Geodynamic context for the deposition of coarse-grained deep-water axial channel systems in the Patagonian Andes: discussion

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Manuscript submitted to Basin Research, 2015. Rejected.

PREAMBLE, 28/4/15

The currently popular deep-sea model for the Cerro Toro and Tres Pasos Formations (Cretaceous) of the proximal Magallanes foreland basin (Chile and Argentina) is exceedingly tenuous, yet many oil companies use these formations as 'outcrop analogs' for passive margin (sic) genuinely deep-sea turbidite reservoirs worldwide, a mistake costing them billions of dollars in my opinion.

Wishing to alert the world geological community to this situation, I submitted the manuscript below in early 2015 to Basin Research, in the form of a Discussion of an interesting and timely article by Ghiglione et al. published in that journal in late 2014. However, not only did the editor assign only one reviewer but also, bafflingly, chose one of the chief proponents of the deep-water model; indeed, 17 of his publications are cited in my manuscript. Predictably, the reviewer urged rejection.

Of the many objections raised by the reviewer with which I disagree, I shall here mention just one. His report says: "First off, there is no continental slope in a foreland basin, and Hubbard et al (2010) do not propose that there is." Yet the first line of the abstract of Fildani & Hubbard (2008) says: "The Cretaceous Tres Pasos Formation is interpreted as a continental slope depositional system"; and the title of Romans, Hubbard & Graham (2009), published in the journal Sedimentology, is "Stratigraphic evolution of an outcropping continental slope system, Tres Pasos Formation ...".

I strongly feel that Basin Research should have appointed two or three completely impartial reviewers (as is normal practice), especially given the economic importance of the topic.

In the hope that the great deal of thought and background reading that went into my manuscript is not wasted, it is offered below so that interested readers (and oil companies) can assess for themselves the relative merits of the deep-water model versus the earlier and, in my judgment, better shallow-water interpretation.

Roger Higgs, Bude, April 2015

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The recent article in Basin Research by Ghiglione et al. (2014) concerns the tectonic context of enigmatic conglomeratic "deep-water channels" (Lago Sofia Member) encased in "abyssal turbidites" of the Upper Cretaceous Cerro Toro Formation, in the proximal (western) Austral/Magallanes foreland basin of Argentina and Chile. The topic is economically important as several authors have recommended these channels, and others in overlying supposed continental-slope strata (Tres Pasos Formation; Ghiglione et al. figs 2-4), as outcrop analogues for incontestably deep-sea-channel oil reservoirs explored and exploited below the passive margins of Africa, Brazil, the Gulf of Mexico and elsewhere (Beaubouef 2004; Bernhardt et al. 2008; Fildani & Hubbard 2008; Hubbard et al. 2008; Fletcher et al. 2012; Macauley & Hubbard 2013). However, the outcrops are so remote that very few seasoned oil-industry sedimentologists have visited (as opposed to numerous doctoral students; see below). Others must rely on the literature, backed by their own global experience, to evaluate the prevalent deep-sea interpretation. In this discussion I propose that, like many other outcropping “deep-sea turbidites” worldwide, the supposed abyssal or bathyal Toro-Pasos environment was largely shallower than 100 m. The confusion partly reflects sedimentologists' under-appreciation of non-actualistic environments (Higgs 2014).

Ghiglione et al. accept the popular model of a foreland basin for the Toro channel system (TCS), but propose a wedge-top instead of the generally agreed foredeep setting, based on a seismic profile (their fig. 6a) that shows an angular discordance interpreted by them as a TCS-age tectonic unconformity. TCS channels are known only in outcrops farther west (see "Lago Sofia Conglomerates" in Ghiglione et el. fig. 4b, c, d cross sections).

Publications from 1979 onward, cited below, unanimously invoked deep water (100s or 1000s m) for the TCS, based largely on the nature of the enclosing turbiditic strata, particularly the ichnology and perceived lack of wave-influenced sedimentary structures, but also based on foraminifera from the equivalent interval in worryingly distant boreholes (200 km away; see below). The water body that hosted the TCS is widely agreed to have been a deep-sea trough, closed in the north (e.g. Bernhardt et al. 2012 and references therein). TCS channels merge southward (i.e. tributaries); their widths are kilometric and lengths can exceed 100 km (e.g. Ghiglione et al. fig. 3). Lateral confinement is variably interpreted as the result of: (1) a combination of levees and incision (Winn & Dott 1979; Beauboeuf 2004); (2) incision alone (Coleman 2000); and (3) active flanking thrust anticlines (Gonzales & Aydin 2008). Incision is obvious in mountain exposures (e.g. figures in Jobe et al. 2010) but levees are unproven (de Ruig & Hubbard 2006). Following from their wedge-top interpretation, Ghiglione et al. adopt the third model (fig. 9), admitting that this is a "peculiar geometry" (p. 730), in a "singular foreland basin" (p. 727).

Use of the words "peculiar" and "singular" by Ghiglione et al. (also "remarkable", p. 726) raises questions about their interpretations, and about the TCS deep-sea model. This Discussion offers seven reinterpretations and/or conclusions:

1. the foreland basin was of peripheral type rather than retroarc;

2. the unconformity is instead an incision (i.e. another TCS channel), i.e. not evidence of a wedge-top setting;

3. the TCS channels were not confined by structure;

4. the Toro supposed deep-sea trough was instead a shelf-depth gulf, ending at a continental slope somewhere to the south;

5. the TCS channels are submarine-canyon heads that indented the gulf;

6. the succeeding Tres Pasos Formation is a stack of delta-slope clinothems, rather than a single continental-slope clinothem; and

7. the TCS and Pasos channels are inappropriate analogues for sinuous, leveed, deep-sea-channel petroleum reservoirs.

AUSTRAL/MAGALLANES FORELAND BASIN IS OF PERIPHERAL, NOT RETROARC TYPE

Following Winn & Dott (1979), the consensus view is that the basin was of the retroarc variety (e.g. Fosdick et al. 2011). In contrast, Arbe (1989) proposed that the basin was of peripheral type, produced by collision following ocean closure between South America and a western sliver continent. This alternative view was later proven by plate reconstructions showing that this "Rocas Verdes Ocean" was very wide (1000s km; Vérard et al. 2012 fig. 5c-e). Ghiglione et al. did not explicitly call the basin peripheral, but do imply this by stating "Our data support the idea that the collision of the western rim of Rocas Verdes Basin was an orogenic building process itself" and by republishing (fig. 10a), in modified form, figure 5h of Vérard et al. (2012).

Thus, the Austral-Magallanes basin evolved from an ocean-facing passive-margin shelf (Arbe 1989 fig. 5.3, area B) to a peripheral foreland basin (fig. 6.3). This begs the question of how much the water depth increased, if at all.

REINTERPRETATION OF LAGO ARGENTINO UNCONFORMITY

"The Lago Argentino ... angular unconformity", a concave-up reflector dipping east in the eastern 15 km of the seismic profile (Ghiglione et al. p. 736 and Fig. 6a), is reinterpreted here as the western wall of a buried incised canyon. The concave-up reflector is onlapped ("westward onlap", p. 736), but also truncates reflectors below (not mentioned by Ghiglione et al.). West of the onlap edge, Ghiglione et al. infer a paraconformity coinciding with the regional "abyssal platform" (p. 727). The implied composite geometry is thus a stepped unconformity (see cartoon annotated "CoU" and "CoP" in their fig. 2, right-hand side), formed at abyssal depths; the type of current(s) responsible was not addressed by Ghiglione et al..

The "unconformity" is instead interpreted here as another TCS incised channel, with sidelapping fill. Indeed the estimated age of the "onlapping" interval (Ghiglione et al. fig. 2; Coniacian) compares with ?Coniacian and Santonian radiometric ages of the outcropping TCS (Bernhardt et al. 2012). Moreover, the proposed (here) Lago Argentino Channel could well be sub-parallel to the outcropping channels, which trend SSE (pale green "deep-water channels" on map of Ghiglione et al. fig. 3). The channel's estimated half-width (on seismic) is about 15 km, as opposed to the 3.5 km width of the outcropping "Wildcat channel complex" (Jobe et al. 2010 fig. 4; see below), so the latter is possibly a tributary of the former. Similarly the calculated thickness of the "onlapping" section (600 m; Ghiglione et al. p. 736, 737) exceeds that of the Wildcat fill (300 m). The Argentino channel is predicted to continue under Cenozoic strata SE of the seismic line (Ghiglione et al. figs 2, 4), offering petroleum exploration potential.

TCS NOT CONFINED BY SYN-DEPOSITIONAL STRUCTURES

Ghiglione et al. (p. 740) state "it is clearly noticeable that the deposition of conglomeratic channels was confined between main anticlines within the internal domain (Fig. 3)". On the contrary, in their figure 3 (map), the two western tributaries cross-cut, with slight to moderate obliquity, fold axes and also a thrust. The three mapped channels' divergence (c. 30°) also contradicts structural control.

RESURRECTION OF TORO SHELFAL MODEL

Cecioni (1957) interpreted the Cerro Toro Formation as “Flysch … deposited in a neritic environment not deeper than 100 meters”, based on abundant *Chondrites*, then believed to be algae; and the overlying Tres Pasos Formation as even shallower “molasse”. Other authors agreed with the flysch and molasse designations (Zeil 1958; Katz 1963; Scott 1966; DeVries & Lindholm 1994). The Sofia channeled conglomerates were interpreted as fluvioglacial (in part) by Cecioni (1957); and as shallow marine by Zeil (1958), cited by Scott (1966), who concurred that “It is possible that the part of the Cerro Toro Formation containing most of the sandstone and conglomerate beds was deposited at shelf depths” (p. 104).

A rival deep-sea model for the Toro was proposed by Winn & Dott (1977, 1979), and for the Pasos by Smith (1977, thesis cited in Winn & Dott 1979). These reinterpretations were endorsed in a 2005-2014 flurry of publications in major international journals (including Bernhardt et al. 2012 in Basin Research), based mainly on doctoral theses from a single university (see references in reviews by Romans et al. 2011, Hubbard et al. 2014). However, the Toro's previous shelf model is consistent with:

(1) plentiful *Inoceramus* (Cecioni 1957), common in Cretaceous outer-shelf deposits worldwide (Kauffman 1967);

(2) "Many fine-grained sandstone or siltstone beds ... (with) ... low-amplitude convolute lamination" (Scott 1966 p. 82) lacking directionality and capped by domes. A 3D drawing (Scott 1966 fig. 9) strongly resembles accretionary HCS capped by hummocks, i.e. these beds are possibly storm-wave-modified hyperpycnites or shoreface-derived tempestites. Another drawing (Winn & Dott 1979, fig. 8b) is also suggestive of HCS;

(3) low-relief (< 1 m) undulatory mud-draped scours in sand (DeVries & Lindholm 1994, Beauboeuf 2004 fig. 5b; Jobe et al 2010 fig. 3g), attributable to storm-wave erosion without sand supply (cf. Walker et al. 1983 fig. 1); and

(4) a diverse ichnofauna (Hubbard & Shultz 2008; Jobe et al. 2010; López & Olivero 2014) assignable to the *Skolithos*, *Cruziana* and *Zoophycos* ichnofacies, all long known in shelf strata (Frey et al. 1990 fig. 1), as is even the *Nereites* ichnofacies (e.g. Olivero et al. 2010 and references therein), proving that "ichnofacies are not intended to be paleobathometers" because "water depth per se is rarely, if ever, a governing factor" (Frey et al. 1990 p. 155).

Many of the 1977-2014 papers applied to the Toro and Pasos a 1-2 km water-depth estimate of Natland et al. (1974), but this was based on benthic foraminifera in equivalent strata in boreholes far (200 km) to the SE where, moreover, the interval is ten times thinner. Furthermore, the 1-2 km estimate is based on 4 particular species belonging to 4 benthic genera, of which only 1 (species unstated) is among the 28 listed by Katz (1963), 8 to species level, from the Toro outcrops and two boreholes there. Additionally there is the problem of what depth-regulating mechanism could have maintained a constant depth-window of 1-2 km throughout deposition of such a great thickness (Toro plus Pasos > 4 km [Katz 1963], i.e. > 8 km pre-compaction). What prevented shallowing beyond 1 km? In any case Higgs (2014) argued that bathyal assemblages in classical 'miogeosynclinal' flysch are only *pseudo*-bathyal, reflecting two factors: (A) mimicking, in a shelf-depth gulf, of the dysoxic seabed of a continental-slope OMZ (i.e. background mud everywhere; dysoxia by gulf thermohaline stratification). Dysoxia also explains the lack of reported Toro benthic megafossils other than *Inoceramus* (Kauffman 1975); and (B) fluvio-deltaic reworking of benthic taxa from near-coeval offscraped deep-sea flysch exposed in the orogen, i.e. taxa were reworked from 'eugeosynclinal flysch' and deposited in shelfal 'miogeosynclinal flysch' (terms of Abbate et al. 1970). The list of Katz (1963) includes *Saccammina* and *?Spiroloculina*, undeniably shelf genera. Most micropalaeontologists would interpret these as redeposited into deeper water by turbidity currents from a coeval shelf, but they are more likely *in situ*. As only 11 of the 28 Toro taxa are agglutinants, the term “flysch-type assemblage” (Kaminski & Gradstein, 2005) is not applicable.

For these reasons the Toro supposed deep-sea trough can be reinterpreted as a semi-enclosed shelfal gulf ("flysch shelf"' of Higgs 2014). The axial length was at least 100 km (cf. Toro present outcrop length in Ghiglione et al. fig. 3, and modern 200 km NW Adriatic shelf). The gulf's width, between orogenic front and forebulge crest, could have been as little as 100 km (Decelles & GIles 1996), in which case the lateral gradient exceeded the axial gradient. The Toro gulf deepened axially southward, presumably ending at a continental slope fronting a narrow remnant ocean closing by diachronous collision (Dickinson 1976 fig. 25). The collision suture, migrating south, was 'shadowed' by the southward prograding Toro shelf (and the succeeding Pasos delta slope; see below).

Toro turbidites were probably megaflood river-fed hyperpycnites fed via the basin-axial trunk river and its delta. Palaeocontinental reconstructions make early collision in the south likely (at a salient; cf. Ghiglione et al. fig. 10a), raising a sill, isolating an "ocean lake" (Higgs 2014) which, given a positive water balance, would have freshened at lowstand, favouring hyperpycnicity (Higgs 1991 fig. 20; cf. "enclosed small ocean basin of lowered salinity" of Burne 1973 p. 129). The sill would also curtail eustatic falls in the lake, limiting forced emergence to the innermost shelf, so even at lowstand the 'flysch shelf' was almost entirely under water. Moreover the shelf could not emerge autogenically because (A) storm-wave shaving limited sediment aggradation (Higgs 1991, 2004, 2010a) and (B) 'easy hyperpycnicity' (delta bypass) halted shore progradation (Higgs 2014). In combination, storm-shaving and the sill allow thick (km) shelf successions to accumulate within a narrow water-depth window (c. 10-150 m; contrast literature consensus on 1-2 km water depth for Cerro Toro Formation, about 2 km thick [Katz 1963]). Toro event beds with HCS are megastorm beds (storm-wave-modified hyperypcnites or shoreface-derived tempestites), easily misinterpreted as turbidites (unless HCS is present) due to combined-flow-ripple asymmetry.

Toro injectites (Scott 1966; Winn & Dott 1979; Shultz & Hubbard 2005; Hubbard et al. 2007) reflect foreland-basin seismicity. Interpreted "slumps" have mostly N-S fold axes (sub-parallel to the Toro's overall SSE palaeocurrents) and verge E more often than W (Scott 1966; Winn & Dott 1979). These might be genuine slumps, reflecting a relatively steep lateral gradient (see above); or they may be seismites, essentially *in situ*; or the folds might be early tectonic (intrafolial).

TCS "ABYSSAL" CHANNELS REINTERPRETED AS SUBMARINE CANYON TRIBUTARIES, ON A SHELF

Mapping at Sierra del Toro reveals a cobble-rich linear incision (palaeocanyon), recurring at four stratigraphic levels, with intervening canyon-free intervals (Jobe et al. 2010 figs 1c, 2a). Three of the four "channel complexes" (Jobe et al. 2010) comprise a stack of amalgamated (or nearly so) single canyons; in two of these, each canyon axis is offset slightly (< 2 km) orogenward or cratonward from the previous one, suggesting fore- and back-stepping of the basin axis, possibly controlled by compressive pulses in the orogen. The third, Wildcat channel complex is 3.5 km wide at the top, 300 m thick and very slightly sinuous (Jobe et al. 2010). The Wildcat widens upward and has stepped walls and packaged fill (Jobe et al. 2010 fig. 4), suggesting amalgamation of successively cut-and-filled canyons, individually 20-60 m deep, and each progressively wider than its predecessor. The aggradational, sidelapping fill of conglomerate, sandstone, mudstone was interpreted largely as debrites and turbidites by Jobe et al. (2010). Conglomerates are largely non-stratified, with subordinate parallel- and cross-stratified intervals (sets dm-m thick; Winn & Dott 1977). Palaeocurrents determined from flutes and imbrication were dominantly toward the southern quadrant (Scott 1966; Winn & Dott 1979; Jobe et el. 2010). There is no persuasive outcrop evidence for levees (nor are any visible in the Ghiglione et al. seismic profile), so applying the term “overbank” (Winn & Dott 1977, 1979; Jobe et al. 2010) to the relatively poorly exposed enveloping strata is unjustified.

Cecione (1957) interpreted the TCS as glaciofluvial canyon fills. Instead most later workers (1977-2014) invoked an incised channel, perched on giant inferred levees or not, crossing a deep-sea fan or basin plain, in front of a submarine slope about 1 km high (e.g. Winn & Dott 1979 figs 9, 14; Hubbard et al. 2008 fig. 15; Romans et al. 2011 fig. 9). In contrast, in the context of the new shelfal-gulf model, the TCS (including Argentino Canyon) is interpreted here as the stratigraphically recurring head, and tributaries, of a submarine canyon indenting the Toro shelf. Stratigraphic restriction of the TCS to the middle Cerro Toro Formation (e.g. Ghiglione et al. fig. 2), and its recurrence at four or more levels, may reflect a Turonian-Santonian glacioeustatic low upon which five shorter-term, exceptionally low lowstands were superimposed (Miller et al. 2005 fig. 3). Canyons may have originated by slumping at fault-controlled fluid seeps on the continental slope (Orange et al. 1997) and lengthened upslope, into the shelf, by retrogressive failure. Each of the five falls, though curtailed by the ocean-lake's sill (see above), may have forced the (incised) basin-axial river mouth to advance far enough onto the shelf for the canyon to capture hyperpycnal flows. Flows exiting the incised valley accelerated into the canyon (gradient increase), causing downcutting and headward erosion (knickpoint retreat). Tributary submarine canyons, perhaps initiated by seeps on long-lived, intra-shelf faults, likewise grew headward, connecting to incised valleys containing orogen-tapping cobbly rivers with mountain catchments. Toro canyon filling, during relative sea-level rise, was largely by orogen-sourced, cobbly debrites (initiated by catastrophic rainfall) arriving via the tributary incised valleys. Lateral clast-size asymmetry in a canyon (Jobe et al. 2010) may record veering of debris flows issuing from a tributary canyon. Parallel- and cross-stratified gravels are attributable to tractional reworking of debrites by hyperpycnal flows co-generated by the same rainfall event and emanating from the same mountain tributaries and/or from the axial trunk river, but outlasting the debris flow by days or weeks, eventually depositing a sandy hyperpycnite down-canyon and/or on top of the reworked debrite. During fair weather (i.e. between floods and storms), mud settled in the canyon and on the adjacent shelf. After the canyon was full, gravelly debrite deposition ended (gradient too low). Hyperpycnal flows were then free to expand laterally onto the shelf, depositing unconfined hyperpycnites.

A partial modern analogue of the TCS is the Swatch of No Ground, a submarine-canyon head up to 15 km wide and reaching more than 100 km into the northern Bay of Bengal shelf (e.g. Kuehl et al. 2005 fig, 4).

TRES PASOS FORMATION: DELTA SLOPE, NOT CONTINENTAL SLOPE

The overlying Pasos "molasse" was radically reinterpreted as continental-slope mudstones containing slope-channel sandstones by Fildani & Hubbard (2008) and Hubbard et al. (2010, 2012), based on a supposed single set of S-dipping clinoforms about 800 m tall (i.e. fitting the deep-sea model of the underlying Toro), inferred from oblique satellite images of a rugged outcrop region. However, due to extensive cover of vegetation, scree and Quaternary valley deposits the clinoforms are very tenuous (dashed lines in Fildani & Hubbard 2008 slide 6, Hubbard et al. 2010, fig. 3 and Bauer & Hubbard 2012 slide 9) and are rejected here. Moreover, reported ultra-low diversity of benthic forams and absence of planktics in the Pasos (Herm 1966) negate the continental-slope model. The sandy “slope channels” are mostly narrow (100s m), thin (m-10s m) and weakly sinuous; vertical amalgamation is common, with or without significant lateral offset of the channel axis (Macauley & Hubbard 2013). Even though "the fine-grained out-of-channel deposits are mostly covered by vegetation in the study area and therefore actual levee morphology ... is not observed" (p. 159) and "Direct observation of the surface that demarcates the base of the large-scale conduit is not possible in the study area" (p. 156), Macauley & Hubbard (2013) assumed that Pasos channels have levees and that amalgamated channels are confined within master incisions, both based on published seismic geometries from deep-sea passive-margin channels presumed to be analogous, thus introducing circularity. The diverse ichnofauna (Hubbard & Shultz 2008; Hubbard et al. 2010, 2012), both inside and outside the channels, is again non-definitive, assignable to the eurybathic *Skolithos*, *Cruziana* and *Zoophycos* ichnofacies.

The continental-slope model is untenable. Instead the Pasos is interpretable as a stack of thin (< 30 m) S-prograding muddy delta-slope clinothems, Each clinothem reflects a basin-axial delta prograding onto a shelf during a highstand (eustatic, Milankovitch-band?). Pasos clinoforms evade detection at outcrop due to their very low dip (< 0.5°?; cf. Pleistocene "shelf delta" of Suter & Berryhill 1985; contrast 2° in Pasos continental-slope model, Hubbard et al. 2010 fig. 4) and the lack of long (km) continuous exposures parallel to depositional dip. Southward progradation of Pasos clinothems onto a Toro-type shelf is consistent with radiometric evidence for southward younging of the Toro-Pasos transition (Bernhardt et al. 2012).

Pasos “slope channels” are reinterpreted here as delta distributaries, overdeepened (incised) by falling-stage and lowstand hyperpycnal erosion, each passing shelfward into a delta-slope erosional gully. Hyperpyncal flows were frequent and sustained during fall- and lowstand due to trunk-river incision, whereby flooding rivers were confined, less able to decelerate by overbanking, hence suspended-sand content was high (Higgs 2010b). Flows exiting the distributary accelerated (due to increase in gradient onto delta slope), producing a knickpoint that retreated erosively. Thus distributaries became long (km-10s km?), funnel-shaped inlets (non-estuarine; no evidence for tides reported in Pasos; insignificant tides expected in 'ocean-lake' at lowstand). Distributaries/gullies were filled with sandy hyperpycnites (some influenced by waves) and muddy hypo-/mesopycnites during rises. "Wavy ... lamination" (Romans et al. 2007, 2009) in thin (< 30 cm) sand beds inside (and outside?) the channels might reflect wave influence.

Interpreted “mass transport deposits” (MTDs) of variable thickness (m-10s m), common outside the channels (Armitage et al. 2009), are consistent with the delta-slope model. Transgressive ravinement lags are predictable between clinothems (except where eroded by an overlying incised distributary) but may have been missed (steep terrain hence narrow traverses; poor “out-of-channel” exposure) or misinterpreted as thin (cm) debrites. Subtle upward coarsening of background mud in each clinothem is predicted but not yet reported. Upward-thickening successions of delta-slope sandy hyperpycnites are not expected, as hyperpycnites were delivered directly to the shelf via the erosional gullies. Pasos foram scarcity is consistent with high clay fallout from a near-permanent, fair-weather, delta-fed hypopycnal plume.

UNSUITABILITY AS OUTCROP ANALOGUES

Mutti et al. (2003, p. 751-752) cautioned that "turbidite sedimentation of divergent continental margins differs dramatically from that recorded by ancient foredeep basins". Five crucial differences make the Toro (TCS) and Pasos channels highly unsuitable as analogues for truly deep-water (100s-1000s m), sinuous, leveed-channel petroleum reservoirs of *passive-margin* continental slopes and base-of-slope fans (e.g. Africa, Brazil, Gulf of Mexico):

(1) very different tectonic setting (foreland basin), hence (A) continental basement instead of oceanic or transitional, (B) nearby tectonic highlands, affecting sediment volume, calibre (e.g. Toro cobble conglomerate) and composition (influencing porosity-permeability); and (C) frequent strong earthquakes (injectites, seismites);

(2) three-way confinement in the Toro flysch gulf (contrast one-way on passive margins), hence little or no sand redistribution by contour currents;

(3) low sinuosity and probable lack of levees of Toro shelf-indenting canyons and Pasos incised distributaries/delta-front gullies, unlike strongly sinuous, leveed, deep-water, passive-margin channels (e.g. Mayall et al. 2006). This is sure to result in very different sand/gravel distribution, geometry and connectivity, both inside and outside the channels;

(4) much smaller width and depth of Pasos channels compared to typical passive-margin-slope channels (Macauley & Hubbard 2013 fig. 13); and

(5) shelf storm erosion, affecting Toro sand-body architecture (amalgamation, truncation).

On the other hand, Hubbard et al. (2005), De Ruig & Hubbard (2006) and Hubbard et al. (2009) justifiably proposed the TCS channels as an outcrop analog for foreland-basin sandstone-and-conglomerate gas reservoirs in Austria (Oligo-Miocene Puchkirchen and Hall Formations), interpreting these reservoirs as the deposits of a low-sinuosity, deep-marine channel. The first and third of these publications invoked levees in the Austrian example, while the second stated that none are evident on seismic profiles. The Austrian channel is interpreted here, like the TCS, as a submarine-canyon head indenting the otherwise shelfal Austrian *Molasse* Basin (emphasis added).

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