Fieldtrip Guidebook

Deep-Water Deposits of the Cretaceous Cerro Toro and Tres Pasos Formations, Magallanes Basin, Chilean Patagonia

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INTRODUCTION

The 2006 SPODDS Patagonia field trip is designed to accomplish two primary objectives: (1) to highlight the key facies and stratigraphic architectures that represent our current state of knowledge of Magallanes basin turbidite systems, and (2) to update participants of our current and future research activities in southern Chile. We will spend the first three days investigating outcrops of the Cerro Toro Formation, famous for its immense conglomeratic channel-fill deposits, and the final two days looking at the slope deposits of the overlying Tres Pasos Formation. The locations will be visited from north to south (relative proximal to distal) for each formation, which will allow us to discuss the relationships we observe within a regional stratigraphic and paleogeographic context.

With respect to the variety of deep-water features in the region, these outcrops are second-to-none. We will examine coarse-grained channel-fill and channel-margin relationships, seismic-scale conglomerate-filled injections, sand-rich accumulations filling complex slump-scar accommodation space, and a growth-faulted intraslope mini-basin fill. The SPODDS approach emphasizes investigation at multiple scales and, as such, we will discuss sedimentation mechanics of individual sediment gravity flow deposits, distribution and architecture of facies and sedimentary bodies at the sub-seismic scale, regional stratigraphic relationships, and basin-scale evolution.

GEOLOGIC CONTEXT

Tectonic History and Paleogeographic Setting

The Magallanes foreland basin is an elongate, north-south oriented trough located adjacent to the Patagonian Andes. The basin has a retro-arc heritage, as an oceanic back-arc basin (Rocas Verde basin) was first initiated in the region during the latest Jurassic to Early Cretaceous by rifting associated with the break-up of Gondwana (Dalziel, 1981; Wilson, 1991). Strata of the Jurassic Tobífera Formation, characterized by volcaniclastic strata and rhyolitic volcanic rocks, as well as thin-bedded shallow marine sandstone and mudstone of the Zapata Formation, record deposition in the back-arc setting (Wilson, 1991; Fildani and Hessler, 2005); oceanic crust, formed in association with the development of this basin, is preserved in the Rocas Verde ophiolite complex, present in the proximal portion of the adjacent fold-thrust belt (Dalziel, 1974, 1981). Initiation of the Andean Orogeny and associated fold-thrust belt development spawned the transition from an extensional back-arc to a compressional foreland basin setting (Wilson, 1991). The onset of turbiditic deposition, represented by the Punta Barrosa Formation, records this transition (Wilson, 1991; Fildani and Hessler, 2005). Deep-water conditions persisted in the Ultima Esperanza District region of the Magallanes foreland basin for a period of approximately 15 Ma, through deposition of the Cerro Toro and Tres Pasos formations (Fig. 1; Natland et al., 1974; Wilson, 1991; Fildani et al., 2003). Upward shallowing in the basin is recorded by deposits of the Dorotea Formation during the Late Cretaceous and Tertiary (Katz, 1963).
These foreland basin strata have since been incorporated into the fold-thrust belt and are now exposed in the foothills of the Andes. Structural complications associated with the fold-thrust belt decrease in intensity eastward. Cerro Toro Formation exposures are broadly folded and contain minor reverse faults in some locations. The Tres Pasos Formation is exposed in homoclinally-dipping cuestas or hogbacks that contain little to no post-depositional faulting/folding. Miocene igneous intrusions, associated with magmatic events that created the Paine massif, locally disrupt the Upper Cretaceous strata in areas close to the laccolith. Pleistocene and early Holocene glaciation that sculpted the outcrops and scenery we see today represents the most recent geologic episode to affect this region.

**Cerro Toro Formation**

Conglomerate and sandstone of the Cerro Toro Formation crops out in a north-south belt for > 100 km, extending from the Chile-Argentina border in the north, to at least as far south as Cerro Rotonda, south of Puerto Natales (Fig. 2). Sediment of the Cerro Toro Formation accumulated in a narrow foredeep constrained by the Andean thrust-front to the west, and the South American craton to the east (Wilson, 1991). Upper Cretaceous shallow- and non-marine strata equivalent to the Cerro Toro and Tres Pasos formations have been identified 60-90 km north of the study area in Argentina; a southward prograding delta has been interpreted in the area, which supplied sediment into the axial trough of the deep-marine basin (Macellari et al., 1989). To the south, the basin extends for at least hundreds of kilometers, as evidenced by conglomerate beds roughly equivalent to those of the Cerro Toro Formation on Tierra del Fuego (Dott et al., 1982). Coarse-grained sediments were focused within an immense channel belt that was present along the axis of the Magallanes Basin foredeep. Gravel and sand originated from the actively uplifting Andean fold-thrust belt to the west (Cecioni, 1957), likely transported to the basin via a series of conduits that cut across the western basin slope (cf. Crane and Lowe, 2001).

The Cerro Toro Formation has been most extensively studied at the Silla Syncline (Fig. 2), where tectonic folding has resulted in the three-dimensional exposure of channel strata (e.g. Scott, 1966; Winn and Dott, 1979; De Vries and Lindholm, 1994; Coleman, 2000; Beaubouef, 2004; Crane, 2004). Results and conclusions based on research recently completed by SPODDS student, Will Crane (2004), serve as our guide to these exposures on **DAY 1** of the field trip. Of particular interest to turbidite researchers is the relationship of the coarse-grained channel-fill to the finer-grained and thin-bedded out-of-channel deposits. Some interpret the Silla Syncline as a channel-levee complex (e.g. Beaubouef, 2004) whereas others do not (e.g. Crane, 2004). We will investigate and discuss key channel-margin relationships that address this interpretation.

With the focus in the Silla Syncline area, many of the channelized strata exposed at other locations have been neglected. Scott (1966) undertook the most extensive study of the formation to date, analyzing the Cerro Toro Formation from Cerro Benitez just north of Puerto Natales, to north of Laguna Azul (Fig. 2). We will visit Cerro Toro Formation outcrops at Sierra del Toro (Hubbard et al., in press a) on **DAY 2** and the southern end of the Cordillera Manuel Señoret at Cerro Benitez (Hubbard et al., 2006) on **DAY 3**. The stratigraphy of the Cerro Toro Formation at these locations is dominated by a conglomeratic member > 400 m in thickness (the informally named Lago Sofia Member of Katz, 1963). It is encased in bathyal mudstone (1000-2000 m paleo-water depth; Natland et al., 1974), and the entire formation has a cumulative thickness of approximately 2000 m. We will compare the character of the channel-fill and channel-margin deposits at both locations. In addition, we will examine the impressive conglomerate injectite network (Schmitt, 1991; Hubbard et al., 2006) underlying the main channel-complex at Cerro Benitez on **DAY 3**. A comprehensive assessment of the sedimentology and stratigraphic architecture of the Cerro Toro Formation in the Cordillera Manuel Señoret (Fig. 2) is the primary goal of Steve Hubbard’s soon-to-be-completed Ph.D. research.

One of the most stunning channel-margin exposures in the Cerro Toro Formation is present on the north face of Cerro Mocho. A SPODDS contingent has spent numerous days working this
outcrop, however, accessibility is too difficult for it to be visited on this field trip. A short overview of this outcrop is provided in the supplemental book to the fieldtrip, found on the SPODDS website (Hubbard et al., in press b). Hubbard et al. (in press a) provided an overview of part of the Cerro Toro outcrop belt at Sierra del Toro; Zane Jobe will study these deposits in detail for his PhD work. Anne Bernhardt will follow up on the work of Will Crane (2004) at the Silla Syncline. During this field season, Jake Covault will do reconnaissance work on the Cerro Toro Formation at Cerro Rotonda to determine if it represents a worthwhile, or logistically feasible, thesis research project.

**Tres Pasos Formation**

The Tres Pasos Formation is exposed in a belt parallel to and directly east of the Cerro Toro Formation (Fig. 2). The Tres Pasos Formation represents the transition from bathyal water depths in the underlying upper mud-rich portion of the Cerro Toro Formation to the deltaic and shallow-marine strata of the overlying Dorotea Formation (Smith, 1977). During the latest Cretaceous deep-water sedimentation ceased in this area as the delta-slope system migrated south and filled in this deep marine basin. The Tres Pasos Formation represents the slope component of this prograding depositional system.

Mike Shultz’s (2004) Ph.D. research identified key outcrops and documented the facies and architectural variability of this slope system. The Tres Pasos Formation is dominated by shale and mud-rich mass transport complexes punctuated by lenticular sandstone-rich lenses of variable thickness (10-100 m) and extent (few tens of meters to > 1 km). At two of the locations we will visit, facies distribution and sandstone body geometry are directly influenced by underlying topography, which is a fundamental aspect of slope systems. Sierra Contreras (DAY 4) exposes superb examples of mud-rich mass transport complexes and sand-rich deposits filling in evacuated slump scars at seismic scale (Shultz et al, 2005; in press). On DAY 5 we will examine a growth-faulted slope mini-basin fill complete with sandstone dikes parallel to the synthetic and antithetic faults at El Chingue Bluff (Shultz and Hubbard, 2005). If time permits we will also visit a thick, amalgamated sandstone succession at Laguna Figueroa interpreted as a base-of-slope accumulation.

Another Tres Pasos outcrop that is being worked on by SPODDS (Brian Romans), but will not be visited during this particular trip, is Cerro Divisadero near the northern limit of the outcrop belt. Information about this research is included in the supplemental book (Romans et al., in press). Additionally, Dominic Armitage, and possibly Jake Covault, will be starting projects to examine the exposures of the Tres Pasos Formation in greater detail.

**ROADLOG: PUERTO NATALES TO TORRES DEL PAINE**

On your journey from Punta Arenas to the Hostería Pehoe you need to fill your gas tank in the town of Puerto Natales (Fig. 3). There is an Esso station on the left, a few hundred meters beyond the official entrance to the town. The drive from here to the Hostería Pehoe is approximately 2 hours. This roadlog (in km) will introduce you the local geography and some of the geologic features that we will be discussing for the next five days.

0: *Set trip odometer at Esso station in Puerto Natales* – the body of water here is an inland arm of the Pacific Ocean called Seno Ultima Esperanza.

8: *Airfield* – the prominent high ridge to your right is Sierra Dorotea; the vegetated lower slope is the shale-rich uppermost Tres Pasos Formation and the deltaic Dorotea Formation makes up the cliff-forming sandstone units at the top.
17: *End of pavement* – directly in front of you is the backside dip-slope of Cerro Benitez; we will visit Cerro Toro Formation outcrops on the northern side of this mountain on DAY 3.

22: View of Cerro Mocho (Cerro Toro Formation) to the front-left.

29: View of Jorge Mont (Tres Pasos Formation) ahead and Cerro Mocho (Cerro Toro Formation) again to the left.

34: Up the valley to the right is the type section of the Tres Pasos Formation.

37: To the left, up the valley, is a view of Cerro Ventana, Cerro Campana, and Cerro Castillo, respectively. These mountains are all capped by conglomeratic channel-fill deposits of the Cerro Toro Formation.

39: At crest of this hill, the view to forward and to the right of lake are sand-rich Laguna Figueroa outcrops of Tres Pasos Formation. If time permits, we will visit this locale on DAY 5.

49: If you’re lucky and it is clear the view to the left and off in the distance is the spectacular Paine Massif. The relatively smaller Cerro Castillo (‘castle hill’) is in the foreground.

57: The outcrops in the distance across the valley that are dipping to the right (east) are the Dorotea Formation.

60: *Town of Cerro Castillo* – turn left to go to Torres del Paine.

66: Sandstone benches on left (Tres Pasos Formation) disappear in valley road is in and then reappear on other side (north) of road. Note recent glacial terraces cross-cutting dipping Cretaceous strata.

77: The view to the left is east face of Sierra del Toro (Cerro Toro Formation); we will visit the north face of this mountain on DAY 2. The view to the right is the El Chingue Bluff outcrop (Tres Pasos Formation), which we will visit on DAY 5.

89: *Major intersection* – turn left here to go to Torres del Paine (in view, if weather is clear). To the right is to town of Cerro Guido, Rio Baguales outcrops (Paleocene nonmarine and younger volcanic and volcaniclastic sediments of the Sierra Baguales). Watch along the side of the road in the next 10 km, you will likely see some ñandu, a large flightless bird, and some guanaco, which are similar to llamas.

96: *Lago Sarmiento vista and parking lot* – if the weather is clear this is a beautiful stop to gaze at the Paine Massif off to the west and take some photographs. The low hills to the left of the Paine are the Silla Syncline (Cerro Toro Formation), which we will visit on DAY 1. To the south you can see the north face of Sierra del Toro (Cerro Toro Formation), which we will visit on DAY 2. To the north is a view of the south face of Sierra Contreras (Tres Pasos Formation). We will visit the well-exposed west face of that mountain on DAY 4.

End of log.
SCHEDULE

Night of 3/19 (Su): Group gathers at Hosteria Pehoe, Torres del Paine Park

**DAY 1** - 3/20 (M): Channel margin relations in the Cerro Toro Formation, Silla Syncline, Torres del Paine National Park
Night of 3/20 (M): Hosteria Pehoe

**DAY 2** - 3/21 (T): Channel fill sequences, Cerro Toro Formation, Sierra del Toro
Night of 3/21 (T): Hosteria El Pionero, Cerro Castillo

**DAY 3** - 3/22 (W): Channel fill sequences and associated reservoir-scale clastic injections, Cerro Toro Formation, Lago Sofia
Night of 3/22 (W): Hosteria El Pionero, Cerro Castillo

**DAY 4** - 3/23 (Th): Slope slump scars mini-basins and turbidite fills, slope mass transport complexes, Tres Pasos Formation, Sierra Contreras
Night of 3/23 (Th): Hosteria El Pionero, Cerro Castillo

**DAY 5** - 3/24 (F): A.M.: Exposures at El Chingue Bluff of the Tres Pasos Formation slope system displaying a growth-faulted, sand-filled mini-basin, as well as sandstone dikes synthetic and antithetic to the bounding fault; P.M.: Base-of-slope sand-rich sequence, Tres Pasos Formation, Lago Figueroa (if time permits)
Night of 3/24 (F): Final gathering at Costa Australis Hotel, Puerto Natales

Day of 3/25 (Sa) Drive to Punta Arenas and depart for home
REFERENCES


Winn, R.D., and Dott, R.H., Jr., 1979, Deep-water fan-channel conglomerates of Late Cretaceous age, southern Chile: Sedimentology, v. 26, p. 203-228.
### Fig. i.1. Generalized stratigraphy of the Magallanes basin (adapted from Natland et al., 1974, Wilson, 1991, and Fildani et al., 2003).
Fig. i.2. Landsat image of the Ultima Esperanza District with outline for fieldtrip day-log. Outcrops of Cerro Toro Formation conglomerate highlighted in red. Map at bottom right show locations of study area with respect to southern South America (compare locations of the Torres del Paine and Puerto Natales).
Fig. i.3. Map of Ultima Esperanza District with important fieldtrip locations and roads.
Day: Monday, March 20
Destination: Silla Syncline

Channelized sediment gravity-flow deposits of the Cerro Toro Formation will be examined at the Silla Syncline in the Torres del Paine National Park. In this classic locality, the complex relationship between coarse-grained channel, and fine-grained out-of-channel deposits can be assessed.

In terms of regional paleogeography, it has been suggested that deposits at the Silla Syncline accumulated within a tributary that fed into a roughly north-south flowing channel belt that occupied the axis of the Magallanes basin foredeep.

Related Figures:

Fig. 1.1. Overview of the syncline with the location of the day’s planned traverse.

Fig. 1.2. Cross-section through the syncline showing the relationship of the various, coarse-grained channelized sediment bodies. Nomenclature adapted from the work of Crane (2004).

Fig. 1.3. Some examples of the stratigraphic architecture observed in the study area, as well as a representative detailed measured section.

Fig. 1.4. An evolutionary model that accounts for deposition and resultant architecture observed within the Paine C channel complex.

Related SPODDS Research: Crane (2004); Crane and Lowe (2001)

Accommodations (March 20): Hosteria Pahoe at Lago Pehoe, Torres del Paine
Fig. 1.1. Aerial photograph of the Silla Syncline showing the location of the the cross-section in Fig. 1.2 and the traverse planned for 3/20.
Fig. 1.2. North-south trending cross-section through the Cerro Toro Formation at the Silla Syncline showing the distribution of major coarse-grained units associated with channelized deposition. See Fig. 1.1 for section location (modified from Crane, 2004).
Fig. 1.3. Strata of the Cerro Toro Formation at the Silla Syncline. (A) Lateral pinch-out onto an erosional surface to the west of Laguna Melizzas. (B) Section through the Paine Member, west limb, Silla Syncline. (C) Measured section through the strata in B. The major lithofacies elements are presented, including: A - Sand matrix, clast-supported pebble to cobble conglomerate, B - Thick-bedded medium to coarse sandstone with thin interbedded mudstone, C - siltstone and mudstone with thin interbedded fine sandstone, and D - mud-matrix supported pebble diamictite (modified from Crane, 2004).
Fig. 1.4. Schematic models showing cyclic development of the Paine C channel complex. (A) Deposition of Laguna Negra debris-flow deposit (LN) and overlying units. (B) Major incision (surface 2). (C) Filling of channel 2 by sand (north) and gravel. (D) Gravel and sand sedimentation is followed by fining-upward sequence culminating in thick Illmd-ss and Illmd unit deposited within and outside of the channel. This fine unit was deposited both by currents moving within the channel and by regional flows moving from north to south. (E-G) Second cycle of channel erosion and filling. (H-I) Third cycle, with channel shifted to south, down regional paleoslope (modified from Crane, 2004).
Day: Tuesday, March 21
Destination: Sierra del Toro

In this locality, the coarse-grained sediment gravity-flow deposits of the Cerro Toro Formation are associated with less fine-grained material relative to the stratigraphic succession at the Silla Syncline. The sedimentary package here consists of up to 200 m of sandstone, and both sandy and muddy matrix conglomerate with very little interbedded mudstone. Significant incision at the base of the succession is evident. Paleogeographically, it is postulated that these strata represent deposition along the margin of the axial channel belt that occupied the Magallanes foredeep, in a proximal position.

Related Figures:

Fig. 2.1. Interpretive paleogeographic setting of the Upper Cretaceous Cerro Toro Formation showing the locality of the various SPODDS study areas visited on the fieldtrip.

Fig. 2.2. Photomosaic and line-drawing interpretation of channel element at Sierra del Toro (paleoflow was roughly into the outcrop).

Fig. 2.3. Correlated measured sections and paleocurrents.

Fig. 2.4. Facies of the Cerro Toro Formation at Sierra del Toro.

Related SPODDS Research: Steve Hubbard and Brian Romans worked on this site in 2003 and 2004 as part of thesis reconnaissance work (Hubbard et al., in press a). Zane Jobe will work on the detailed stratigraphic architecture of channel deposits on this mountain for his thesis research.

Accommodations (March 21): Hosteria El Pionero, Village of Cerro Castillo
Fig. 2.1. Interpreted paleogeographic reconstruction of the Magallanes basin during deposition of the Cerro Toro Formation (not to scale). The approximate width of the axial channel belt is 5-9 km. The location of the various outcrop locations visited on the fieldtrip are indicated (modified from thesis work of Steve Hubbard).
Figure 2.2 (A). The Sarmiento Vista outcrop on the northeastern face of Sierra del Toro. Paleocurrent indicators through most of the stratigraphy suggest that the channel flowed southwards (this is a strike section). The lower part of the channel form deposit is <1000 m (3281 ft) wide and the relief on the margin is 180 m (590 ft); this relief is accomplished over a lateral distance of 250 m (820 ft). Notably, the uppermost conglomerate layer (demarcated at the top and bottom by white arrows) extends over a lateral extent of several kilometers. Rectangle represents the area shown in detail in the line drawing below. Red lines correspond to the locations of the measured sections in Fig. 2.3 (modified from Hubbard et al., in press a).

Figure 2.2 (B). Sedimentary lithologies and stratigraphic surfaces as traced from the area defined within the rectangle in Figure 2.2A. A master surface defines the margin between coarse channel deposits and finer out-of-channel units (defined by the heavy black line). The coarsest material within the channel form body is present in the channel axis, fining laterally towards the margins of the deposit. It is possible that the non-amalgamated turbidite facies present within the channel form element represent overbank deposits. Mapping of facies relationships at the edge of the channel (just east of section Sarmiento Vista #1) is significantly impeded by scree cover (modified from Hubbard et al., in press a).
Fig. 2.3. The stratigraphic succession at Sarmiento Vista is characterized by alternating intervals of sandy matrix conglomerate/sandstone and muddy matrix conglomerate that can be correlated across the outcrop. Paleocurrent measurements indicate that flow within the lower, confined part of the channel was predominantly to the south. The uppermost beds, characterized by an abrupt, eastward shift in paleocurrent direction, may be linked to a change in channel orientation that was associated with a significant broadening of the channel body from <1 km (0.63 mi) to at least 2.5 km (1.56 mi). The cause of the channel broadening is not known, although it may have been related to an increase in sediment supply into the basin. Note that the stratigraphic thicknesses of the sections are in meters (100 m = 328 ft), and that their locations are presented in Figs. 2.2 (A and B) (modified from Hubbard et al., in press a).
Fig. 2.4. Characteristics of channel fill at Sierra del Toro. (A) Plane laminations and climbing ripples deposited from gravity flows overspilling the channel margin (increments on measuring staff are 0.1 m (0.3 ft) each). (B) Thick succession of high density turbidites. (C) Close-up of erosive channel margin (dashed line) highlighting a thin, on-lapping shale bed (large arrow) and abundant shale rip-up clasts (small arrows). (D) Thick succession of traction structured conglomerate at the top of the outcrop, characterized by well-developed clast imbrication. (E) Large raft block within a thick, sandy turbidity current deposit (person for scale approximately 1.78 m (70 in) tall). (F) Cross-stratified sandstone. (G) Gravel-filled incision cut into fine-grained slump deposits (unit person standing on) at the base of the channel (modified from Hubbard et al., in press a).
Day: Wednesday, March 22 (A.M.)
Destination: Lago Sofia

This field stop will focus on the site of the immense gravel injections in the basal Cerro Toro Formation at Lago Sofia first recognized by Scott (1966). The injectites emanate from the margins of conglomeratic channelform sedimentary bodies, and are analogous in many respects to similar features in Paleogene strata of the North Sea basin. We will examine channel and overbank facies, and walk the path of a large bifurcating intrusion that cuts almost 130 m of thin-bedded turbiditic strata.

Related Figures:

Fig. 3A.1. Oblique aerial photograph of the clastic dike complex at Cerro Benitez.

Fig. 3A.2. Thin-bedded turbidite beds (background facies).

Fig. 3A.3. Sedimentological characteristics of intrusions.

Fig. 3A.4. Overview of various injectite architectures.

Fig. 3A.5. Cross-sectional geometry and size of various channel deposits and injectite bodies from the Cerro Toro Formation and the North Sea basin.

Related SPODDS Research: Steve Hubbard and Brian Romans mapped these features in 2004 and 2005, and the paper stemming from this research is in press (Hubbard et al., 2006).
Fig. 3A.1. (A) Oblique aerial photograph of the entire channel/intrusion complex at Lago Sofia. (B) Line trace of photograph in (A), showing the distribution of the various facies in the study area. Channel and injectite bodies are labeled C1 - C3 and I1 - I4 respectively. Note the location of intrusive deposits in close proximity to the margins of the underlying channel bodies (modified from Hubbard et al., 2006).
Fig. 3A.2. (A) Overview of thin-bedded sandstone and mudstone host rock. (B, C) Photographs of sandy gravity-flow deposits characterized by primary sedimentary structures and soft sediment deformation. (D) Up-turned sandstone beds adjacent to vertical (injected) conglomeratic body. (E) Thin-bedded units dipping beneath, and adjacent to, conglomeratic channel form body. This structural deformation results from differential compaction of fine-grained units and coarse-grained, conglomeratic facies (modified from Hubbard et al., 2006).
Fig. 3A.3 Injected lithofacies in the Cerro Toro Formation. (A) Ripped-up turbiditic sandstone and mudstone beds in injected conglomerate. (B) Muddy matrix-supported conglomerate. (C) Armoured mud-clast floating in matrix-supported conglomerate. (D) Sub-vertical sandstone layer at margin of unstratified conglomerate characterized by flute-like grooves. (E) Groove on margin of unstratified conglomerate body. (F) Normally graded injectite deposit (modified from Hubbard et al., 2006).
Fig. 3A.4. (A) Overview of large injectite oriented approximately perpendicular to bedding. (B) Where the injectite thins and is vertical, bedding within the surrounding host-rock was bent upwards in response to the flow of remobilized sediment (modified from Hubbard et al., 2006).
Fig. 3A.5. Cross-sectional geometry and size of various channel deposits and injectite bodies. A) Generalized 3-D block diagram of depositional units and injectites in the Cerro Toro Formation with 2-D outlines of channel bodies C1 (B) and C2 (C). (D) Winged channel bodies from the Alba Field, UK. (E) Injectite body within the Balder Formation (UK) enlarged from box in (F). Note that all drawings in B-E are drawn at the same scale. Box in (D) highlights a relatively small injectite most comparable in scale to the C2 injectite in the Cerro Toro Formation. (F) Variable large-scale injectite/depositional bodies of the Balder Formation. Winged channel bodies from the UK (G) and Norwegian (I) sectors of the North Sea. (H) Outline of bifurcating injectite associated with Alba sandstones. Data in (D) through (I) modified from MacLeod et al. (1999), Duranti et al. (2002), Jolly and Lonergan (2002), Hurst et al. (2003), and Huuse et al. (2004) (figure from Hubbard et al., 2006).
Day: Wednesday, March 22 (P.M.)
Destination: Lago Sofia/Cerro Benitez

On this afternoon, we visit the thick conglomeratic succession in the Cerro Toro Formation at Cerro Benitez; deposits were influenced by traction processes, as evidenced by abundant low-angle cross stratification and barforms up to 8 m high. We observe the internal architecture of the channel belt from a distance before walking up to the base of the conglomeratic succession to examine the stepped channel margin of the system. Inner levee deposits will also be examined.

Related Figures:

Fig. 3B.1. Overview photomosaic of axial channel belt deposits at Cerro Benitez.

Fig. 3B.2. Internal architecture of axial channel belt deposits.

Fig. 3B.3. Close-up of stepped channel margin and laterally equivalent inner levee deposits at the base of the conglomeratic member in the Cerro Toro Formation.

Related SPODDS Research: Steve Hubbard’s thesis work included the detailed sedimentologic and stratigraphic analysis of deposits at Cerro Benitez.

Accommodations (March 21): Hosteria El Pionero, Village of Cerro Castillo
Fig. 3B.1. (A) Overview of axial channel belt deposits at Cerro Benitez; paleoflow was into the outcrop. (B) Line drawing trace of photomosaic in A. (C) Palinspastic reconstruction of the channel belt, with rose diagrams showing paleocurrent vectors from within the channel belt, and in laterally equivalent overbank deposits (from thesis work of Steve Hubbard).
Fig. 3B.2. (A) Detailed photomosaic of the internal architecture of the axial channel belt at Cerro Benitez (see Fig. 3B.1 for location). (B) Line-drawing trace of Part A, showing large westward/southwestward migrating barform. (C) Section measured through the channel belt along the base of the cliff (dark grey layers represent muddy matrix conglomerate, white layers represent sandy matrix conglomerate, and light grey layers represent sandstone) (from thesis work of Steve Hubbard).
Fig. 3B.3. Stepped channel margin at the base of Cerro Benitez and laterally equivalent inner levee deposits.
**Day:** Thursday, March 23  
**Destination:** Sierra Contreras

The west face of Sierra Contreras consists of two thick-bedded turbiditic sandstone units (individually up to 60 m thick), which collectively form the basal Tres Pasos Formation. Both of these units overlie thick mass transport complex deposits. The units are interpreted to represent infill of accommodation produced by slope failure. Extensive exposure of both coarse- and fine-grained strata make this exposure of the Tres Pasos Formation a useful analog system for hydrocarbon reservoirs in mud-rich, structurally complex slope environments such as the Gulf of Mexico and West Africa. Also note the listric, basinward failure scarp from which the upper MTC originated.

**Related Figures:**

Fig. 4.1 Overview of the west face of Contreras.

Fig. 4.2 Detailed photo of slope sandstone package architecture and detailed measured sections.

**Related SPODDS Research:** Mike Shultz’s thesis work (Shultz, 2004), published in Shultz et al. (2005) and Shultz et al. (in press).

**Accommodations** (March 23): Hosteria El Pionero, Village of Cerro Castillo
Fig. 4.1 (A) Photomosaic and (B) line-drawing interpretation of the west face, Sierra Contreras (modified after Shultz et al., 2005; in press). Two thick coarse-grained or slumped gravity flow packages are present, encased in thin-bedded silty mudstone (T1 and T2). Thick-bedded turbiditic sandstone dominated units (S1/C1 and S2/C2) overlie mass transport complexes (MTC1,2). In MTC2, a lateral evolution from rotated intact strata above a listric failure surface through a fully homogenized debris-flow can be observed. Both the lower and upper sandstone bodies consist of lower laterally variable sandstone beds (C1 and C2, respectively), and upper, sheet-like sandstone beds (S1 and S2, respectively). Detailed measured sections through the two sandstone units are shown and their internal architecture is discussed in Fig. 4.2.
Fig. 4.2. (A) Detailed photomosaic of the Sierra Contreras outcrop highlighting the C2 and S2 sandstone units (see previous page for the approximate location). (B, C) Detailed measured sections from sandstone units present at the Sierra Contreras (from Shultz et. al., in press).
**Day:** Friday, March 24 (A.M.)  
**Destination:** El Chingue Bluff

On this day, the outcrop visited is representative of the basal part of the Tres Pasos Formation. At El Chingue Bluff, a rare outcrop exposure of a growth-fault bounded slope minibasin and the tabular gravity-flow deposits that accumulated within it is preserved. The seismic-scale exposure is particularly interesting as an analog to ponded slope-minibasin fill in hydrocarbon-prone areas such as the Gulf of Mexico and West Africa. Also intriguing are downward-directed clastic dikes whose orientations parallel growth-faults in the underlying fine-grained strata of the Upper Cerro Toro Formation.

**Related Figures:**

Fig. 5A.1. Overview of El Chingue Bluff.

Fig. 5A.2. Measured section through the turbiditic sequence interpreted to have been ponded into a depression on the paleoslope.

Fig. 5A.3. Facies of the Tres Pasos Formation at El Chingue Bluff.

Fig. 5A.4. Outline of growth-fault at El Chingue Bluff with seismic analogs from West Africa.


**Accommodations** (March 24): Costa Australis Hotel, Puerto Natales
Fig. 5A.1. (A) Photomosaic of El Chingue Bluff. (B) Line-drawing of photomosaic in A. The turbiditic sandstone package (TSP) is present at the top of the bluff. Clastic dikes (thin dashed lines) dip from the top left to the bottom right (in a southerly direction) at the northern end of the outcrop, and from the top right to the bottom left (in a northerly direction) at the southern end of the exposure, consistent with growth faults in underlying strata (thick lines). (C) Detail of synthetic growth fault (white arrow) with similarly oriented clastic dikes. (D) Relationship of clastic dikes and the growth fault with the base of the TSP. Stratigraphic horizons are drawn schematically for clarity. (E) Oblique aerial photograph of El Chingue Bluff, showing relationship to overlying channelized sandstone body. Note the increased thickness of the TSP across the growth fault to the north. (F) Line drawing traced from box in part E showing internal stratigraphic layering within the TSP, including onlapping of beds onto tilted substrate to the north (modified from Shultz and Hubbard, 2005).
Fig. 5A.2. (A) Measured section through the turbiditic sandstone package at El Chingue Bluff. Note the bundling of coarse-grained sandstone sedimentation units into separate cycles separated by pervasively bioturbated mudstone intervals. Deposits of these bundles coarsen-upwards, associated beds get thicker (and are more amalgamated) towards the tops of cycles. Rose diagrams indicate flute cast orientations. MTC = mass transport complexes. (B) Overview of the sandstone package showing the tabularity of individual sandstone beds. North is towards the top of the photo (modified from Shultz and Hubbard, 2005).
FIG. 5A.3. (A-B) Thin-bedded turbidites (0-23 m); (C) Thalassinoides on the sole of a turbiditic sandstone bed (45.2 m); (D-E) Thick-bedded turbidites at 28 m and 48 m respectively. (F-G) Ophiomorpha with U-shape morphology, a morphology most commonly associated with shallow marine facies (53.2 m). (H) The trace fossil Asterosoma in a thick-bedded turbiditic sandstone at 53.2 m. (I) Ophiomorpha at 52.5 m. (J) Chaotic deposits consisting of large, deformed sandstone rafts (indicated by arrows) in sandy mudstone matrix (61 m); (K) Chondrites on thin-bedded turbidite bedding plane (25.5 m) (modified from Shultz and Hubbard, 2005).
Fig. 5A.4. (A) Photograph of the turbiditic sandstone package at El Chingue Bluff showing the growth faulted base and overlying unfauluted chaotic deposits. (B-C) High-resolution near-surface seismic images of a submarine channel intersecting a large growth fault, offshore Nigeria (images from Adeogba et al., 2005). (B) Relief seismic profile along the axis of the channel/fan complex presented in plan-view in part C. Where the channel intersects a growth fault complex, the significant topographic shift resulted in ponding of sandstone into a lobe-like sedimentary body.
**Day:** Friday, March 24 (P.M.)  
**Destination:** Laguna Figueroa

If time permits, at this outcrop we will examine the well-exposed middle member of the Tres Pasos Formation. Highly scoured channel fill sequences are preserved in this locality, associated with common, thick-bedded high-density turbidity current deposits.

**Related Figures:**

- **Fig. 5B.1.** Photograph of a thick-succession of the Tres Pasos Formation at Laguna Figueroa.
- **Fig. 5B.2.** Measured section through strata that will be visited.
- **Fig. 5B.3.** Facies of the Tres Pasos Formation at Laguna Figueroa.

**Related SPODDS Research:** Mike Shultz’s completed thesis (Shultz, 2004).

**Accommodations** (March 24): Costa Australis Hotel, Puerto Natales
Fig. 5B.1. Photograph of a portion of the detailed measured stratigraphic section (Fig. 5B.2) at Laguna Figueroa. Section was measured about 200 m laterally away from the photograph, and is therefore not strictly correlative. Bases of coarse-grained cycles at 110 m and 155 m (Fig. 5B.2) are indicated. Note upward-thinning nature of channel-fill cycles (arrows), and scour or channelization in fine-grained lithofacies in the upper part of channel-fill sequence (white arrow). Person (circled) for scale (from Shultz, 2004).
Fig. 5B.2. Detailed measured section through the middle member of the Tres Pasos Formation at Laguna Figueroa. Rose diagrams plot orientation of flute casts. Numbers 1-10 denote cyclical successions consisting of thick-bedded sandstone and intraclast conglomerate separated by thin-bedded sandstone and fine-grained lithofacies (from Shultz, 2004).
Fig. 5B.3. Lithofacies characteristics in the Tres Pasos Formation at Laguna Figueroa. (A) Traction-deposition-dominated sedimentation unit with imbricated rip-up clast conglomerate (present at the bases of channel fill successions. (B) Laminated thick-bedded turbidity-current deposit. (C) High-density turbidity current deposit (S3 division overlain by a Tt division). (D) Thin-bedded turbidites (characterized by Bouma sequence) typical of the tops of channel fill successions. (E) Slump deposit showing contorted, yet intact, fine-grained beds. (F) Draped erosional scour at 155 m (Fig. 5B.2), in middle part of channel fill succession (from Shultz, 2004).