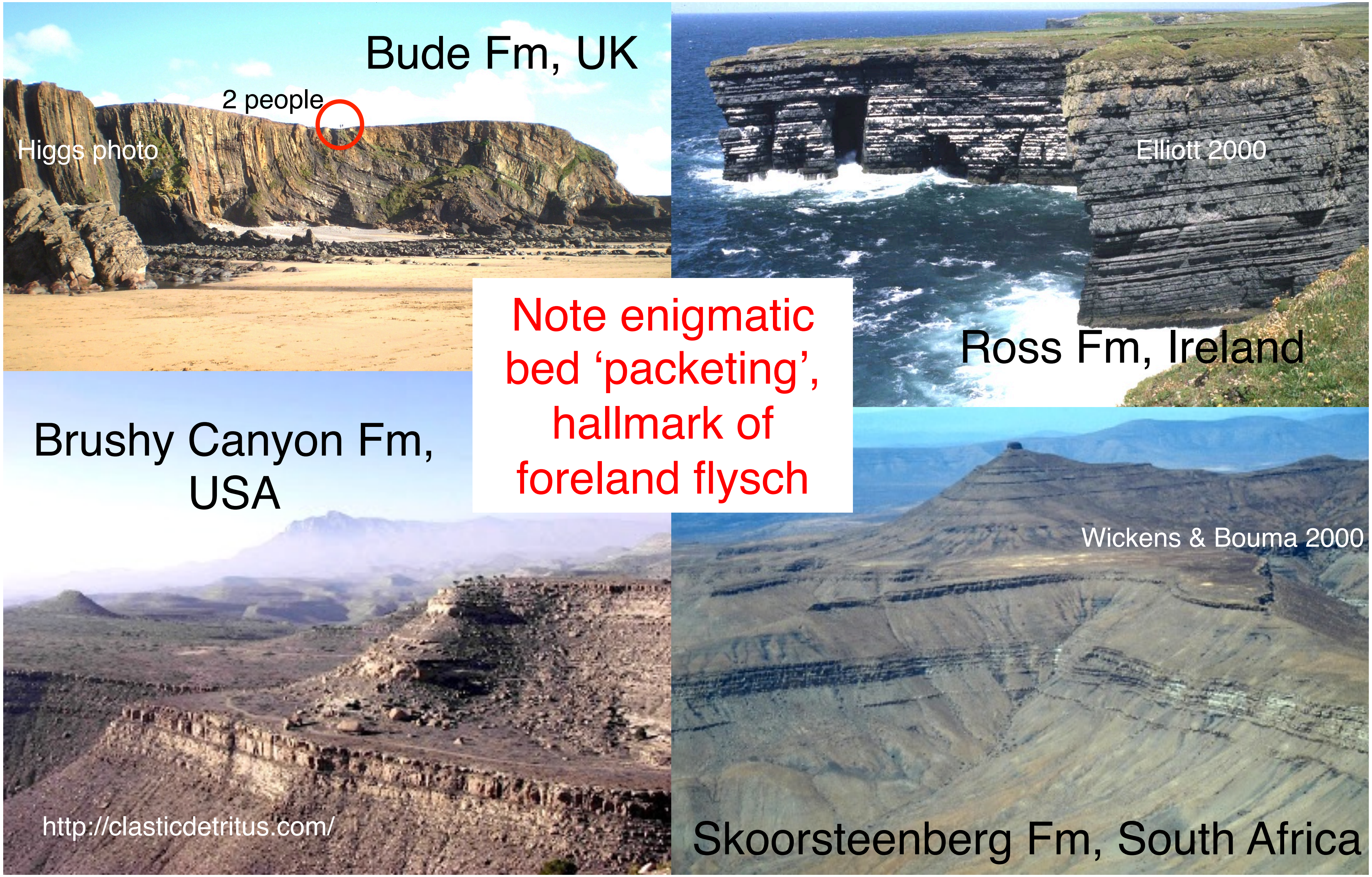
Famous Carbo-Permian flysch formations



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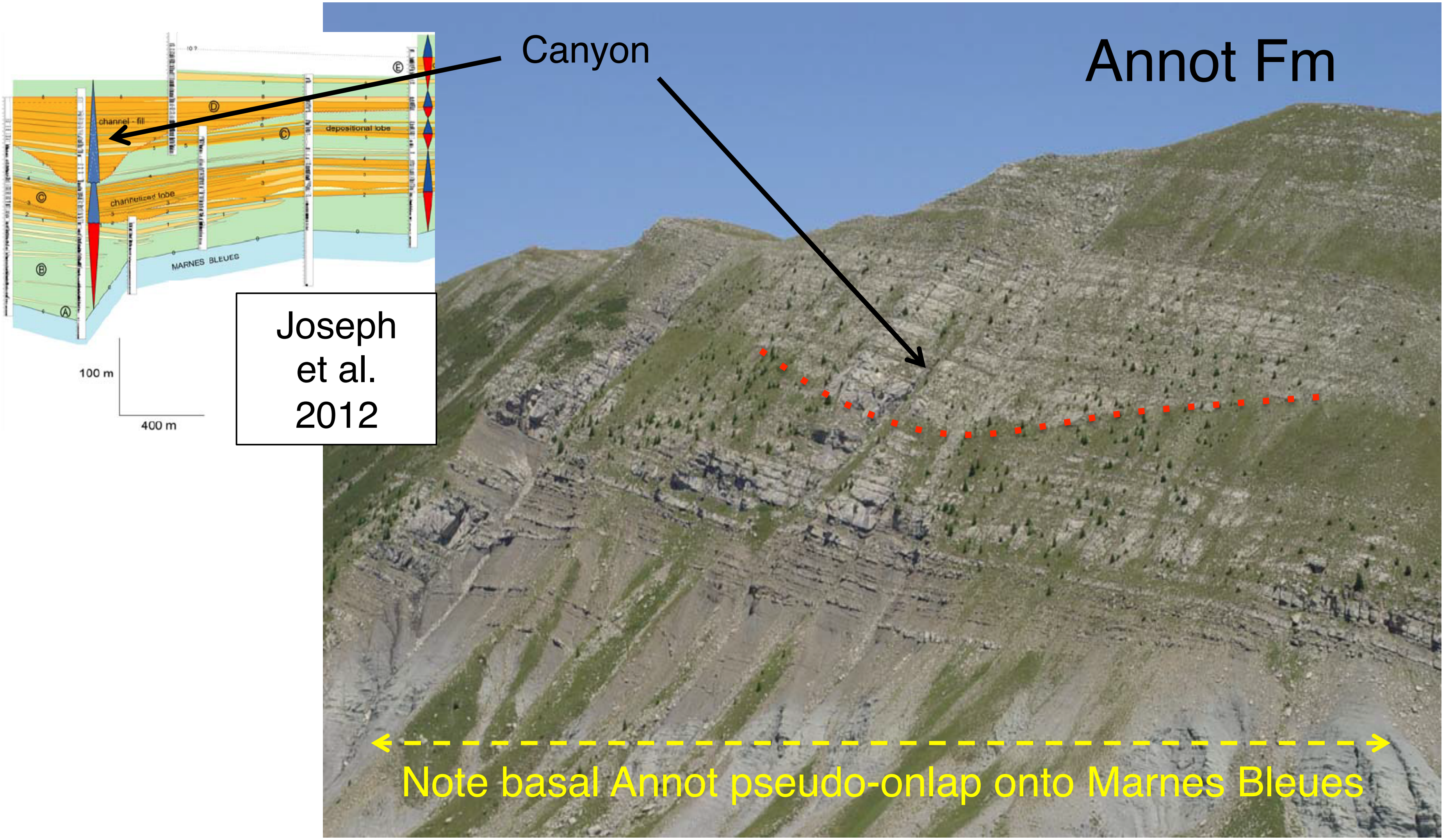
All foreland flysch has two main sand body geometries:
1. tabular (at outcrop scale)
2. incised (i.e. canyons; no proven levees)



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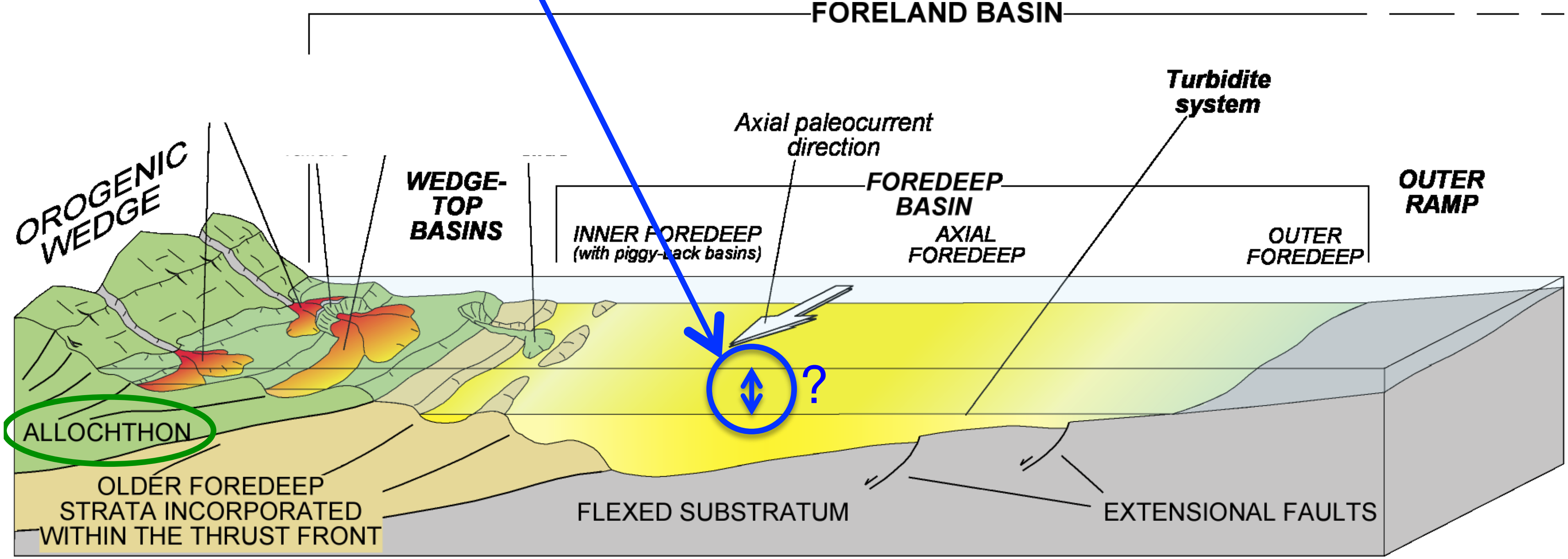
Water depth of foreland flysch?



Roveri et al. 2002, based on Marnoso-arenacea Fm

Consensus on 400-800 m depths
for Annot, Hecho, Marnoso, based on
benthic forams & trace fossils...

poses another problem...

How did so much sediment accumulate
in such a narrow depth-window?
i.e. what prevented shallowing to
shelf depths & beyond?

Hecho max thickness 4.5 km (> 7 km decompacted)
Annot > 1.2 km   Marnoso > 3.5 km

TRACE FOSSILS ARE UNHELPFUL IN INTERPRETING WATER DEPTH

"ichnofacies are not intended to be paleobathometers” as "water depth per se is rarely, if ever, a governing factor"
(Frey et al.,1990)

Skolithos, Cruziana & *Zoophycos* ichnofacies are well known in shelf strata
(Frey et al., 1990, fig. 1)

as is, latterly, the *Nereites* ichnofacies
(Uchman et al., 2004; Olivero et al., 2010)

BENTHIC FORAMS ARE UNRELIABLE AS WATER-DEPTH INDICATORS

due to ...

reworking of deep-sea forams from subduction flysch into foreland flysch (red arrows) in suspension in rivers feeding hypo-, meso- & hyperpycnal flows (Higgs 2014).

Globally greatly underappreciated

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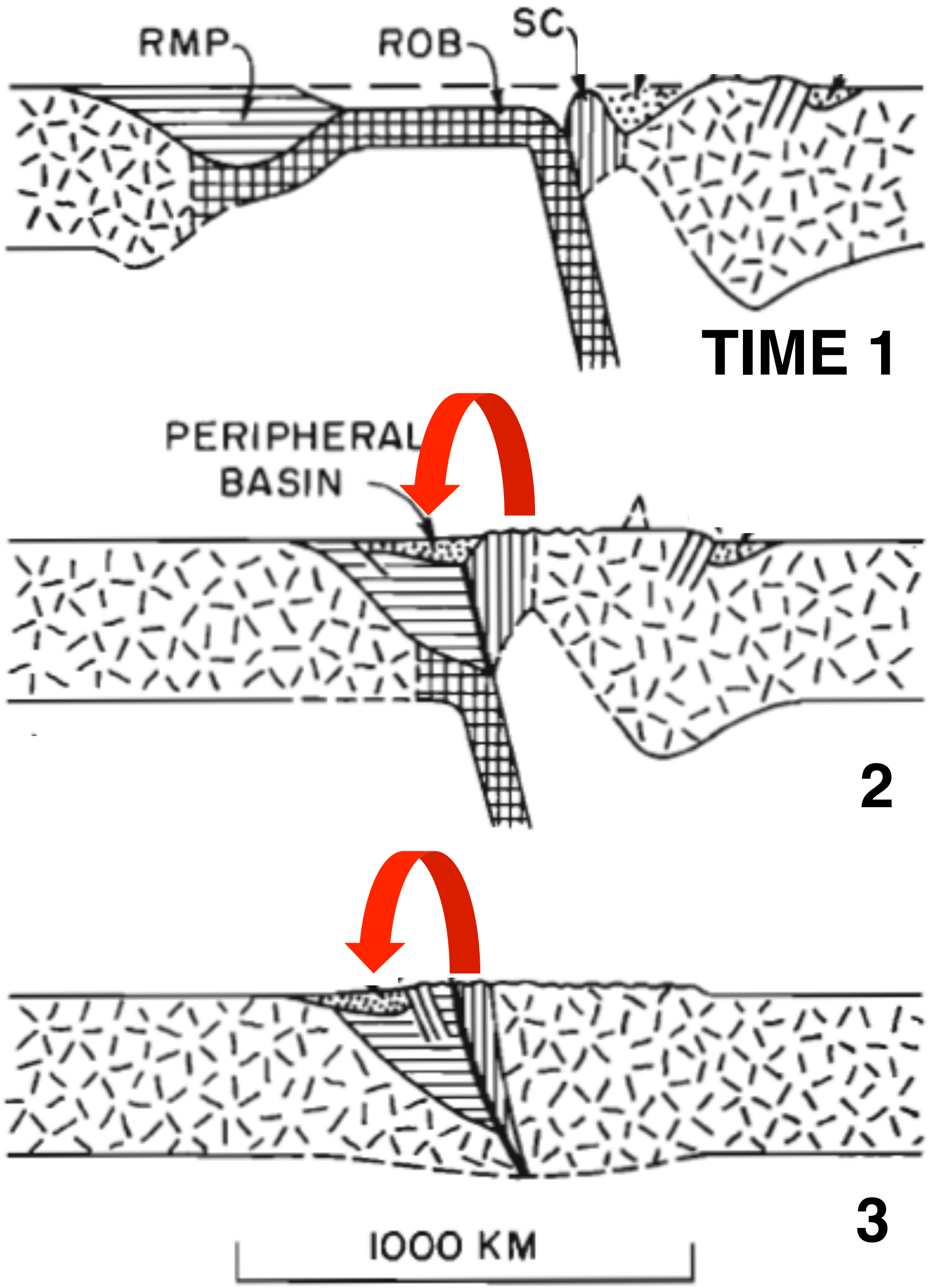
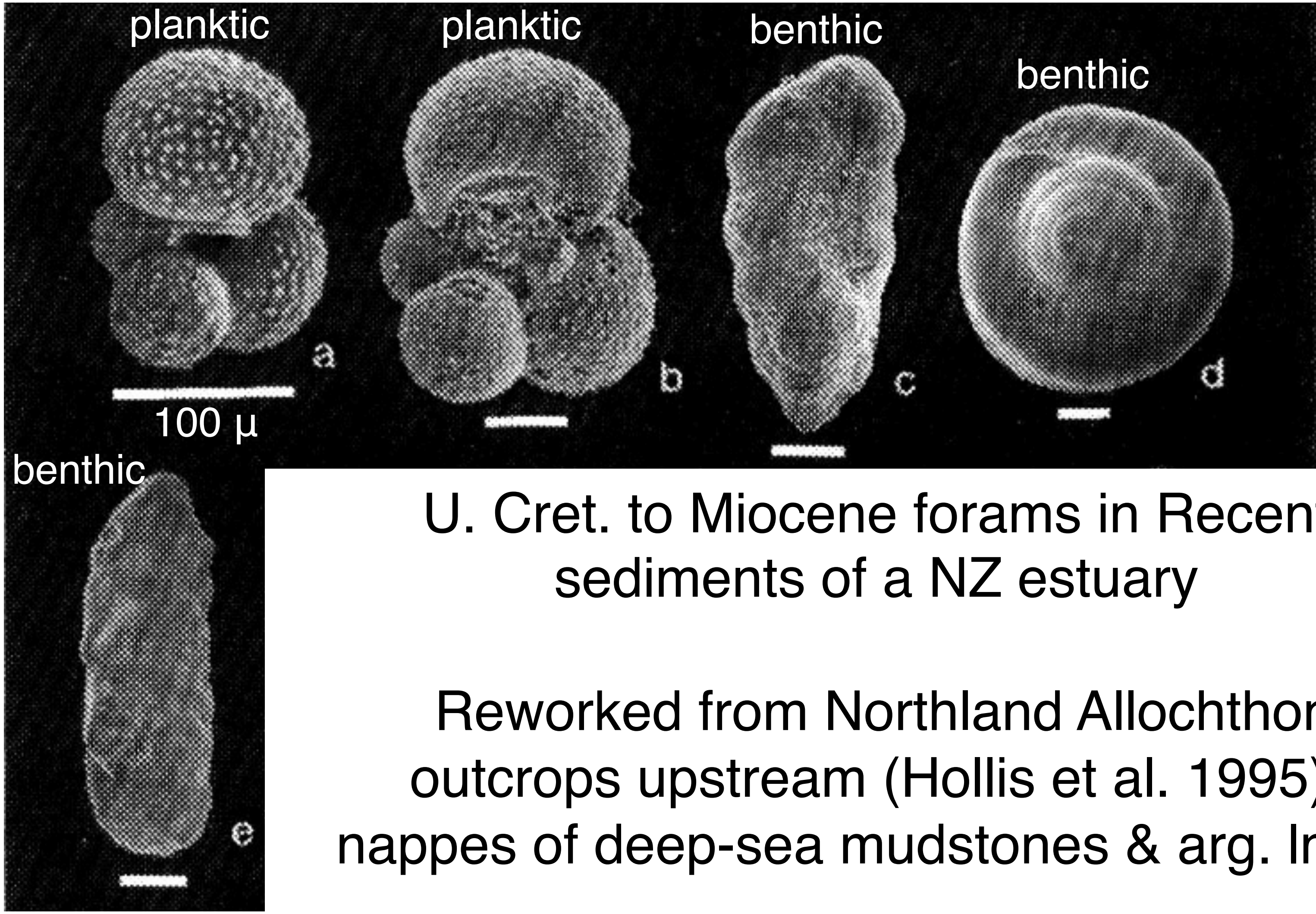


Fluvial reworking of forams: Example 1



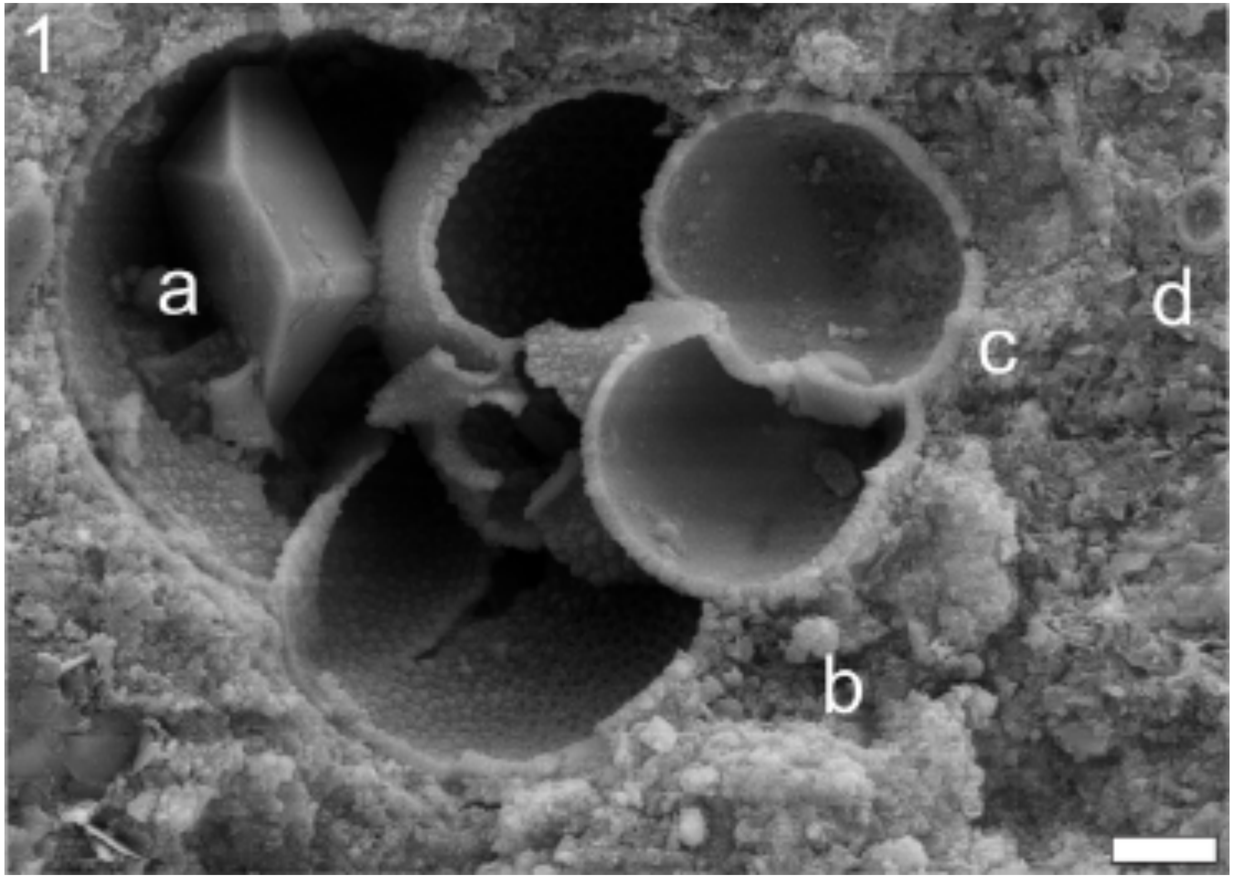
SEM photos

U. Cret. to Miocene forams in Recent sediments of a NZ estuary

Reworked from Northland Allochthon outcrops upstream (Hollis et al. 1995), nappes of deep-sea mudstones & arg. lmsts

b-e identified to species level. Lack of abrasion damage suggests suspension transport

Fluvial reworking of forams: Example 2



SEM
plate

10 µ

Cretaceous planktic foram in Eocene marl, Jordan, interpreted by Alqudah et al. (2014; also Alqudah pers. comm.) as fluvially reworked & deposited on shelf. Lack of evident outer-wall damage suggests suspension transport. Hollow chambers would facilitate suspension (buoyancy).

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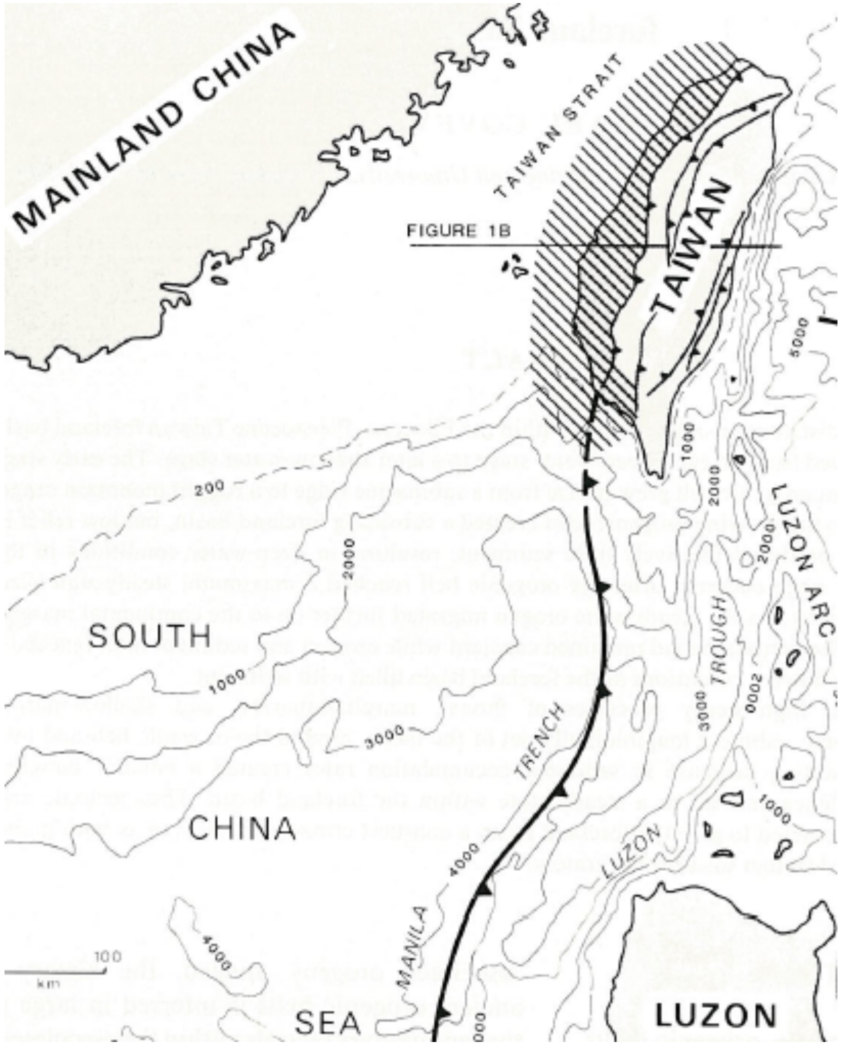
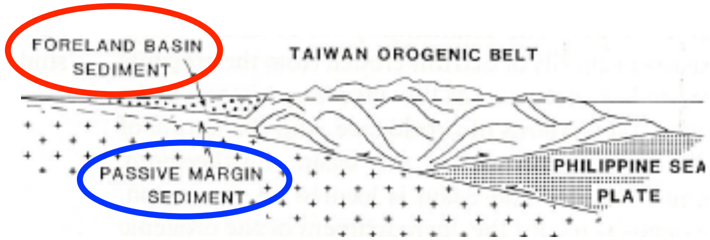
Two lines of evidence suggest
shelf water depths for foreland flysch:

1. sedimentary studies in the active
Taiwan peripheral foreland basin (6.5-0Ma)

2. sedimentary structures
suggestive of waves



Covey 1986



Taiwan Foreland Basin, 6.5-0 Ma, still youthful

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Taiwan Foreland Basin

Covey (1986) invoked an “early, deep-water stage” based on a mudstone interval interpreted as “probably deeper than 200 m”.

IN CONTRAST ...

Castelltort et al. (2010) interpreted entire basin fill, including thin (< 150m) intervals of “prodelta turbidites”, as no deeper than shelfal, stating ...

“This adds to the examples of ‘shallow turbidites’ increasingly ... found in foreland basins (Mutti et al. 2007). The classical early ‘under-filled’ stages of foreland basins must perhaps be not necessarily assumed ‘deep’ ”

Castelltort et al. (2010)

ALSO, ALL FORELAND FLYSCH SHOWS EVIDENCE FOR WAVES

in the form of frequent event beds of fine or vf sand showing ...

1. HCS (usually interpreted by deep-water proponents as an "HCS-lookalike" formed by turbidity-current internal waves, not yet demonstrated in flumes)

2. long (dm)-wavelength asymmetrical cross lamination (combined flow; Myrow & Southard 1991)

3. small or large near-symmetrical ripples (combined-flow)

4. truncation (vertically, laterally) by mud-draped scours (MDS), attributable to storm waves unaccompanied by any sand-supplying current

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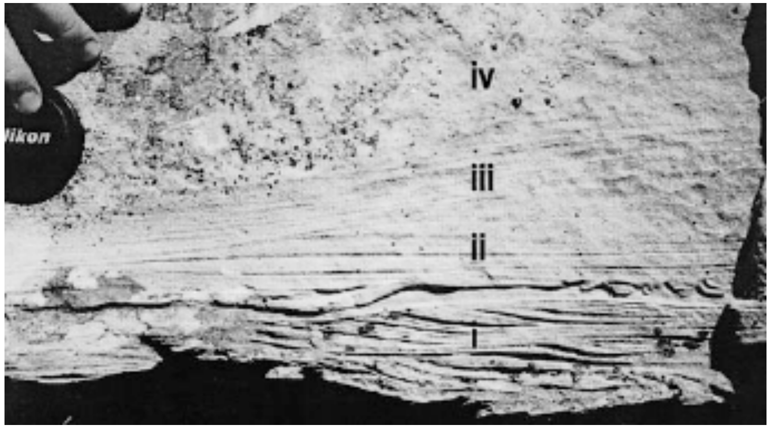
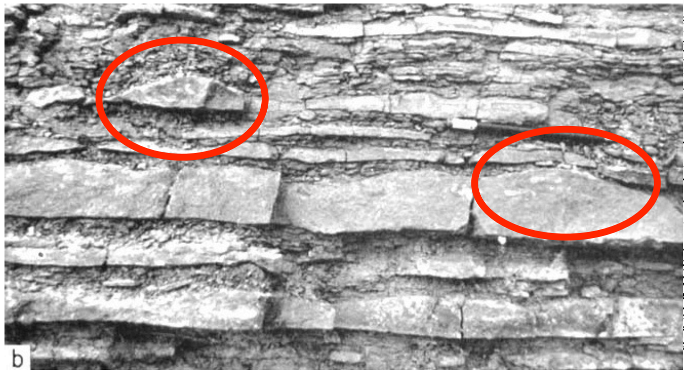
HCS & near-symmetrical ripples in foreland flysch



Marnoso-arenacea Fm, "interval of curving and slightly fanning lamination (iii) reminiscent of hummocky cross-stratification" (Kneller & McCaffrey 2003)

Annot Fm. "The laminasets are slightly wavy, sometimes forming upwards-growing ... bedding due to symmetric ripples that look like small hummocks in a 3D view" (Guillocheau et al. 2004)



Hecho Gp, Mutti 1977. Irregular ripples; some symmetrical

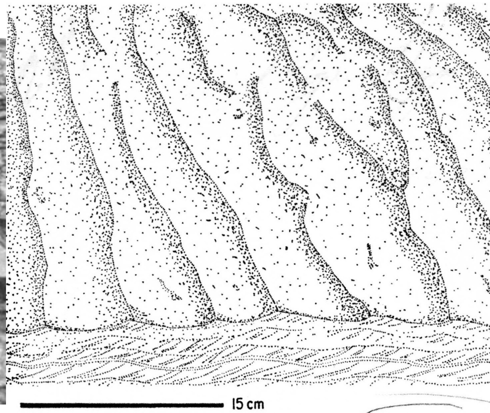
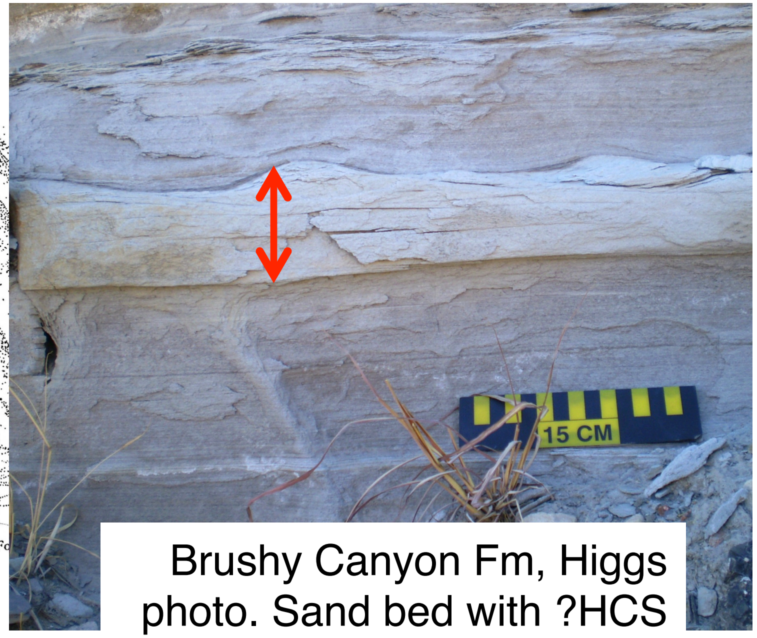


Figure 17. Wave-dominated combined-flow ripples from the Brushy Canyon Fo

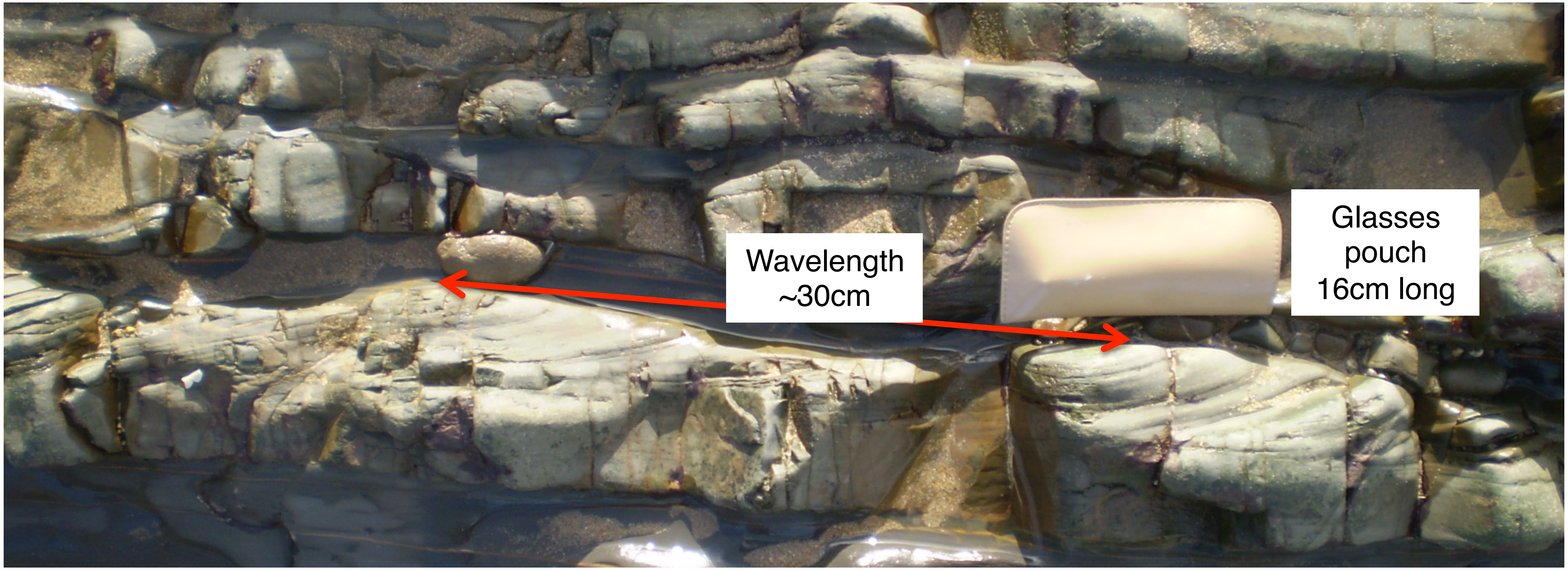
"Wave-dominated combined flow ripples from the Brushy Canyon Formation" (Harms 1969)



Brushy Canyon Fm, Higgs photo. Sand bed with ?HCS & near-symmetrical ripples

Higgs 2015 AAPG Lisbon

Large near-symmetrical ripples in vf sand in two successive event beds, Bude Fm

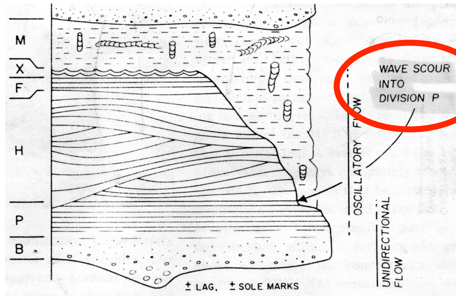


Both the weak asymmetry & long wavelength indicate combined flow (waves + one-way current), based on flume studies in fine sand (Myrow & Southard 1991). In sand finer than ~0.15mm, one-way flows can only form small ripples (wavelength < ~20cm), succeeded by plane bed (Harms et al. 1982, figs 2.4a, 2.5)

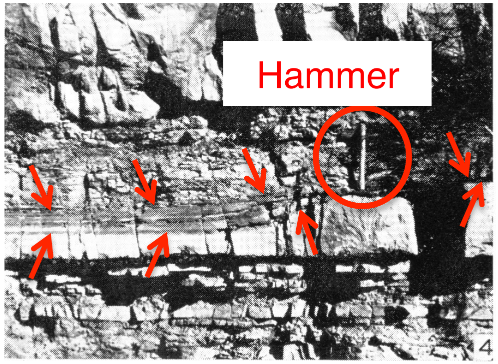
Mud-draped scours (MDS), characteristic of tempestites

Goldring & Bridges 1973: most shelf event-bed tops show "shallow scours overlain by shales. The scour surfaces ... have a relief of up to 60 cm"

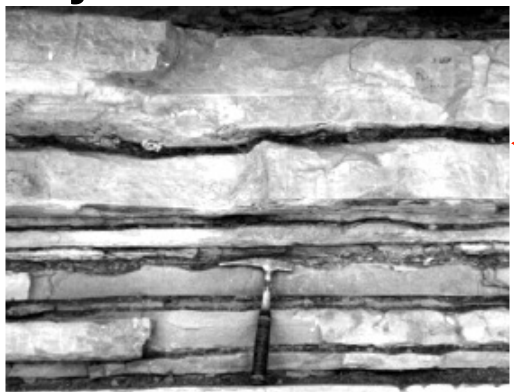
Walker et al. 1983 ideal storm bed, including a mud-draped "wave scour"



MDS in foreland flysch:



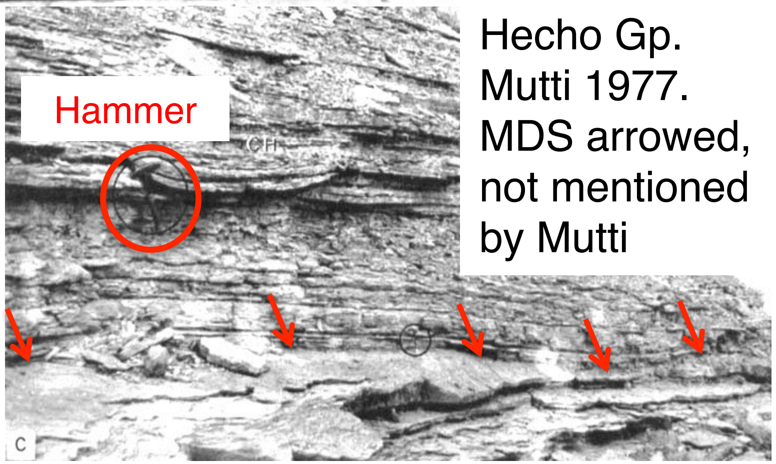
Annot Fm. "Scour and fill structure, filled up with finer material than the surroundings" (Bouma 1962). In fact *two* mud-draped scours (arrowed).



MDS

Annot Fm, Joseph et al. 2012

Marnoso-arenacea Fm. Tinterri et al. 2011



Hecho Gp. Mutti 1977. MDS arrowed, not mentioned by Mutti

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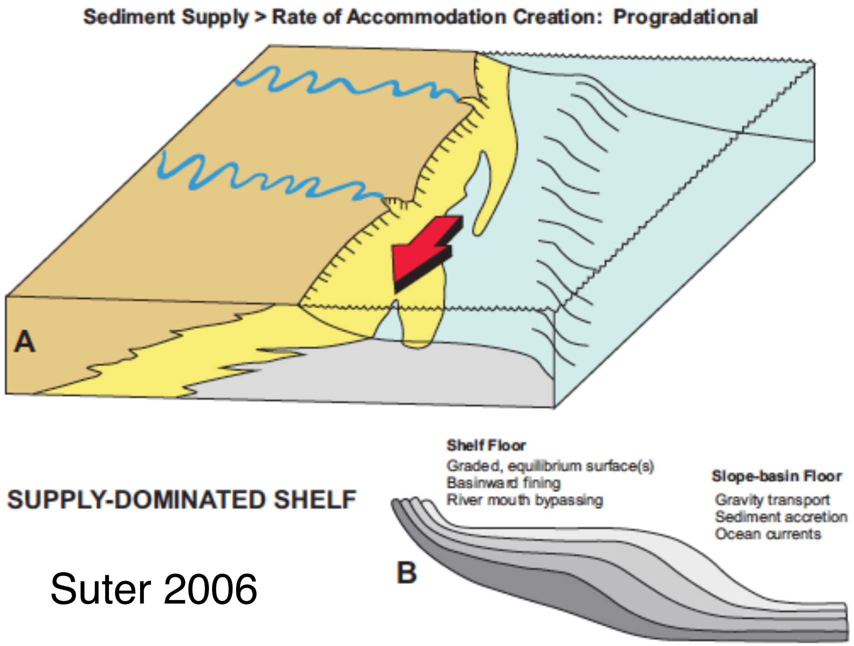
SO THE EVIDENCE SUGGESTS
FORELAND FLYSCH IS SHELFAL

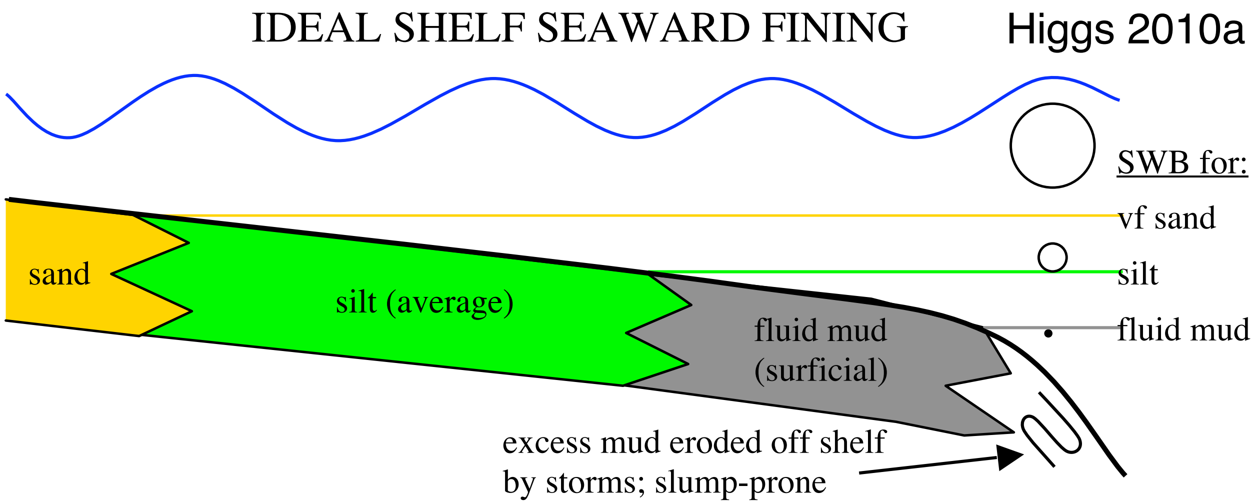
WHY DO SHELVES EXIST? ...



Suter 2006

A universal equilibrium shelf profile exists, maintained by storm erosion (Seilacher 1982)

Each grain size has its own storm wavebase



Each storm shaves off excess aggraded sediment, leaving an erosion surface (sharp base of a storm sand bed; or a mud-draped scour)

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Modest (10s m) falls & rises do not lower or raise the equililibrium profile (by erosion or drowning respectively)

because

shelf gradient is near-linear, so any rise or fall alters depth (wave power) & proximality (delivered grain size) equally (%), thus the grain-size arrays (background & event) simply shift inward or outward (Higgs 2014)

Equilibrium-shelf model does not apply to:

(1) inner-shelf areas overrun by delta progradation
(outweighs rare storm erosion)

(2) times of extreme glacioeustatic amplitude
(>100m, e.g. Quat), when

- much or all of shelf undergoes lowstand forced exposure &

- is again out of equilibrium after ensuing extreme rise & ravinement, drowning the shelf to below storm wavebase

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AGENDA

1. Peripheral foreland basins & adjoining remnant oceans: recap
2. Definition of foreland flysch e.g. Annot, Hecho, Marnoso-arenacea
3. Foreland flysch water depth
4. Foreland flysch salinity
5. Remnant oceans inevitably become isolated ‘ocean lakes’
6. New depositional model: foreland ‘flysch shelf’
7. Poor ‘outcrop analog’
8. No modern analog
9. Conclusions & References

Evidence that our 10 flysch basins were hyposaline at times, i.e. lakes

1. Many micropaleo samples are barren (e.g. Marnoso outcrop, Di Giulio et al. 2013), despite sampling bias (darkest/finest facies)

2. >50% of Hecho borehole samples lack planktics but yield benthics (Jones et al. 2005). Benthics reworked or brackish-tolerant?

3. Bude & Ross: marine fossils (goniatites) are confined to < 5 thin (cm-dm) bands, yet Bude is 1300m thick & Ross 450m (Higgs 1991, 2004)

4. Marine fossils unknown in Skoorsteenberg Fm (Higgs 2010b). Limited ichnofauna (refs in Higgs 2010b) consistent with freshwater lake (lakes depauperate until Mesozoic; refs in Higgs 2004).

... continued

Evidence for lowered salinity at times
continued...

5. A unique fish in Bude Fm is consistent with endemism in an isolated lake (brackish or fresh), i.e. newly evolved fish could not escape (Higgs 1988)

6. Apart from reworked fusulinids in Brushy (refs in Higgs 2015), no benthic forams are known in our five Pzc formations. Pzc planktics & (probably) deep-sea benthics did not exist (Gooday 1994), i.e. unavailable for reworking from subduction complex.

7. Lacks of evidence for persistent currents (contour or tidal) suggests isolation from world ocean, i.e. lake

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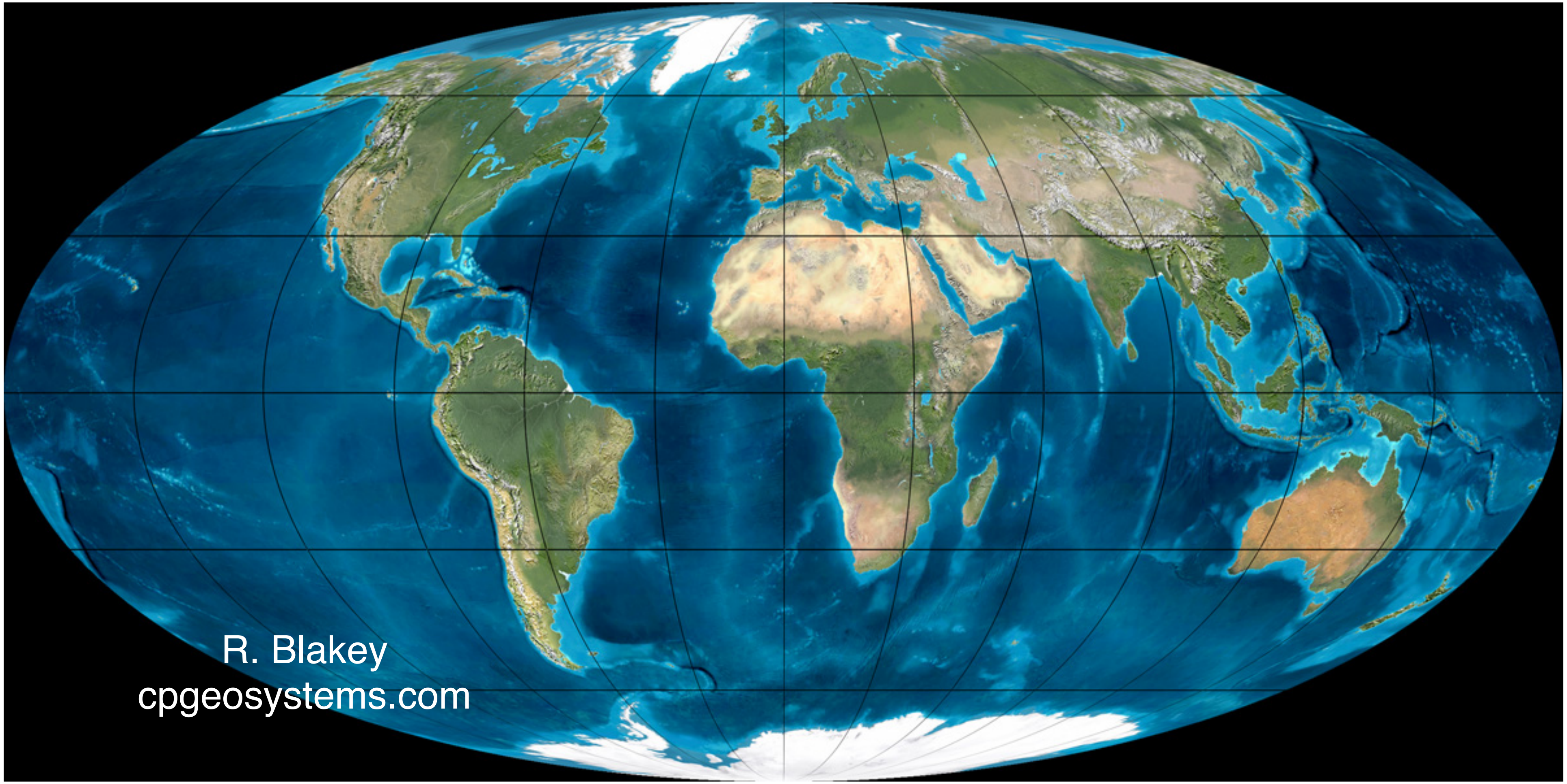
Most continental margins are "jaggedly irregular" (term of Dewey & Burke 1974)



so, inevitably, when long margins collide (next slide) ...

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... salients collide early,

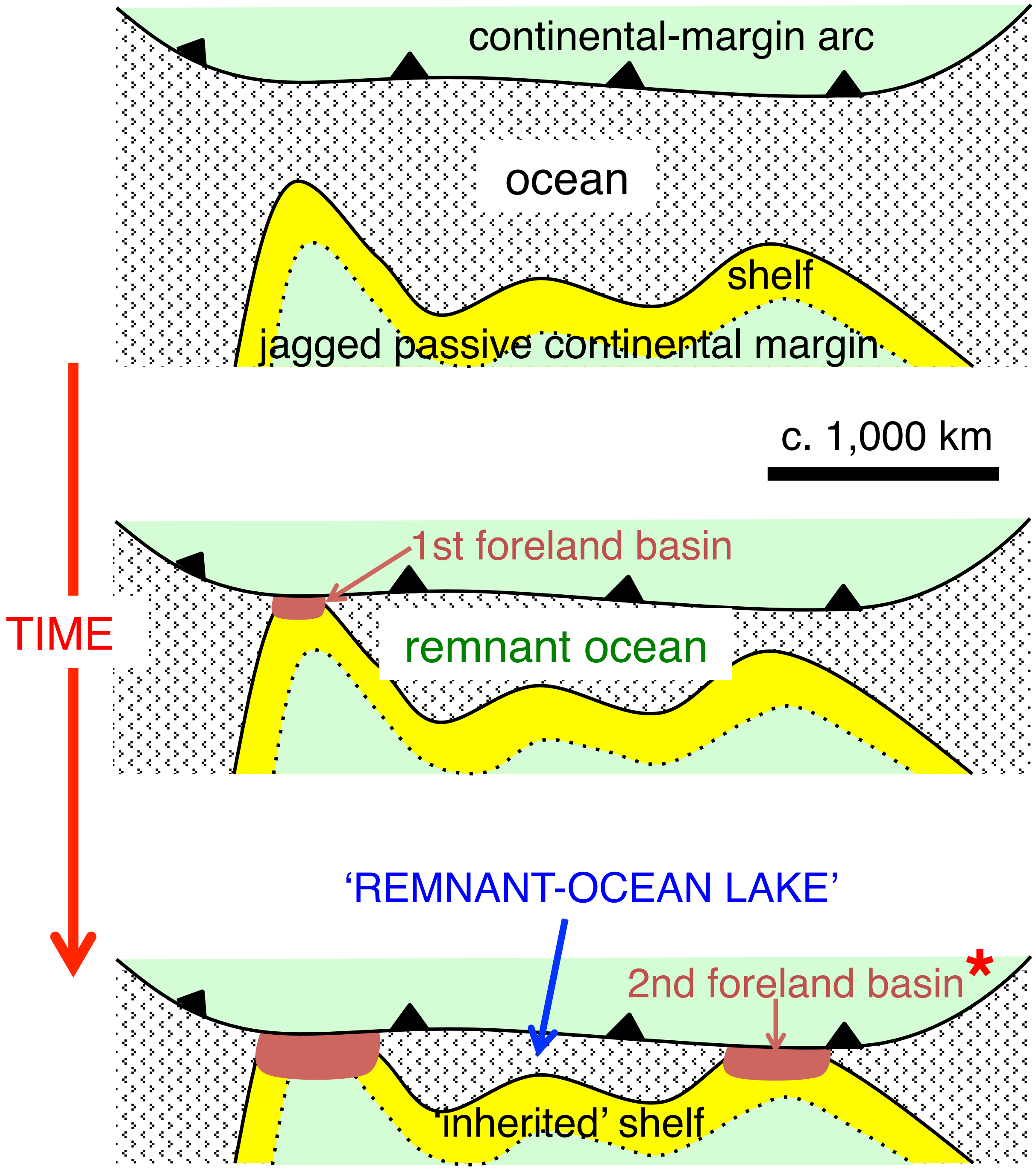
pinching off sectors of

remnant ocean,

forming

'REMNANT-OCEAN LAKES'

dammed at each end by a foreland basin's overfilled (alluvial) sector



* = initial lake sill; alluvial isthmus, crossed by a spillway (incised gorge); no modern example

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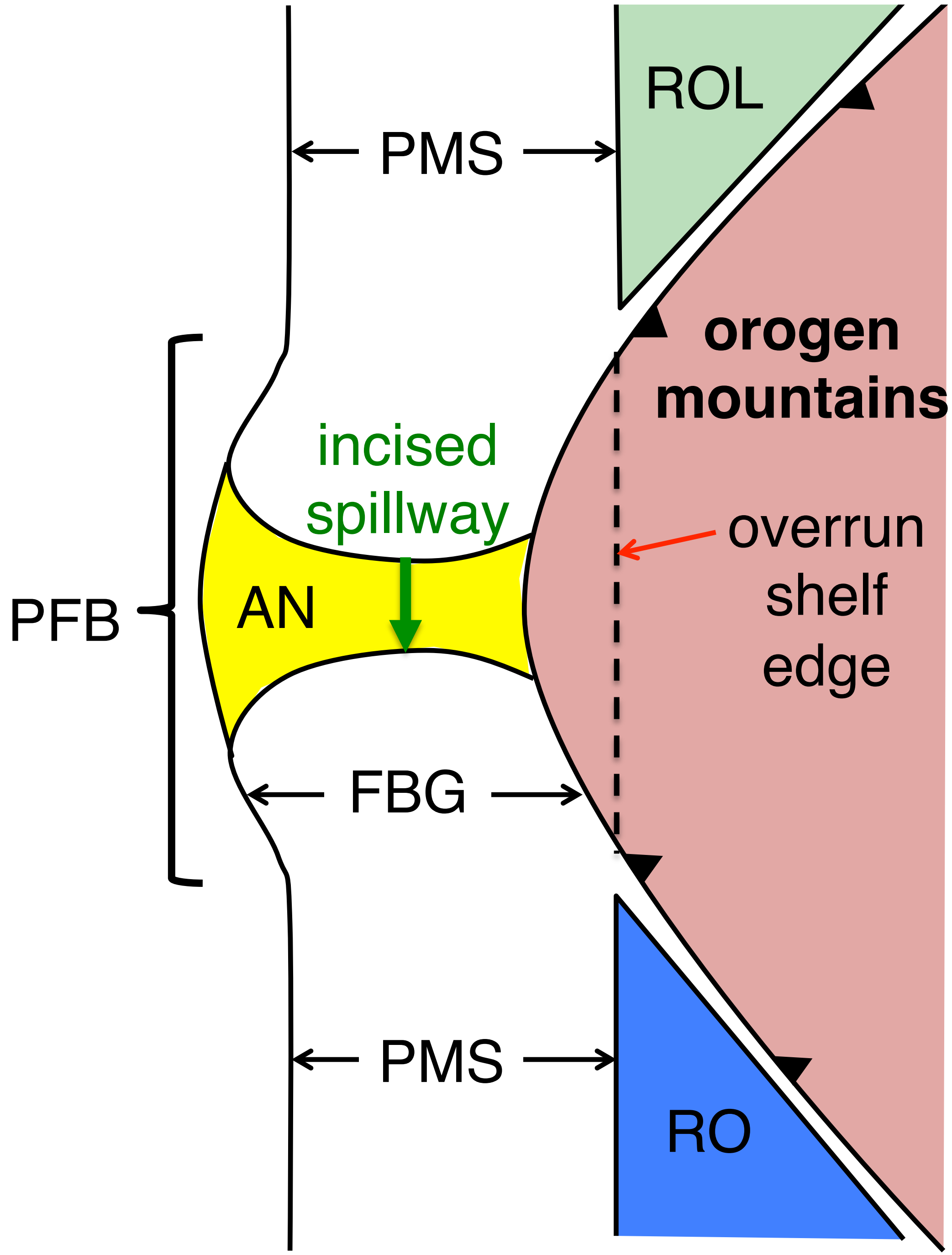
At the 2nd collision site, a growing alluvial neck (AN) dams the remnant ocean (RO), forming a ‘remnant-ocean lake’ (ROL)

Thrust front later advances beyond the lake spillway (cf. Slide 7), uplifting it, making the gorge incise deeper (cf. Bosporus)

PFB = peripheral foreland basin

FBG = foreland-basin gulf

PMS = passive-margin shelf



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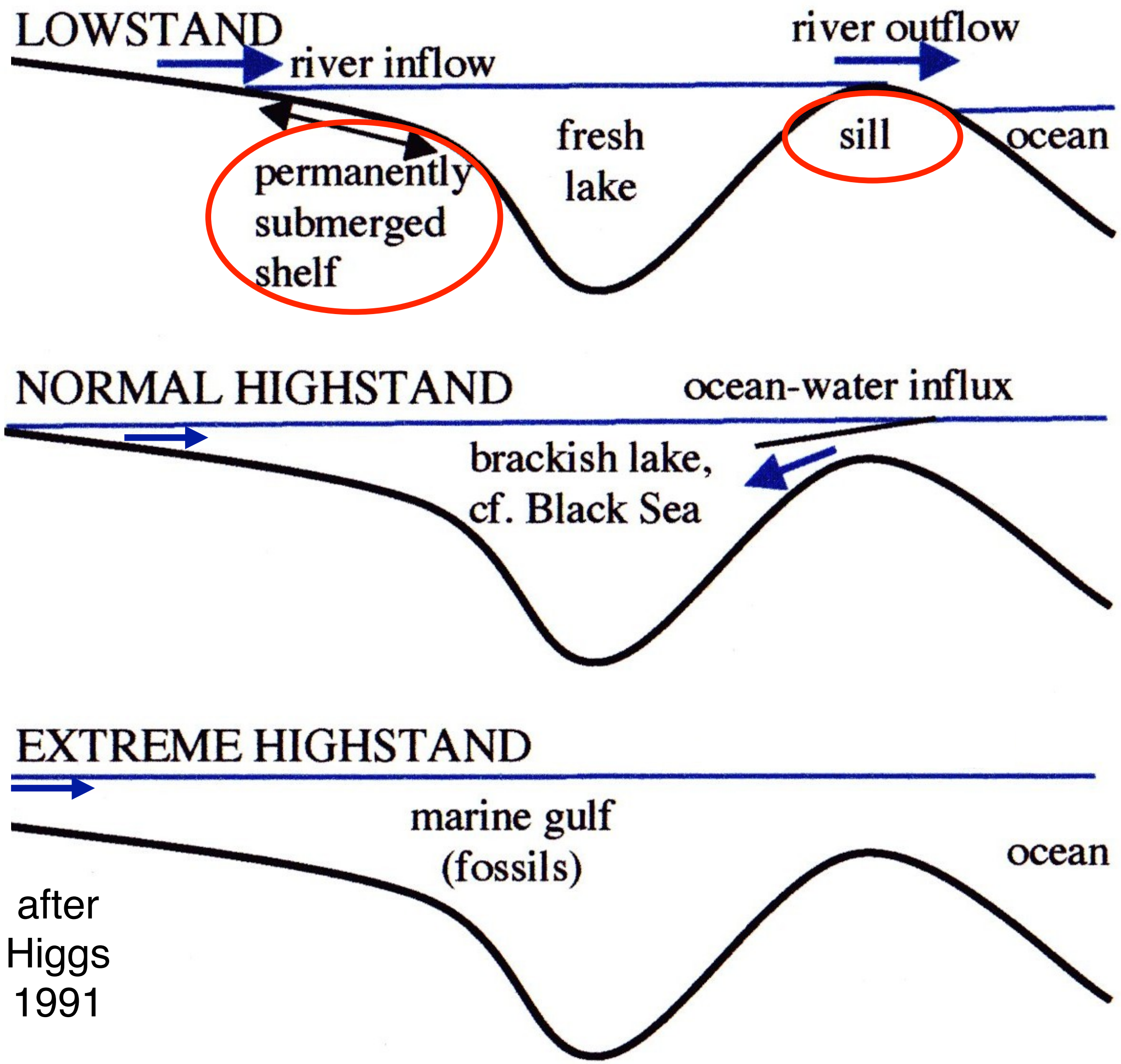
If lowstand input of river- & rain water exceeds evaporation, ocean lake turns fresh ...



after Higgs 1991

... by gradual desalination due to successive hyperpycnal flows (Higgs 1991) ... "progressive overturn" (new term)

Highstand salinity depends on relative volumes of river- & ocean inflow (mixed by progressive overturn & storm stirring)

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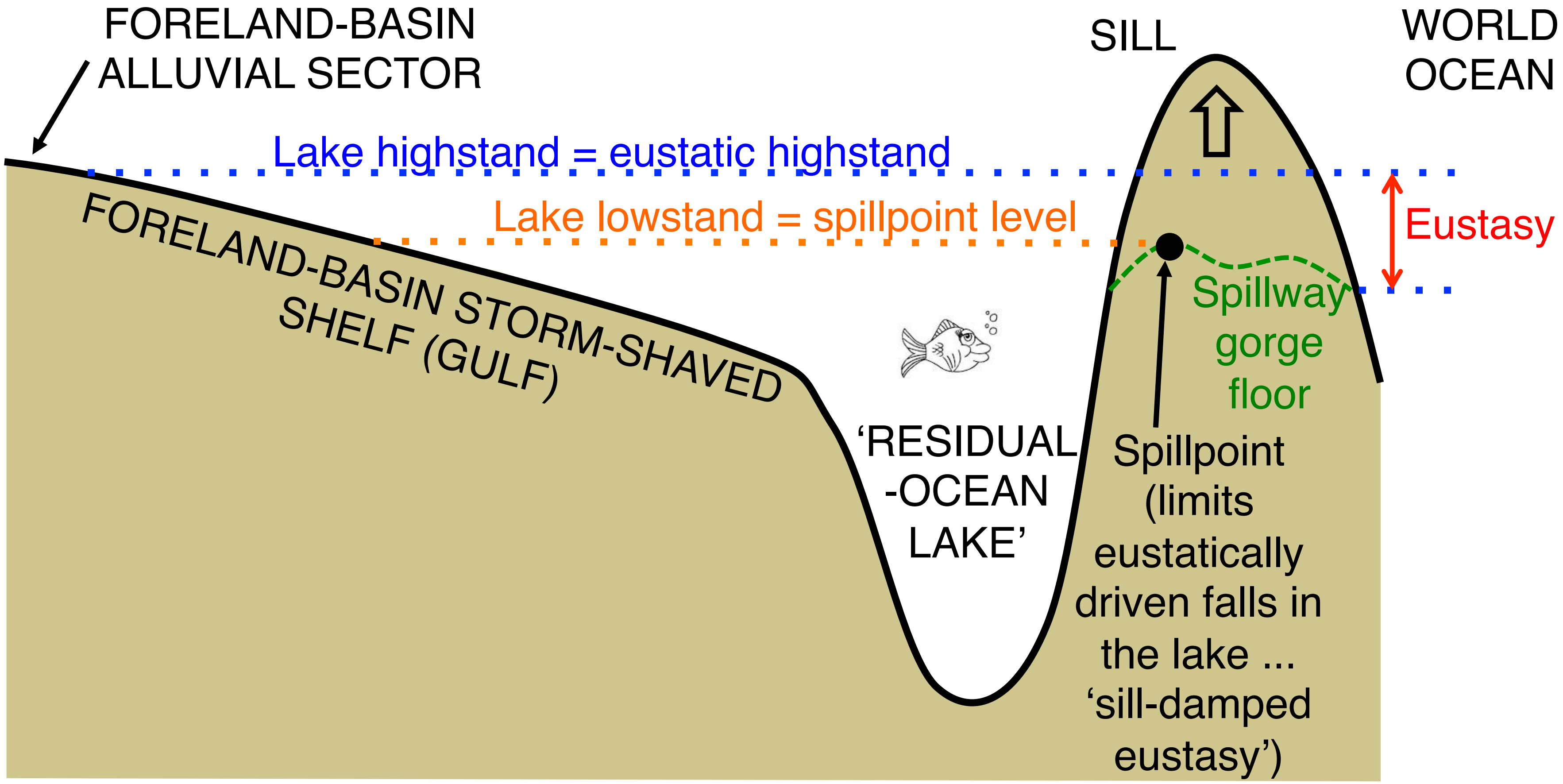
RESIDUAL-OCEAN LAKE MODEL (CROSS SECTION)

(non-arid climate; otherwise lake undergoes lowstand evaporative drawdown & becomes hypersaline, e.g. Messinian Mediterranean)



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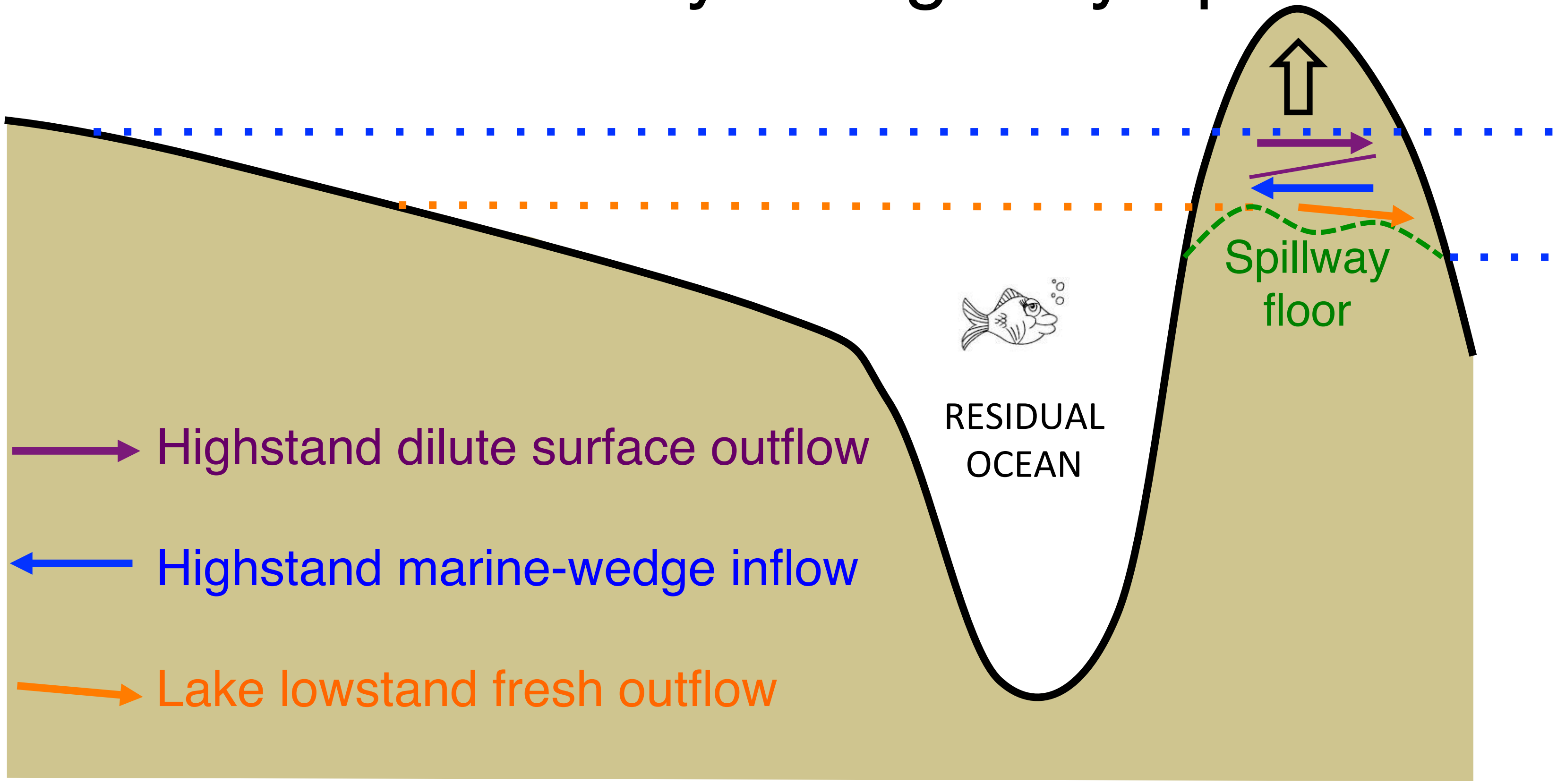
Spillway water movements, assuming freshwater (rivers, rain) entering lowstand lake exceeds evaporation, i.e. lake hydrologically open



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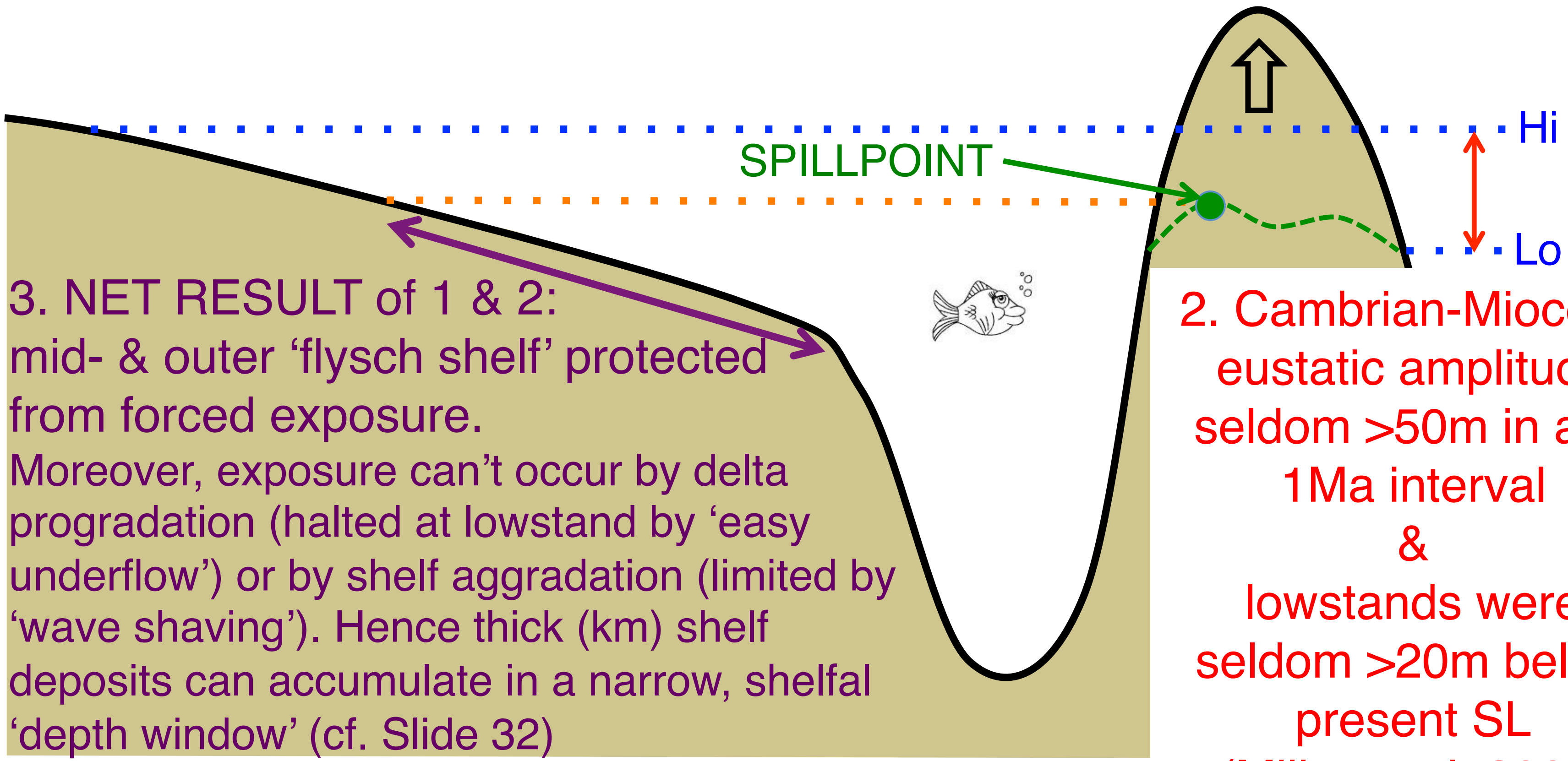
1. Spillpoint (SP) elevation is inevitably between eustatic highstand & lowstand (cf. Bosporus) because ...

- SP can't fall below eustatic lowstand (= base level)

- SP can't rise above eustatic highstand, as spillway incises (by outflow & inflow; prevous slide) faster than uplift



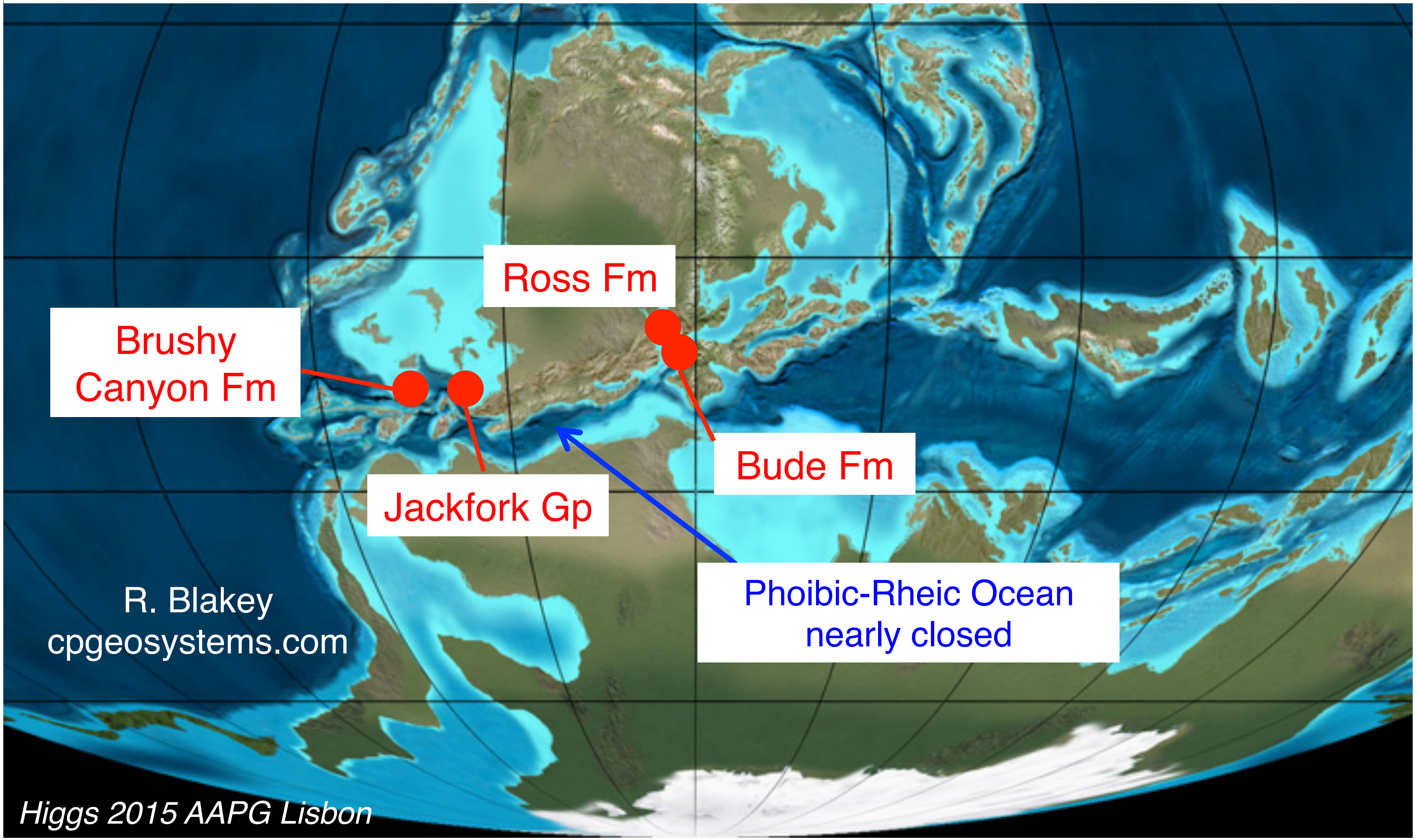
3. NET RESULT of 1 & 2:
mid- & outer 'flysch shelf' protected from forced exposure.
Moreover, exposure can't occur by delta progradation (halted at lowstand by 'easy underflow') or by shelf aggradation (limited by 'wave shaving'). Hence thick (km) shelf deposits can accumulate in a narrow, shelfal 'depth window' (cf. Slide 32)

2. Cambrian-Miocene eustatic amplitude seldom >50m in any 1Ma interval
&
lowstands were seldom >20m below present SL
(Miller et al. 2005; Haq & Schutter 2008)

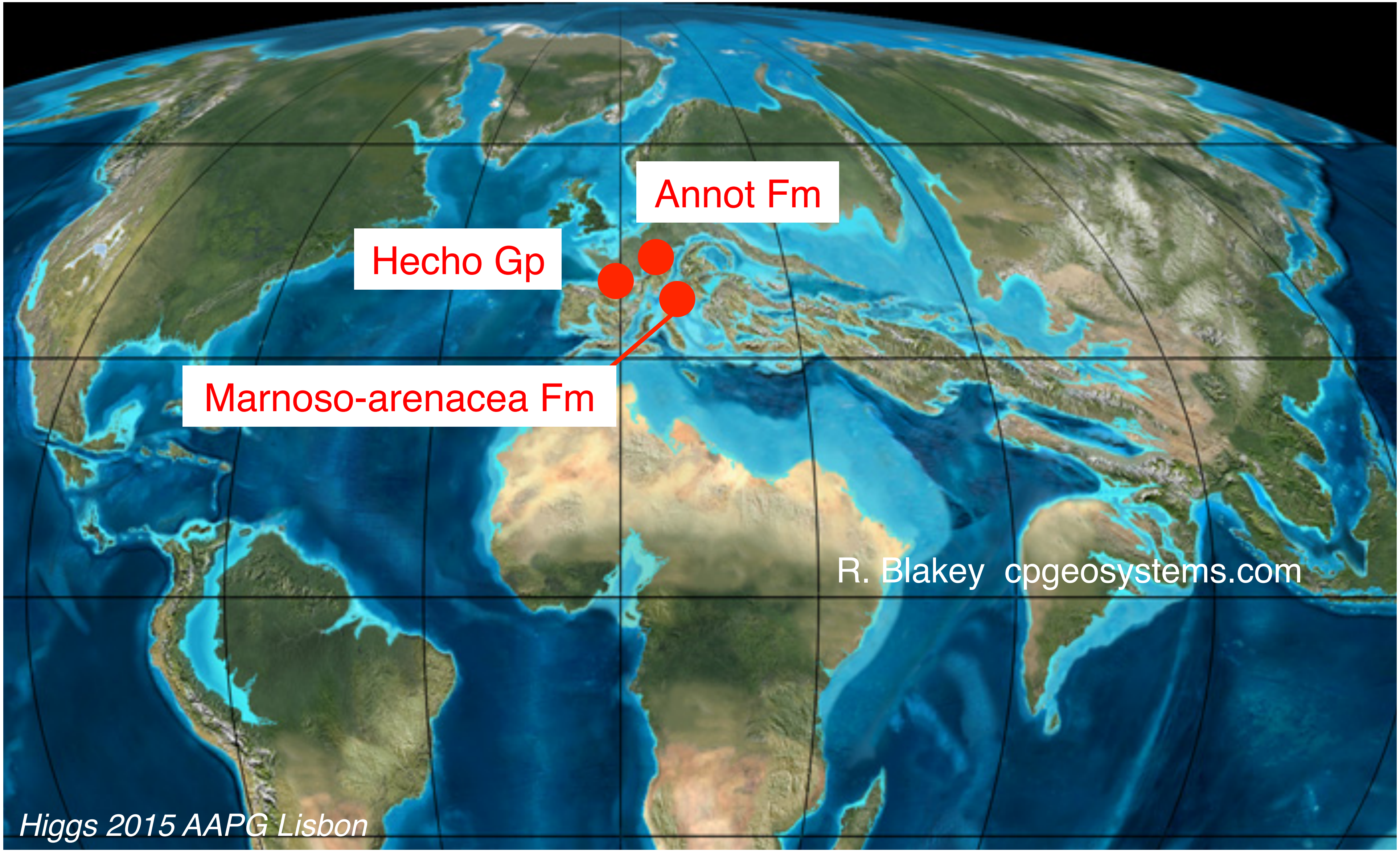
All foreland-flysch formations share the same megatectonic setting, i.e. long “jagged” collision belt (next 2 slides)

Expect remnant-ocean lakes!

340Ma Mississippian. Long jagged collision belt, future Variscan-Alleghenian- Ouachita-Marathon orogen. Bude, Ross & Jackfork deposition began within 30 Myr, Brushy within 80 Ma



50 Ma. Long ribbon microcontinents colliding in Europe. Hecho deposition underway. Annot to start within 15 Myr, Marnoso within 35 Myr



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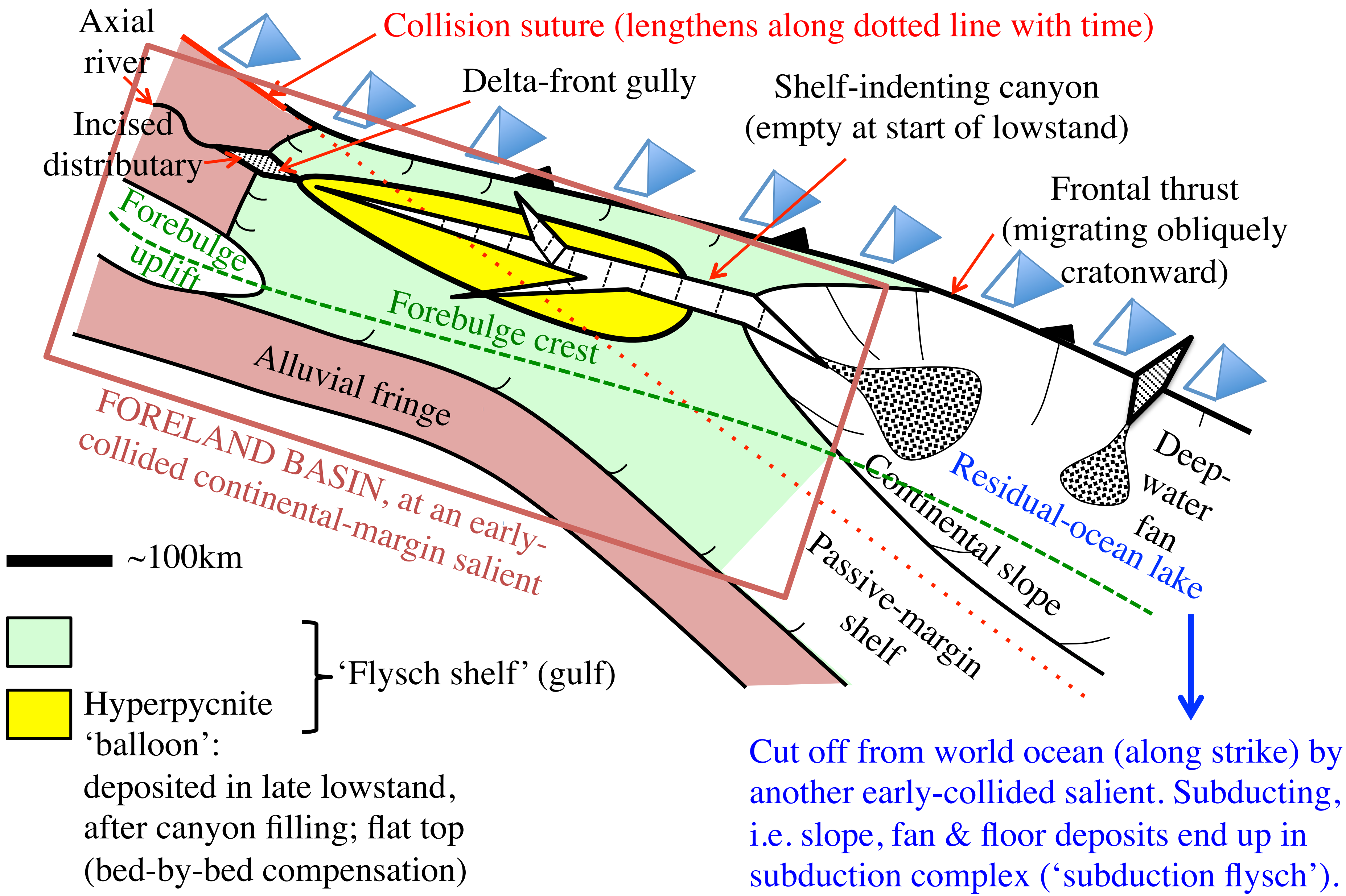
Fresh (lake) water is **much** more prone to underflow than sea water, which requires underflow sediment concentrations at least 50 times greater (Mulder & Syvitski 1995).

i.e. low salinity greatly facilitates hyperpycnal flow (river-fed turbidites) therefore

Foreland-flysch sandstone event beds are interpretable as megaflood hyperpycnites (mostly Bouma [1962] beds* & Lowe [1982] beds) & wave-modifed hyperpycnites (Myrow et al. 2002)

* the Bouma (1962) sequence was defined from Annot Fm

SHELFAL 'FLYSCH GULF' MODEL



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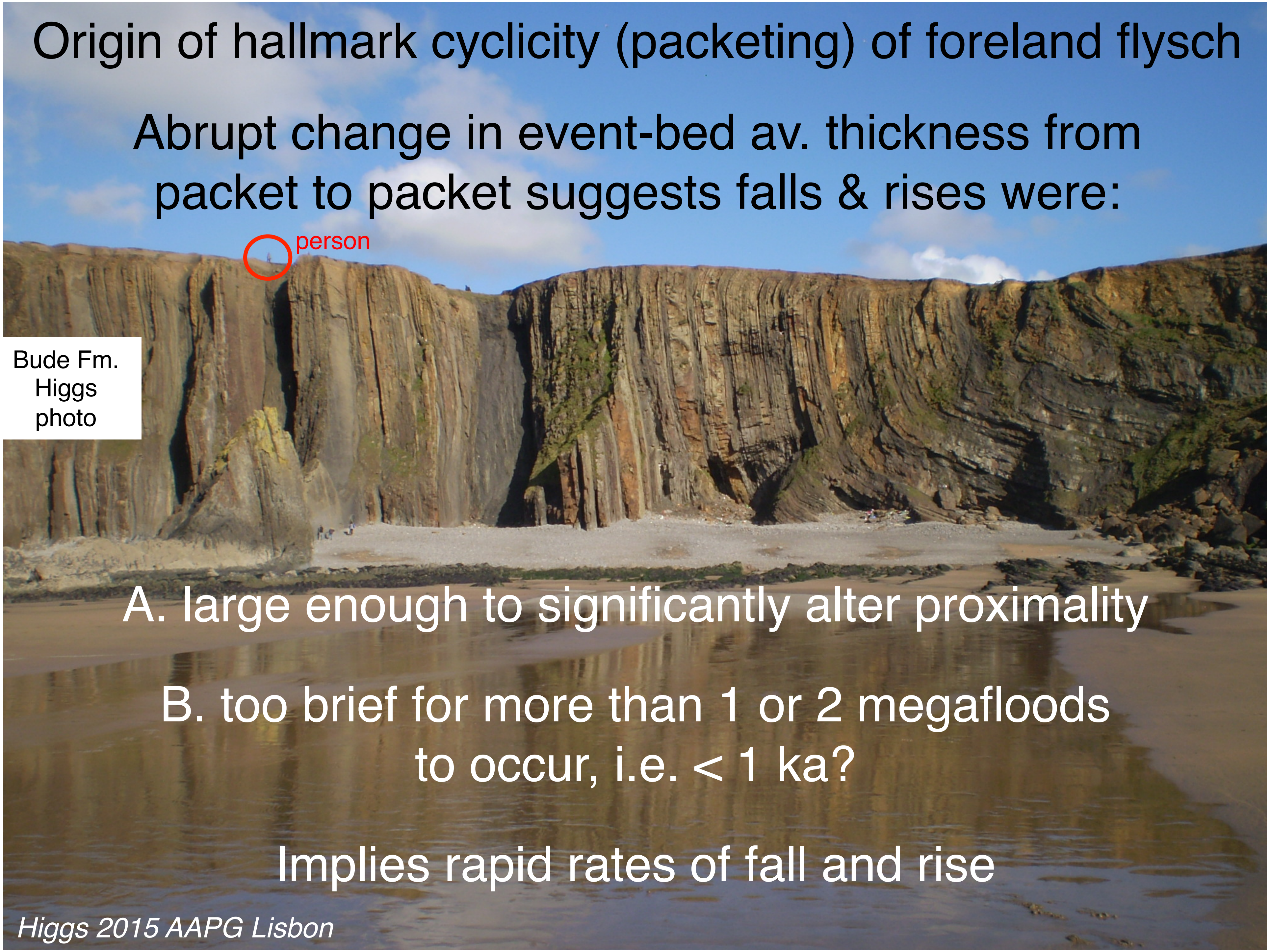
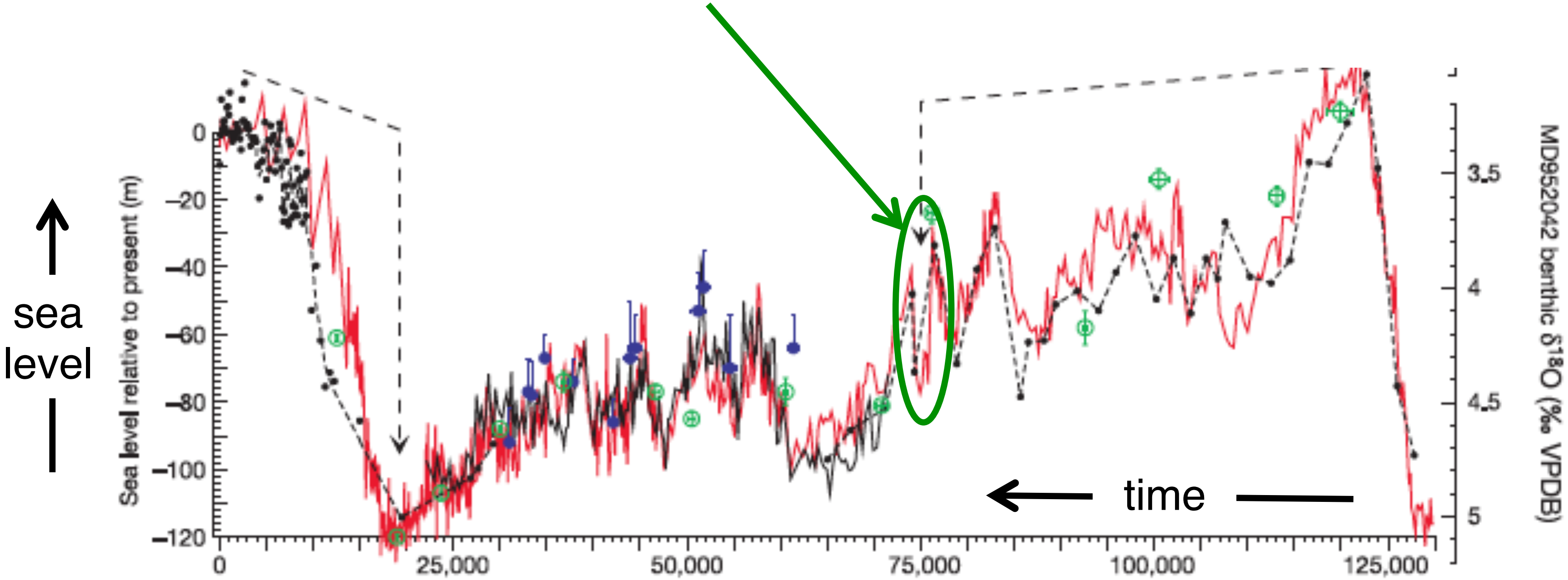

Origin of hallmark cyclicity (packeting) of foreland flysch
Abrupt change in event-bed av. thickness from packet to packet suggests falls & rises were:
person
Bude Fm. Higgs photo
A. large enough to significantly alter proximality
B. too brief for more than 1 or 2 megafloods to occur, i.e. < 1 ka?
Implies rapid rates of fall and rise
Higgs 2015 AAPG Lisbon

High-res. (centennial) sampling of Late Quat. foram O2-isotopes reveals that Milankovitch 20ka, 40ka & 100ka cycles are convolved with:

high-frequency solar(?) glacioeustatic cycles,
period ~2ka, ave. amplitude ~20m,
i.e. rises & falls very fast, ave. ~2cm/yr

e.g. ~40m fall, followed by ~30m rise, each in ~1ka,
i.e. extreme rates up to 4cm/yr !



Siddall et al. 2003. Black = Red Sea (high res. solid; low res. dashed)
Red = Shackleton et al. 2000, Atlantic

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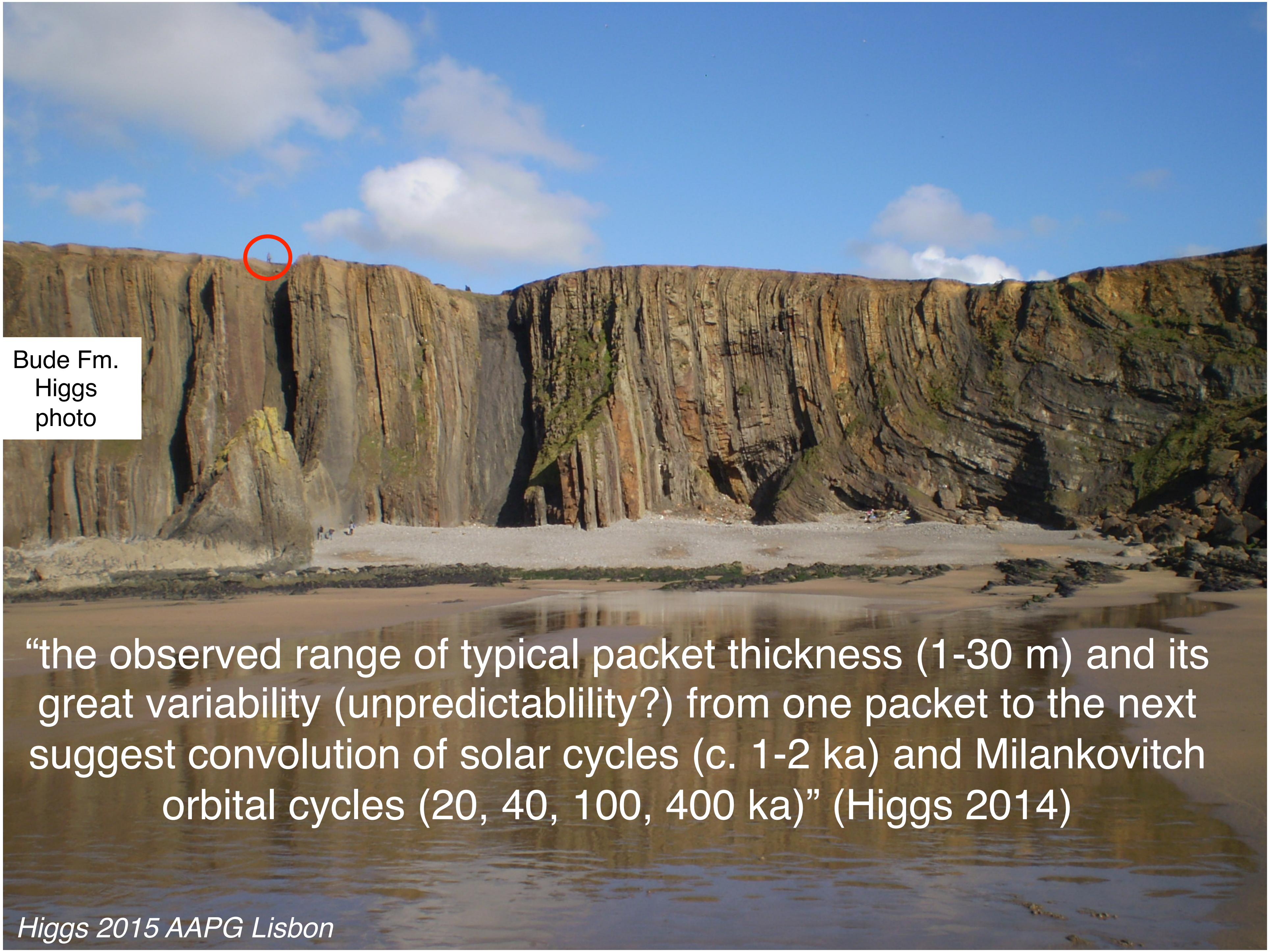
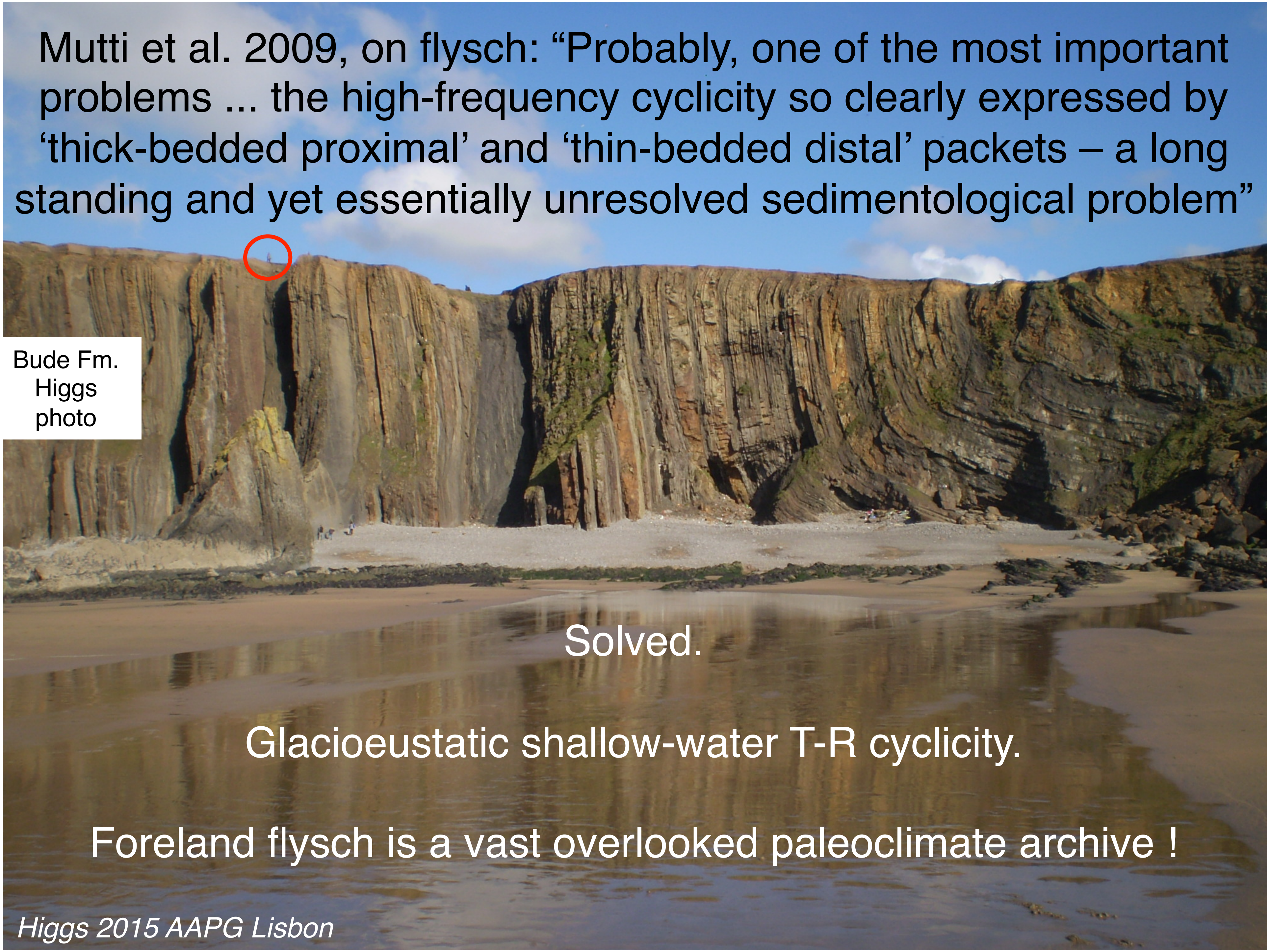

Bude Fm.
Higgs
photo
“the observed range of typical packet thickness (1-30 m) and its great variability (unpredictablility?) from one packet to the next suggest convolution of solar cycles (c. 1-2 ka) and Milankovitch orbital cycles (20, 40, 100, 400 ka)” (Higgs 2014)
Higgs 2015 AAPG Lisbon


Mutti et al. 2009, on flysch: "Probably, one of the most important problems ... the high-frequency cyclicity so clearly expressed by 'thick-bedded proximal' and 'thin-bedded distal' packets – a long standing and yet essentially unresolved sedimentological problem"
Bude Fm. Higgs photo
Solved.
Glacioeustatic shallow-water T-R cyclicity.
Foreland flysch is a vast overlooked paleoclimate archive !
Higgs 2015 AAPG Lisbon

The joy of cliff (wave-polished) exposures ...

Arrowed unit shows mud pseudo-clast injected upward, others stoped from (more cohesive) mud layer above, foundering miniature sand volcanoes & no evident vergence. Interpretation: in situ seismite

Would be interpreted in core as a debrite, with very different environmental implications (e.g. gradient)

"Slurry bed" grading laterally into stratified equivalent lacking dewatering features, i.e. the "slurry" was formed in situ (seismite)

This would be missed in core or mediocre exposure !

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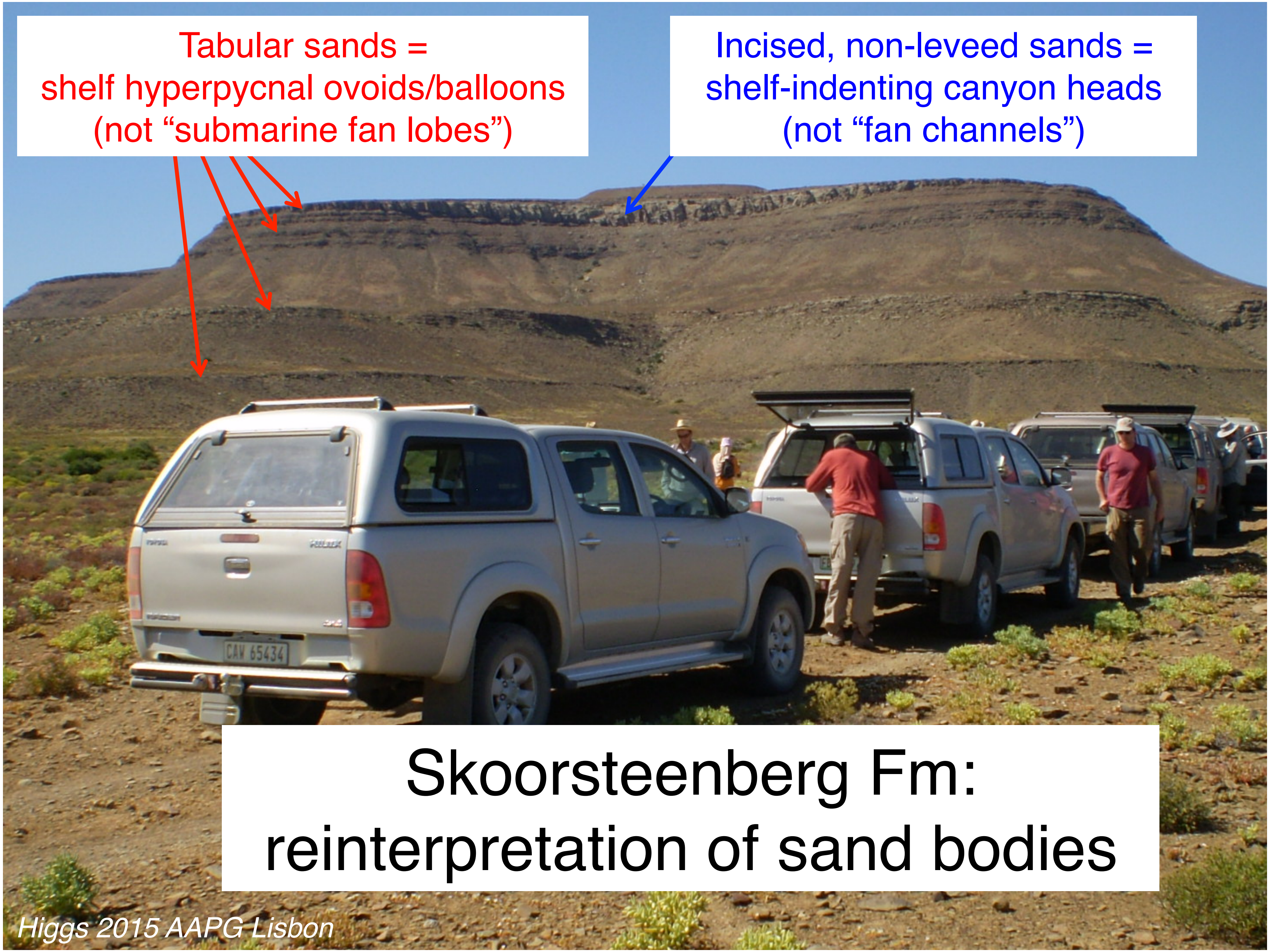
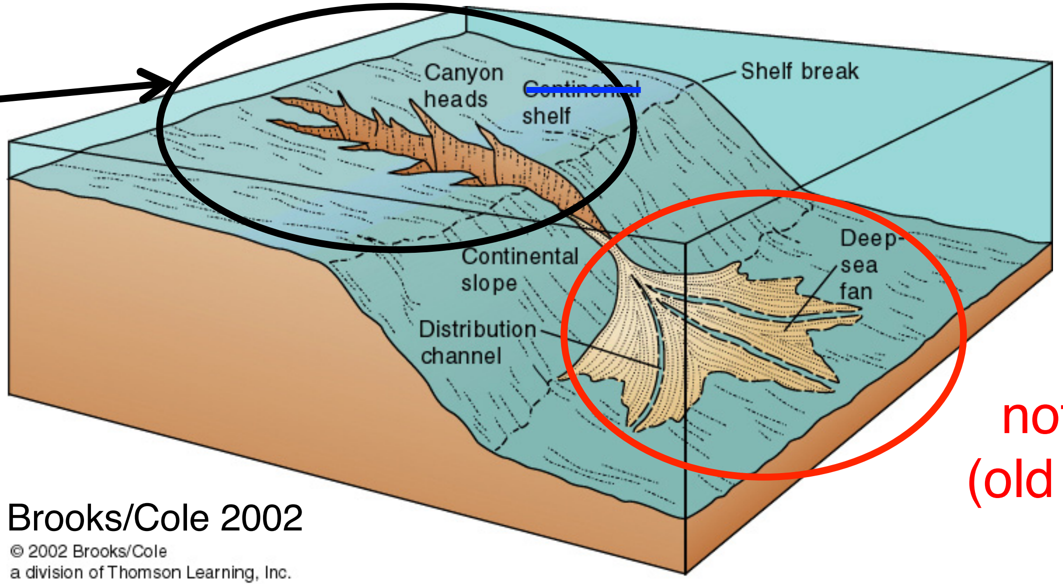
7. Poor ‘outcrop analog’ (Higgs 2004, 2009, 2010d, 2014, 2015)

8. No modern analog

9. Conclusions & References


Tabular sands =
shelf hyperpycnal ovoids/balloons
(not “submarine fan lobes”)
Incised, non-leveed sands =
shelf-indenting canyon heads
(not “fan channels”)
Skoorsteenberg Fm:
reinterpretation of sand bodies
Higgs 2015 AAPG Lisbon

Foreland flysch deposited here (confined in a gulf, beside an ocean lake)

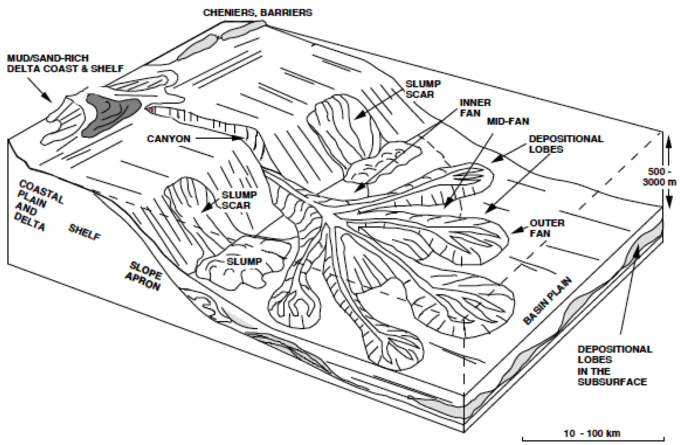


not here (old model)

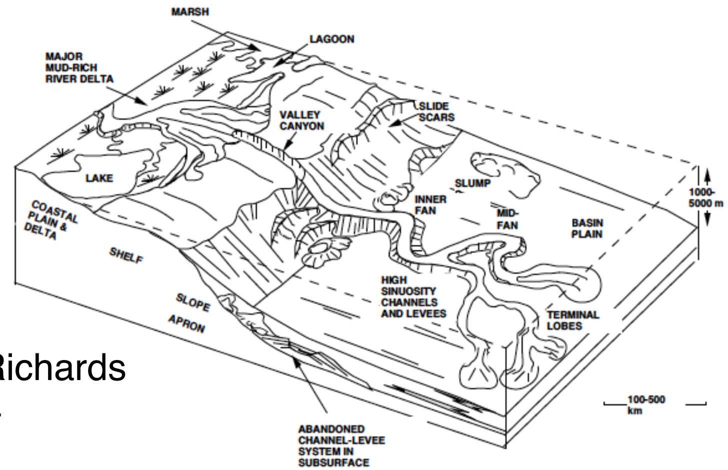
Brooks/Cole 2002

© 2002 Brooks/Cole a division of Thomson Learning, Inc.

thus foreland flysch is poor 'outcrop analog' for oil reservoirs deposited here ...



Reading & Richards 1994



For a start .... deep-sea channels have levees & bifurcate downflow, while shelf-indenting submarine canyons *lack* levees & bifurcate *up*flow.

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Unsuitability of foreland flysch as 'outcrop analogs' for passive-margin deep-sea reservoirs

Mutti et al. (2003, p. 751-752) cautioned: "turbidite sedimentation of divergent continental margins differs dramatically from that recorded by ancient foredeep basins"

Crucial differences making foreland flysch poor analogs for oil reservoirs deposited in *truly deep-water* (100s-1000s m) *on passive-margins (*e.g. Africa, Brazil, GoM):

(1) very different tectonic setting (foreland basin), hence (A) basement is continental versus oceanic or transitional, (B) nearby tectonic highlands, affecting sediment volume, calibre & composition (influencing poro-perm); & (C) frequent strong earthquakes (injectites, seismites)

(2) foreland flysch gulfs have 3-way confinement & minimal connection to world ocean (contrast passive margins, with 1-way confinement & full connection), hence little or no sand redistribution by tidal or contour currents

(3) flysch-shelf-indenting canyons have low sinuosity, lack levees, bifurcate upflow & deepen downflow, unlike strongly sinuous, leveed, deep-water, passive-margin channels (e.g. Mayall et al. 2006), thus intra- and extra-"channel" sand distribution, geometry & connectivity must differ greatly

... continued

Unsuitability of foreland flysch as 'outcrop analogs' for passive-margin deep-sea reservoirs

(continued)

(4) foreland flysch hyperpycnite balloons lack channels & lobes

(5) deep-sea-fan channels feed overbank splays & terminal lobes, whereas flysch-shelf-indenting canyon heads/tributaries do not;

(6) flysch-shelf storm erosion (mud draped scours) affects sand-body architecture (amalgamation, truncation)

(7) slump-generated turbidity currents are more likely on continental slopes (tall, favoring ignition), while hyperpycnal turbidity currents are less favored (normal marine salinity). Slump-induced turbidity currents are certain to differ significantly from hyperpycnal ones, e.g. in terms of duration (briefer) & velocity (higher), hence runout distance, competence, capacity & susceptibility to Coriolis deflection. These factors again affect predictions of sand distribution, geometries, dimensions, granulometry & matrix content (affecting poro-perm). Thus, deep-sea-fan lobes are likely to differ substantially from flysch-shelf hyperpycnite balloons in properties like length, volume, grain-size distribution & interconnectedness

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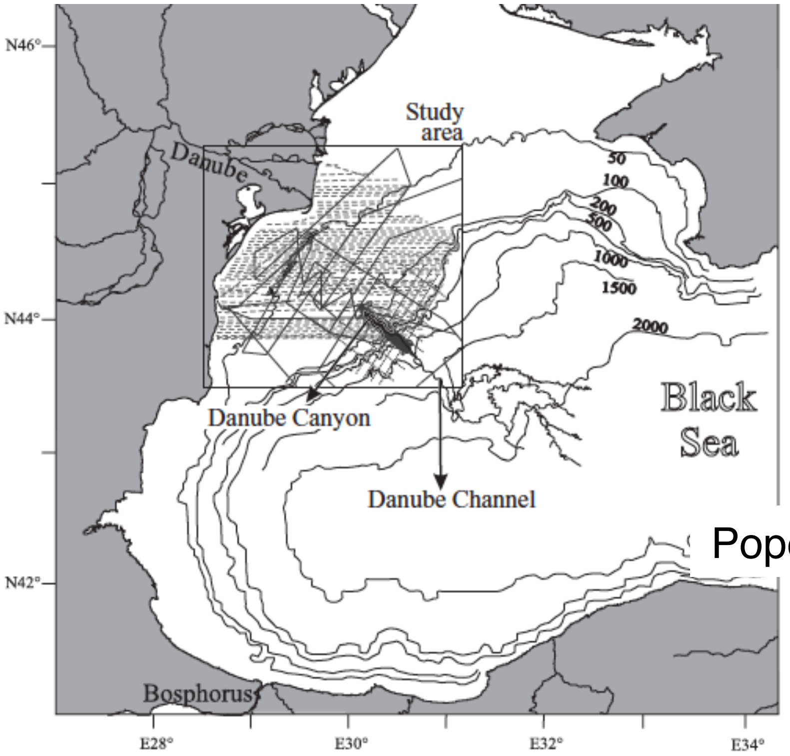
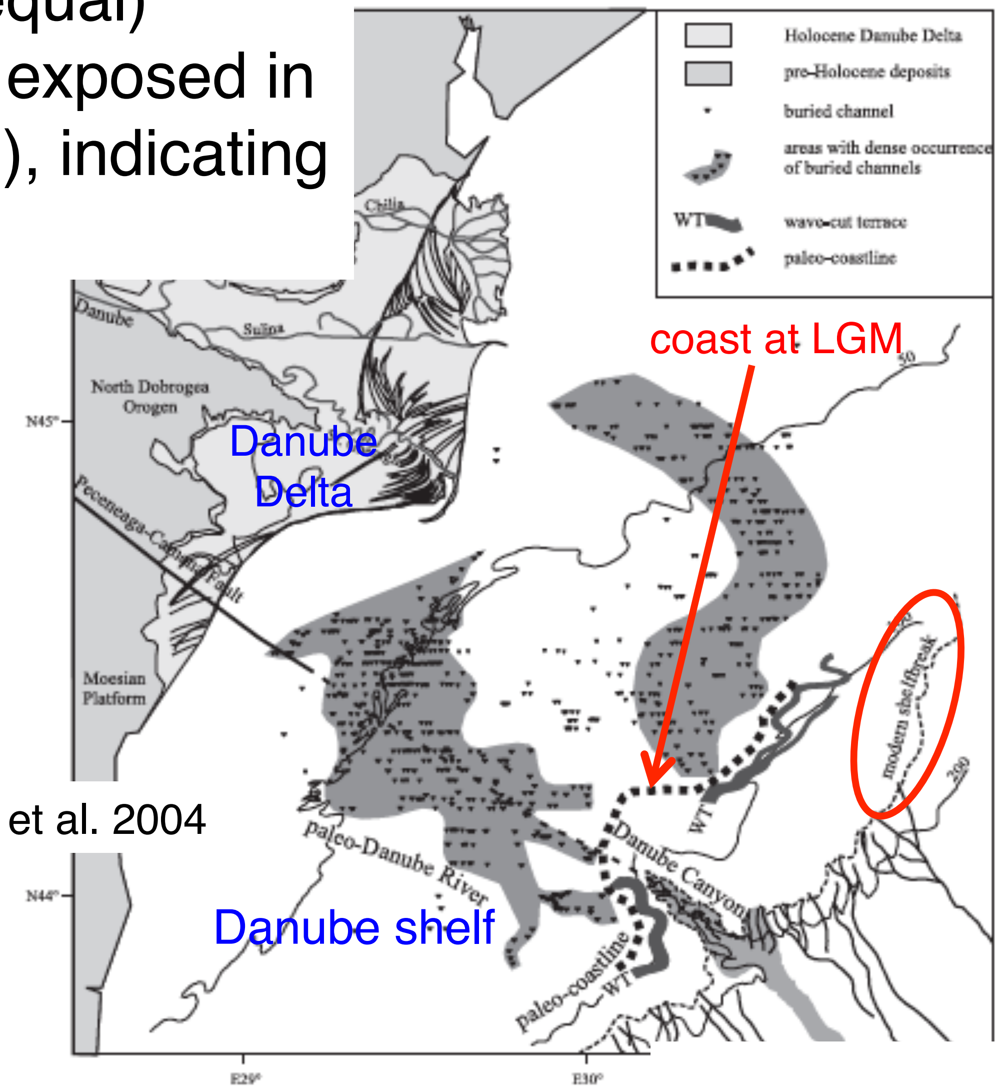
No modern analog. *Partial* analog = Black Sea ...

- ocean floored
- currently in highstand (brackish; fresh & marine ingress are roughly equal)
- but entire Danube shelf was exposed in Last Glacial Maximum (LGM), indicating evaporative drawdown





Popescu et al. 2004

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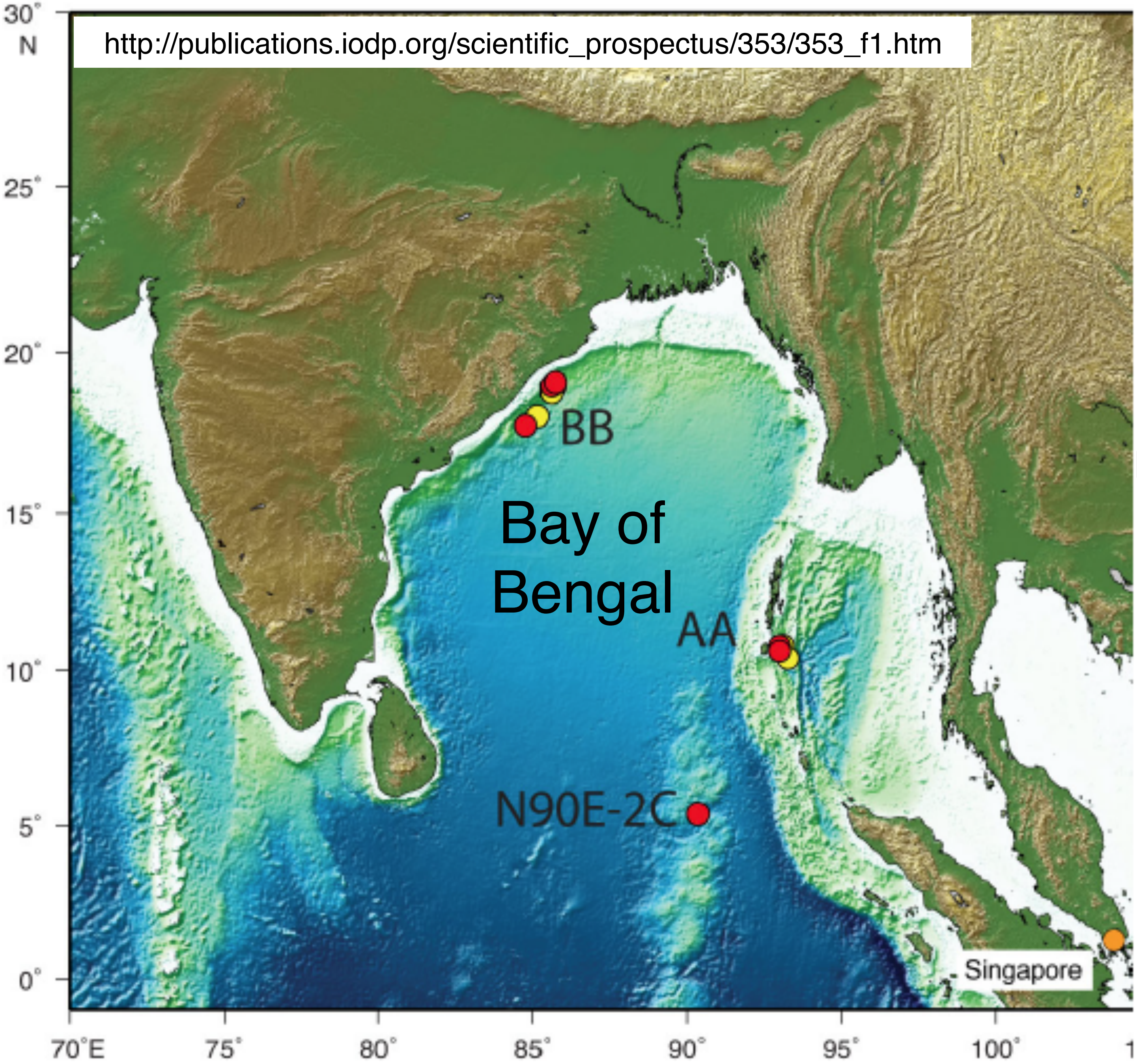

Bay of Bengal could become a residual-ocean lake, if India rotates in future.

Note Ganges-Brahmaputra Delta along strike, draining Himalayan foreland basin

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MAIN CONCLUSIONS

Foreland flysch ...

- shelfal
- mainly hyperpycnites & wave-modified hyperpycnites
- inappropriate & misleading as ‘outcrop analog’ for passive-margin deep-sea reservoirs
- no modern analog

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…continued next slide

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