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Shelf Model for "Deep-Sea" Flysch Turbidites and Implications for Outcrop Analogs*

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Abstract

Published traits of classic Cenozoic 'HAM' (Hecho, Annot, Marnoso-arenacea) flysch of Europe include: peripheral foreland basins; hallmark flysch cyclicity of alternating packets of thinner/thicker "turbidites"; mainly axial flow (flutes); intercalated *Skolithos*, *Cruziana*, *Zoophycos*, and *Nereites* ichnofacies; "bathyal" forams; intermittent beds with HCS; common mud-draped scours (MDSs; wave erosion?); and intra-HAM turbiditic canyons. Contrary to HAM's traditional deep-sea-fan/basin-plain interpretation, the MDSs and HCS suggest a shelf origin. All four ichnofacies are known in shelf strata. The envisaged HAM flysch shelves were basin-axial epeiric gulfs 100s of km long (cf. modern Adriatic 200 km NW shelf), confined laterally by orogen and forebulge, and indented by submarine canyons. The HCS beds are interpretable as tempestites; and HAM turbidites as flood hyperpycnites. The cyclicity is attributable to very rapid glacioeustatic rises/falls. Preventing subaerial exposure: (A) the shelf length exceeded the reach of axial-delta progradations; (B) published syn-HAM short-term (less than 1 Ma) glacioeustatic amplitude was only 20-50 m; and (C) each megastorm shaved the aggrading shelf back down to its intrinsic wave-graded equilibrium profile, sweeping the excess over the shelf edge. The "bathyal" forams reflect: (1) mimicking of slope OMZ conditions (muddy dysoxic bottom) on the flysch shelf by a fairweather mud blanket and permanent subtropical water stratification (river-diluted lid); and (2) reworking of near-coeval benthic forams (from true bathyal flysch mud/marl exposed in the adjacent accretionary-wedge mountains, offscraped from vanished remnant ocean), transported in suspension (tests empty, buoyant, unabraded) by river floods and deposited in hypo-/meso-/hyperpycnal shelf mud. A restricted-glacioeustasy (again non-actualistic) shelf model also applies to 7 older flysch formations: Cerro Toro (Chile, U. Cret.) and Carbo-Permian Bude (UK), Ross (Ireland), Brushy Canyon, Jackfork (USA), Skoorsteenberg and Laingsburg (S Africa). Like HAM, most are popular as outcrop analogs for passive margin deep-sea reservoirs (base-of-slope fans; leveed sinuous channels; slope minibasins), despite major contrasts affecting reservoir architecture, such as: (1) syn-flysch tectonism; (2) flysch-gulf three-way confinement (proximal, lateral), unlike passive-margin fans (one-way, hence contour-current reworking); (3) HAM flysch storm erosion; and (4) lack of proven HAM leveed channels.

Introduction

This article is based on an exhaustive literature review, backed by the author's observations on turbidites over 30 years. The term "Flysch", initially defined as a specific Swiss formation in 1827 (Caron et al. 1989 review), has since been applied worldwide to other formations dominated by event beds usually interpreted as deep-water, orogenically related turbidites. Most units dubbed flysch are in the Alps and Carpathians of Europe; they typically have Cretaceous to Eocene microfossil ages, "flysch-type" agglutinant-dominated benthic-foraminiferal assemblages, and are interpretable as accretionary-wedge nappes of trench and oceanic strata scraped off subducted remnant-ocean lithosphere (e.g. Rasser et al. 2008 review). In contrast, the famous 'HAM' flysch formations (Hecho, Spain; Annot, France; Marnoso-arenacea, Italy) are largely younger (Eocene, Eo-Oligocene, Miocene), yield mixed calcareous-agglutinant benthics (Sztrákos and du Fornel 2003; Jones et al. 2005; Pickering and Corregidor 2005; Di Giulio et al. 2013), and overlie *continental* lithosphere in front of (and partly overrun by) trench-flysch nappes. Thus, two flysch settings exist, internal (early) and external (late), differentiated long ago ("eugeosynclinal-" and "miogeosynclinal flysch"; Abbate et al. 1970). For the external Swiss flysch, Homewood and Lateltin (1988) advocated abandoning the name "flysch", recommending its use in a strictly geodynamic sense for (interpreted) pre- and syn-collisional clastics, as opposed to post-collisional molasse. Hence these authors viewed the Taveyannaz and Val d'Illiez (and Annot) Sandstones, traditionally called flysch, as turbiditic molasse instead, although deep water was still assumed, in keeping with the model of foreland basins initially being "underfilled" (Allen et al. 1986). However, Taveyannaz trochoidal ripples (Sinclair 1992) and upward gradation of the Val d'Illiez into "littoral deposits of the Lower Marine Molasse" (Caron et al. 1999 p. 39) suggest only shelfal depths.

Other Shared Aspects of Hecho, Annot and Marnoso Flysch

By general accord, HAM flysch accumulated in three under filled, peripheral foreland basins, each hosting an axial marine gulf > 100 km long and < 100 km wide, with a fan delta or base-of-slope fan proximally and a deep-water (min. 100s m) basin plain distally (summaries and references in Remacha et al. 2003, Das Gupta and Pickering 2008, Tinterri et al. 2011, Joseph et al. 2012). Down-gulf a diachronously subducting remnant ocean is inferable (Dickinson 1976, Figure 25) and up-gulf an overfilled (alluvial) foreland-basin sector. Other published HAM traits are: (1) large thickness (Hecho c. 4 km, Annot > 1 km, Marnoso c. 3 km); (2) background mudstone or marl; (3) mainly axial turbidite supply (based on flutes, grooves, ripples); (4) coarse-grained turbidites (some granuley/pebbly) occur proximally; (5) mainly fine-grained turbidites distally (Bouma Sequence is based on Annot Fm [Bouma 1962]); (6) hallmark cyclicity of alternating tabular "packets" typically 1-30 m thick, differing sharply in mean turbidite thickness (clear thickening- or thinning-upward rare); (7) intra-HAM "channels" (incised, m-km wide, 5 to > 100 m deep), lacking proven levees or strong sinuosity; (8) diverse ichnofauna (Uchman 1995, 2001; Broucke et al. 2004; Guillocheau et al. 2004; Heard and Pickering 2008; Monaco et al. 2010; Phillips et al. 2011), all intervals assignable to the *Skolithos*, *Nereites*, *Zoophycos* or *Cruziana* ichnofacies; (9) some beds (cm-dm) have hummocky cross stratification (HCS) or a lookalike, and/or near-symmetrical to symmetrical ripples (Sinclair 1993; Broucke et al. 2004; Guillocheau et al. 2004; Mulder et al. 2010; Gordon et al. 2011), even in the "basin plain" (Remacha et al. 2005; Muzzi Magalhaes and Tinterri 2010; Tinterri and Muzzi Magalhaes 2011); and (10) common mud-draped scours (MDSs; Bouma 1962 plate C4; Mutti 1977 Figure 6C at pencil; Tinterri et al. 2011 Figures 15, 17, 52).

New Shelf-flysch Depositional Model

The authors cited above interpreted HAM benthic forams as indicating bathyal depths (except shelfal uppermost Marnoso). This begs the question of what prevented shallowing to shelf depths while > 6 km (Hecho, Marnoso decompacted) accumulated. This problem, plus the presence of HCS and MDSs, suggests instead a storm-shaved shelf (Higgs 2004, 2010a), the MDSs recording storm-wave erosion without sand supply. All four HAM ichnofacies are now known in ancient shelf strata, even the *Nereites* ichnofacies (e.g. Olivero et al. 2010 and references therein), formerly considered bathyal-abyssal. MDSs and HCS characterize tempestites globally (Walker 1983 Figure 1 ideal bed). However, most workers attribute MDSs and HCS (or lookalikes) in HAM to turbidity-current internal waves and hydraulic jumps, except Sinclair (1993) who interpreted the Annot as locally shelfal, based on HCS and symmetrical ripples. Shelf-storm MDSs include mud-on-mud types (Schieber 1994), hard to see in outcrop (present in HAM?).

The proposed ‘flysch shelves’ were epeiric gulfs > 100 km long, confined laterally by orogen and forebulge (cf. Mutti et al. 2003 Figure 1; note depth unspecified), and ending down-gulf at a continental slope into the remnant ocean. A partial analog is the modern Adriatic, a foreland-basin gulf 800 km long with a 200 km NW shelf. (The shelf splits SE around two deep-water “pits”, which coincide with Triassic halokinetic evaporites at depth, suggesting they reflect subsidence by salt dissolution and/or withdrawal.) Submarine canyons indented the HAM shelves. Decimetric HAM turbidites are interpreted here as megaflood hyperpycnites (centennial) supplied from a gulf-head delta, possibly explaining Bouma A enigmatic lack of lamination (Leclair and Arnott 2005) in terms of hyperpycnal flow too slow for traction (< 25 cm/sec for fine sand; Sundborg Chart). Beds with HCS are megastorm tempestites (millennial). Reported “slurry” and “hybrid beds” (cm-dm) and “slumps” (m) may, in fact, be *in situ* seismites (Higgs 1991, 2004, 2010b, 2010c). Hecho “megabreccias” (Payros et al. 1999) of shallow-water carbonate are interpretable as *in situ*, each reflecting a forebulge incursion (updoming, hence change to carbonate deposition) that ended by instantaneous subsidence (5-10 m?; cf. Gastaldo et al. 2004), causing both seismic brecciation and reversion to clastic deposition. Marnoso calcareous “megaturbidites” showing up-gulf transport (Ricci Lucchi and Valmori 1980) may be tsunamiites with forebulge-derived carbonate grains. In the new shelf model, Annot and Marnoso “olistostromes” were derived subaerially from the advancing accretionary-wedge nappes (Kerckhove 1969 Figure 77), not subaqueously (Lucente and Pini 2008 Figure 10); the few examples thicker than 100 m, hard to reconcile with a shelf, could be submarine-canyon fills or tectonically thickened. The Marnoso “olistostromal carpet” can be interpreted as a diachronous sheet of shelf-fan-delta deposits, largely debrites (including olistostromes), beheaded and tectonized by the advancing nappe sole thrust.

Basal Annot Pseudo-sidelap

Interpreted Annot steep onlap onto the Marnes Bleues (references in Sinclair 2000) implies an unconformity (e.g. Joseph et al. 2012 Figure 5), contradicting microfossil evidence for diachronous gradation (younging cratonward; Joseph et al. 2012 Figure 7). In reality the apparent onlap (in fact apparent sidelap) is an artifact of: (A) each successive hyperpyncite (and its Bouma E cap) pinching out a few meters farther onto the retreating forebulge; (B) marl interbeds continuing much farther (km?), while erosionally thinned beneath each hyperpycnite; and (C) much greater compactability (mechanico-chemical) of marl than sand or Bouma E silty mud, exaggerating the apparent forebulge-flank gradient (pinchout climb angle) to c. 10-15°, which decompacts to < 1°. Thus, previous workers mistakenly invoked steep, high-relief, inherited basin-floor topography. Local multi-directional supposed onlap, taken to indicate confined sub-basins (e.g. Sinclair 2000 Figure 5), may instead reflect forebulge non-linearity (crustal inhomogeneities) or rotations. Consistent with the shelf (gulf) model, the mid-gulf water depth need not have exceeded 100 m if: (1) the bulge-flank seabed gradient (marl “slope”) was < 0.1° (cf. modern Taiwan Strait quasi-analog); (2) the distance from each sand-bed pinchout to the coeval forebulge crest was < 30 km; and (3) the bulge crest was < 20 m deep or subaerial.

What Prevented Shelf Subaerial Emergence?

Preventing emergence: (1) Eocene-Miocene short-term (< 1 Ma) glacioeustatic amplitude was low (20-80 m; Miller et al. 2005 Figure 3; contrast Quaternary continental shelves entirely exposed by extreme falls); (2) storm erosion limited aggradation (see below); and (3) shelf length far exceeded axial-delta progradations (see below). A conceptual, storm-wave-graded, equilibrium shelf profile is inferred, fining offshore due to the seaward decrease in seabed storm-wave power (Higgs 1987, 2004, 2010a). In contrast, modern continental shelves are steeper, transgressive-ravinement surfaces, mainly relict apart from inshore “subaqueous deltas” (references in Higgs 2010a), interpreted here as highstand nascent equilibrium shelves building seaward. Thus flysch shelves have no modern analog (the present is not always the key to the past).

HAM Pseudo-bathyal Foram Assemblages Due to Non-actualism and Reworking

Foram bathymetric interpretation is beset by pitfalls, e.g. inconsistency (sampling, preparation, identifications), reworking, redeposition, dissolution (seabed, subsurface, outcrop), cuttings contamination (caving), fragmentary knowledge of modern distributions, ancient environments with no modern analog, endemism (e.g. Murray 2006). All authors interpreted HAM bathyal forams as *in situ* and any accompanying, unarguably shelf taxa as redeposited by turbidity currents. An alternative interpretation is that the shelf taxa are *in situ*, while the rest constitute a ‘pseudo-bathyal assemblage’ reflecting two processes: (1) flysch-shelf replication of the muddy dysoxic seabed of a slope oxygen-minimum-zone (OMZ) by (A) fairweather mud blanketing the entire shelf, unlike modern shelves’ extensive relict- or tidally worked transgressive sand; and (B) SW Europe’s humid-subtropical paleoclimate (references via Google), causing permanent shelf-floor dysoxia due to water stratification (river-diluted brackish lid; winter cooling too weak for overturn). Again there is no modern analog, i.e. a shelf-depth, non-overturning, blind gulf. In effect, the OMZ of the (down-gulf) continental slope expanded upward and into the HAM gulfs. Dysoxia also explains the scarcity of reported HAM mollusks; and (2) reworking of (slightly) older benthic forams from true bathyal flysch exposed in the adjacent accretionary-wedge mountains.

Sinclair (1993) interpreted benthic forams in his Annot mudstone samples as a slope assemblage reworked into shelf strata; all individuals were abraded. Most workers assume that benthic-foram reworking invariably causes tractional abrasion. However, abrasion is not inevitable, as shown by pristine (identifiable to species) benthic forams reworked from subaerially uplifted older strata, in Recent Adriatic nearshore and New Zealand estuary sediments (Jorissen 1988; Hollis et al. 1995). Elsewhere, reworked benthic species occur in Pleistocene and Miocene deposits (Crouch 1954; Grunert 2013), though the source outcrops could have been submarine (e.g. canyon walls). Bernard and Major (1956) inferred suspension transport, possibly aided by trapped air in test chambers, to account for abundant pristine Cretaceous forams (not stated whether planktic or benthic) in modern river sands 100 miles downstream from the inferred source outcrop.

Foram reworking in foreland basins is more likely than in others, as the adjacent accretionary-wedge mountains contain abundant forams in uplifted trench-slope-basin and offscraped trench and remnant-ocean-floor deposits. It is proposed that robust benthic tests, scarcely damaged by dissolution during their brief residence time in mountain soils (immature due to frequent erosional removal), are liberated by flood erosion. Tests lacking authigenic glauconite (depositional environment too deep) or diagenetic calcite fill (pre-uplift burial too shallow/brief) are buoyed by intra-cameral water or gas (methane generated in host mudrock, or CO_2 from test dissolution), thus travel in suspension (no abrasion) in rivers and then in muddy delta plumes, and settle in shelf hyperpycnite Bouma E divisions and also in clay-silt meso- and hypopycnites (smaller, annual-decadal floods), enclosed in fairweather mud/marl. Such pristine, near-coeval (within 1-5 Ma) benthics could easily be misinterpreted as *in situ*, since obvious age discrepancies would be rare, given the long average age-range of benthic species. (This longevity may, in fact, be partly an artifact of wholesale reworking in foreland basins globally.) Delicate planktics, on the other hand, much more prone to dissolution (Nguyen et al. 2009), would tend to dissolve extensively or completely in soils. Nevertheless, examples are known of planktics identifiable to species level despite subaerial reworking (unmasked by discrepant, short-ranging ages; e.g. Pirkenseer et al. 2011). Reworked benthics are unknown in modern Rhone pro-delta shelf mud (cored to 8 m, 400 years BP; Goineau et al. 2011; Fanget et al. 2013), possibly because marine mudrocks in highland areas of the Rhone drainage basin (including Annot) are too old to contain diagenetically unfilled forams. Scarcity of glauconite in Hecho and Marnoso sandstones (none reported in Annot) suggests that most of the forams in the donor muds (between sand beds) were reworked, i.e. lacked protoplasm to promote intra-cameral glauconite growth.

Origin of HAM flysch Cyclicity: Glacioeustatic Water-depth Fluctuations

The origin of HAM's "high-frequency cyclicity so clearly expressed by 'thick-bedded proximal' and 'thin-bedded distal' packets (is) a long standing and yet essentially unresolved sedimentological problem" (Mutti et al. 2009 p. 304-305). Lobe switching due to channel avulsion is an unlikely cause, as HAM flysch lacks proven leveed channels. Mutti et al. (1999, 2009) invoked Milankovitch orbitally driven climate (rainfall) cyclicity, controlling the frequency of hyperpycnal flows (into supposed deep water). Instead the packeting is attributed here to flysch-shelf water-depth oscillations, thinner- and thicker-bedded packets recording high- and lowstands respectively. The abrupt change in event-bed average thickness from packet to packet (rather than gradual upward thickening or thinning) suggests falls and rises large enough (2-20 m?) to significantly alter the proximality (i.e. river-mouth proximity, governing average event-bed thickness), yet too brief (0.1-1 ka?) for more than one or two megafloods or megastorms to occur. These two inferences imply that falls and rises were very rapid (c. 2 cm/yr). Glacioeustasy is a likely cause, given that (A) it has operated throughout Cenozoic time (Miller et al. 2005) and (B) a high-resolution oxygen-isotope study proved late Pleistocene glacioeustatic sea-level cycles (Siddall et al. 2003 Figure 4) with very similar periodicity (c. 1-2 ka), amplitudes (2-35 m) and rates (up to 2 cm/yr) as those inferred here for HAM flysch. Prior to that study, Pleistocene polar air-temperature cycles of similar period were known (Dansgaard et al. 1984), but the amplitude of any associated sea-level change was not. These and Holocene climate cycles of similar periodicity are thought to reflect centennial-millennial fluctuations in solar energy output (Dansgaard et al. 1984; Van Geel et al. 1999; Bond et al. 2001). Accentuating the packet-to-packet jump in bed thickness, hyperpycnicity was 'easier' at lowstand, as the basin-axial river was incised into the delta plain, curbing its expansion (deceleration) onto the interfluves during floods, ensuring high water velocity (turbidity, density), hence hyperpycnal flows of greater frequency and duration, causing most river-supplied sediment to bypass the delta, favoring shelf aggradation at the expense of delta progradation (see below). The estimated 2 cm/yr rate of HAM rises and falls is > 20 times faster than typical foreland-basin subsidence. If subsidence was, say, 400 m/Ma (compacted), a 2 ka solar cycle would produce a cyclothem only 0.8 m thick, comprising one thicker- and one thinner-bedded packet. Thus 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). The variability must also partly reflect temporal variations in subsidence rate, including probable episodes of uplift (forebulge incursions) and meter-scale instantaneous-subsidence events (see above).

Maintenance of Shelf Equilibrium Profile During Sea-level Fall, Rise, and Stillstand

Lack of reported gutters in HAM flysch suggests that storms never eroded deeply enough (> c. 1 m?) into the shelf to expose firm mud. A further inference is that sea-level falls did not appreciably lower the shelf equilibrium profile (by storm erosion). This conservation of equilibrium implies that the parallel increase in both proximality (hence, delivered grain size) and seabed storm-wave power (erosional competence) induced by each fall were in balance. This deduction complies with the Plint-Nummedal (2000) FSST model, in which falling-stage storm erosion is confined to the (concave-up) shoreface, forming a guttered “regressive surface of marine erosion”, passing seaward into a correlative conformity on the (near-planar) shelf. The next HAM rise simply lengthened the equilibrium profile landward again (without disrupting equilibrium), drowning the contiguous delta plain (see below), deepening the water everywhere (by 2-20 m), initiating a thinner-bedded packet on the (now outer) shelf. At stillstand (low- or highstand), shelf shallowing by deposition of mud and hyperpycnites (outpacing subsidence) was countered by erosion each time a megastorm occurred, shaving the shelf back down (cm-dm) to the equilibrium profile, sweeping the eroded excess over the shelf edge, leaving behind a thin (cm-dm), subsidence-accommodated increment, capped by a tempestite (with or without HCS) or a MDS.

HAM Absolute Water-depth Range

HAM deposition was bracketed between lowstand fairweather wave base (c. 10 m?) and the highstand shelf edge (c. 150 m?), except in the outer reaches of shelf-indenting canyons, whose axial water depths possibly reached 300 m. This narrow HAM depth window was governed by ‘storm shaving’ and low-amplitude glacioeustasy. By these two mechanisms, thick (km) shelf successions can potentially accumulate, never exposed subaerially (Higgs 2010a).

Shelf Model Applied to Other Flysch Formations

A similar shelf model with submarine canyons and restricted glacioeustatic amplitude suits 7 other formations to which the term “flysch” can or has been applied (van Waterschoot van der Gracht 1931; Cecioni 1957; Keunen 1963; Beach 1977) and which are generally agreed to occupy foreland basins: the Cerro Toro (U. Cretaceous, Chile), interpreted by Cecioni (1957) as “Flysch … (of) ... a neritic environment not deeper than 100 m”, but reinterpreted by many later authors as deposited in c. 1-2 km of water, based largely on the interpreted ecology of benthic forams from the equivalent interval in boreholes 200 km away (Natland et al. 1974); and 6 Carbo-Permian formations, the Bude (UK), Ross (Ireland), Brushy Canyon, Jackfork (USA), Laingsburg and Skoorsteenberg (South Africa), all 6 here called ‘Bude-type turbidites’ (Bude was first to be studied purely sedimentologically; Reading 1963), characterized by thick (5 - 20 m) packets of amalgamated yet thin (< 40 cm) and fine-grained beds. The 6 have long been interpreted as deep marine; most are popular as reservoir outcrop analogs (see below). All 6 lie along two long (1000s km) intra-Pangean sutures and are faunally depauperate, suggesting each contiguous remnant ocean was isolated by early collision of a continental promontory, raising a sill, limiting entry of world-ocean water (Burne 1973; Higgs 2010c), forming a brackish ‘ocean lake’ (cf. Black Sea). Whenever world sea level fell below the sill crest, the lake remained perched at this level (outflow at spill point), topped up by river inflow and potentially turning fresh (Higgs 1991 Figure 20). The incongruous, thin-bed amalgamation may reflect weak cohesion of lowstand fresh-water mud (easily resuspended; Higgs 1991). Publications show that most of the 6 have HCS (or a lookalike) and MDSs. Gardner and Sonnenfeld (1996) described (p. 31 and Figure 13) "a distinct style of stratification, herein informally referred to as plow-and-fill ... misinterpreted as ... hummocky to swaley cross-stratification" (see also Mulder et al. 2010 p. 168). The Jackfork has MDSs (Slatt et al. 2000) and possible HCS (Tillman 1994). The Brushy and Jackfork were previously interpreted as shallow-water deposits (King 1948; Bokman 1953; Newell et al. 1953). The Bude, Ross and Skoorsteenberg were interpreted as shelf hyperpycnites by Higgs (1991, 2004, 2008). Ross MDSs include megaflutes (Elliott 2000), known on a modern shelf (Shaw et al. 2013). Jackfork, Laingsburg and Skoorsteenberg average paleocurrents are orogen-parallel, suggesting a HAM-like flysch shelf (gulf). In contrast, paleocurrents of the Brushy and much of the Bude and Ross are orogenward, suggesting deposition on an ocean lake's inherited "passive" shelf, but with seismites and rapid subsidence, due to approach of the accretionary-wedge load. Thus the Brushy, Bude and Ross are not foreland-basin deposits.

Other formations interpretable as shelf flysch from published descriptions include: Brenton Loch (Permian, Falklands); Champsaur (Eocene or Oligocene, France); Deutenhausen (Oligocene, Austria); Gres de Ville (Oligocene, France, shelfal according to Evans et al. 2004); Mackellar (Permian, Antarctica); Ripon (Permian, South Africa); Taveyannaz and Val d'Illiez (Eocene or Oligocene, Switzerland); and subsurface Puchkirchen and Hall, both dominated by a shelf-indenting submarine canyon (Oligo-Miocene, Austria).

Do Deep-water Underfilled Peripheral Foreland Basins Exist?

The conventional deep-water interpretation of flysch spawned the idea of an initial "underfilled" (Allen et al. 1986) foreland-basin stage, attributed by Covey (1986) to subsidence (by orogen load) exceeding the sediment supply from the supposedly still-submerged orogen. In Covey's study of the Taiwan Foreland Basin (Plio-Quaternary), he found no flysch so equated the "early, deep-water stage" (p. 88) with a mudstone interval interpreted as deposited "probably deeper than 200 m" (p. 80). However, Castelltort et al. (2010) interpreted the same basin fill, including thin (< 150 m) intervals of "prodelta turbidites", as no deeper than shelfal from the outset, stating (p. 69): "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'". Shelfal HAM flysch likewise indicates that the underfilled stage is not *very* underfilled. The author further proposes that shelf flysch typifies the underfilled stage of *any* foreland basin with (1) a humid climate, (2) low eustatic amplitude, (3) an axial gulf (rather than an open-ended strait), such that an axial river delivered enough floodwater (large catchment) to sustain long-runout hyperpyncal flows, and (4) negligible tides (to which foreland-basin gulfs are predisposed due to the likelihood that they or the adjoining remnant ocean will have a relatively narrow/shallow neck [at an impinging continental salient; cf. Strait of Gibraltar], limiting tidal interchange with the world ocean). The Taiwan example fails to satisfy conditions 2-4. The flysch-free(?) Late Cretaceous Western Interior Seaway (a *retroarc* foreland basin; North America) was a strait until Maastrichtian time, i.e. only small, lateral catchments.

During the underfilled stage, storm erosion (augmented by tidal currents, if any) is frequent enough to prevent sediment from aggrading more than a meter or so above the shelf equilibrium profile. In Taiwan, Covey (1986) invoked a similar "steady state" (*after* the supposed deep-water, underfilled stage) to account for the great thickness (up to 2 km) of shallow-marine sandstone and mudstone by "tide and storm currents ... able to carry enough sediment out of the basin to produce a balance between subsidence and sediment accumulation".

The deep-sea (2-3 km) Timor Trough, widely considered a modern underfilled peripheral foreland basin (e.g. Sinclair 1997), in fact is intraplate (i.e. not peripheral), centred c. 200 km S of the Banda Arc-Australia collision suture. The trough began to form in Pliocene time when northward subduction at the collision zone jammed and flipped to southward at the Wetar Thrust (N of Banda Arc; Audley-Charles 1986 Figure 2B). The trough's great depth reflects rapid subsidence due to loading by a vast, back-thrusted nappe of Australian upper continental crust (Audley-Charles 2011 Figure 8), rather than by a mere subduction accretionary wedge (Dickinson 1974 Figure 11). This exemplifies a "pre-arc foreland basin", a little-known type usually erased by arc magmatism after the downgoing plate reaches melting depth (Higgs 2009a). The Colville foreland basin (Alaska), with Early Cretaceous deep water shown by clinoforms c. 1 km tall, is another probable example, reflecting northward subduction under the "North Slope Microplate" (Shephard et al. 2013 Figure 6).

Delta-slope Cycles Inboard of Shelf Flysch

Where preservation and exposure allow, shelf flysch is seen to interweave proximally with muddy intervals usually interpreted as "basin slope" deposits, e.g. inner Hecho at Ainsa (Mutti et al. 1999 Figures 19, 25); inner Brushy (Beauboeuf et al. 1999 Figure 4); Bideford Formation north of Bude (Higgs 2004 Figure 3). At Ainsa, thick (100s m) "muddy slope" clinothems were inferred (Mutti et al. 1999 Figure 19), to fit the supposed deep-water basin plain down-gulf (Jaca). Instead, the flysch-shelf model invokes a stack of thinner (10s m) clinothems, each recording progradation of the basin-axial delta onto the flysch shelf during a Milankovitch highstand. Progradation during intervening lowstands was negligible due to river incision and 'easy underflow' (see above). The lowstand paleosoil on each successive delta plain was removed by the subsequent transgression (ravinement), leaving a truncated clinothem comprising a delta-slope foreset grading down into a prodelta toeset. Predicted ravinement lags (sequence boundaries) may have been overlooked or misinterpreted as thin (cm) debrites. Clinoform dips may be too subtle (< 0.5° in Pleistocene examples; Suter and Berryhill 1985) to detect without excellent exposure, seismic profiles, or closely spaced boreholes (correlations). Within each clinothem, upward progradational thickening of delta-slope tempestites and/or hyperpycnites is expected, but may be masked by sliding and slumping (e.g. "MTCs" of Pickering and Corregidor 2005), typical of delta slopes. Supposed deep-sea "slope channels" (Ainsa; inner Brushy) are incisional and lack demonstrable levees, so are reinterpreted here as incised valleys, cut fluvially during falls; their narrowness (50-500 m) and shallowness (5-40 m) are consistent with low eustatic amplitudes. Based on published descriptions, valley fills are interpreted here as shallow-marine (m-10s m) sandy-gravelly hyperpycnites, debrites and background mud, deposited during early highstand. Similarly, Annot-feeder "fan deltas" (St Antonin Conglomerate) may instead be gravelly incised-valley fills, vertically amalgamated, cut into poorly exposed delta-slope muddy clinothems (cf. Joseph et al. 2012 Figure 19). The concept of hyperpycnite-filled incised valleys is new, contrasting with the usual estuarine model; a likely prerequisite is little or no tidal current. Another possible example occurs in Utah, where Cretaceous marine shales contain channels interpreted as river-cut (Hampson et al. 1999) and hyperpycnally filled (Pattison et al. 2007, who invoked hyperpycnal cutting).

Shelf Flysch as Outcrop Analogs

Use of improper outcrop analogs risks billions of dollars in (A) non-optimum well placement and (B) unrealistic production- and reserves forecasts causing unwarranted field development or non-development (Higgs 2009b). The HAM, Brushy, Toro, Jackfork, Ross and Skoorsteenberg shelf-flysch formations are popular as analogs for truly deep-water, passive-margin turbidite reservoirs (i.e. base-of-slope fans; sinuous leveed slope channels; slope minibasins; e.g. Africa, Brazil, Gulf of Mexico), even though "turbidite sedimentation of divergent continental margins differs dramatically from that recorded by ancient foredeep basins" (Mutti et al. 2003 p. 751-752). Seven major contrasts are bound to cause great differences in sand distribution, geometries, architectures and granulometry: (1) active versus passive tectonic setting. For example, foreland basins have nearby highlands (affecting sediment volume and calibre) and, along with remnant oceans, are prone to strong earthquakes (injectites, seismites); (2) flysch-gulf three-way confinement (proximal, lateral), unlike mini-basins (four-way) and base-of-slope fans (one-way, hence potential reworking by contour currents); (3) flysch-shelf storm erosion (affecting sand-bed amalgamations/truncations); (4) shelf-flysch "channels" are entirely incisional (shelf-indenting canyons; no levees), implying very different intra-/extra-channel sand distribution and geometries; (5) Bude-type fresh-water premature amalgamation is inapplicable in the sea; (6) slump-generated turbidity currents are more likely on continental slopes (tall, favoring ignition) than on low delta slopes inboard of flysch shelves. Slump-induced currents would differ from hyperpycnal flows in duration and velocity, hence in runout distance, competence, capacity and susceptibility to Coriolis deflection, affecting sand-body granulometry, matrix content (poro-perm), distribution, shapes and dimensions; and (7) mass transport deposits are voluminous on continental slopes. On the other hand, shelf-flysch outcrops are good analogs (including 'self-analogs') for shelf-flysch reservoirs (productive Brushy, Jackfork, Marnoso, Puchkirchen-Hall).

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Shelf model for “deep-sea” flysch turbidites & implications for outcrop analogs

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SHEET 1 (of 3) - ABSTRACT & GENERAL

1. ABSTRACT

Published traits of classic Cenozoic ‘HAM’ (Hecho, Annot, Marnoso-arenacea) flysch of Europe include: peripheral foreland basins; hallmark flysch cyclicity of alternating packets of thinner/thicker "turbidites"; mainly axial flow (flutes); intercalated *Skolithos, Cruziana, Zoophycos* and *Nereites* ichnofacies; “bathyal” forams; intermittent beds with HCS; common mud-draped scours (MDSs; wave erosion?); and intra-HAM turbiditic canyons. Contrary to HAM’s traditional deep-sea-fan/basin-plain interpretation, the MDSs and HCS suggest a shelf origin. All four ichnofacies are known in shelf strata.

The envisaged HAM flysch shelves were basin-axial epeiric gulfs 100s of km long (cf. modern Adriatic 200km NW shelf), confined laterally by orogen and forebulge, and indented by submarine canyons. The HCS beds are interpretable as tempestites; and HAM turbidites as flood hyperpycnites. The cyclicity is attributable to very rapid glacioeustatic rises/falls. Preventing subaerial exposure: (A) the shelf length exceeded the reach of axial-delta progradations; (B) published syn-HAM short-term (<1Ma) glacioeustatic amplitude was only 20-50m; and (C) each megastorm shaved the aggrading shelf back down to its intrinsic wave-graded equilibrium profile, sweeping the excess over the shelf edge. The “bathyal” forams reflect: (1) mimicking of slope OMZ conditions (muddy dysoxic bottom) on the flysch shelf by a fairweather mud blanket and permanent subtropical water stratification (river-diluted lid); and (2) reworking of near-coeval benthic forams (from true bathyal flysch mud/marl exposed in the adjacent accretionary-wedge mountains, offscraped from vanished remnant ocean), transported in suspension (tests empty, buoyant, unabraded) by river floods and deposited in hypo-/meso-/hyperpycnal shelf mud.

A restricted-glacioeustasy (again non-actualistic) shelf model also applies to 7 older flysch formations: Cerro Toro (Chile, U. Cret.) and Carbo-Permian Bude (UK), Ross (Ireland), Brushy Canyon, Jackfork (USA), Skoorsteenberg and Laingsburg (S Africa). Like HAM, most are popular as outcrop analogs for passive margin deep-sea reservoirs (base-of-slope fans; leveed sinuous channels; slope minibasins), despite 4 major contrasts affecting reservoir architecture: (1) syn-flysch tectonism; (2) flysch-gulf 3-way confinement (proximal, lateral), unlike passive-margin fans (1-way, hence contour-current reworking); (3) HAM flysch storm erosion; and (4) lack of proven HAM leveed channels.

2. INTRODUCTION

For decades industry has used famous flysch formations as ‘outcrop analogs’ for deep-sea turbidite reservoirs globally. Costly error?

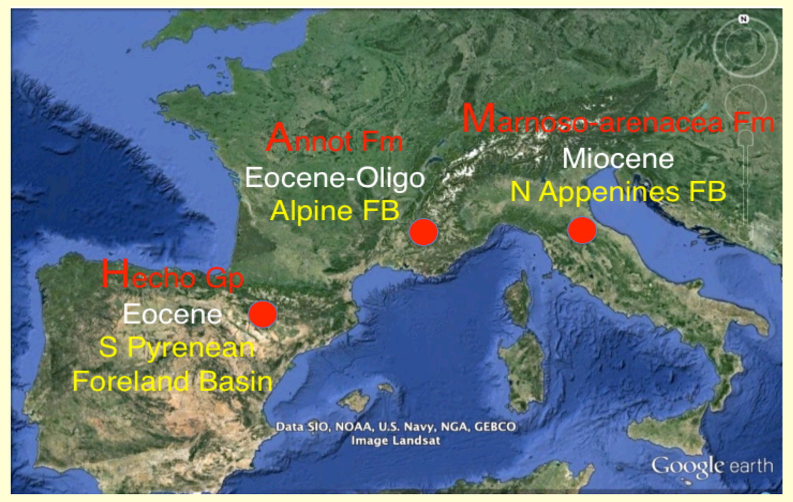
3. STUDY BASIS

Literature survey & 30 yrs studying turbidites

4. FLYSCH - A DEFINITION

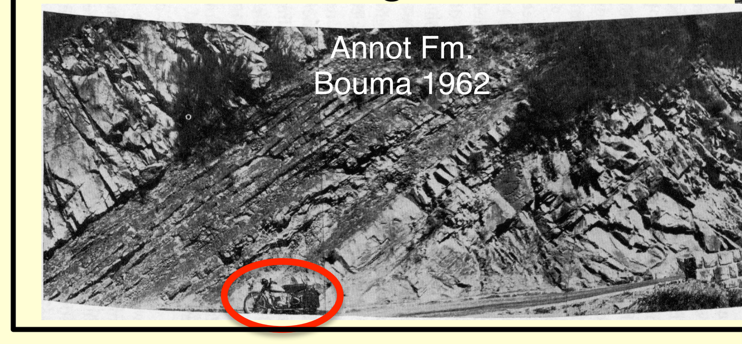
Thick (100s m to km) formations dominated by event beds historically interpreted as deep-water, orogenically related turbidites

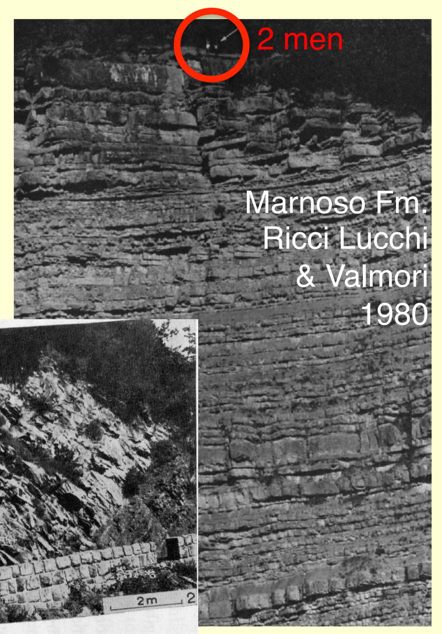
5. *HAM* FLYSCH LOCATION



6. TYPICAL OUTCROPS

Thinner- & thicker-bedded tabular “packets” (1-30 m). Single beds are mm-m thick & can fill/overspill shallow scours. Amalg’n common.





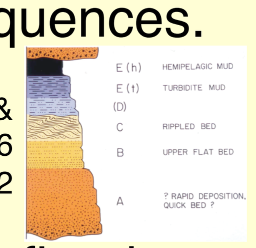
7. HYPERPYCNITES

HAM turbidites are popularly interp’d (after Mutti et al. 2003) as river-fed. Many show partial Lowe- &/or Bouma sequences.

Bouma Sequence

‘Type Fm’= Annot!

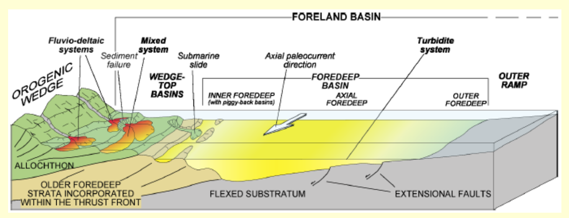
Posamentier & Walker 2006 after Bouma 1962



HAM turbidites record megafloods (centuries apart?)

8. AGREED BASIN SETTING

Axial marine gulf of three “underfilled” peripheral foreland basins



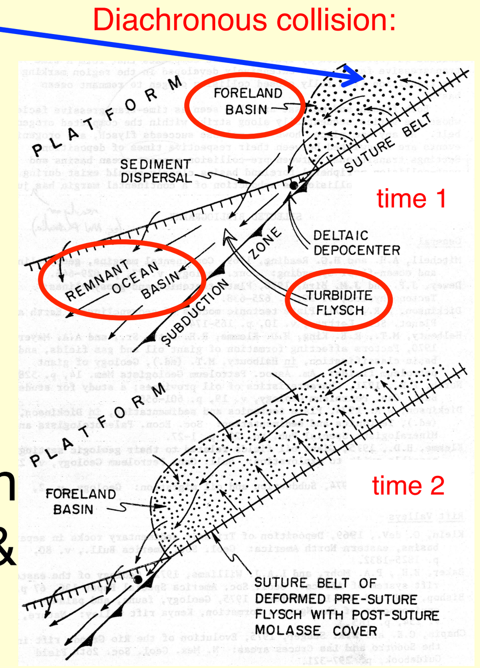
Roveri et al. 2002. NB water depth not shown. Axial supply (arrow) reflects typical diachronous closure of precursor remnant ocean, hence basin-axial drainage (trunk river; Sec. 9).

9. ‘FORELAND FLYSCH’ (e.g. *HAM*) vs ‘NAPPE FLYSCH’

Fluvio-deltaic molasse (stipple) can overlie supra-continental turbidites (Dickinson 1974). Dickinson classed these foreland turbidites as flysch (contrast Homewood & Lateltin 1988), along with remnant-ocean flysch

BUT only the latter ends up offscraped into subduction-accretion nappes (green allochthon in Sec. 8 fig; contrast beige & yellow ‘foreland flysch’, external, younger & less deformed)

Diachronous collision:



Dickinson 1976

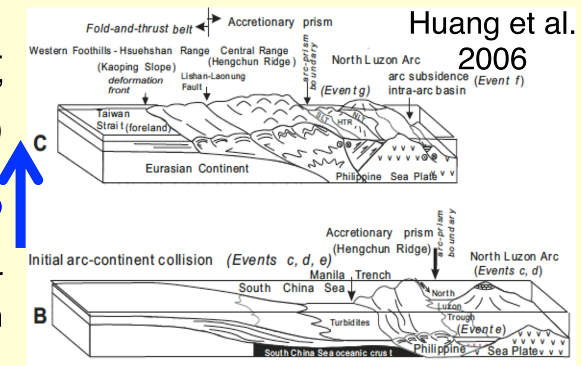
10. *HAM* WATER DEPTH

0.2-2 km widely agreed, based on (A) benthic forams, (B) *Nereites* ichnofacies (among others) & (C) supposed lack of storm-wave-influenced sed. structures

But these criteria are tenuous (Secs 15, 21, 22)

Note also:

(1) Castelltort et al. (2010) idea that “underfilled” peripheral foreland basins (UPFBs) never exceed shelf depth, e.g Taiwan...

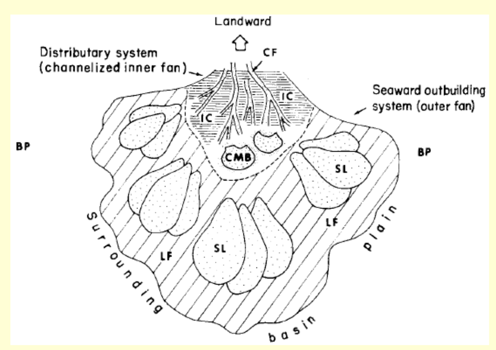


(2) deep S Adriatic (Sec. 20 fig), a supposed UPFB (Sinclair 1997), is more likely a halite-withdrawal- or dissolution basin (buried Trias salt)

(3) Timor Trough, supposed UPFB, is more likely a “pre-arc foreland basin” (Higgs 2009)

11. *HAM* EARLY DEPOSITIONAL MODEL:

Radial deep-sea fan

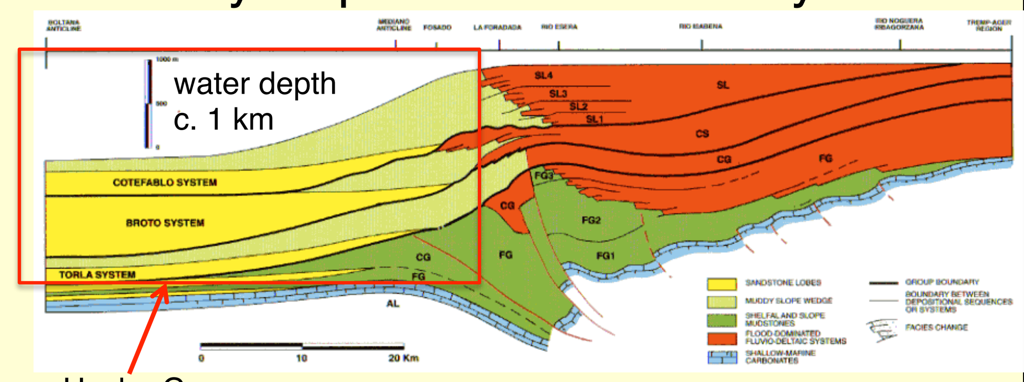


Mutti 1977 ...

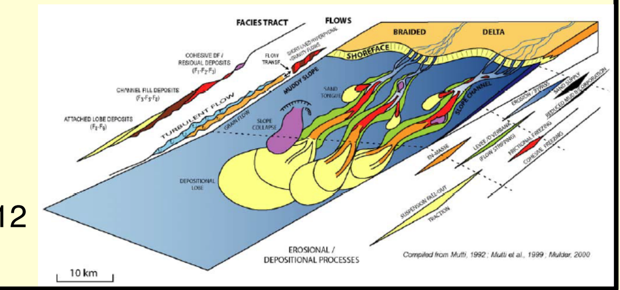
“The model does not take into account the ... elongate basin configuration”

12. *HAM* CURRENT POPULAR MODEL:

Deep-sea (“bathyal”) basin-floor lobes fed by slope channels or canyons



Hecho Gp.
Mutti et al. 1999



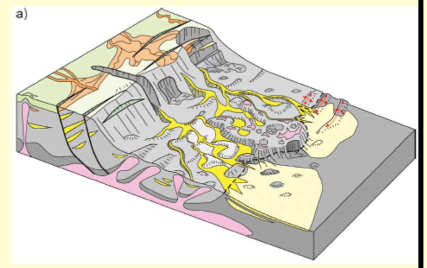
Annot Fm.
Joseph et al. 2012

13. OUTCROP ANALOGS

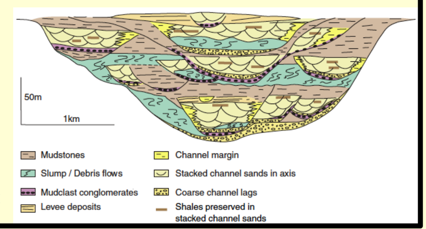
Oil companies use *HAM* (& lookalike Jackfork, Brushy, Skoorsteenberg) as ‘outcrop analogs’ for *passive-margin*, *deep-sea* turbidite reservoirs i.e. minibasins, slope channels, fans

e.g. subsurface offshore Africa, Brazil, Gulf of Mexico:

Channels 10s-100s km long crossing a (halokinetic) slope & feeding base-of-slope fans. Channels have low to high sinuosity & may be either leveed or cut into syn-depositional highs.



Slope composite channel cross section. Note highly heterogeneous fill (contrast Sec. 23 fig.).



Mayall et al. 2006, 2010 exploration-production models based on seismic

14. PERIL OF WEAK ANALOGS

Improper outcrop analogs (e.g. wrong environment & tectonic setting) mean that sandstone parameters measured from (usually 2D) exposures, such as net:gross, connectivity, grain-size gradient, & channel styles, will not apply to the supposedly analogous reservoirs.

Thus, in technologically costly exploration or production areas (e.g. deep ocean), use of incorrect analogs risks $billions in:

(A) non-optimum placement of wells/perforations &

(B) unrealistic predictions of flow rates & reserves, hence unwarranted declaration of project commerciality (or non-commerciality!)

Shelf model for "deep-sea" flysch turbidites & implications for outcrop analogs

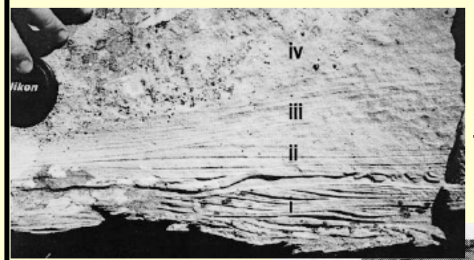
Roger Higgs, Geoclastica Ltd, Bude Turbidite Research Centre, UK

SHEET 2 (of 3) - EVIDENCE FOR WAVES & NEW SHELF MODEL

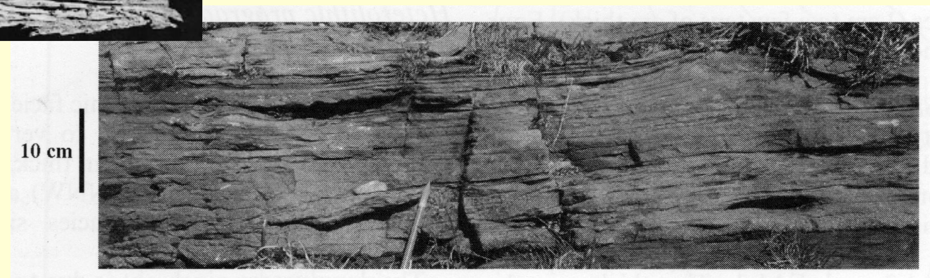
15. *HAM* = SHELF DEPOSITS? COLLECTIVE EVIDENCE

(1-3 from the literature; 4 not)

1. Occasional event beds with HCS
Interpreted by most HAM workers as an HCS lookalike formed by antidunes or by supra-turbidity-current internal waves



Marnoso "interval of curving and slightly fanning lamination (iii) reminiscent of hummocky cross-stratification" (Kneller & McCaffrey 2003). This "turbidite" is interpreted here as a storm-wave-modified hyperpycnite.

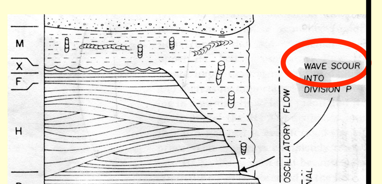


Annot. "The laminasets are slightly wavy, sometimes forming upwards-growing ... bedding due to symmetric ripples that look like small hummocks in a 3D view" (Guillocheau et al. 2004)

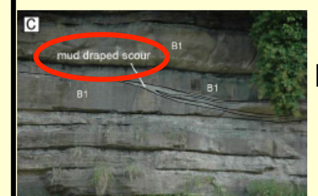
2. Occasional event beds with symmetrical or near-sym. (combined-flow) ripples

3. Occasional sand beds incised or truncated by a mud-draped scour (MDS)

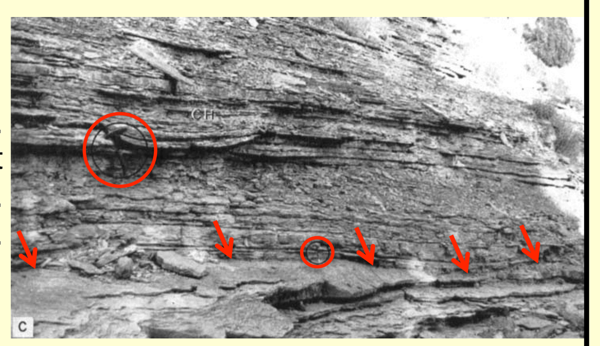
Goldring & Bridges 1973: most shelf event-bed tops show "shallow scours overlain by shales. The scour surfaces ... have a relief of up to 60 cm"



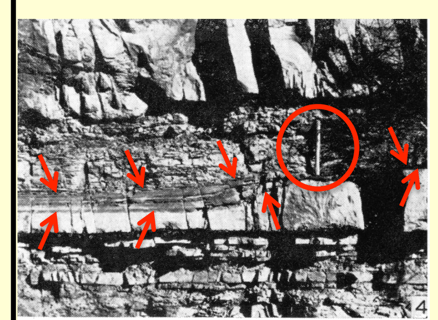
Walker et al. 1983 ideal storm bed



Marnoso. Tinterri et al. 2011



Hecho. Mutti 1977. MDS (arrowed; not mentioned by Mutti). Hammer & pencil circled.



Annot. "Scour and fill structure, filled up with finer material than the surroundings" (Bouma 1962).

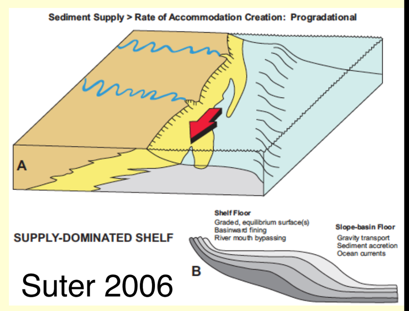
In fact *two* mud-draped scours (arrowed). Hammer circled.

4. 'Depth-window problem': how to accumulate > 6 km (Hecho or Marnoso decompacted) entirely within 0.2-2 km depth limits? i.e. what prevented shallowing to shelf depths?

Better model: *HAM* deposition on a wave-planed equilibrium shelf surface (Sec. 16). Each event bed with HCS or sym. ripples records a megastorm (millennial?).

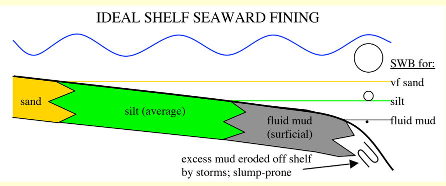
16. WHY SHELVES EXIST

An equilibrium shelf profile exists, maintained by storm erosion

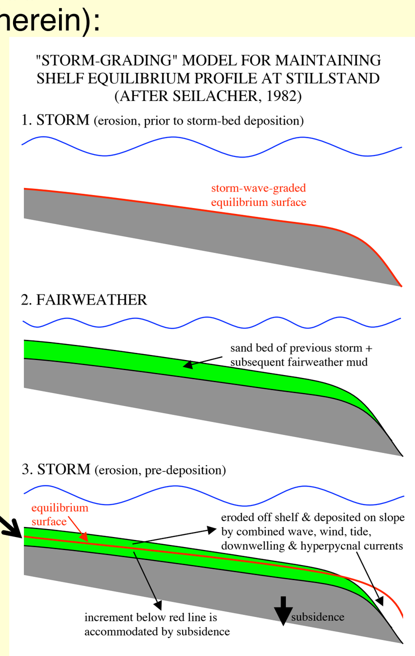


Suter 2006

Each storm shaves off excess aggraded sediment (Higgs 2010 & refs therein):



Each grain size has its own storm wavebase



Storm-erosion surface is either: (A) a MDS (if no accompanying sand supply) or (B) base of a storm bed (with HCS and/or combined-flow ripples)

HAM's lack of gutters or candidate wave-winnowed lags implies falls did not appreciably lower the equil. profile (by wave erosion), i.e. fall caused harmonious (balanced) increases in proximality (delivered grain size) & seabed wave power.

Model does not apply to:

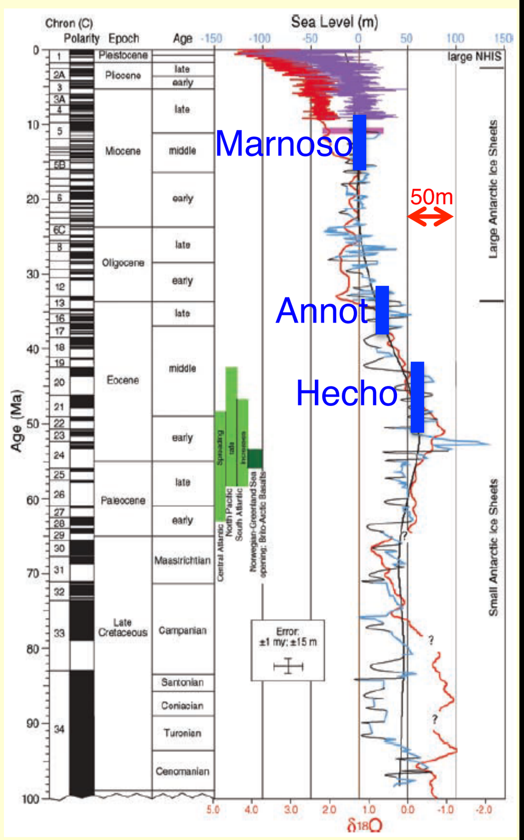
(1) inner-shelf areas overrun by deltas (progradation outweighs rare storm erosion; cf. Sec. 26) &

(2) entire shelf at times of extreme glacioeustasy (e.g. Plio-Quat; Sec. 17), when shelf is out of equilibrium (i) during lowstand exposure & (ii) after subsequent extreme rise (> 100 m) & ravinement, drowning the shelf to below storm wavebase

17. *HAM* AGE & GLACIOEUSTASY

HAM short-term (< 1 Ma) glacioeustasy only 20-50 m

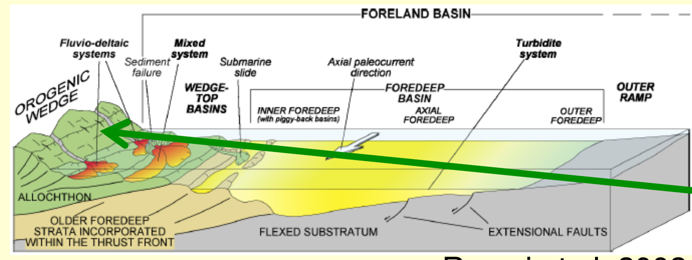
i.e. mid- & outer shelf never emerged subaerially



Miller et al. 2005

18. *HAM* NEW MODEL: CONFINED 'FLYSCH SHELF' (shelf-depth gulf)

Same fig. applies! ... except yellow is shelfal (not deep-sea), incl. shelf-indenting canyons (Sec. 23 fig.)



Roveri et al. 2002

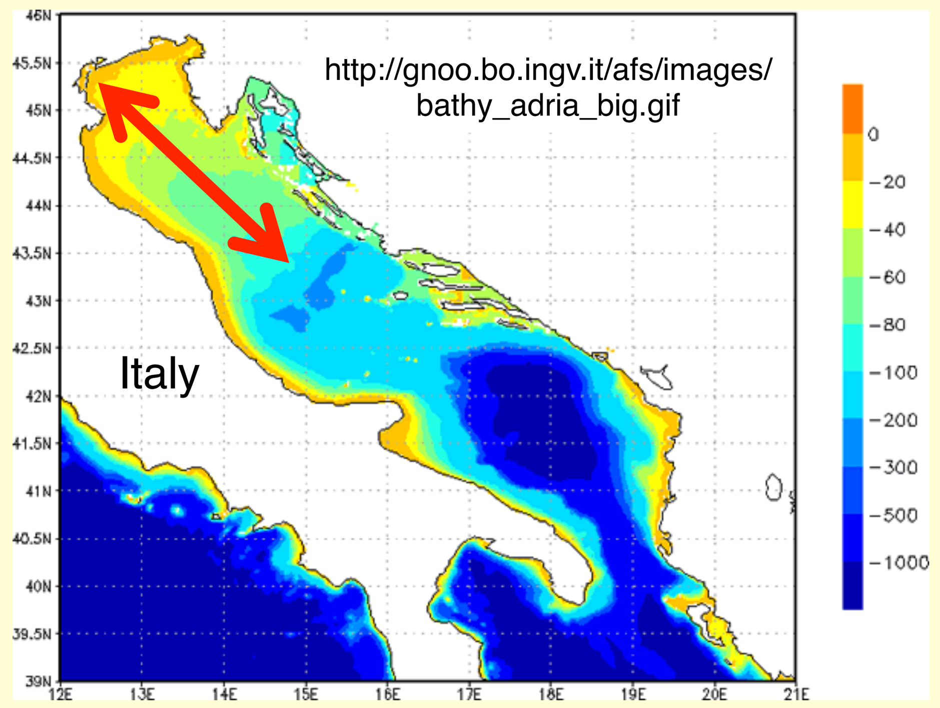
Applies also to: Jackfork Gp (Pennsylvanian, USA), Skoorsteenberg Fm (Permian, S Africa), Cerro Toro Fm (U. Cret., Chile) & others, all characterized by low-amplitude eustasy

19. *HAM* 'FLYSCH SHELF': NO MODERN ANALOG

i.e. shelf-depth gulf with low-amplitude glacioeustasy (contrast Quat.)

20. MODERN PART-ANALOG: ADRIATIC NW SHELF

... a gulf-confined shelf 200 km long



Analogous physiographically but not eustatically (extreme Quat. ampl., cf. Secs 16, 17) or climatically (winter overturn, cf. Sec. 22)

21. *HAM* ICHNOFAUNA REINTERPRETED AS SHELFAL

Entire *HAM* assignable to *Skolithos, Cruziana, Zoophycos* & *Nereites* ichnofacies. Usual interp'n: deep-sea with shallow-water "immigrants" (*Skolithos, Cruziana*). However, all 4 ichnofacies are now globally well known in shelf strata (e.g. Olivero et al. 2010 & refs therein).

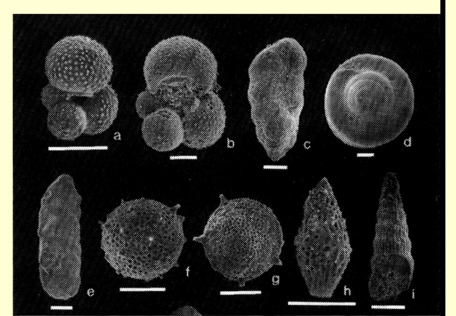
22. *HAM* "BATHYAL" FORAMS REINTERPRETED AS DUE TO (A) FLUVIAL REWORKING & (B) SLOPE MIMICKING

(A) Benthics in uplifted remnant-ocean strata (Sec. 9) in nappe highlands were reworked by fluvial floods & deposited from river plumes on flysch shelf

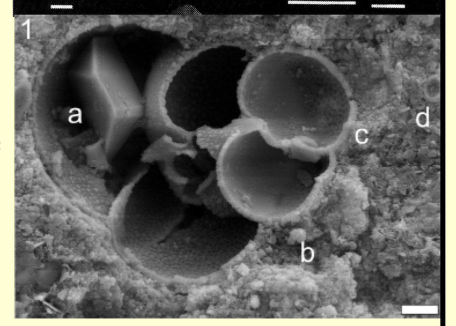
Have micropaleontologists historically missed global wholesale foram reworking, involving river-flood transport in suspension, causing little or no abrasion damage?

e.g. ...

Well preserved U. Cret. to Mio. planktic (a, b) & benthic (c-e) forams in Recent sediments of a NZ estuary, probably reworked from upstream river-valley outcrops of Northland Allochthon (Hollis et al. 1995) comprising nappes of deep-sea strata. Scale 100 microns. SEM photos of picked specimens.



Cret. planktic foram (*Heterohelix*) in Eocene marl, Jordan. The foram is interpreted as fluvially reworked & then deposited on a shelf (Alqudah et al. 2014; Alqudah pers. comm.). Lack of evident outer-wall damage suggests suspension transport. Hollow chambers would facilitate suspension (buoyancy). Scale 10 microns. SEM plate.



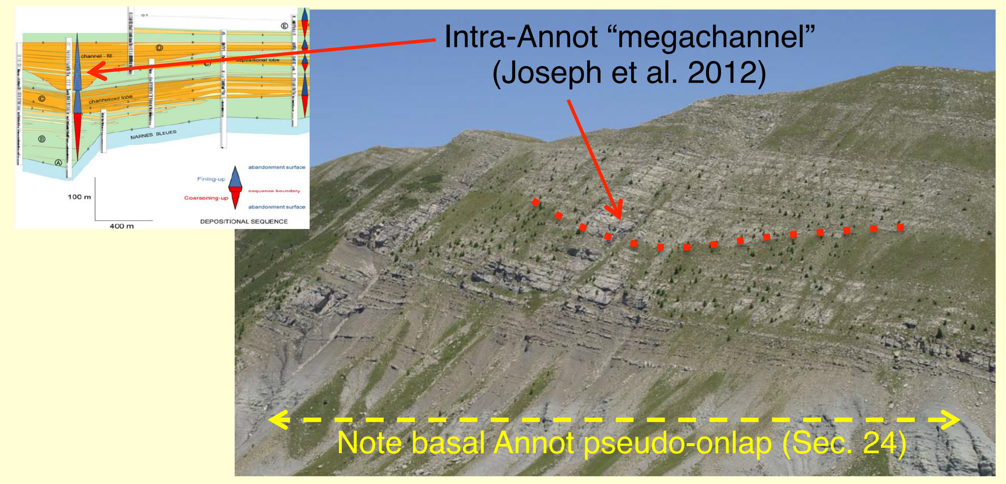
(B) 'Flysch shelf' mimicked a slope (dysoxic, muddy) by:

(i) fairweather mud blanket (contrast sandy transgressed modern shelves) &

(ii) water stratification (subtropical; no overturn; permanent river-diluted lid)

23. *HAM* "SLOPE CHANNELS" REINTERPRETED AS SHELF-INDENTING SUBMARINE CANYONS

(branching; filled with hyperpycnites)



Joseph et al. 2012: "Because of the abrupt border of the incision and the lack of overbank deposits, this "megachannel"-like feature is tentatively interpreted either as the result of a sudden cut-off (large scour), or an erosive scar induced by gravity sliding on the slope." No evidence for internal or external levees in this photo. Low sinuosity predicted (not observable in 2D exposures), based on (A) modern shelf canyons & (B) lack of lateral accretion.

Shelf model for "deep-sea" flysch turbidites & implications for outcrop analogs

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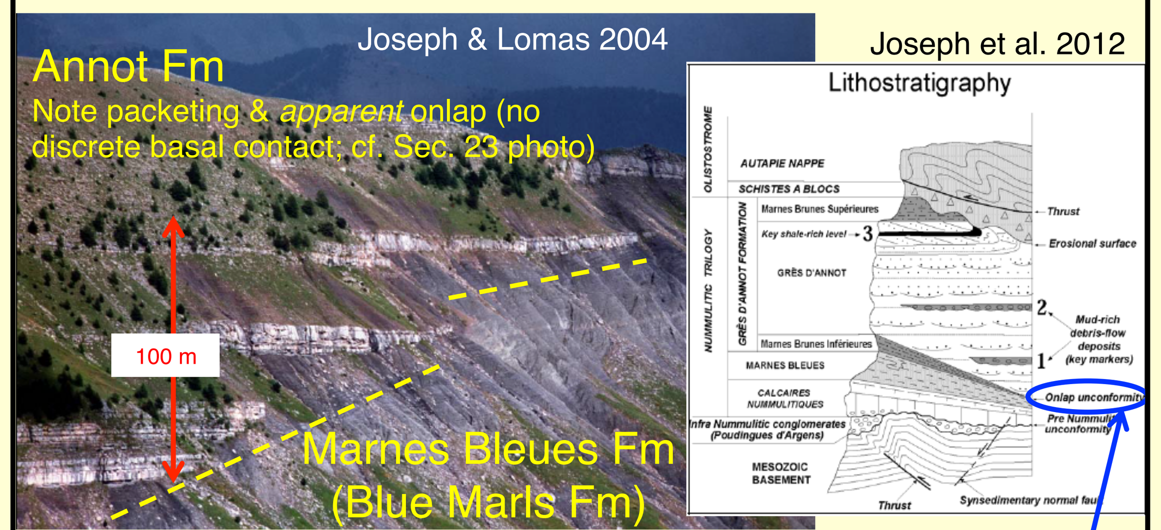
SHEET 3 (of 3) - FURTHER INTERPRETATIONS & CONCLUSIONS

24. ANNOT FALSE ONLAP

Most authors interpret Annot Fm as steeply onlapping the Marnes Bleues (e.g. Sinclair 2000 & refs therein).

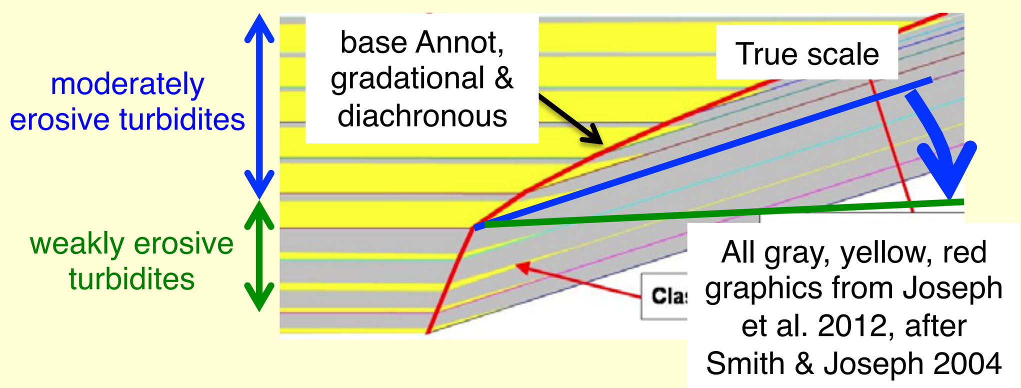


Such steep/high basin-floor topography would negate new shelf model.

Onlap implies .... unconformity
But micropaleontology shows contact is conformable & regionally diachronous (Sztrákos & du Fornel 2003).

In fact the "onlap" is pseudo-*sidelap* onto migrating forebulge ....

Successive turbidites (& their Bouma E mud caps) show advancing pinchout onto forebulge flank (migrating cratonward) ....



.... while intervening marl beds (thinned by erosion under each turbidite) continue (uneroded) up forebulge.

Differential compaction (marl has high mechanical-chemical compactability) greatly exaggerates the "slope" angle....

3:1 decompaction of 'mud wedge' (between blue line & overlying red line) restores its base to < 1 degree dip (green line).

25. INTERPRETATION OF 'PACKETING' (CYCLICITY)

... rapid glacioeustatic fluctuations in water depth & proximality on a shelf

Origin of *HAM* "high-frequency cyclicity so clearly expressed by 'thick-bedded proximal' and 'thin-bedded distal' packets (is) a long standing ... problem" (Mutti et al. 2009).

Abrupt packet-to-packet change in event-bed av. thickness suggests falls & rises were:

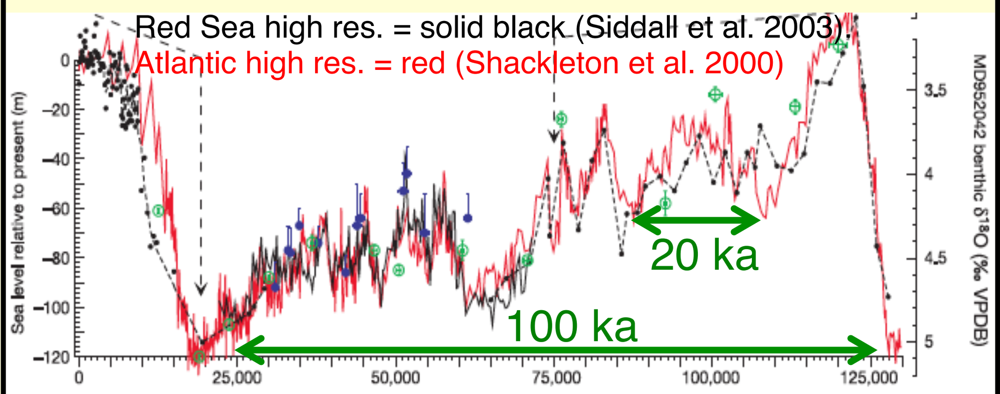
(A) large enough (2-20 m?) to significantly alter river-mouth proximity (controlling event-bed thickness),

yet ...

(B) too brief (0.1-1 ka?) for more than 1 or 2 (if any) events to occur ...

i.e. falls & rises v. rapid, c. 2 cm/yr

cf. Quat. foram O2-isotope studies ...



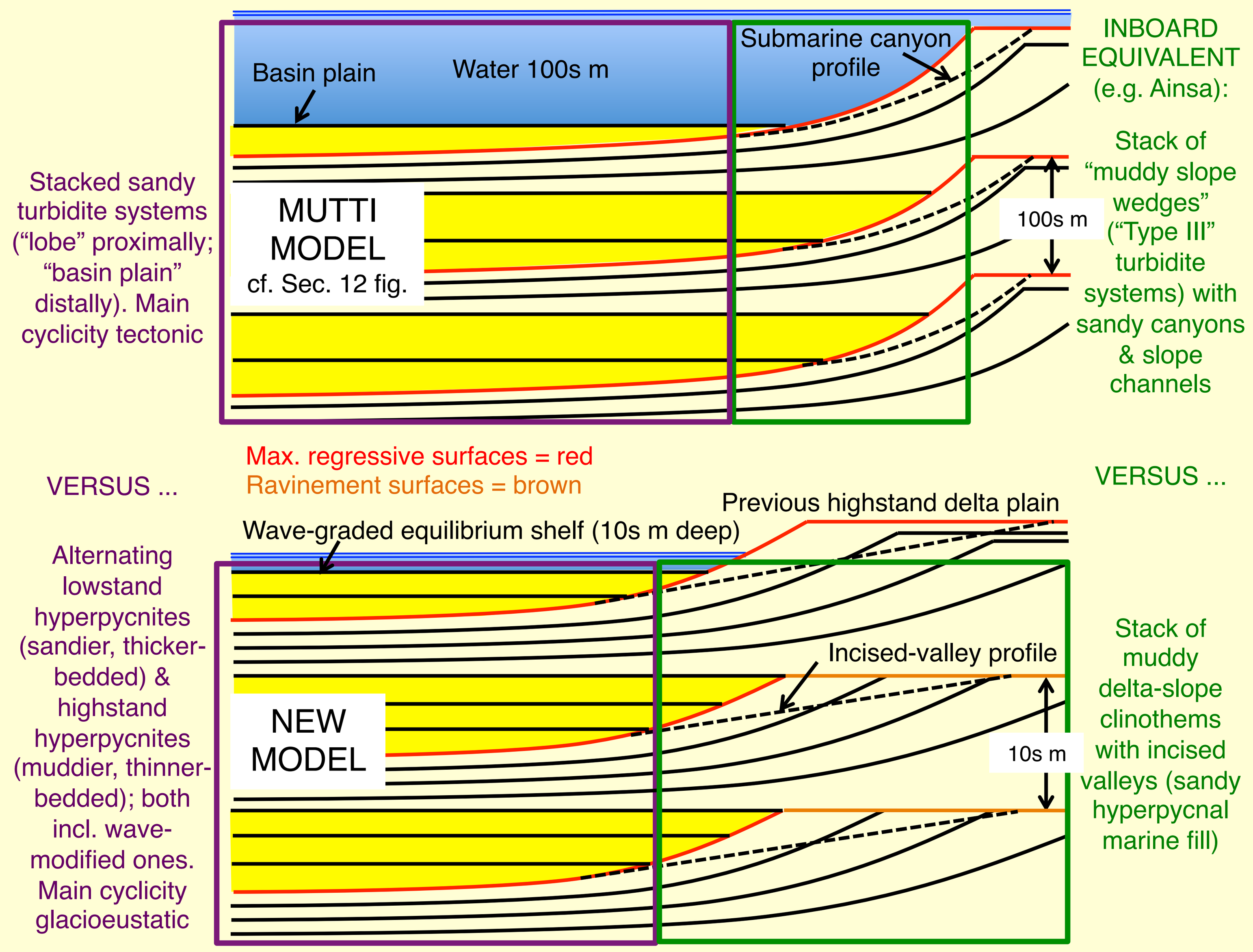
revealing that shortest cycles lasted 1-2 ka (solar), with av. amplitude c. 10 m (range c. 5-40 m).
Several rises & falls of c. 20 m lasted c. 1 ka, i.e. 2 cm/yr
Superimposed on Milankovitch 20 & 100 ka cycles.

Cycle convolution explains *HAM* packet-thickness variability (& unpredictability?)

Is *HAM* a vast, overlooked archive of global paleotemp. & sea level?!

26. INTERP'D BASIN ARCHITECTURE

(section parallel to basin axis)



New model: shelf flysch interweaves proximally with delta-front clinothems 10s m tall containing incised valleys (cf. proximal Brushy Canyon Fm; Beauboeuf et al. 1999 fig. 4).

During highstands, gulf-head delta (Sec. 9 fig.) prograded part-way onto shelf.

During lowstands: no progradation, as river confinement (incised into delta plain) raised flood velocity (more suspended sed.), hence hyperpycnal flow more frequent/sustained, thus all riverborne sed. bypassed to shelf.

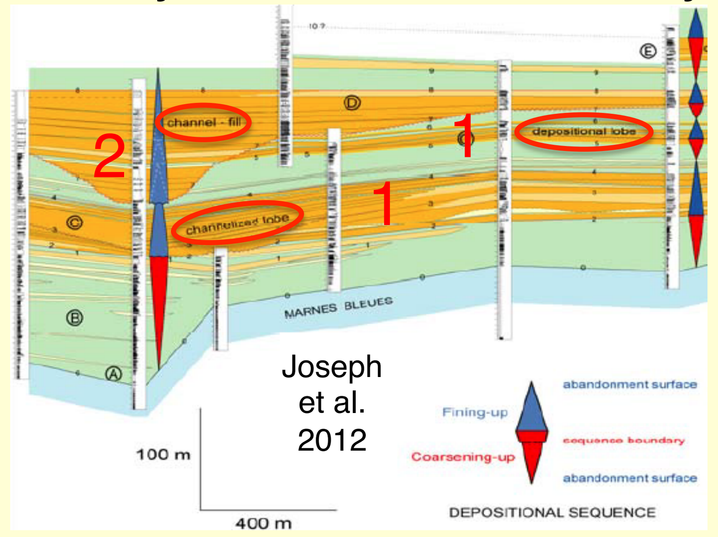
27. *HAM* PREDICTED 3D SAND GEOMETRY based on

(i) mainly 2D exposures & (ii) interp'd shelf env.

1. Basin-wide (10s km), basin-length (100-200 km) sheets (m-10s m thick) of amalg'd & near-amalg'd, tongue-shaped, compensated hyperpycnal sand beds (cm-m thick), incised by ...

2. low-sinuosity inner submarine canyons

cf. ...



Contrast unconfined passive-margin deep-sea fans fed by sinuous channels, some leveed (Sec. 13 figs)

28. MAIN CONCLUSIONS

1. Hecho, Annot & Marnoso classic flysch formations (& lookalike Brushy, Bude, Jackfork, Ross, Skoorsteenberg, etc.) are shelfal, not "deep sea"

therefore are ...

2. poor outcrop analogs for exploration/production of passive-margin deep-sea-turbidite reservoirs

due to major environmental contrasts whereby shelf flysch differs strongly in sand-body size, geometry, architecture, heterogeneity, granulometry, etc.. These contrasts include ...

Active tectonism, hence seismites (pseudo-slumps), likely injectites. faster subsidence, smaller catchments, nearer highlands (gravel supply)

Three-way confinement (proximal, lateral), unlike passive-margin fans (1-way, hence prone to contour-current reworking) & slope minibasins (4-way)

Wave scour, truncating & amalgamating sand beds. Storm shaving would limit height/survival of any shelf accretionary topography (levees, lobes)

D. Shelf-flysch "channels" are all(?) incisional & weakly sinuous (shelf-indenting canyons), unlike deep-sea highly sinuous channels, some with levees, i.e. intra-channel *and* overbank sands (cf. Sec. 13 figs)

29. ACKNOWLEDGEMENTS

For sedimentological discussions literally on the Bude flysch at various times since 1982, I thank Drs P.A. Allen, P.J. Brenchley, L.A. Buatois, R. Goldring, P.M. Myrow, H.G. Reading, J.B. Southard & R.G. Walker. For sharing opinions on benthic-foram reworking, I am grateful to Drs A.-S. Fanget, J. Frampton, A. Goineau, J.W. Murray, J. Nagy, C. Pirkenseer & K. Sztrákos.

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