PS Stratigraphic Architecture of a Structurally Confined, Ponded Submarine Fan: An Outcrop Study of the Guaso I Turbidite System (Ainsa Basin, Southern Spanish Pyrenees)*

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Abstract

Ponded, structurally confined submarine fan systems are common features near earth's continental margins. These systems often form significant hydrocarbon reservoirs, and they can occur in a wide variety of tectonic settings, including salt-withdrawal mini-basins, extensional-contractional systems (e.g., Mississippi fan fold-belt, and offshore Nigeria), transtensional regions, foreland basins, and fore-arc basins. The Eocene Guaso turbidite system crops out in the Ainsa Basin, a piggyback basin within the South Pyrenean foreland basin system. Outcrops of the Guaso I (GI), a fourth-order cycle within the Guaso turbidite system, reveal a structurally confined, distributive submarine fan.

GI outcrops provide a rare opportunity to document stratigraphic architecture, as well as proximal-to-distal changes in gross thickness, net-sand thickness, lithofacies associations, and reservoir quality for a structurally confined submarine fan. The strata in the proximal slope depositional setting are dominated by mass-transport-deposits (MTDs), sandy debrites, mud-filled channels, and occasional pebble- or sandstone-filled channels. Net-sand values are relatively low (< 10 m) in this area, and gross thickness increases downslope. The medial slope setting contains bedded mudstones, as well as sandstone-filled channels and levees. Net-sand and gross thickness values are higher than in the proximal slope setting. Near the basin's depocenter, the GI is comprised of mudstone overlain by a thin MTD, which is in turn overlain by ~ 80 m of vertically connected sandstone (with some minor siltstones). The vertical succession of this dominantly sandstone package is: (1) basal lobes; (2) distributary channels and lobes; (3) interbedded very-fine-sandstones and siltstones. This region has the highest net-sand and gross thickness (~ 150 m) values of the entire system. Near the distal and lateral fan margins, there are minor sandstone-filled channels and thin, tabular sandstone beds intercalated with laminated mudstone. This depositional region has the lowest net-sand values (1-3 m) of the entire GI system.

Stratigraphic stacking patterns document that the GI fan increased in depositional area through time. As depositional area increased, successive lobes and channels increased in the degree of compensational stacking. Data collected in this study can be used to predict architectural and facies patterns in ponded strata of structurally confined turbidite systems in the subsurface.

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Stratigraphic Architecture of a Structurally Confined, Ponded Submarine Fan: An Outcrop Study of the Guaso I Turbidite System (Ainsa Basin, Southern Spanish Pyrenees)

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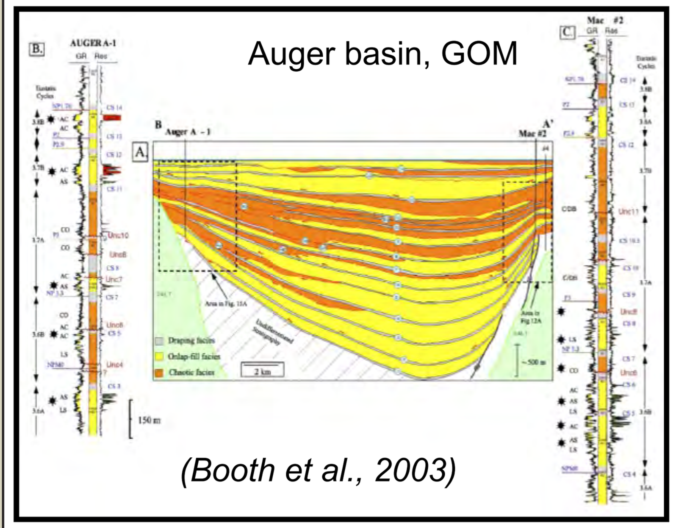
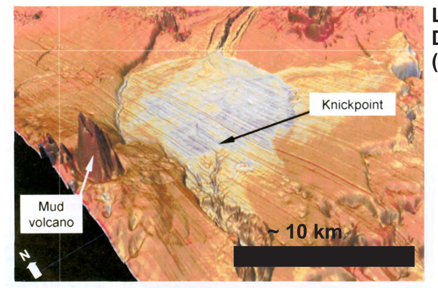
Introduction

- Structurally confined turbidite systems are prolific hydrocarbon reservoirs around the world, from the Gulf of Mexico to southern California to offshore West Africa.
- These reservoirs are most commonly characterized with seismic, well, and/or conventional core data. Each of these datasets, however, has limitations in either detail or spatial extent.
- Detailed stratigraphic field studies in analogous deepwater basins, such as the Ainsa basin, will yield critical quantitative data regarding styles of longitudinal, lateral, and temporal variations in reservoir architecture.

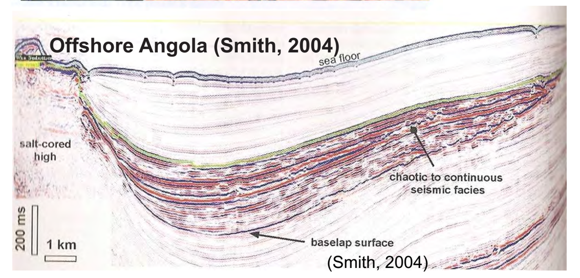
Examples of structurally confined deepwater basins:

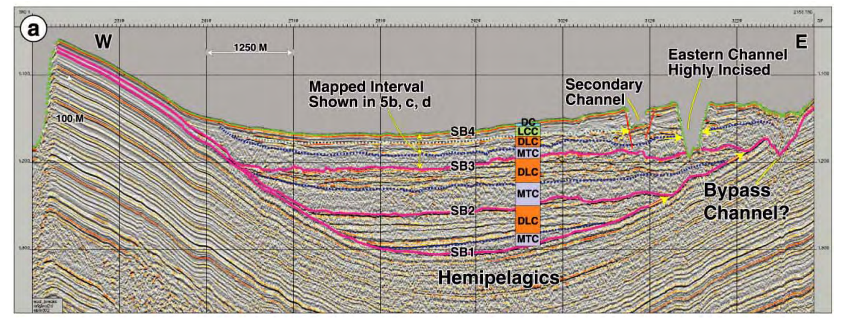


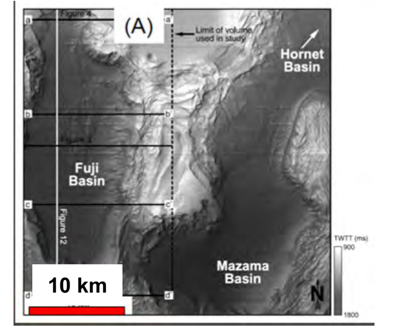
(Booth et al., 2003)



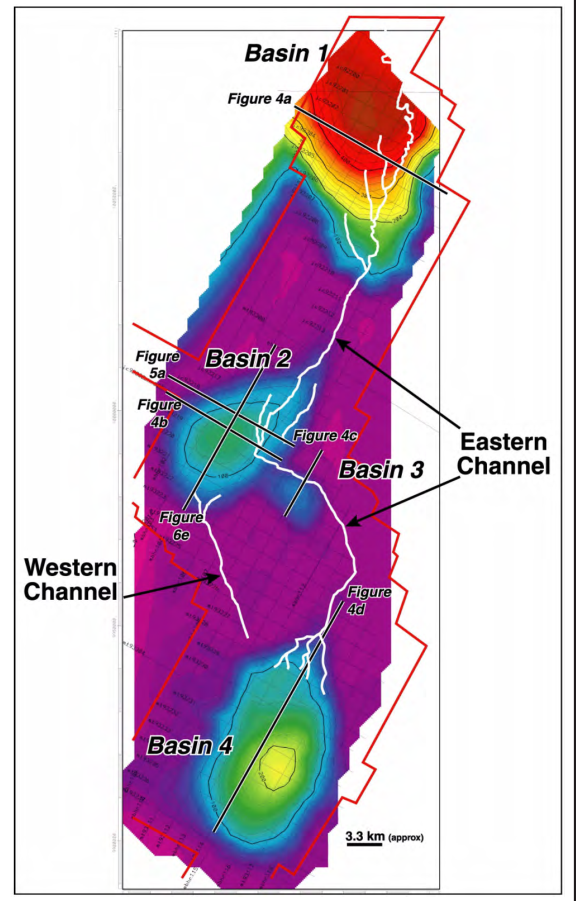
Left: Western Niger Delta slope (Smith, 2004)


Offshore Angola (Smith, 2004)


Basin II, East Breaks area, GOM (Beaubouef and Friedmann, 2000)



Fuji and Mazama basins (Madof et al., 2009)



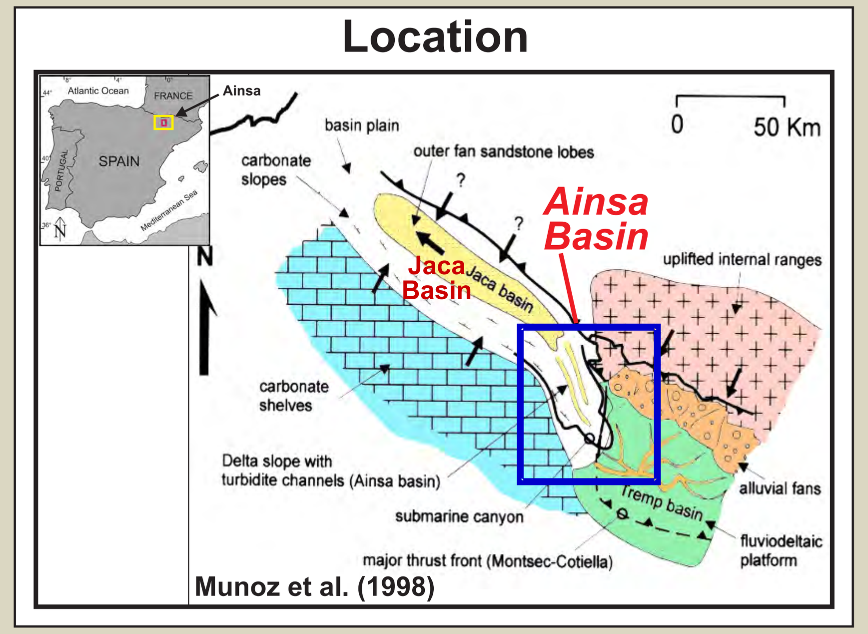
East Breaks area, GOM (Beaubouef and Friedmann, 2000)

Data/methods

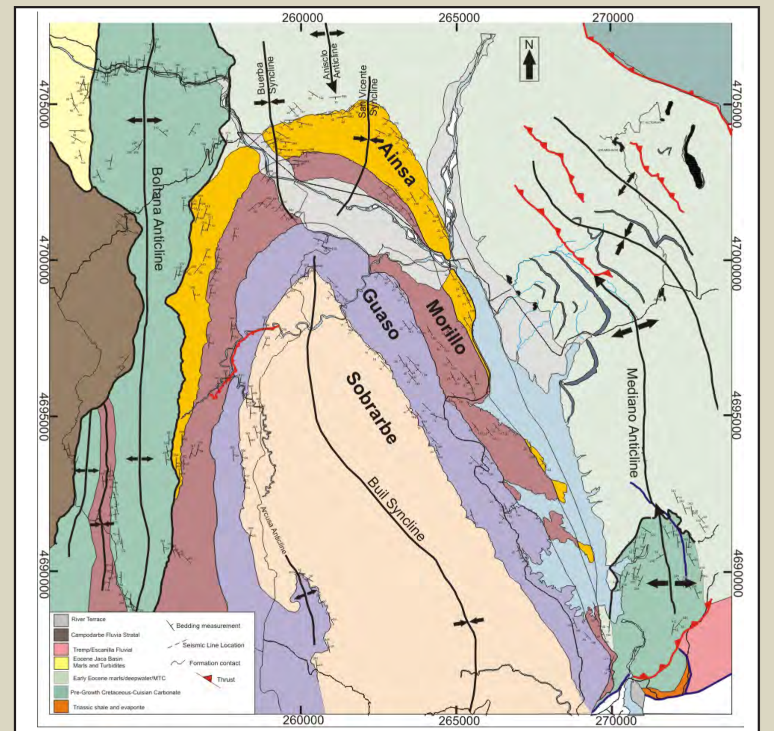
- Field mapping of cycle-bounding condensed sections, sandstone bodies, and mass-transport-deposits (*MTDs*, i.e. slumps, slides, debris-flow deposits) was conducted.
- We define *cycles* based on condensed sections, not speculative sequence boundaries.
- Measured 30 sections (1,980 m total); 429 paleocurrent measurements in the Guaso I.
- We observed four principal architectural elements and 14 facies types.
- We correlated measured sections, and interpreted time-significant surfaces within the Guaso I cycle. We used these correlations to construct stratigraphic cross-sections.
- We used the thickness and net-sandstone values to create isopach maps (gross-thickness and net-sandstone).
- Paleogeographic reconstruction using above correlations and paleocurrent data.

Geologic Setting

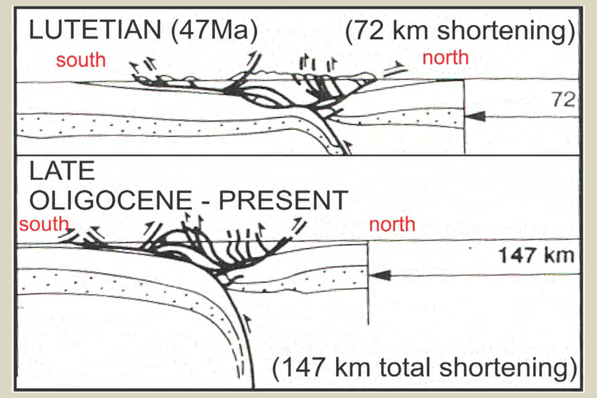
Ainsa basin, southern Spanish Pyrenees



Munoz et al. (1998)

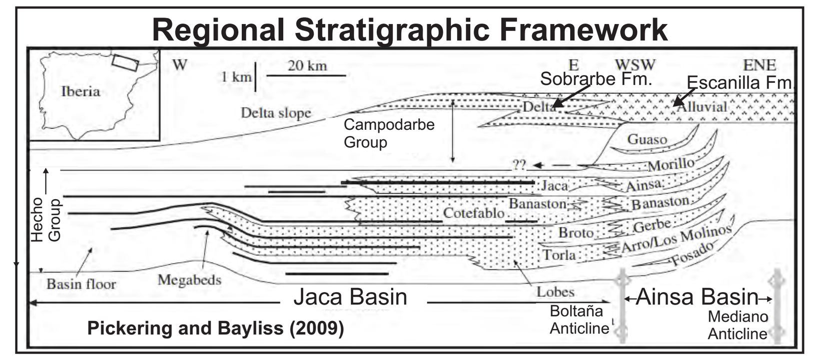

Above: Geologic map of Ainsa basin (Hoffman, 2009).

- In the early Eocene, the Ainsa basin developed as a foredeep south and west of the Montsec thrust sheet in the South Pyrenean foreland basin system (Fernandez et al., 2004).
- As thrusting propagated toward the foreland in the middle Eocene, the Ainsa basin evolved into a piggyback basin (Fernandez et al., 2004; Hoffman, 2009).
- The entire Guaso system was deposited in ~ 800 ka (Pickering and Bayliss, 2009).

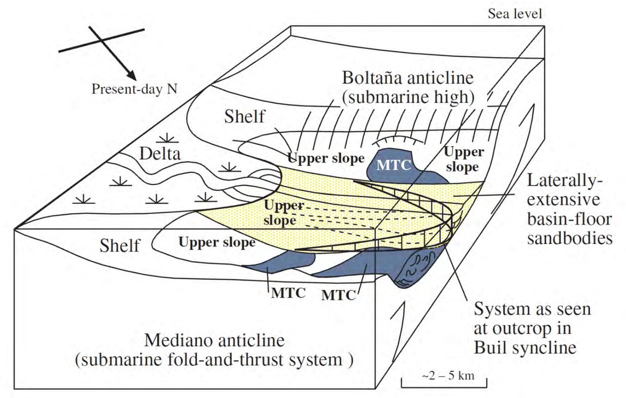


Above: Puigdefabregas et al. (2000)

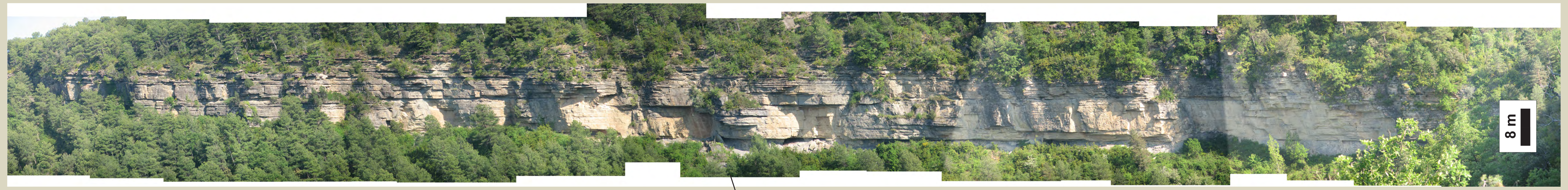
Previous Work



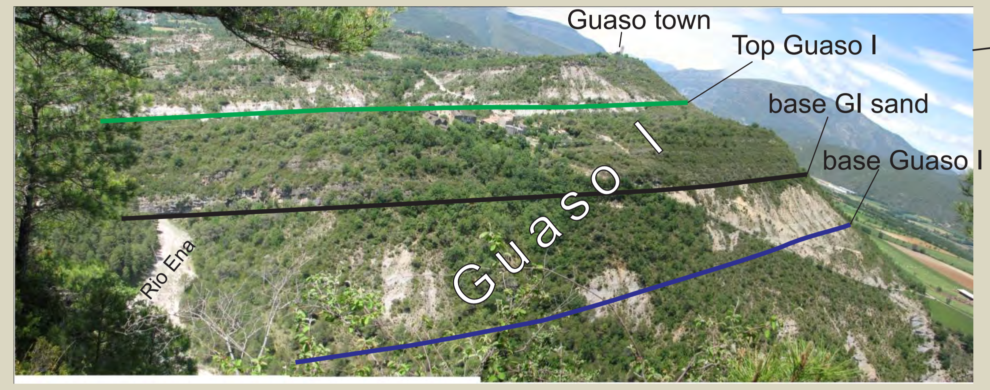
Pickering and Bayliss (2009)


Sutcliffe and Pickering (2009)

- Sutcliffe and Pickering (2009) interpreted the Guaso as a structurally confined, delta-fed, low-gradient deepwater clastic depositional system.
- Pickering and Bayliss (2009) interpreted that the Guaso system was sourced from the south, between the two growth anticlines.
- In our present study, we offer a different interpretation for the Guaso (specifically, Guaso I) turbidite system.

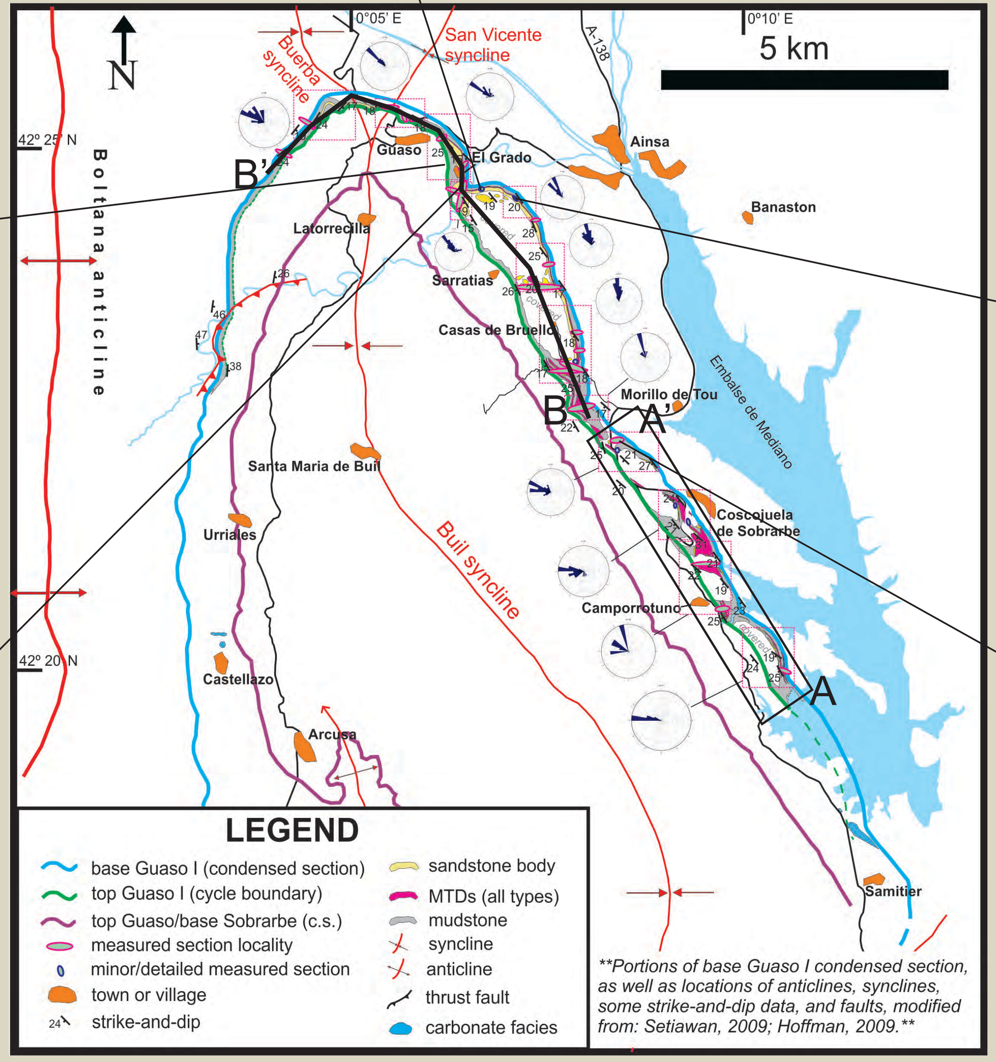


•Above: Proximal lobe elements near Rio Ena. There are tabular beds, as well as beds and bedsets that thicken, thin, and exhibit erosional relief. View is looking south.



•Above: View looking northwest toward El Grado village and Guaso town.


•Above: Lobe complex exposed at Rio Ena. View looking ~ west-northwest.

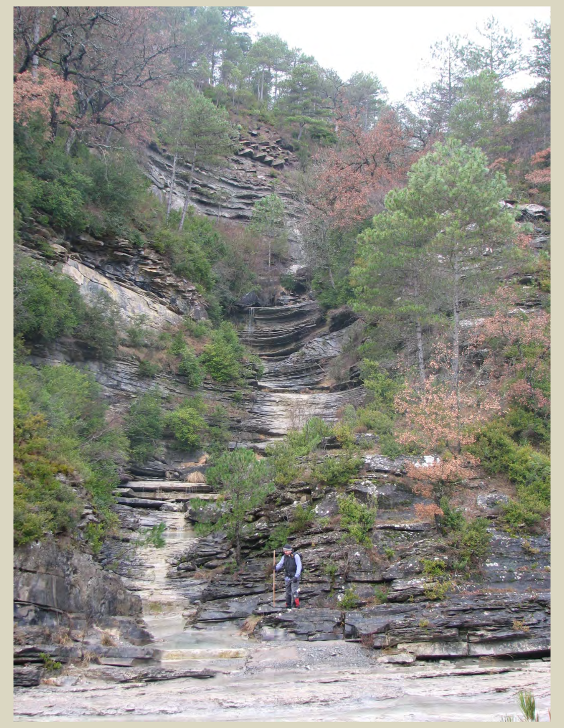


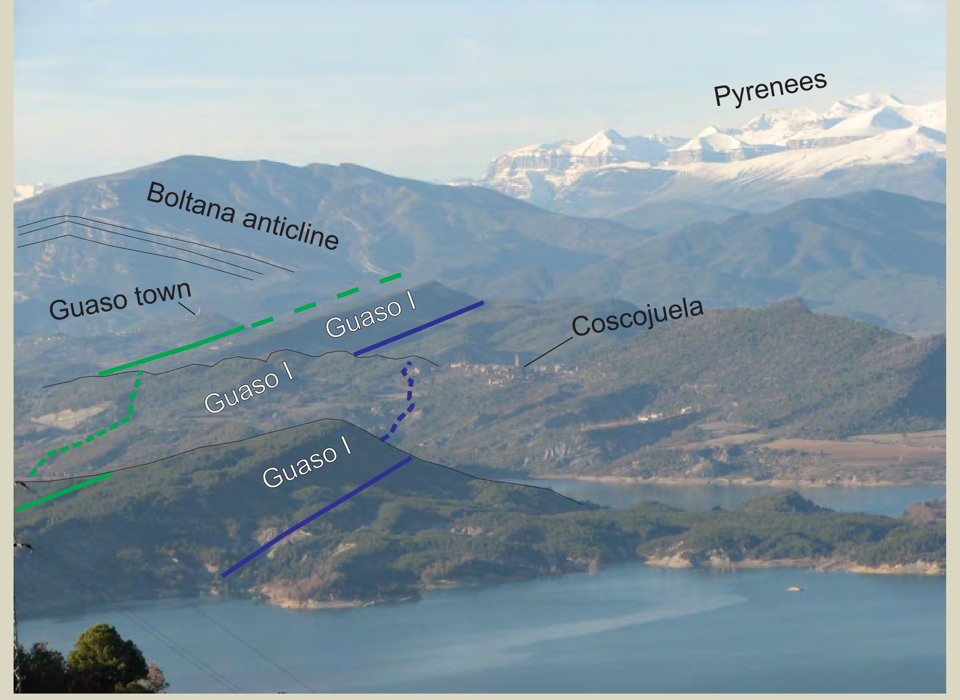
Geologic map of Guaso system


• Left: Tabular Guaso I beds at Osqueta da Calura trail marker, east of the Rio Ena outcrop. These beds are the most proximal lobe deposits. Note field geologist for scale.

• Below: Slope channel complex exposed immediately east of Highway A-138. See Page 2 for an annotated interpretation of this channel complex.

- The Ainsa basin is currently expressed as the Buil syncline.
- This basin is bounded by the Mediano and Boltana anticlines, to the east and west, respectively. These structures were active in the middle Eocene during the deposition of the basin's deepwater clastic systems.
- The Guaso I turbidite sandstone outcrops are mostly located along the basin's east flank.


• Left: Outcrop exposure at "Waterfall Canyon" along Rio Ena. See measured section in cross-section B-B'. (Note person for scale.)



• Right: View looking northwest, along strike of Guaso system.

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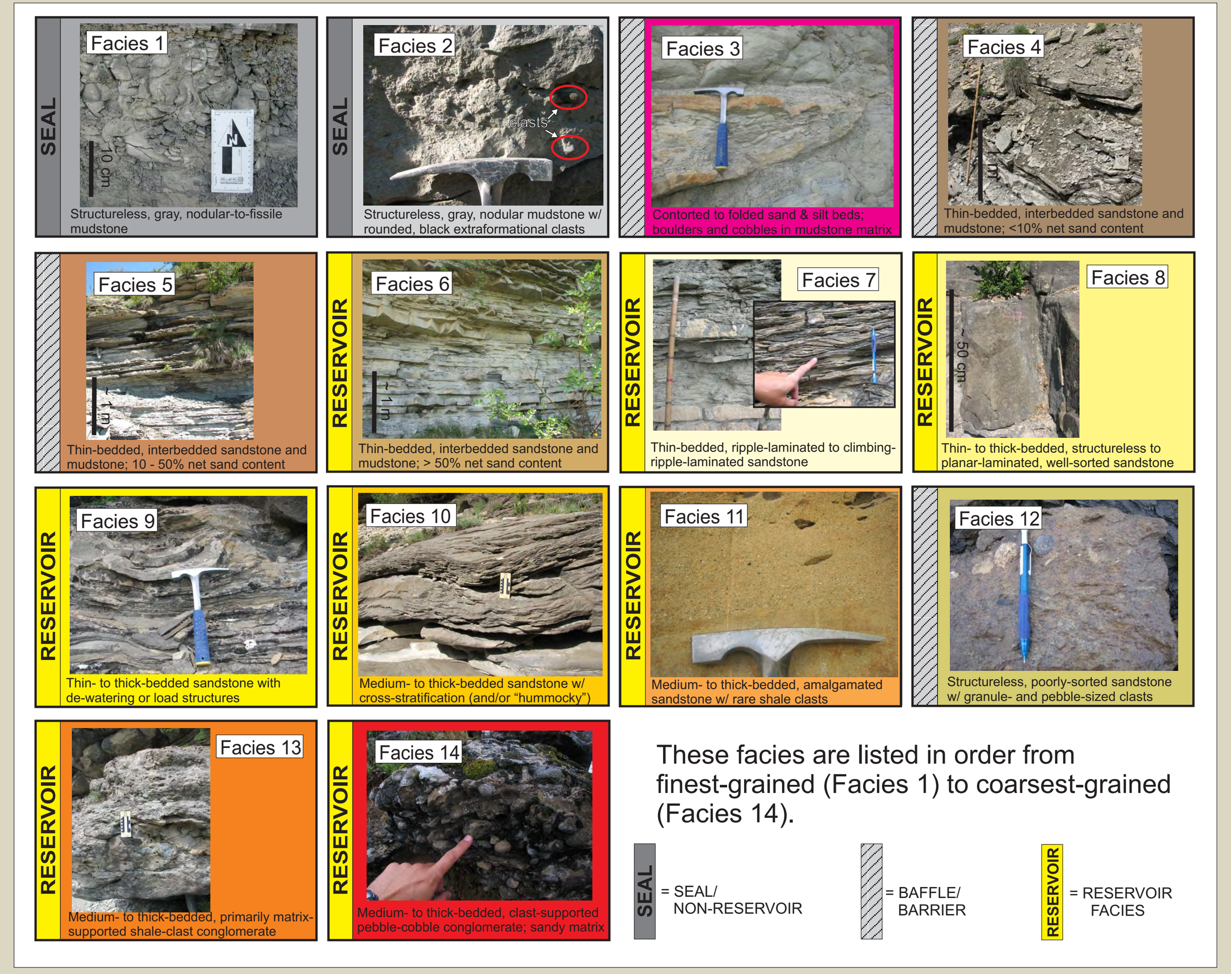
Facies

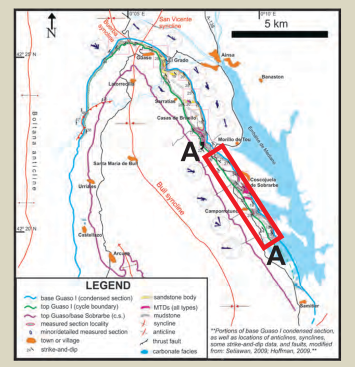


These facies are listed in order from finest-grained (Facies 1) to coarsest-grained (Facies 14).

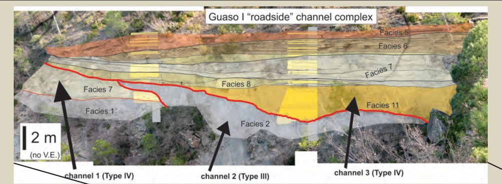
SEAL/ NON-RESERVOIR; BAFFLE/ BARRIER; RESERVOIR FACIES

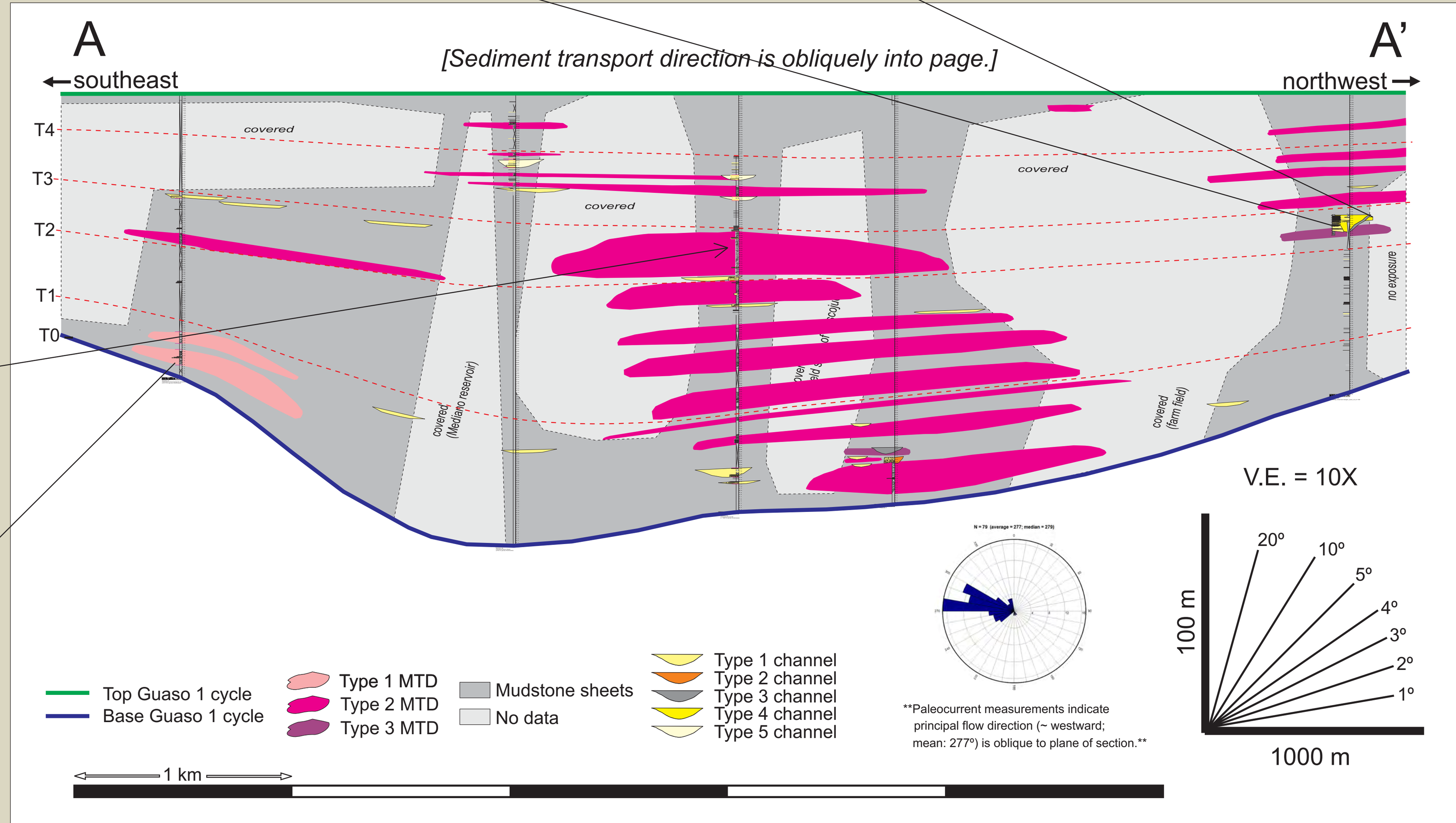
Facies	Reservoir facies?	Description	Modal grain size(s)	Net-sand content (%)	Interpreted sediment support mechanism	Interpreted depositional process	Interpreted flow type	Relative sediment concentration during transport
1		Structureless, gray, nodular-to-fissile mudstone	clay	0	hindered settling; possibly fluid turbulence	suspension	hypo-pycnal plume; fine-grained turbidity current	low
2		Structureless, gray, nodular mudstone w/ black and dark gray clasts (granule- or pebble-sized) of chert, mudstone, and carbonate; mudstone matrix comprises > 95% of this facies	clay [clasts: granules-pebbles]	0	matrix strength	frictional freezing, cohesive freezing	debris-flow	high
3		Contorted to folded sandstone, siltstone, and claystone beds; turbidite sandstone and siltstone cobbles and boulders randomly distributed in the mudstone matrix	BI-MODAL: clay; fine-sand	0*	matrix strength	frictional freezing, cohesive freezing	*slumps*, *slides* (sensu Martinsen and Bakken, 1990)	high
4		Thin-bedded, interbedded sandstone and mudstone; < 10% net-sand content	fine silt [sand fraction: very fine sand]	< 10	fluid turbulence	suspension and tractive sedimentation	turbidity current	low
5		Thin-bedded, interbedded sandstone and mudstone; 10 - 50% net-sand content	fine silt [sand fraction: very fine sand]	10 - 50	fluid turbulence	suspension and tractive sedimentation	turbidity current	low
6	R	Thin-bedded, interbedded sandstone and mudstone; > 50% net-sand content	fine sand [mudstone fraction: fine silt]	> 50	fluid turbulence	suspension and tractive sedimentation	turbidity current	low
7	R	Thin-bedded, ripple-laminated to climbing-ripple-laminated sandstone	very fine sand	~ 90	fluid turbulence	tractive sedimentation (lower-flow-regime)	turbidity current	low
8	R	Thin- to thick-bedded, structureless to planar-laminated, well-sorted sandstone; amalgamation surfaces can be present	fine sand	100	fluid turbulence	suspension [structureless]; tractive [planar-laminated]	turbidity current	low
9	R	Thin- to thick-bedded sandstone with dewatering or load structures (flame structures, contorted bedding, etc.)	fine sand	> 90	fluid turbulence	initial suspension or tractive sedimentation, followed by de-watering, or loading from above	turbidity current	low
10	R	Medium- to thick-bedded sandstone with large-scale cross-stratification (hummocky bedforms common)	fine sand	> 95	fluid turbulence	tractive sedimentation, w/ some deposition due to suspension fallout	turbidity current	low
11	R	Medium- to thick-bedded, amalgamated structureless sandstone w/ rare horizontally-aligned shale clasts (elongate pebbles); normal grading common, as well as common fluted bases of beds	medium sand	95	fluid turbulence	suspension	turbidity current	low-medium
12		Structureless, poorly-sorted sandstone w/ rare granule- and pebble-sized clasts (~ 5%); clasts are rounded carbonates and sub-angular sandstone	medium sand [clasts: pebbles]	0%	matrix strength	frictional freezing, cohesive freezing	debris-flow, or possibly a "hybrid flow"	high
13	R	Medium- to thick-bedded, primarily matrix-supported shale clast conglomerate (shale clasts are elongate pebbles and compose < 40%); matrix is medium sand	medium sand [clasts: pebbles]	~ 70	fluid turbulence	suspension	turbidity current	medium
14	R	Medium- to thick-bedded, pebble-cobble conglomerate in sandy matrix (~ 60%); clasts are rounded carbonate and sandstone; this facies scours into underlying contorted mudstone facies	fine-upper sand [clasts: pebbles]	60	dispersive pressure and fluid turbulence	tractive/bedload	turbidity current ("high-concentration")	high

Cross-section A-A'

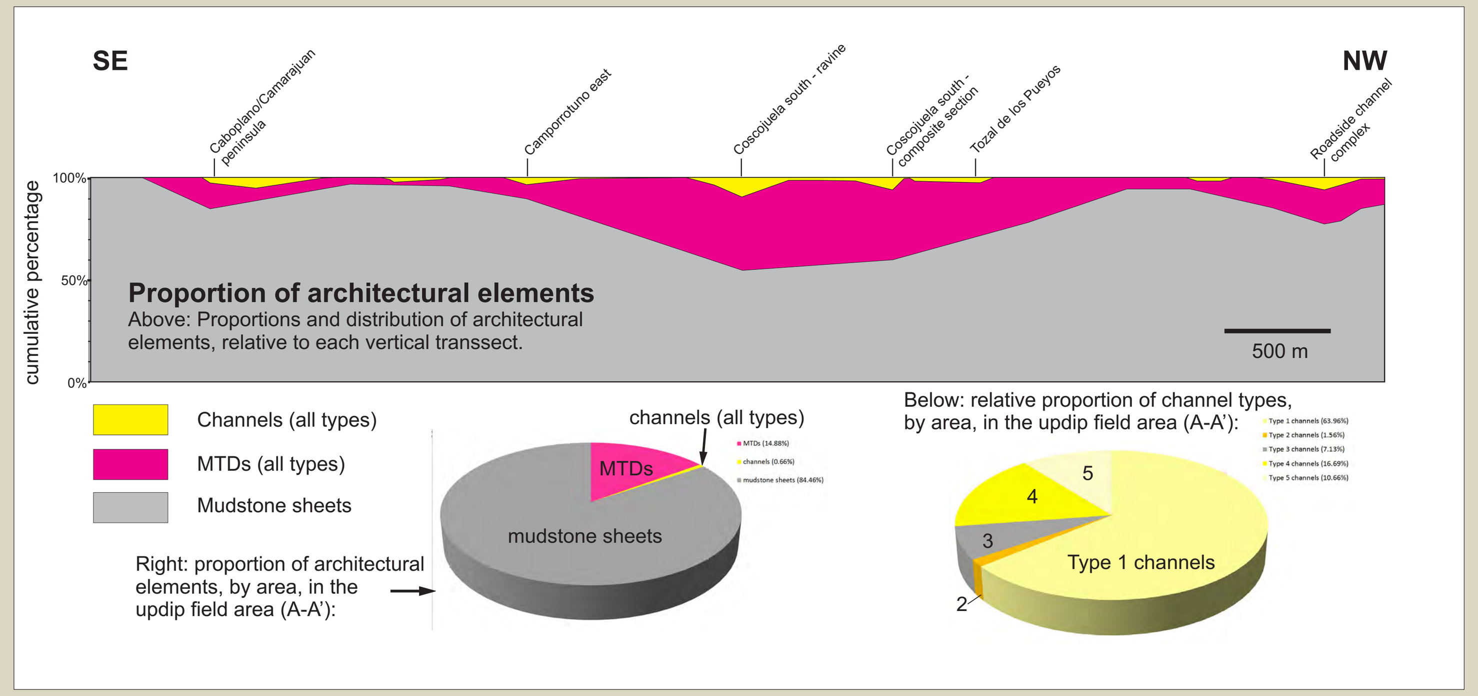


Left: location of cross-section A-A'





- Cross-section A-A' and accompanying paleocurrent data indicate that this area was the entry point for Guaso I sediments, which were transported from east to west.
- These sediments were then deposited on the basin floor to the northwest.
- This area contains abundant MTDs and Type 1 channel elements.
- MTDs are thickest in the axis of this feeder system.



Architectural elements

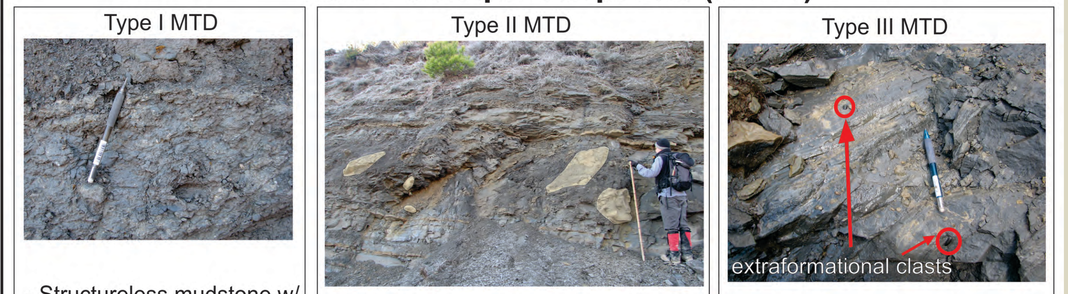
MUDSTONE SHEETS

- Common facies: Facies 1, 4
- Laterally extensive
- Interpretation: turbidite mudstones, distal hypopycnal plume deposits

LOBES

- Common facies: Facies 8, 9, 5, 6; 10 (transitional facies)
- Laterally extensive
- Interpretation: loss of confinement and deposition downdip of channel mouth

Mass-transport deposits (MTDs)



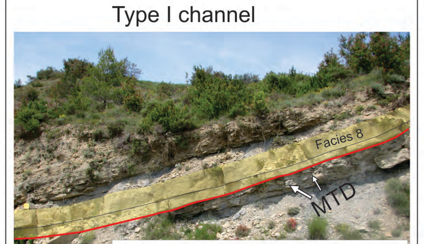
Type I MTD
- Structureless mudstone w/ angular carbonate clasts and granules
- Common facies: 2, 3, 12
- Interpretation: debris-flow deposit

Type II MTD
- Structureless mudstone w/ contorted or folded sandstone and siltstone beds; "floating" sand rafts and boulders
- Common facies: 3, 12
- Interpretation: slump or slide

Type III MTD
- Structureless mudstone w/ well-rounded extraformational clasts
- Common facies: 2
- Interpretation: muddy debris-flow deposit

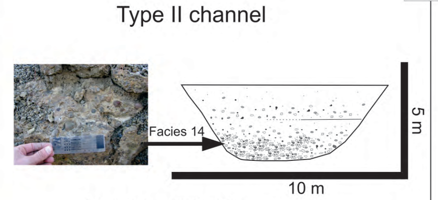
CHANNELS

Type I channel



- High aspect ratio (> 100:1)
- Comprised of one, maybe two stories
- Minor erosion at base
- Tend to overlie MTDs or mudstones

Type II channel

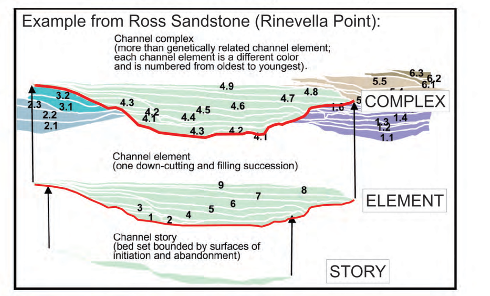


- Very low aspect ratio
- Location: proximal slope
- Thick-bedded channel infill: pebble-cobble conglomerate (Facies 14), medium-grained sand
- Erosional base of channel

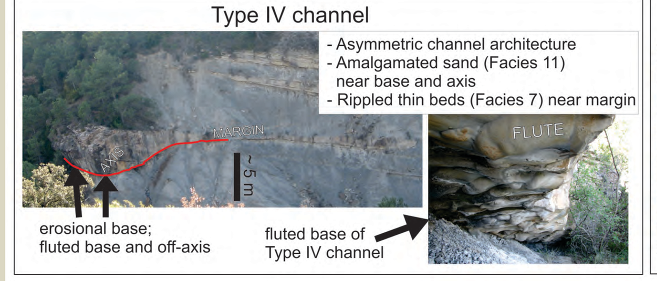
Type III channel

- Low aspect ratio (< 30:1)
- Location: proximal (to medial?) slope
- Channel infill: mostly Facies 2, capped by Facies 11, 12, and/or 14
- This channel type transitions to Type IV downslope

Channel hierarchy
(modified from Ross, 2007)

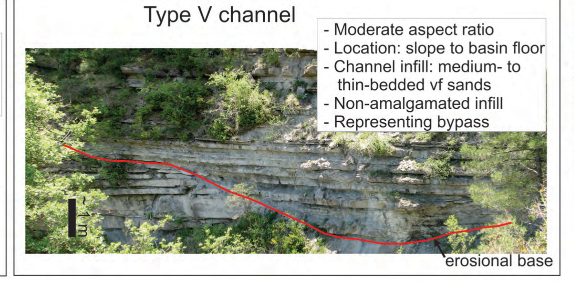


Type IV channel



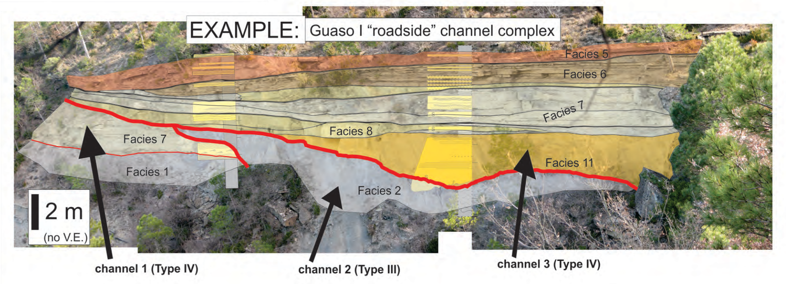
- Asymmetric channel architecture
- Amalgamated sand (Facies 11) near base and axis
- Rippled thin beds (Facies 7) near margin

Type V channel

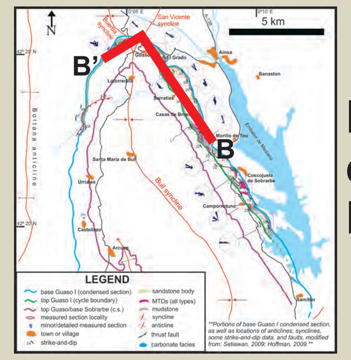


- Moderate aspect ratio
- Location: slope to basin floor
- Channel infill: medium- to thin-bedded w/ sands
- Non-amalgamated infill
- Representing bypass

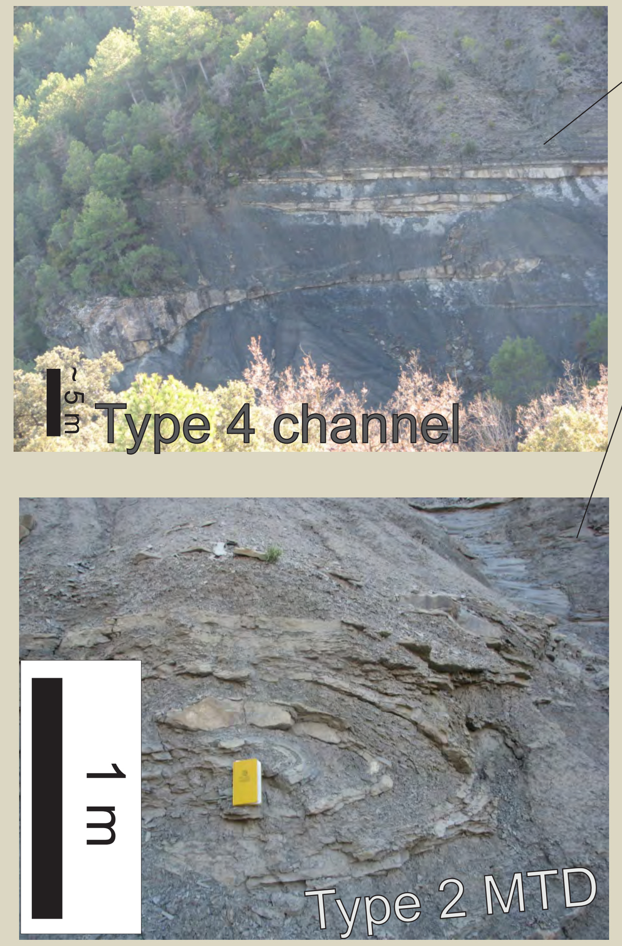
EXAMPLE: Guaso I "roadside" channel complex

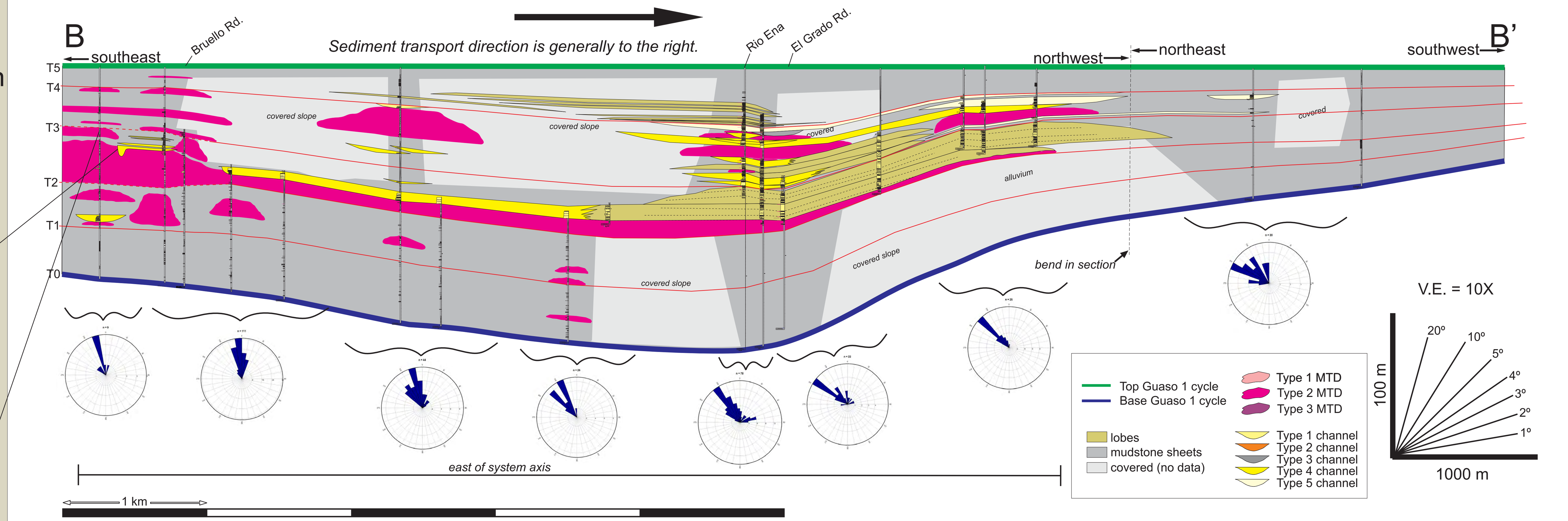


Cross-section B-B'

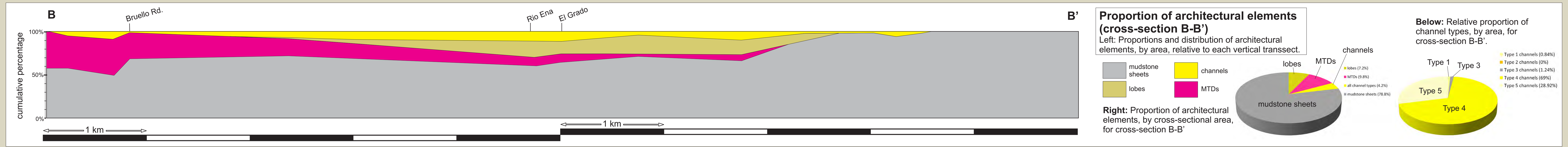


Left: location of cross-section B-B'

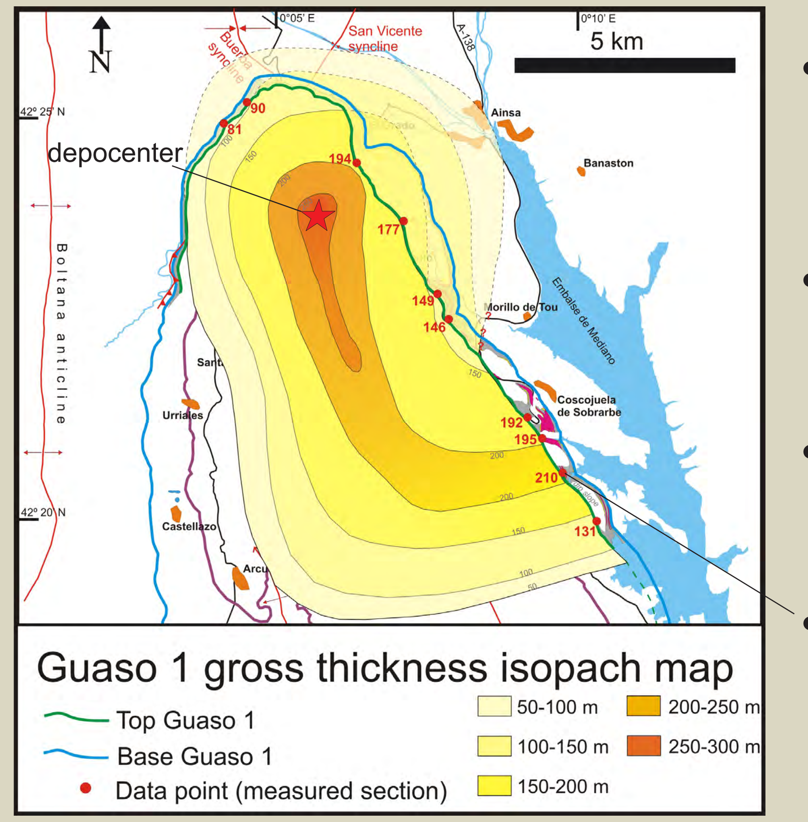




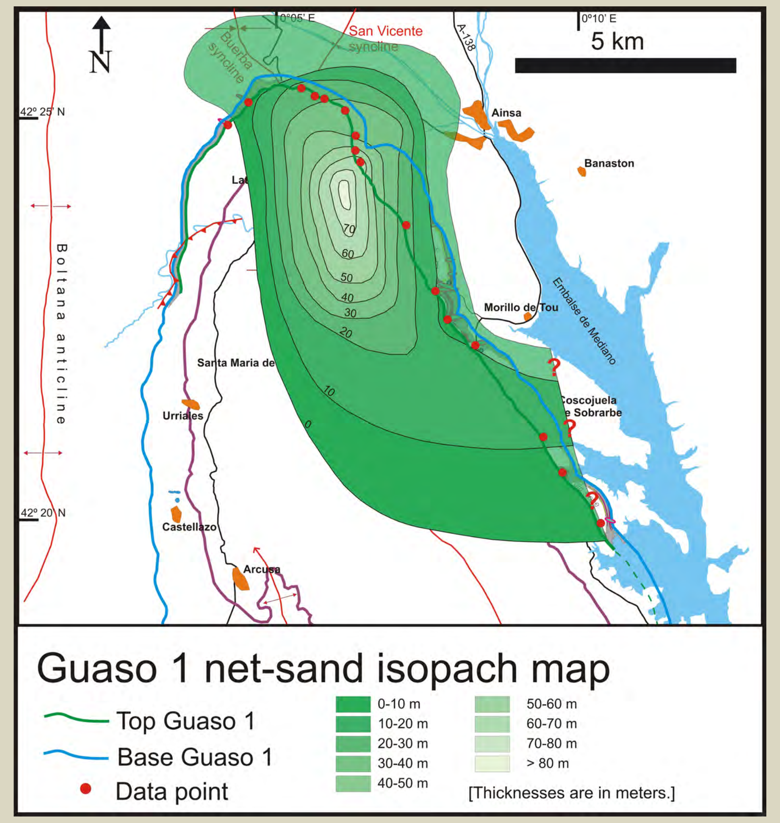
- MTDs are abundant in the southeast part of cross-section B-B'; they decrease in abundance to the northwest (downslope).
- Lobes generally increase in abundance to the northwest; they are most abundant near the depocenter. Beyond the depocenter, the abundance of lobes decreases.
- The Type 4 channel overlying the MTD immediately above surface T2 is present in continuous outcrop for ~ 3 km. (Paleocurrents are generally parallel to strike.) This channel feeds the basal lobes at Rio Ena.
- This cross-section seems to suggest that there are no Guaso I sand bodies near the depocenter below surface T2. However, paleocurrent data and stratigraphic relationships illustrated in cross-section A-A' suggest that B-B' is an off-axis cross-sectional slice; it is inferred here that there are sandy Guaso I lobes in a more axial position (to the southwest).
- 37.6% of the area of cross-section B-B' is covered or removed by erosion.



Isopach Maps

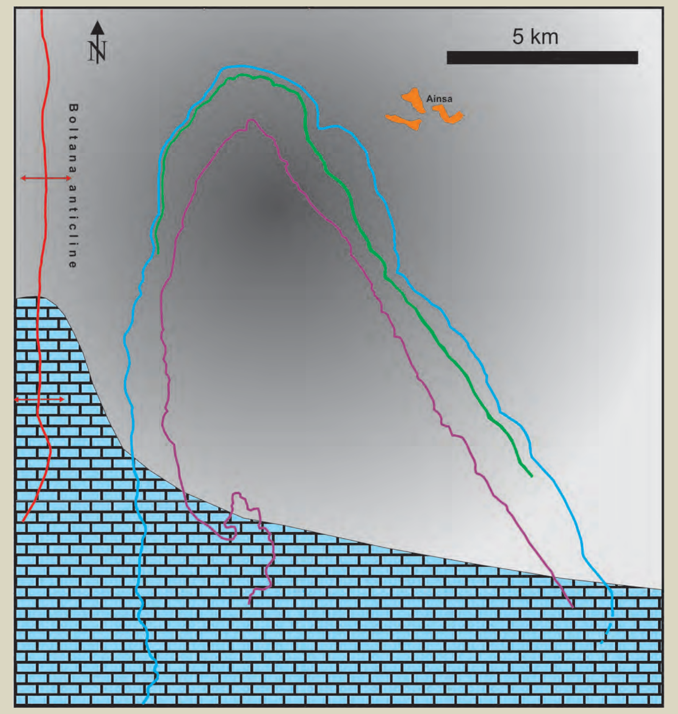


- Measured sections and correlation panels yielded stratigraphic values which were used to create gross-thickness and net-sandstone isopach maps.
- We offer a complete subsurface interpretation of the Guaso I system, constrained by outcrop data.
- The Guaso I system is thickest in the subsurface, ~ 2 km southwest of the Rio Ena locality. This is defined as the depocenter.
- The Guaso I is also very thick on the slope (at outcrops immediately east of Camporrotuno) – in the updip "feeder area" of the system.

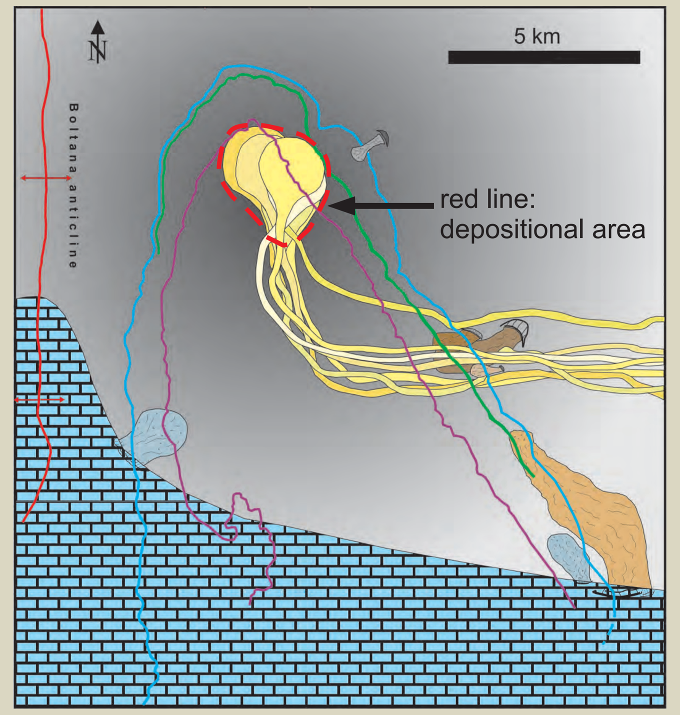


- The Guaso I system has the highest net-sandstone values near the depocenter (located southwest of the Rio Ena locality).
- This trend is indicative of out-of-grade systems (*sensu* Pyles et al., 2010), e.g. Ross sandstone and Annot sandstone.
- High net-sandstone content is present in areas dominated by deposition of lobes and distributary channels.
- Paleocurrent data, measured sections, and field mapping indicate that the Guaso I channels' entry point from the east is entirely exposed in outcrop. This is illustrated by the net-sandstone "zero lines."

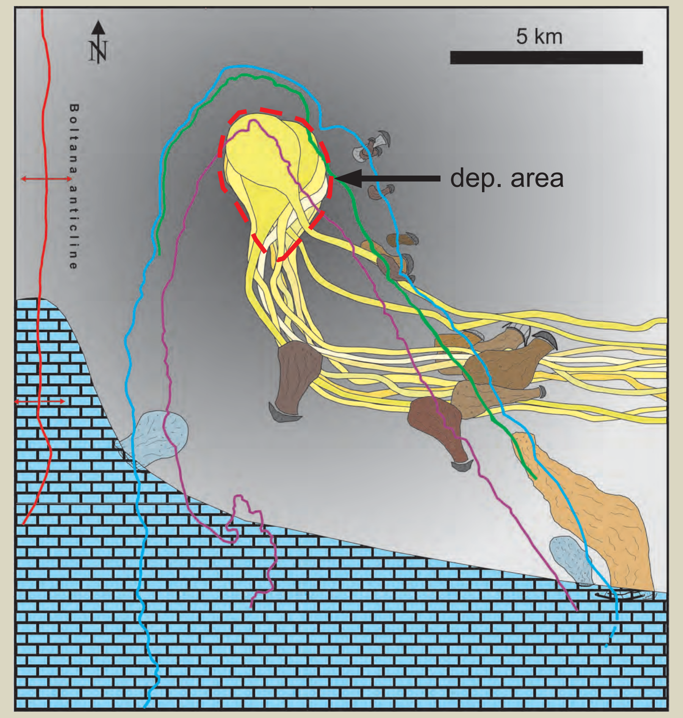
Stratigraphic Evolution and Paleogeography



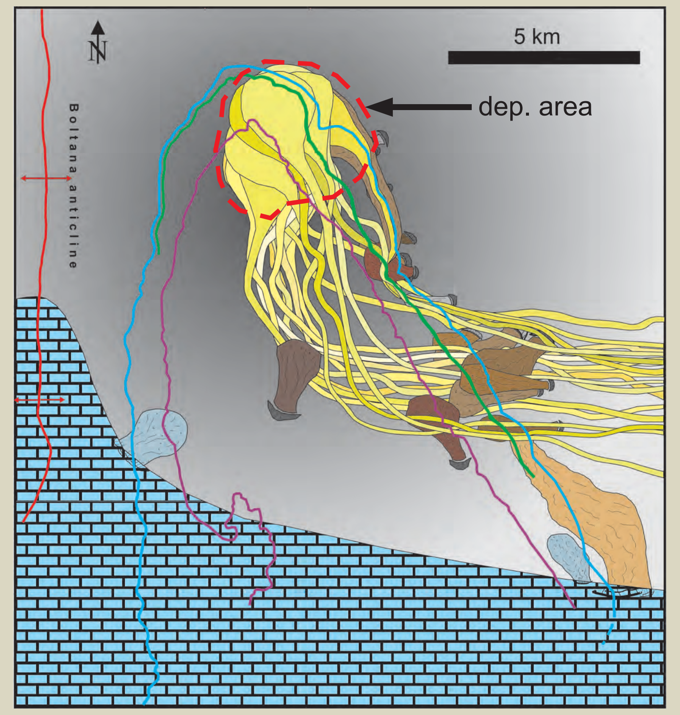
- Guaso I system at ***T0***: At this time, deposition in the basin is primarily hemi-pelagic. This basal Guaso condensed section is the boundary between the Guaso and Morillo systems. (The darker the shading is on the map, the greater the paleo-depth. The blue line represents the base of Guaso I, a condensed section. The green line represents the top of the Guaso I.)



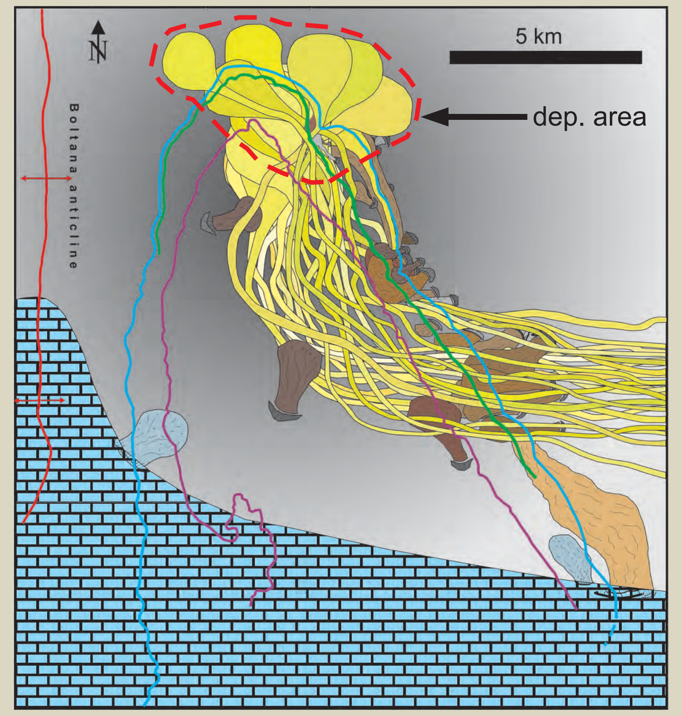
- Guaso I system, ***T0-T1***: Initiation of submarine fan, with basal lobe complexes deposited in a confined area on the basin floor. Minor slumping and debris-flows from updip and carbonate shelf-edge. [Note red dashed line outlining the depositional area, for each stage.]



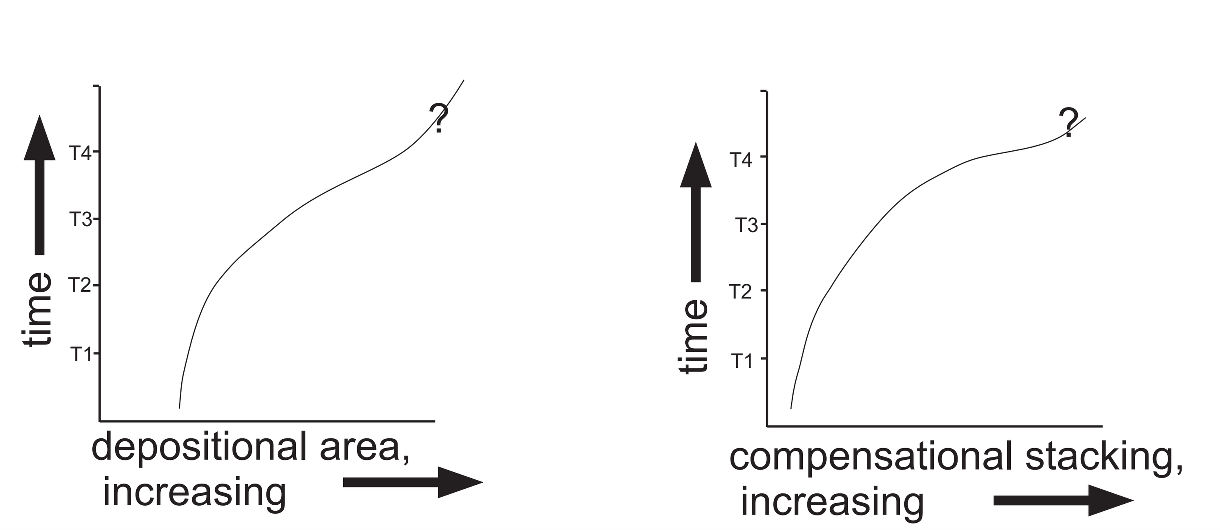
- Guaso I system, ***T1-T2***: Slope channels continue to feed basin floor lobe complexes. Deposition from one lobe complex to the next is primarily aggradational. Basin floor is still relatively confined. *Note*: basin floor lobes have not yet intersected the position of the future outcrop belt (at Rio Ena); pervasive MTDs create a "thick" in the updip "feeder" area.



- Guaso I system, ***T2-T3***: System begins to fill the confined basin floor; lobe complexes (e.g., base of Rio Ena section) during this time are deposited farther north relative to previous lobe complexes. A:S ratio decreases (due to decrease in effective subsidence?). Note slope channel (*exposed continuously in outcrop along Guaso ridge*) feeding lobes at base of Rio Ena outcrop.



- Guaso I system, ***T3-T4***: A:S ratio continues to decrease. Depositional area increases markedly. Compensational stacking (and *rate of compensational stacking*) of lobes increases. The sand-rich turbidite system has "advanced" beyond the original depocenter of ***T0-T2***.

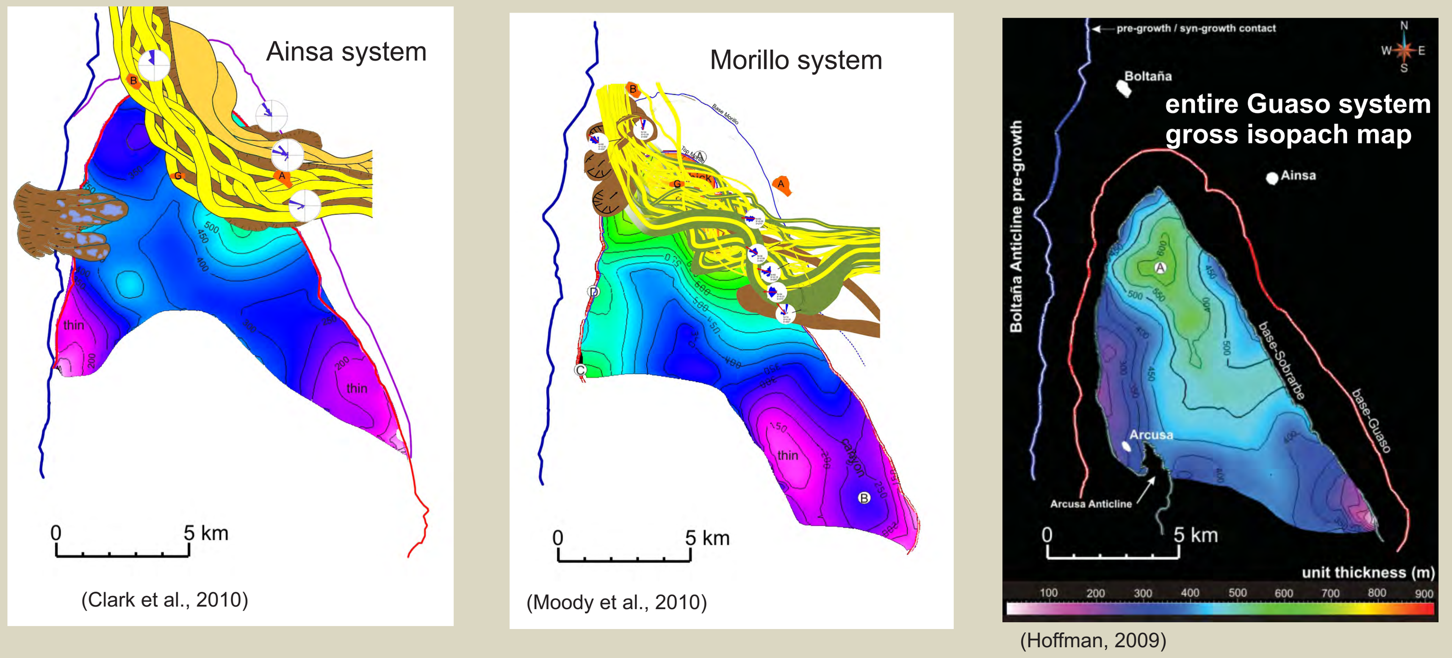


- Left: These concept diagrams illustrate that the *rate of increase* of both depositional area and compensational stacking increases through time, at least until T4 in the Guaso I system.
- For future work: How large must depositional area (effectively, the size of the basin at that point in time) become before the rate of increase in compensational stacking goes to zero and then becomes negative? This value of depositional area is a critical factor governing stratigraphic/reservoir architecture in confined and semi-confined basins.

- There are pervasive, thick MTDs and numerous erosional channels on the slope (in the updip "feeder area" illustrated on cross-section A-A').
- The basin floor is first dominated by lobes, and later, channels and lobes (similar to the "distributary channel-lobe complexes" of Beaubouef and Friedmann, 2000).
- MTD abundance decreases toward the depocenter; MTDs are completely absent in distal locations closer to the Boltana anticline. This calls in to question tectonic movement on the Boltana as the cause of MTDs in this system.
- [Note: Please see corresponding time surfaces (T0-T4) as illustrated in cross-sections A-A' and B-B'.]

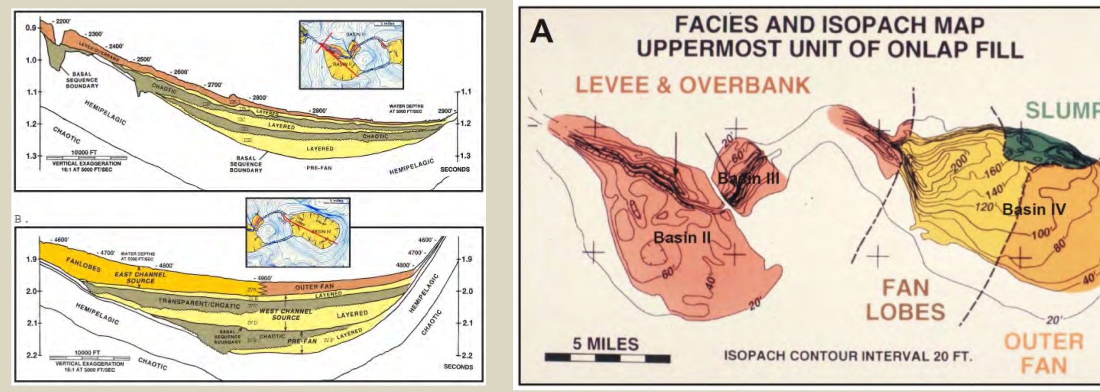
Applications

Isopach maps



- If a depositional system (reservoir) can be identified as out-of-grade, it is very likely that any gross isopach "thicks" will also be the location of highest sandstone content.
- The Ainsa system and Morillo system (above) are both dominated by channels in the Ainsa basin, feeding lobes distally (in the Jaca basin to the northwest). Even in these non-ponded out-of-grade systems, the gross isopach "thick" represents the highest sandstone content in the basin.

Reservoir studies of confined turbidite systems



Winker and Booth, 2000

- This study yields insight into turbidite sandstone reservoir and MTD distribution, as well as stacking patterns *within* a fourth-order cycle.
- The results of this study are much more detailed than the resolution of 3-D seismic data and seismic facies analysis.
- This study also documents an erosive "basal" sandstone contact which might be considered a sequence boundary in the absence of other data. Caution should always be applied to sequence boundary interpretations in the subsurface or in the field, especially when there are only 2-dimensional data available.

Conclusions

- The Guaso I turbidite system is a structurally confined 4th-order submarine fan.
- The Guaso I system offers near-continuous exposures from the slope down to near the depocenter and beyond.
- The Guaso I is an out-of-grade system. There are erosional channels and pervasive mass-transport-deposits on the slope, and the depocenter (location of highest gross-thickness value) is on the basin floor. Maximum sandstone content is near the depocenter.
- Maximum sandstone content *exposed at outcrops of the Guaso I* is located at the Rio Ena locality. However, maximum sandstone content for the system is located in the subsurface 2 km southwest of Rio Ena.
- Effective subsidence was highest in the early stages (***T0-T2***) of Guaso I deposition. Later stages exhibit decreased accommodation relative to sediment supply.
- Depositional area and degree of compensational stacking increased through time. The system evolved from primarily aggradational stacking (element- and complex-scale) near the depocenter to a more distributive depositional pattern (at ***T4***) as the area increased.
- This study demonstrates that in out-of-grade, confined deepwater systems, isopach thicks on the slope are largely due to thick complexes of MTDs ("MTCs") and channels, while isopach thicks on the basin floor are attributed to distributary channels and lobes (*not* MTDs).

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