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Deep-water foreland basin deposits of the Cerro Toro Formation, Magallanes basin, Chile: architectural elements of a sinuous basin axial channel belt

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ABSTRACT

Coarse-grained deep-water strata of the Cerro Toro Formation in the Cordillera Manuel Señoret, southern Chile, represent the deposits of a major channel belt (4 to 8 km wide by >100 km long) that occupied the foredeep of the Magallanes basin during the Late Cretaceous. Channel belt deposits comprise a *ca* 400 m thick conglomeratic interval (informally named the 'Lago Sofia Member') encased in bathyal fine-grained units. Facies of the Lago Sofia Member include sandy matrix conglomerate (that show evidence of traction-dominated deposition and sedimentation from turbulent gravity flows), muddy matrix conglomerate (graded units interpreted as coarse-grained slurry-flow deposits) and massive sandstone beds (high-density turbidity current deposits). Interbedded sandstone and mudstone intervals are present locally, interpreted as inner levée deposits. The channel belt was characterized by a low sinuousity planform architecture, as inferred from outcrop mapping and extensive palaeocurrent measurements. Laterally adjacent to the Lago Sofia Member are interbedded mudstone and sandstone facies derived from gravity flows that spilled over the channel belt margin. A levée interpretation for these fine-grained units is based on several observations, which include: (i) palaeocurrent measurements that indicate flows diverged (50° to 100°) once they spilled over the confining channel margin; (ii) sandstone beds progressively thin, away from the channel belt margin; (iii) evidence that the eroded channel base was not very well indurated, including a stepped margin and injection of coarse-grained channel material into surrounding fine-grained units; and (iv) the presence of sedimentary features common to levées, including slumped units inferring depositional slopes dipping away from the channel margin, lenticular sandstone beds thinning distally from the channel margin, soft sediment deformation and climbing ripples. The tectonic setting and foredeep architecture influenced deposition in the axial channel belt. A significant downstream constriction of the channel belt is reflected by a transition from more tabular units to an internal architecture dominated by lenticular beds associated with a substantially increased degree of scour. Differential propagation of the fold-thrust belt from the west is speculated to have had a major control on basin, and subsequently channel, width. The confining influence of the basin slopes that paralleled the channel belt, as well as the likelihood that numerous conduits fed into the basin along the length of the active fold-thrust belt to the west, suggest that proximal–distal relationships observed from large channels in passive margin settings are not necessarily applicable to axial channels in elongate basins.

Keywords Architectural elements, Cerro Toro Formation, confined channel–levée complex, deep-water stratigraphy, foreland basin, gravity flow deposits.

INTRODUCTION

The study of uplifted foreland basin fill has been particularly influential in the development of classical deep-water facies models, from the bed scale (Kuenen & Magliorini, 1950; Bouma, 1962), through the depositional system scale (Mutti & Ricci Lucchi, 1972; Mutti, 1985) to the basin scale (Dzulynski *et al.*, 1959; Ricci Lucchi, 1985; Mutti *et al.*, 2003). More recent studies of deep-water foreland basin strata, driven in part by the need for reservoir analogues in the oil and gas industry, have focused on the effects of basin confinement on sediment distribution and depositional system development. Examination of outcropping deposits from intraslope minibasins (Shultz & Hubbard, 2005), piggy-back basins (Alexander *et al.*, 1990; Ricci Lucchi, 1990; Sinclair, 2000; Zelilidis, 2003) and from foredeep settings where sea floor topography and/or basin morphology imparted an influence on sediment dispersal (Crabaugh & Steel, 2004; Pickering & Corregidor, 2005; Hodgson *et al.*, 2006), provides insight into the distribution and character of reservoir facies in many hydrocarbon provinces (e.g. West Africa, Gulf of Mexico).

Channels represent an important depositional element in the fill of many deep-water foreland basins (Cronin *et al.*, 1998; McCaffrey *et al.*, 2002; Grecula *et al.*, 2003; Shultz *et al.*, 2005); however, large-scale sinuous channel systems (>2 to 3 km wide) associated with thick successions of constructional overbank sediments have rarely been interpreted in outcropping foreland basin deposits (cf. Mutti *et al.*, 2003). An exception is strata from the Upper Cretaceous Cerro Toro Formation of the Magallanes foreland basin that crop out in the Cordillera Manuel Señoret north of Puerto Natales, Chile (Fig. 1). These strata have not been studied in detail since the 1960s (Scott, 1966) and, as such, they offer an opportunity to evaluate a large channel–levée complex characterized by the excellent outcrop quality typical of uplifted foreland basin fill (three-dimensional exposure at the scale of the depositional system). In the present study the architectural elements associated with the coarse-grained facies that accumulated in the axis of the Magallanes basin foredeep are documented, and a depositional model to account for the observed sediment distribution and sedimentary characteristics is developed. Effects on depositional system behaviour from confining margins of the narrow axis of the Magallanes basin are notable; a downstream constriction (possibly coupled with a change in slope) of the channel system is interpreted from the transition of dominantly planar beds to units characterized by extensive scour, a high degree of lenticularity and the presence of large-scale bedforms and barforms along the length of the depositional system. Numerous architectural aspects of the Cerro Toro Formation outcrops are analogous to those from strata in various hydrocarbon-bearing provinces where oil and gas are being sought (Kolla *et al.*, 2001; Abreu *et al.*, 2003; Samuel *et al.*, 2003; De Ruig & Hubbard, 2006).

BACKGROUND GEOLOGY

The Magallanes foreland basin is an elongate, north- to south-oriented trough located adjacent to the Patagonian Andes, the crustal loading of which was responsible for its genesis (Wilson, 1991). The basin has an oceanic back-arc heritage (Rocas Verdes basin) that 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, 1983, 1991). Strata of the Jurassic Tobífera Formation, characterized by volcaniclastic sedimentary units 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 & Hessler, 2005); oceanic crust, formed in association with the development of this basin, is preserved in the Sarmiento ophiolite complex that is present in the interior portion of the adjacent fold-thrust belt (Dalziel *et al.*, 1974; Dalziel, 1981). Initiation of the Andean orogeny and associated fold-thrust belt development spawned the transition from a back-arc to foreland basin setting (Dalziel, 1986; Wilson, 1991). Sedimentologically, this transition was recorded by deposition of turbiditic strata of the Punta Barrosa Formation (Fig. 1C; Wilson, 1991; Fildani & Hessler, 2005). Deep-water conditions persisted in the Magallanes foreland basin for a period of approximately 20 Myr, through deposition of the Cerro Toro and Tres Pasos Formations (Fig. 1C; Natland *et al.*, 1974; Wilson,

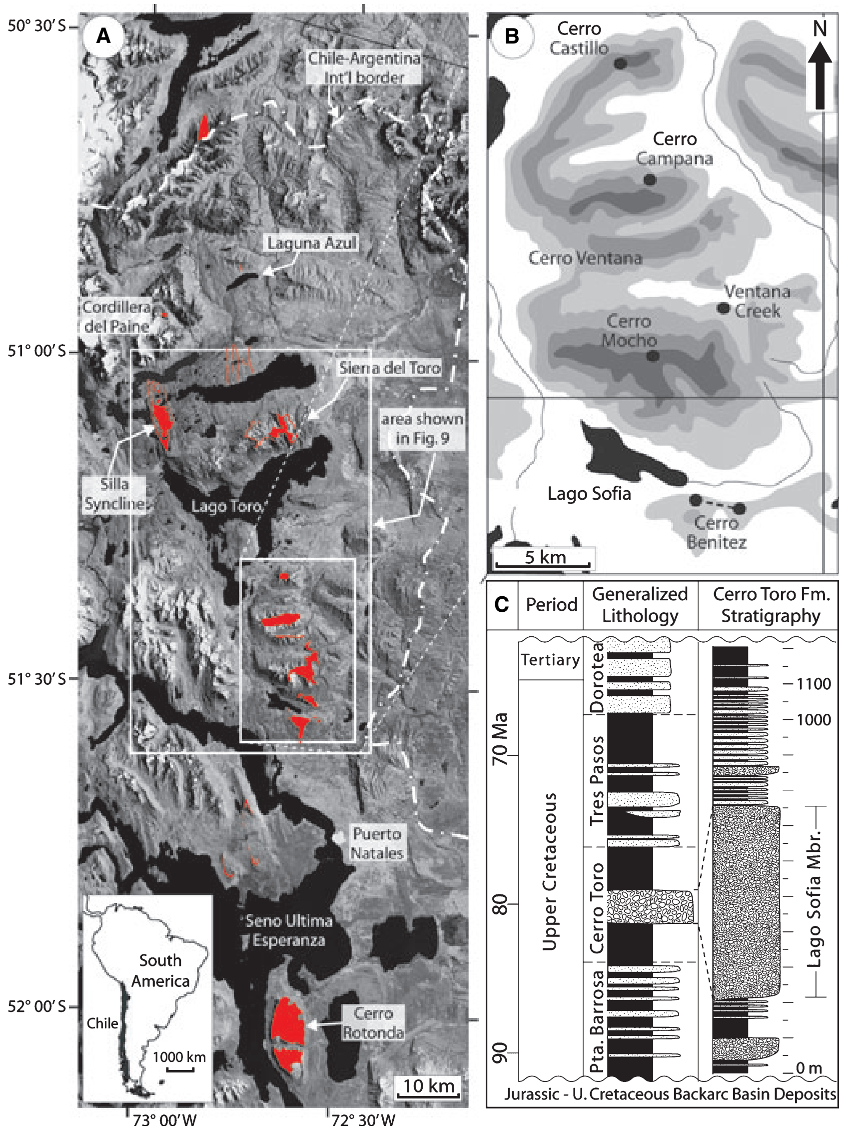

Fig. 1. Study area overview. (A) Landsat image of the Ultima Esperanza District in southern Chile. Red areas denote locations where Cerro Toro Formation conglomerate (Lago Sofia Member) is exposed. Inset map shows location of the study area in southern South America. (B) Detailed map of the Cordillera Manuel Señoret, including the locations where stratigraphic sections were measured (black circles). Shaded grey areas correspond to topographic contours (CI = 250 m); the peaks of Cerro Castillo, Cerro Campana, and Cerro Mocho are between 1000 and 1100 m in elevation. (C) Stratigraphy of the Magallanes foreland basin, with the detailed stratigraphic architecture of the middle part of the Cerro Toro Formation shown on the right.

1991; Fildani *et al.*, 2003). Upward shallowing during the Late Cretaceous and Tertiary is recorded in deposits of the Dorotea Formation (Katz, 1963). These strata were incorporated in the thrust-belt during the Cenozoic, and the excellent outcrop exposures reflect the combination of the geometry of open folds and Late Cenozoic glaciation.

Cerro Toro Formation: palaeogeographic setting and previous studies

Sediments 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 (Ramos, 1989; Wilson, 1991). Upper Cretaceous shallow-marine and non-marine strata equivalent to the Cerro Toro and Tres Pasos Formations have been identified 60 to 90 km north of the study area in Argentina; a southward prograding delta is inferred to have 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 kilometres, as evidenced by deep-water 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 (Fig. 2). Gravel and sand originating from the actively uplifting Andean fold-thrust belt to the west (Cecioni, 1957; Zeil, 1958) were probably

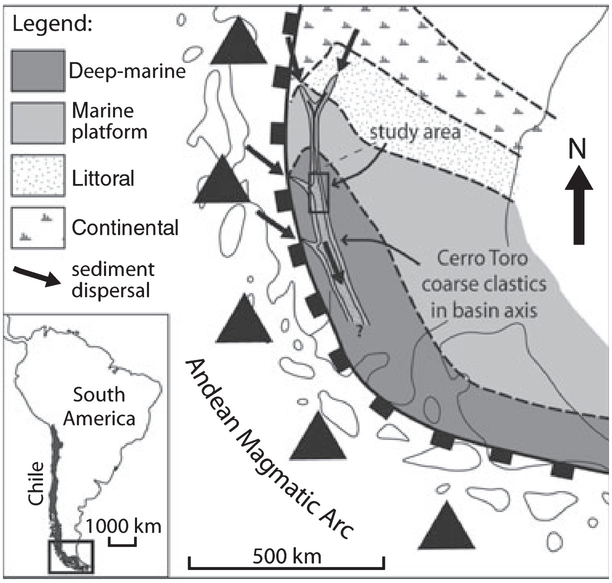

Fig. 2. Simplified palaeogeographic and palaeotectonic reconstruction of the Magallanes foreland basin during deposition of the Cerro Toro Formation (modified from Wilson, 1991 and Hubbard *et al.*, 2005). Sedimentation of coarse material, including gravel, was centralized within a basin axial channel belt that flowed southward for hundreds of kilometres along the basin foredeep. Sediment fed into this channel system from conduits to the north, as well as from various point sources to the west.

transported to the basin via the deltaic system to the north (Macellari *et al.*, 1989), and a series of conduits that cut across the western basin slope (Fig. 2; Crane & Lowe, 2001). Conglomerate and sandstone of the Cerro Toro Formation presently crop out in a north- to south-oriented outcrop belt >100 km in length, extending from the Chile–Argentina border in the north, to as far south as Cerro Rotonda, south of Puerto Natales (Fig. 1A).

The Cerro Toro Formation outcrop belt has been most extensively studied at the Silla Syncline (Fig. 1A), where tectonic folding has resulted in the three-dimensional exposure of channel strata. The excellent exposure quality, coupled with the relatively easy accessibility of the area (located in the Torres del Paine National Park), initially enticed sedimentologists to the area (Scott, 1966; Winn & Dott, 1979). The study of Winn & Dott (1979) established that the formation represented the deposits of a deep-water channel–levée complex. In the 1990s, driven by the prospect of producing oil and gas from analogous channel–levée complex deposit reservoirs, industry scientists and academic researchers began visiting the Silla Syncline to map the stratigraphic architecture of the Cerro Toro Formation (DeVries & Lindholm, 1994; Beaubouef *et al.*, 1996; Coleman, 2000; Crane & Lowe, 2001; Beaubouef, 2004; Crane, 2004).

With the focus in the Silla Syncline area, much of the channellized strata in the formation has been neglected elsewhere over the last three decades. Scott (1966) undertook the most extensive study of the formation to date, analysing the Cerro Toro Formation from Cerro Benitez just north of Puerto Natales, to north of Laguna Azul (Fig. 1). Winn & Dott (1977, 1979) revisited some of the outcrops examined by Scott, but focused much of their efforts on the Silla Syncline and on some immense conglomeratic dunes located just east of Lago Sofia (Fig. 1). A conglomeratic intrusion complex present on the southern shore of Lago Sofia (Fig. 1B), first recognized by Scott (1966), was the focus of a doctoral study by Schmitt (1991). Hubbard *et al.* (2007b) recognized the analogous nature of these features to large-scale intrusions that emanate from the margins of channel bodies in Palaeogene strata of the North Sea basin. A comprehensive assessment of the sedimentology and stratigraphic architecture of the Cerro Toro Formation in the Cordillera Manuel Señoret (Fig. 1B), the primary goal of the present study, was not attempted previously.

A conglomeratic member >400 m in thickness is prevalent in the Cerro Toro Formation at the Cordillera Manuel Señoret (Fig. 1C; the informally named Lago Sofia Member of Katz, 1963); this interval consists of the deposits of the basin axial channel belt. This member is encased in thin-bedded bathyal mudstone and sandstone (1000 to 2000 m water depth; Natland *et al.*, 1974); in part of channel overbank affinity (cf. Winn & Dott, 1979; Beaubouef, 2004). The entire formation has a cumulative thickness of approximately 2000 m. The conglomeratic Lago Sofia Member is immediately underlain by a series of lenticular sandstone beds over a stratigraphic thickness of <100 m (Fig. 1C). In the southern part of the study area, three conglomeratic channelform bodies are present 150 to 200 m below the main Lago Sofia Member (Hubbard *et al.*, 2007b); the largest of these bodies is *ca* 400 m wide and 75 m thick. At its upper contact, the Lago Sofia Member grades from conglomerate through a 100 to 200 m thick section of thick-bedded to thin-bedded, sand-dominated turbiditic beds, into bathyal mudstone-dominated deposits (Fig. 1C).

Cenozoic uplift of the Cerro Toro Formation in the Cordillera Manuel Señoret was associated with structural deformation of the deposits studied. Over most of the study area, gentle folds and low-offset faults are typical; their impact on the stratigraphic architecture of the formation is readily mapped and, therefore, they do not hinder the interpretations made in this study. The Lago Sofia Member was incorporated into thin-skinned thrust faulting at the western ends of Cerro Campana and Cerro Ventana (total shortening observed is at least 1·5 km; see Fig. 1B for location). This tectonic shortening has been factored into palaeogeographic interpretations.

ARCHITECTURAL ELEMENTS

Hierarchical architectural element schemes were originally used to document and characterize various scales of sedimentological observation in non-marine deposits (Brookfield, 1977; Kocurek, 1981; Miall, 1985); an architectural element approach has proven useful for the description and interpretation of deep-water strata (Ghosh & Lowe, 1993; Pickering *et al.*, 1995; Gardner & Borer, 2000; Hickson & Lowe, 2002; Anderson *et al.*, 2006). This study employs the approach first defined by Ghosh & Lowe (1993), where first-order architectural elements are considered to represent individual sedimentary structure divisions within a gravity-flow deposit (e.g. the plane laminated T_b division in the Bouma (1962) sequence or the massive S_3 division of the Lowe (1982) sequence; Fig. 3). Second-order elements represent individual gravity flow deposits (sedimentation units), and third-order elements represent the groupings of similar sedimentation units (equivalent to lithofacies; Fig. 3). Regularly recurring groups of genetically related lithofacies are fourth-order architectural elements. The bounding surfaces of fourth-order elements separate distinctive geometrical sedimentary bodies (e.g. channels). The approach of Ghosh & Lowe (1993) is favoured for this study because, although the outcrops studied are extensive and well-exposed, the immense scale of the depositional system and associated sedimentation units precludes dividing architectural elements using a strict geometric basis. Because of the difficulty in identifying large geometric features (individual sediment bodies in the order of up to 8 km wide), it is advantageous to employ a hierarchical scheme that emphasizes and builds upon the facies information. Bounding surfaces and sediment body geometry are documented and interpreted where identifiable, especially at the margins of the Lago Sofia Member.

In this paper, five third-order architectural element types are described and interpreted, defined primarily on the basis of their lithology or internal character: (i) sandy matrix conglomerate (IIIscg); (ii) muddy matrix conglomerate (IIImcg); (iii) thick-bedded sandstone (IIIss); (iv) thin-bedded sandstone and mudstone (IIIsm); and (v) chaotic units (IIIch) (Table 1). In addition, four fourth-order architectural elements are recognized, associated with deposition in the channel belt thalweg, and a fifth is recognized in out-of-channel strata (Table 1). The genetic relationship of the various fourth-order elements is discussed in context as a fifth-order architectural element (the complete succession of channel belt deposits).

Outcrops of deep-water deposits, such as those in the Magallanes basin, are often utilized as analogues to deposits imaged seismically in the sub-surface (Coleman *et al.*, 2000; Fugelli & Olsen, 2005; Hubbard *et al.*, 2005). It is important to consider that the fourth and fifth orders of

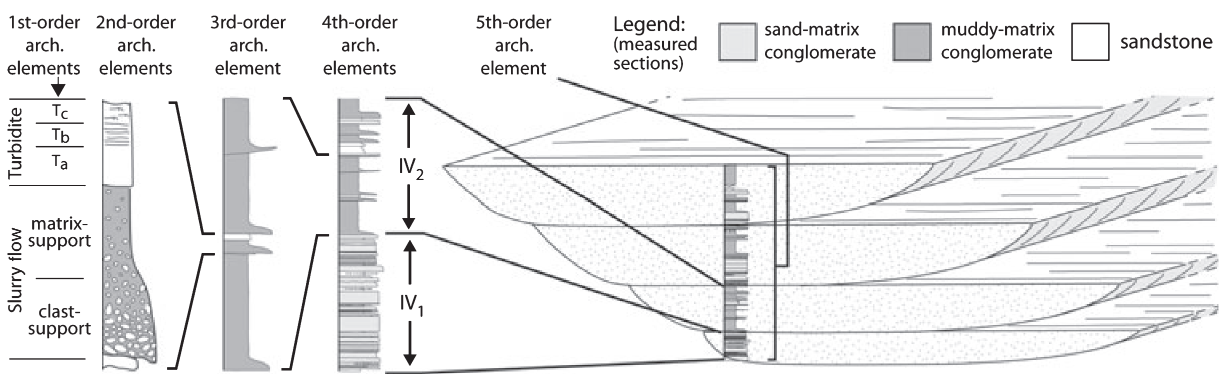

Fig. 3. Overview of the architectural element scheme utilized in this study. First-order elements represent the smallest scale of observation (e.g. individual turbidite divisions); the scheme is open-ended upwards, with the largest order of observation considered in this study represented by that of the entire basin axial channel belt stratigraphic succession (fifth-order element). Note that the fourth-order elements shown are 50 to 60 m thick.

Table 1. Architectural element summary for axial channel deposits of the Cerro Toro Formation, Cordillera Manuel Señoret.

Third-order elements (lithofacies)	Fourth-order elements	Lithologic designation	Interpretation	
IIIscg – sandy matrix conglomerate	IV_1 – dominantly IIIscg, with IIImcg, IIIss and IIIch (laterally persistent sedimentary packages)	Cerro Toro Fm. (Lago Sofia Mbr.)	Axial channel belt fill	Magallanes foreland basin axial channel belt complex set
IIImcg – muddy matrix conglomerate	IV_2 – dominantly IIImcg, with IIIscg and IIIss (laterally persistent sedimentary packages)			
IIIss – thick-bedded sandstone	IV_3 – randomly stacked IIIscg and IIImcg (lesser IIIss) with significant scour			
IIIsm – thin-bedded sandstone and mudstone	IV_4 – dominantly IIIss			
IIIch – chaotic units	IV_5 – dominantly IIIsm, with IIIss and IIIch	Cerro Toro Fm. (fine-grained units)	Overbank deposits and/or distal turbidites	

observation in the Ghosh & Lowe (1993) architectural element scheme represent the smallest scale of observation most likely to be resolvable in even the highest resolution conventional industry-standard seismic data sets. The composite three-dimensional bodies that fourth-order and fifth-order architectural elements comprise correspond to the scale of 'depositional elements' (Mutti & Normark, 1987, 1991), which are commonly used to characterize deep-water strata in modern, high-resolution seismic reflection data sets (Posamentier & Kolla, 2003; De Ruig & Hubbard, 2006).

Third-order architectural elements (lithofacies)

Sandy matrix conglomerate (IIIscg)

Clast-supported conglomerate characterized by a sandy matrix (IIIscg) represents a significant component (*ca* 50% to 60%) of the Lago Sofia Member in the study area (Fig. 4A to D). Sedimentary bodies composed of these units are up to 80 m thick, and are lenticular along depositional strike over 1 to 5 km. Individual units of IIIscg are highly variable, with erosional, planar to undulating bases (relief up to 10 m locally), and thicknesses ranging from 10 cm to 10 m. Clasts are well-rounded and poorly to well-sorted; clasts are as large as 32 cm in diameter, although maximum clast size is in the range of 10 to 20 cm for most beds. Beds <3 m thick are normally graded in some instances and commonly associated with a thin overlying sandstone bed < –20 cm thick (Fig. 4A); inversely graded basal layers < –30 cm thick (traction carpets) are present locally (Fig. 4B). Commonly, however, IIIscg beds are dominated by plane lamination, cross-stratification and/or widespread imbrication of clasts (Fig. 4C and D). Dunes up to 4 m high are present locally (Winn & Dott, 1977). Often, flame and load structures characterize bed contacts, particularly where conglomerate overlies a sandstone bed. Sole markings, including flute casts, are rarely exposed. Mudstone rip-up clasts are moderately abundant and trace fossils are absent.

Sandy matrix conglomerate sedimentation units were deposited through suspension sedimentation, or through traction sedimentation beneath immense high-density turbidity currents (cf. Lowe, 1982). Variability in bed thickness is most often related to differential scouring at the base of turbidity currents. Sandy matrix conglomerate is commonly associated with muddy matrix conglomerate (IIImcg) and lenses of sandstone (IIIss).

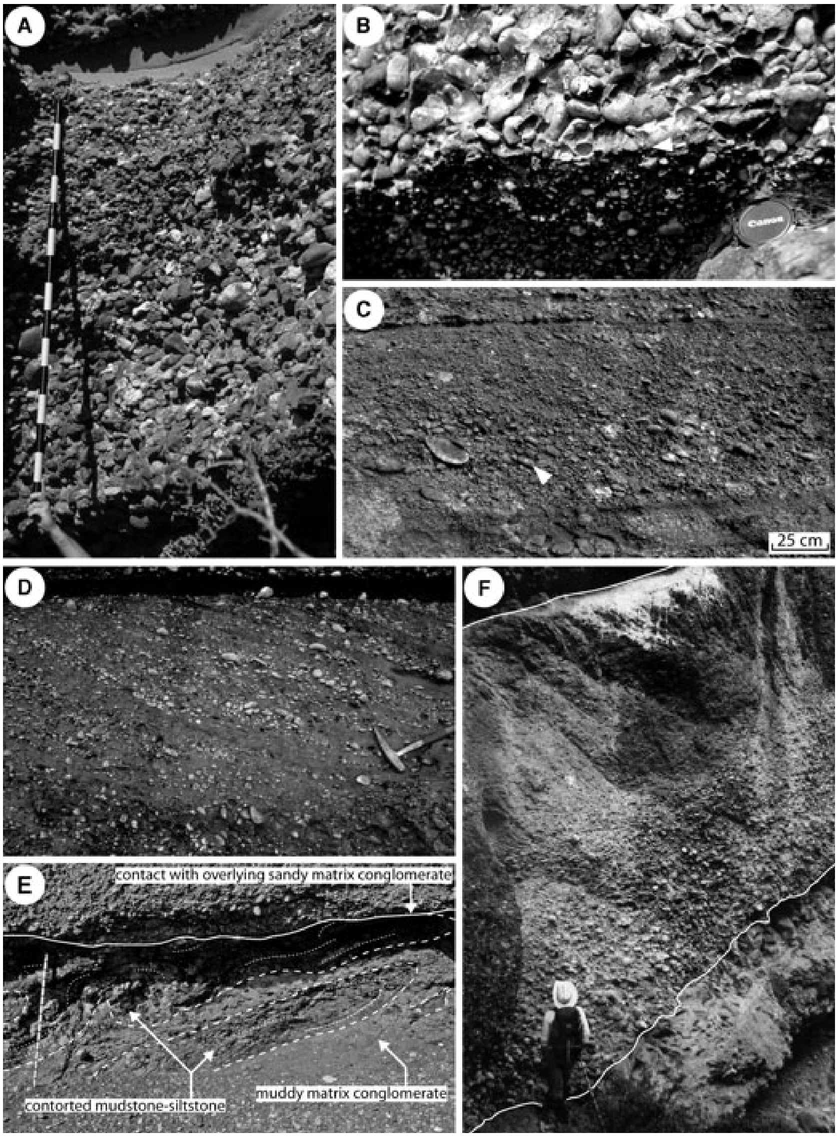

Fig. 4. Third-order architectural elements of the Cerro Toro Formation. (A) Normally graded turbiditic conglomerate sedimentation unit (IIIscg). Divisions on staff are 10 cm long. (B) Inversely graded base of sandy matrix conglomerate bed (IIIscg). Sandy matrix conglomerate beds (IIIscg) were dominantly deposited by traction, characterized by clast imbrication. Lens cap for scale is 58 cm in diameter. (C) Plane lamination and (D) large-scale cross-stratification. Arrow in (C) points to imbricated clasts. Hammer head for scale in (D) is 20 cm long. (E) Rafted sediment block characterized by overturned internal lamination mixed with muddy matrix-supported conglomerate at the top of a slurry bed (IIImcg). Staff is 1·5 m long. (F) Thick muddy matrix conglomeratic bed characterized by clast-support at the base and matrix-support upwards (IIImcg; slurry-flow deposit). Person for scale is 170 cm tall.

Muddy Matrix Conglomerate (IIImcg)

Conglomeratic units with poorly sorted matrix characterized by a high mud or argillaceous component (IIImcg) are an important constituent (*ca* 30% to 45%) of the Lago Sofia Member (Fig. 4E and F). In the Cordillera Manuel Señoret, these beds typically show clast-supported bases and matrix-supported tops (Fig. 4F). The transition from clast-support to matrix-support can be abrupt, or gradual over the entire bed thickness. Successions of IIImcg sedimentation units can be traced for hundreds to thousands of metres laterally, and are commonly 35 to 80 m thick. Basal contacts of individual units are flat or nearly flat (< −5 m relief). Clasts are similar to those in IIIscg, although they tend to be slightly larger on average in the muddier deposits (maximum clast size observed is 45 cm). Along with an upward decrease in clast percentage, normal grading of maximum and average clast size, as well as maximum grain size in the poorly sorted matrix are observed (cf. Crane, 2004;

Hubbard & Shultz, 2008). Large sub-rounded intrabasinal mudstone clasts (raft blocks up to 5 m in diameter) are characteristic of the upper parts of the sedimentation units (Fig. 4E), often in states of partial disaggregation. In rare instances, thin inversely graded basal layers (traction carpets) and flute casts on bed bases are present. Primary physical sedimentary structures are absent in IIImcg. However, deeply penetrating (up to 7 m) sandstone-filled trace fossils (shafts <1 cm in diameter) are present locally (*Glossifungites* ichnofacies, including *Diplocraterion*, *Arenicolites* and *Skolithos*) (Hubbard & Shultz, 2008).

Various researchers have contemplated the origin of graded muddy matrix conglomeratic sedimentation units in the Cerro Toro Formation, as it is apparent that they are not characteristic deposits of debris flows or turbidity currents (cf. Middleton & Hampton, 1976; Lowe, 1982). As the units are characterized by evidence of cohesional and turbulent clast-support, they are perhaps best classified as slurry flow deposits (cf. Lowe & Guy, 2000; Crane, 2004). Winn & Dott (1979) first proposed three possible mechanisms for the development of these units: (i) competence of the gravity flow decreased as it evolved, resulting in the settling of large clasts to a traction-dominated bed-load (cf. Hampton, 1975); (ii) flows started off turbulently and deposited the basal clast-supported zone, transforming into flows with more cohesive strength because of the incorporation of mud; and (iii) turbidity currents were generated from (and outran) parental debris flows (cf. Hampton, 1972). Sohn *et al.* (2002) studied these units in the region of Torres del Paine (Fig. 1A) and favoured an origin similar to the third hypothesis discussed by Winn & Dott (1979): that debris flows were diluted as they moved across the basin floor through detachment and disintegration of an overhanging (hydroplaning) debris flow snout (cf. Mohrig *et al.*, 1998). Sohn *et al.* (2002) suggested that the proportion of IIImcg deposits would decrease down-system as a result of this transformation; however, this is not the case as muddy matrix conglomerate deposits are, in fact, quite abundant down depositional system from where Sohn *et al.* (2002) focused their research (Crane, 2004). Winn & Dott (1979) discounted their first hypothesis for beds characterized by fluted bases; traction carpets and normal grading of clasts and matrix material also support the notion that turbulence was an important factor during sedimentation (Crane, 2004). The abundant mud rafts noted in the upper parts of these sedimentation units suggest that the transformation of these gravity flows took place because of the addition of eroded mud from channel (or canyon) margins, marginal basin slopes and from the channel floor (Winn & Dott, 1979; Hubbard *et al.*, 2007b).

Thick-bedded sandstone (IIIss)

Thick-bedded sandstone is an important third-order architectural element in the Lago Sofia Member (*ca* 5% to 10% of interval in places), and the surrounding fine-grained strata locally (Fig. 5A to C). Packages of this element 10 to 100 m in thickness are laterally mappable over distances of < 1 to 2 km. Sedimentation units are typically identifiable in the field, 25 to 100 cm thick (maximum 4 m), ranging from highly lenticular to planar structures. Mudstone beds (<4 cm to 1 m thick) are rarely associated with IIIss within the Lago Sofia Member, as sandstone units are often amalgamated; mudstone layers are more common, however, where IIIss is present in the fine-grained succession that surrounds the Lago Sofia Member. In some instances, lenticular beds comprise channelform bodies up to 400 m wide and 40 m thick in the fine-grained strata lateral to Lago Sofia conglomerate. Normal grading of the sandstone beds (medium-grained to coarse-grained at the base to fine-grained and very fine-grained towards the top) is common, with thin inversely graded layers (<5 cm thick) at the bases of units locally (traction carpets). Sandstone matrix-supported pebble and granule lags up to 20 cm thick, consisting of disorganized or traction-structured extrabasinal clasts, and mudstone rip-up clasts are common. Sedimentation units are dominantly structureless, locally characterized by dish structures or fluid escape pipes (Fig. 5A), or an upward systematic change in traction structures (Bouma sequence; Fig. 5B). Cross-stratification is abundant locally. In some beds, alternation of Bouma divisions indicates that surging gravity flows were common. Soft sediment deformation, flame structures along intra-sedimentation unit planes and at bed boundaries, load structures and climbing ripples are each important locally (Fig. 5C). Sole marks, including flute casts and tools, are commonly observed on the bases of overhanging beds. Trace fossils are rarely present, including *Palaeophycus*, *Planolites*, *Ophiomorpha* and *Teichichnus*.

Beds of IIIss were deposited from high-density and low-density turbidity currents. Structureless beds represent the suspension fall-out from collapsing high-density flows (S_3 divisions of Lowe,

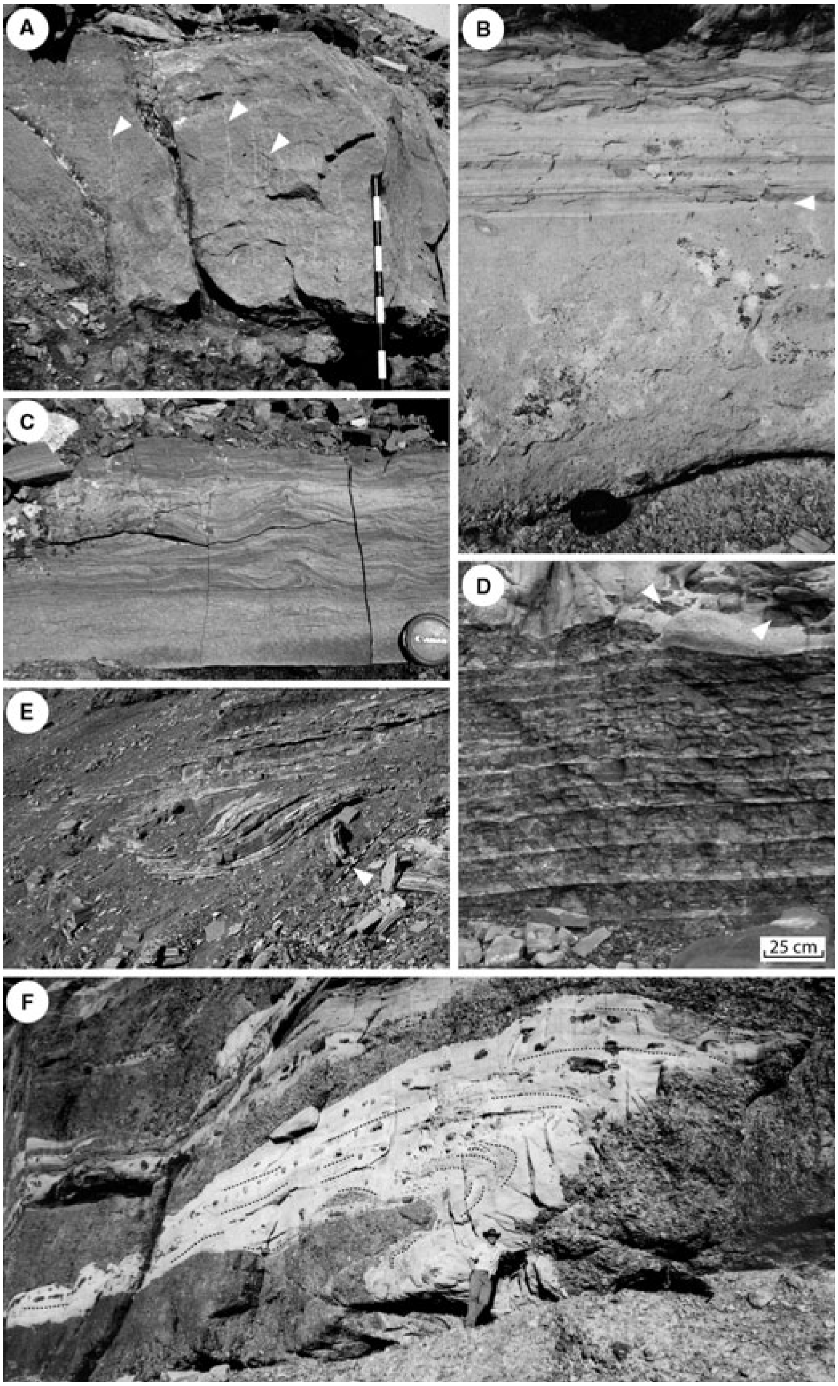

Fig. 5. Third-order architectural elements of the Cerro Toro Formation. (A) Thick sandstone unit (IIIss) characterized by abundant fluid escape pipes (arrows). Divisions on staff are 10 cm long. (B) Turbidity current deposit (IIIss) with a thick, massive lower division, a distinctive break (arrow), and an overlying Bouma sequence (dominated by plane laminations and ripples). Lens cap for scale in (B) and (C) is 58 cm in diameter. (C) Low-density turbidity current deposit characterized by soft-sediment deformation (IIIss). (D) Thin-bedded turbidites consisting of fine-sandstone and siltstone beds <5 cm thick (IIIsm) with an overlying scour surface characterised by angular mudstone rip-up clasts (arrows). (E) Overturned slump deposit (IIIch) associated with interbedded sandstone and mudstone (arrow points to 1·5 m long Jacob staff for scale). (F) Large-scale slump in the conglomeratic Lago Sofia Member. Slumping was to the right (south); dashed lines highlight laminae within the deposit. Person for scale is 195 cm tall.

1982); traction carpets and cross-stratification are also consistent with the interpretation that deposition was from high-density turbidity currents (S_2 and S_1 divisions of Lowe, 1982). The Bouma (1962) sequence is indicative of waning, low-density turbulent flows; beds characterized by thick structureless intervals, overlain with a 20 to 30 cm thick traction structured layer, record deposition from the high-density front of a turbulent flow followed by sedimentation from the low-density turbidity current tail (Fig. 5B).

Thin-bedded sandstone and mudstone (IIIsm)

Although thin-bedded sandstone and mudstone is the most abundant third-order architectural element in the Cerro Toro Formation (Fig. 5D), it is almost completely absent from the Lago Sofia Member. The percentage of sandstone beds in this element is highly variable; the sandstone:mudstone ratio is highest (0·3 to 0·6) proximal to the Lago Sofia Member, both laterally, as well as above and below. Sandstone beds are usually tabular and <20 cm thick (typically 4 to 8 cm), although some beds are lenticular over tens of metres, up to 1 m thick, and characterized by locally erosive bases. Partial to complete Bouma sequences (ripples and plane lamination) are characteristic of the normally graded (upper fine-grained to very fine-grained sandstone and silt) beds, although these divisions are often distorted by soft sediment deformation. Climbing ripples are common to IIIsm in some localities. Organic detritus and mudstone rip-up clasts are locally abundant, particularly in lenticular beds. Flute casts and tool marks are observed on bed bases. Evidence for biogenic reworking is moderate to abundant, the trace fossil suite consisting of *Alcyonidiopsis*, *Arenicolites*, *Chondrites*, *Gyrolithes*, *Helminthoida*, *Helminthopsis*, *Ophiomorpha*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Scolicia*, *Skolithos*, *Spirophyton*, *Thalassinoides* and *Zoophycos*.

Thin-bedded sandstone and mudstone represents deposits of low-density turbidity currents and hemipelagic suspension settling, predominantly in regions outside the main axial channel belt thalweg in the Cerro Toro Formation. Chaotic beds with deformed internal architecture (IIIch) are commonly associated with IIIsm.

Chaotic units (IIIch)

Chaotically bedded, or distorted units (IIIch) represent a volumetrically small, yet sedimentologically significant component of the Cerro Toro Formation, both in the Lago Sofia Member (Fig. 5F) and associated with the fine-grained deposits which encase it (Fig. 5E). IIIch in the Lago Sofia Member is highly irregular in thickness, up to a maximum of 8 m and the basal contact is planar. The internal architecture of units is dominated by distorted and overturned primary laminations (Fig. 5F). IIIch interbedded with packages of the fine-grained IIIsm are commonly <3 m thick, although the maximum observed thickness is 10 to 15 m. A distorted internal architecture, as well as the presence of overlying lenticular sandstone beds (IIIsm or IIIss), is characteristic of these units.

Units of IIIch represent remobilized sedimentary layers generated from slumping and sliding on sloped surfaces (in the Lago Sofia Member and in surrounding fine-grained deposits), as well as large-scale rafted sediment blocks (preserved preferentially in the fine-grained succession associated with IIIsm). Slump-generated topography on the sea floor influenced the distribution of sediment from subsequent gravity flows, as evidenced from the presence of lenticular sandstone beds on top of slumped units locally (Fig. 5E).

Fourth-order and fifth-order architectural elements

It is at the scale of fourth-order elements that the depositional system architecture can start to be defined, as the lateral and vertical relationships between the various lithofacies (i.e. third-order elements) and the geometrical bodies that they comprise are considered (Fig. 3). The types of fourth-order architectural elements associated with deposition in the Lago Sofia conglomerate (axial channel belt thalweg) include: (IV_1) – relatively planar-bedded packages dominated by sandy matrix conglomerate (IIIscg with subordinate IIImcg, IIIss and IIIch); (IV_2) – relatively planar-bedded packages dominated by muddy matrix conglomerate (IIImcg with subordinate IIIscg and IIIss); (IV_3) – randomly stacked conglomerate and sandstone (IIImcg, IIIscg and IIIss) associated with significant scour; and (IV_4) – intervals dominated by thick-bedded sandstone (IIIss, and lesser IIImcg and IIIscg; Table 1). Individual genetic sedimentary bodies, most commonly that of a channel fill in the study area (Fig. 3), are typically comprised of a single fourth-order element. One fourth-order element type is recognized in out-of-channel strata (IV_5), characterized by an abundance of IIIsm, and sporadic occurrences of IIIch and thick accumulations of IIIss. Through the collective consideration of fourth-order elements, the sedimentary processes and facies distribution of the axial channel belt strata as a whole (fifth-order element) are assessed.

Lago Sofia Member conglomerate architectural elements

IV_1, IV_2 and IV_3 dominate the conglomeratic succession in the Cordillera Manuel Señoret. In the northern and central part of the study area, associations IV_1 and IV_2, consisting of relatively planar packages of primarily sandy conglomerate and primarily muddy conglomerate, respectively (each 40 to 80 m thick), systematically alternate through the stratigraphic column (Fig. 6). Evidence of deep scour and extensive erosion is largely absent, in a region where the Lago Sofia conglomerate is at least 8·5 km wide (in an east–west orientation, perpendicular to the basin axis; Fig. 1A).

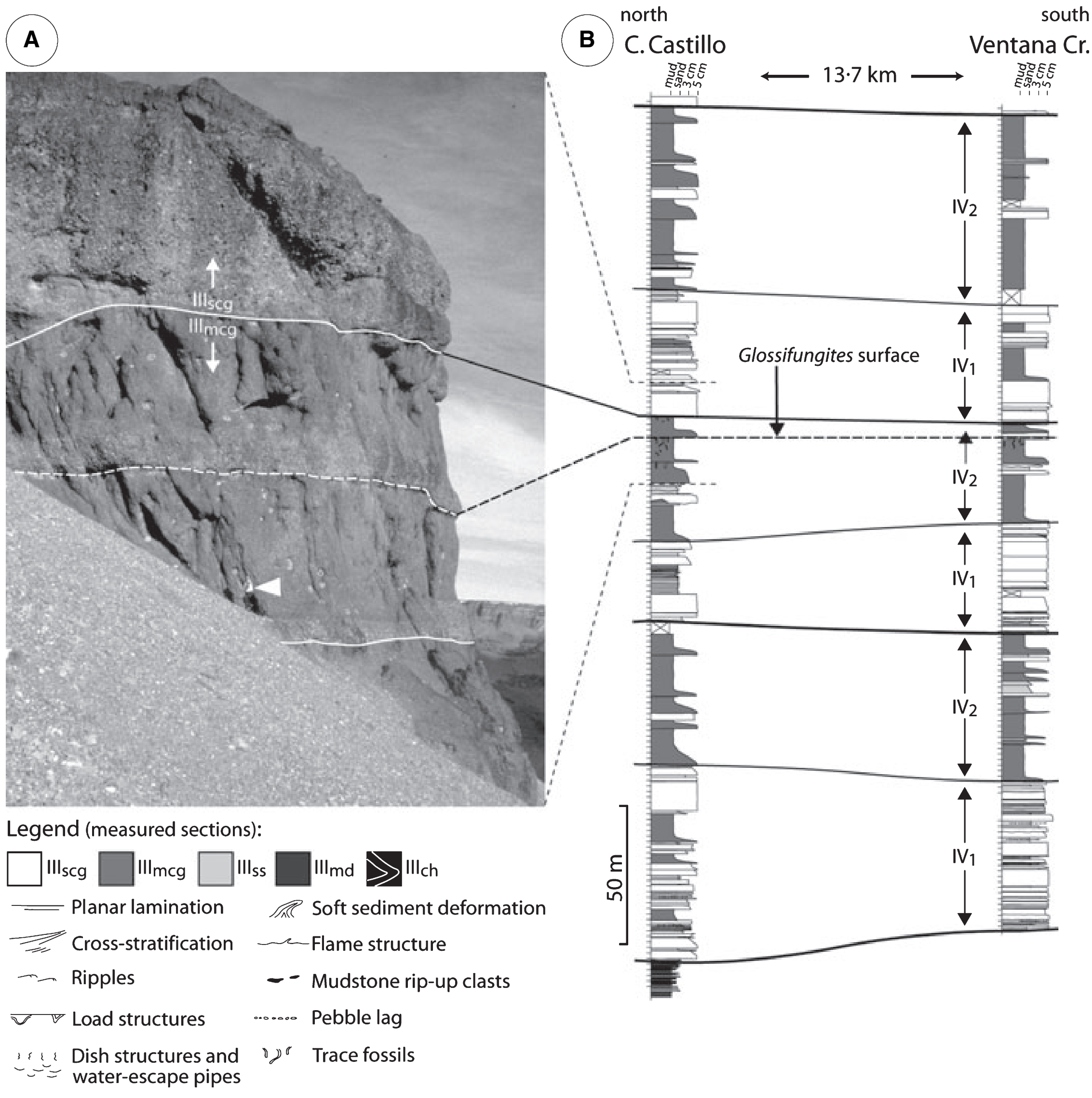

Fig. 6. Fourth-order architectural elements IV_1 and IV_2 in the Lago Sofia Member conglomerate. (A) Outcrop photograph of stacked sedimentation units of IIImcg overlain by a thick IIIscg bed (arrow points to person for scale – 160 cm tall). (B) Stratigraphic cross-section through the north–north central part of the study area showing the alternating packages of dominantly sandy matrix conglomerate (IV_1) and muddy matrix conglomerate (IV_2) characteristic of the channel belt thalweg in the area. The datum utilized is a horizon characterised by distinctive trace fossils of the *Glossifungites* ichnofacies, which can be correlated over much of the channel belt axis. See Fig. 1B for section locations. Legend at lower left consists of symbols and lithologic fill colours used in each of the measured sections depicted in the paper.

The first researchers to examine the formation in this area interpreted a glacio-fluvial channel origin for the conglomerate beds (IIIscg) (Cecioni, 1957); indeed, the dominance of traction structures in sandy conglomerate makes a braided fluvial channel interpretation understandable. In fact, the sedimentary processes that shaped these layers were probably not too far from what Cecioni (1957) interpreted; given the era in which the strata were examined, it would have been difficult to imagine that these processes were possible at the bottom of an ocean basin 1 to 2 km deep. The abundance of low-angle cross-lamination, imbricated clasts indicating a range of palaeoflow directions (45° to 90° spread commonly), erosional incision with low to moderate levels of relief, and lateral pinch-out and interfingering of conglomerate with sandstone units, are all typical of braid bars from fluvial systems (Schlee, 1957; Smith, 1974; Miall, 1992). The interpretation of braided channel characteristics or morphology in the deep-sea, or in ancient deep-sea deposits, is widespread (Hein & Walker, 1982; Beldersen *et al.*, 1984; Piper & Kontopoulos, 1994; Harrison & Graham, 1999), and is used to explain the depositional nature of thick packages of traction-structured IIIscg units in the Cerro Toro Formation.

Thick layers of IIImcg in IV_2 (Fig. 6) are distinct from the stratified intervals of IIIscg in IV_1, and their formation involved a distinctive set of sedimentological processes. Alternating periods where fine-grained material is more, or less, available to the depositional system are not easily explained, but are probably important in understanding the observed stratigraphic architecture (Fig. 6). Relative sea-level lowering (tectonically or eustatically induced) may starve the basin of coarse-grained material periodically (cf. Posamentier *et al.*, 1991), allowing the build up of an extensive mud and silt drape that is subsequently reworked (into muddy conglomeratic flows) when gravel is re-introduced to the basin. However, thick intervals of fine-grained concordant beds are not extensively preserved in the thalweg of the axial channel belt (Lago Sofia Member). The lowering of sea-level has also been observed to destabilize the upper slope, instigating mass-wasting of fine-grained material onto the basin floor (Posamentier *et al.*, 1991). Again, large-scale mass-transport complex deposits are not preserved in the Lago Sofia Member to support such a hypothesis; however, associated chaotic beds (IIIch) are present in laterally equivalent, out-of-channel deposits (Fig. 5E). Sporadic tectonic activity in the Andean catchment area could have been responsible for variable sedimentary input into the basin; however, conclusive evidence to support such a theory has not been observed. Trace fossils of the *Glossifungites* ichnofacies characterize the top of one of the thick, muddy matrix conglomerate-dominated intervals (surface identified in Fig. 6). Hubbard & Shultz (2008) indicate that the amount of time necessary to develop the burrowed horizon is not insignificant and that it probably represents an important discontinuity. Despite this, a cause for the alternation of muddy (IV_2) and sandy conglomerate units (IV_1) in the northern part of the study area remains uncertain, and it is possible that an external forcing mechanism is not responsible for the observed stratigraphic stacking pattern (Smith *et al.*, 2005).

Palaeocurrent measurements indicate that the channel belt flowed in a southerly direction (Scott, 1966; Winn & Dott, 1979). Downstream, in the southern part of the study area at Cerro Benitez (Fig. 1A), the internal architecture of the Lago Sofia Member is significantly different than it is to the north. The widespread, tabular sedimentary packages of IV_1 and IV_2 are replaced by more randomly stacked conglomerate (IIIscg and IIImcg) and sandstone beds (IV_3; Fig. 7); scours are much more prevalent and traction structures in sandy matrix conglomerate beds are distinctive. Specifically, the large-scale dunes identified by Winn & Dott (1977) are nearly exclusive to the southern part of the study area; larger-scale barforms in the order of 15 m high are also present (Fig. 7). Coincidently, the width of the Lago Sofia Member conglomerate outcrop narrows considerably to <5 km (Fig. 1A). The study interprets that the narrowing of the outcrop belt directly reflects the narrowing of the channel belt. The decrease in channel belt width is quite possibly responsible for the observed changes in the downstream sedimentologic and stratigraphic architecture of the channel strata, implying that at least some of the gravity flows that passed through the channel belt felt both margins of the 4 to 8 km wide constriction. Alternatively, the change in channel belt width was associated with a steepening of the depositional slope. Flow non-uniformity associated with downstream constriction (and/or slope variation) along the channel system resulted in an increase in velocity, which was closely linked to an increase in erosion and scouring (cf. Gee *et al.*, 2001; Gee & Gawthorpe, 2006). When evaluating Quaternary sediments on the Monterey Fan, Fildani & Normark (2004)

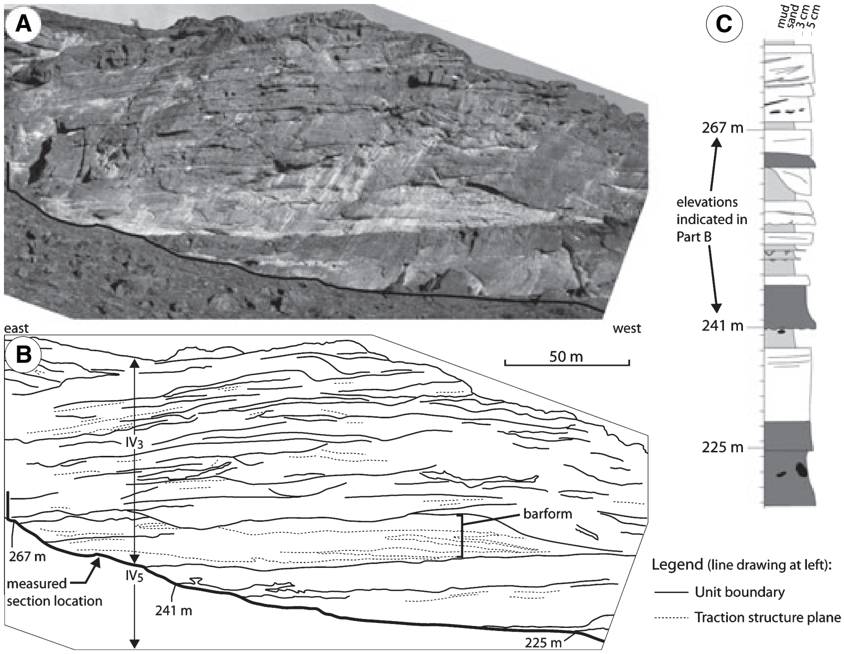

Fig. 7. Fourth-order architectural element IV_3 in the Lago Sofia Member conglomerate. (A) Photograph and (B) line-drawing trace of the complicated internal architecture of the channel belt in the southern part of the study area (location is Cerro Benitez; Fig. 1B). Numerous scours and a large-scale barform (identified in part B) are present in this element, and the stacking of sedimentary units is not ordered (C), in contrast to architectural elements IV_1 and IV_2. Note that the legend for features in the measured section is shown in Fig. 6.

made a similar observation which was attributed to flow non-uniformity; along the length of a channel system, slope gradient changes related to local sea floor topography resulted in the development of a series of ponded areas (characterized by tabular turbiditic sediment) connected by erosional channel conduits.

Architectural element IV_4 is dominated by thick successions of turbiditic sandstone beds (IIIss) within the Lago Sofia Member of the Cerro Toro Formation (Fig. 8). It is most prevalent at the top of the conglomeratic sequence (Fig. 1C), indicating an overall waning of deposition in the axial channel belt. Localized lenses of IV_4 <20 m thick are also present in numerous stratigraphic levels throughout the Lago Sofia Member, commonly associated with channelform bodies 20 to 300 m in cross-sectional width.

Regional channel belt observations and interpretations

The downstream decrease in channel belt width had a profound effect on the internal stratigraphic architecture of the Lago Sofia Member, as evidenced from the change from dominance of IV_1 and IV_2 in the north to that of IV_3 in the south. Mapping the present outline of channel belt conglomerate outcrops in the Cordillera Manuel Señoret shows that sediment distribution is contained within a belt that not only narrowed southward, but was also characterized by a sinuous planform (Fig. 9). To evaluate whether this mapped sediment distribution is not partially a function of fortuitous Quaternary glacial erosion, a vast number ($n > 2500$) of palaeocurrent indicator measurements (from clast imbrications, flute casts, tool marks, ripples and dune foresets) were taken in the field area. Including only measurements from an interval from 100 to 300 m above the base of the thick, Lago Sofia Member conglomerate, rose diagrams are shown to document downstream variability in average palaeocurrent vector from various locations in the channel belt (Fig. 9). In every case, the mean palaeoflow vector roughly parallels the sinuous channel belt margins defined by outcrop mapping of the Lago Sofia Member, suggesting that the mapped planform geometry reflects the architecture of the depositional system. Palaeocurrent measurements and mapping of previous authors confirm this relationship (Fig. 9), and also allow for a more regional palaeogeographic reconstruction of the channel belt. In particular, measurements of Scott (1966) and Crane (2004) in the Silla Syncline, and Hubbard *et al.* (2007a) at Sierra del

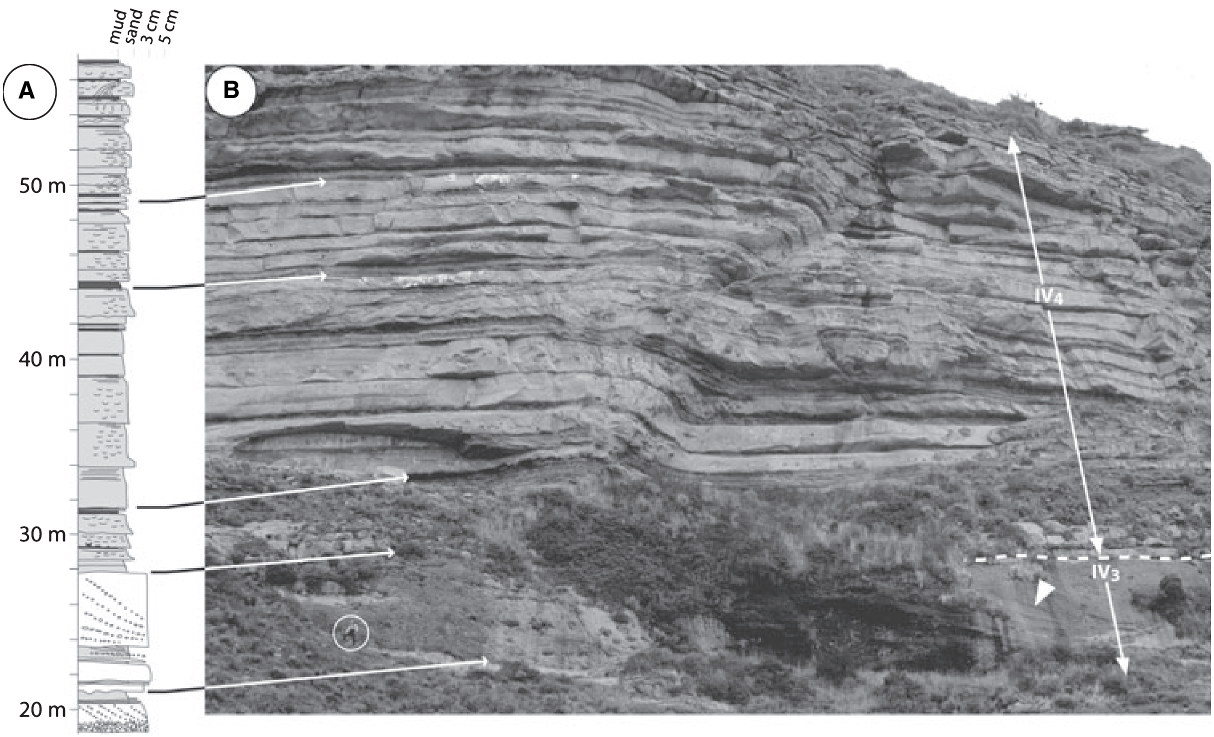

Fig. 8. Fourth-order architectural element IV_4 in the Lago Sofia Member. (A and B) Thick-bedded sandstone is common within the axial channel belt locally, particularly at the top of the coarse-grained sequence (location is Cerro Benitez; Fig. 1B). Conglomeratic interbeds are characterised by large-scale dunes up to 4 m high (at *ca* 25 m in measured section in part A; indicated by arrow in part B). Note person (circled) for scale (160 cm tall) at lower left of photograph in part B.

Toro suggest that two tributaries fed the axial channel belt from the NNW (Fig. 9). Although the data shown from the Silla Syncline and Sierra del Toro are from an apparently comparable stratigraphic level (within the coarse-grained succession) to that plotted from the Cordillera Manuel Señoret, the correlation of units between locations is difficult because of extensive glacial erosion of the formation (particularly in the area of Lago Toro); the basin-scale channel belt outline presented in Fig. 9 (where defined by dashed lines) is therefore speculative.

Fine-grained out-of-channel deposit architectural element

The fourth-order element defined from fine-grained out-of-channel strata that is present lateral to the Lago Sofia conglomerate is not only dominated by thin-bedded turbidites (IIIsm), but is also characterized by the presence of chaotic deposits (IIIch), and discrete bodies of thick-bedded sandstone (IIIss) locally (IV_5; Fig. 10). Similar deposits from the Silla Syncline to the north (Fig. 1) have been the source of considerable debate, specifically related to whether they originated from flows that spilled over the banks of the channel system (levée deposits), or are genetically unrelated to the conglomeratic channellized deposits (Winn & Dott, 1979; DeVries & Lindholm, 1994; Coleman, 2000; Beaubouef, 2004; Crane, 2004). Detailed observations of the Cerro Toro Formation at Silla Syncline were not made in this study.

Numerous characteristics of the thin-bedded sandstone and shale of IV_5 (juxtaposed against conglomeratic channel deposits) reveal its nature: do they have an overbank flow origin or not? Palaeocurrent measurements, lateral sandstone bed thickness and tabularity, evidence for a depositional slope, and vertical grain-size and bed thickness trends can all yield insight into answering this question (Hickson & Lowe, 2002). Figures 11 and 12 show outcrop exposures of the channel margin on the north faces of Cerro Mocho and Cerro Benitez, respectively (see Fig. 1B for location), where tests were carried out to determine the nature of out-of-channel deposits in the study area.

The channel margin at Cerro Mocho is characterized by a stepped profile over a distance of >2 km (Fig. 10A). Sandy turbiditic strata (IV_4) onlap the sharply defined margin of the channel-

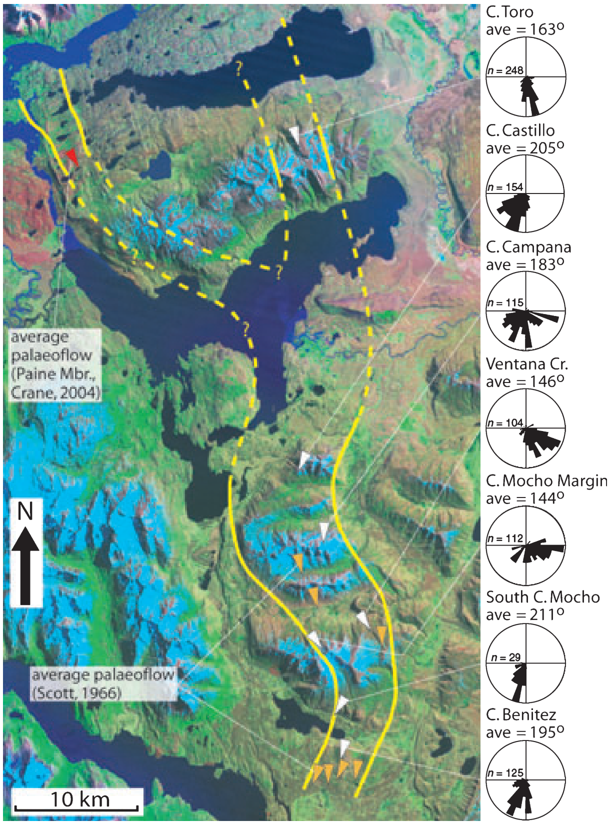

Fig. 9. Mapped conglomeratic outcrop distribution (defined by yellow lines) and mean palaeocurrent measurements within the middle part of the Lago Sofia Member (outline of map area is shown in Fig. 1A). In the Cordillera Manuel Señoret study area (from Cerro Castillo to Cerro Benitez) the sinuous nature of the channel belt is apparent due to the alignment of mean palaeocurrent vectors with the outlined distribution of coarse-grained channel facies; the lack of correlatable exposures to the north of the study area makes the interpretation of this relationship more tenuous, but it is apparent that at least two tributaries fed into the channel belt in the study area. Rose diagrams indicate the number and variability of palaeocurrent vectors in a given location; the arrows indicate the location where measurements were made and the mean flow direction is also indicated.

form body at its westernmost termination (Fig. 10B); a series of palaeocurrent measurements were made from laterally equivalent beds on either side of this margin, and in a thin (<4 m) fine-grained interval that drapes or laps onto the channel margin (cf. Grecula *et al.*, 2003; Fig. 11). Imbricated clasts were measured in conglomerate units, sole marks on the bases of thick-bedded and thin-bedded turbidity current deposits on either side of the channel margin, and ripple foresets in thin out-of-channel sandstone beds. Measurements from within the channel indicate that palaeoflow was to the south-east (mean vectors of 119° to 161°), whereas out-of-channel flows diverged 56° to 98° to the south-west (Fig. 11). A similar amount of divergence is recognized between average palaeocurrent vectors in channel and laterally adjacent out-of-channel deposits at Cerro Benitez (Fig. 12). This flow divergence is consistent with levée deposition as observed in modern settings (Piper & Normark, 1983; Hiscott *et al.*, 1997; Fildani & Normark, 2004), measured from ancient successions (Morris & Busby-Spera, 1990; Hickson & Lowe, 2002), and inferred from ancient overbank lobe deposits associated with levées recognized in 3D seismic data sets (Posamentier & Kolla, 2003; De Ruig & Hubbard, 2006).

Thinning of sandstone beds distally, away from a channel margin has been documented from modern levée deposits (Piper & Deptuck, 1997), and has been interpreted in the Cerro Toro Formation at the Silla Syncline (Beaubouef, 2004). Sandstone and siltstone beds associated with out-of-channel deposits at Cerro Mocho are typically <5 cm in thickness (Figs 5D and 10C) but, because of the excellent outcrop exposure, can be traced for tens to >100 m (Fig. 10B). Two stations at two stratigraphic levels are indicated on Fig. 10B, where sandstone bed thicknesses were examined to capture any systematic bed thickness changes distally, away from the axial channel belt margin. At both levels, the average sandstone bed thickness was *ca* 3 cm directly adjacent to the channel belt. Approximately 115 m from the channel margin at horizon 1 (Fig. 10B), the average bed thickness was 2·2 cm. At horizon 2, the average bed thickness dropped to 1·7 cm over a lateral distance of *ca* 55 m (Fig. 10B). Bed thinning is consistent with a levée interpretation for deposits of IV_5 at Cerro Mocho. As a result of discontinuous exposure of associated units at Cerro Benitez, laterally tracing out-of-channel sandstone beds is not possible.

Successions of levée strata are characterized by upward fining and bed-thinning successions attributed to increasing channel relief over time associated with levée buildup (Manley *et al.*, 1997). Upward fining is accomplished over variable stratigraphic thickness, from tens of metres to hundreds of metres. Frequent up-channel bifurcations and avulsion events result in the development of numerous, relatively thin upward-fining cycles as downstream levées are repeatedly abandoned and reestablished. Downstream of a stable reach of the channel where avulsions are infrequent, subtle and thicker upward fining cycles (>100 m) are preserved

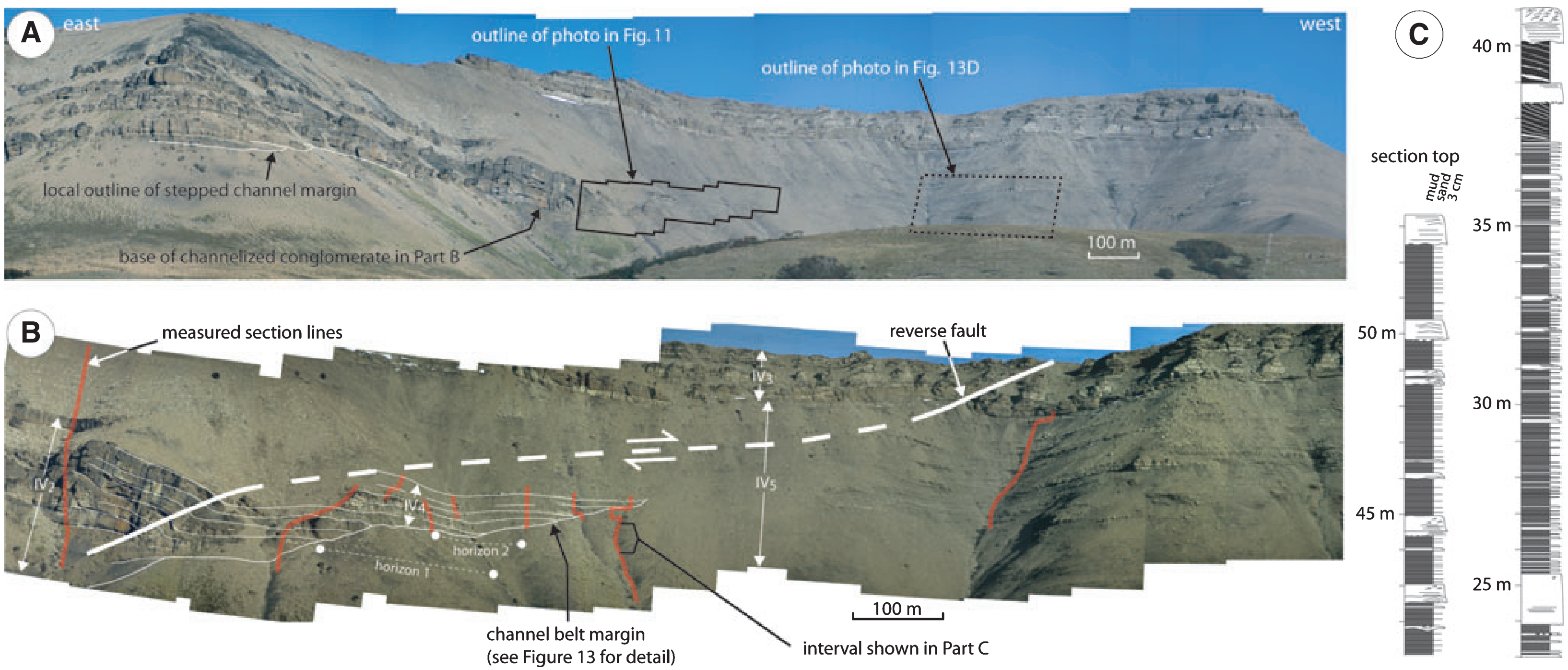

Fig. 10. Fourth-order architectural element IV_5 in the fine-grained out-of-channel deposits in the Cerro Toro Formation. (A) Overview of the channel belt margin on the north face of Cerro Mocho. Palaeoflow was into the plane of the outcrop. Note the stepped channel margin, and the locations of various outcrop photograph panels highlighted in the paper. (B) Close-up of the channel (architectural elements IV_2 and IV_4) and laterally equivalent fine-grained units (IV_5). A series of sections were measured in the area (highlighted by red lines), including that shown in part C through the fine-grained deposits of IV_5. Note the identified horizons 1 and 2 beneath the channel belt margin in part B, along which lateral bed thickness changes were documented. The legend for features in the measured section is shown in Fig. 6.

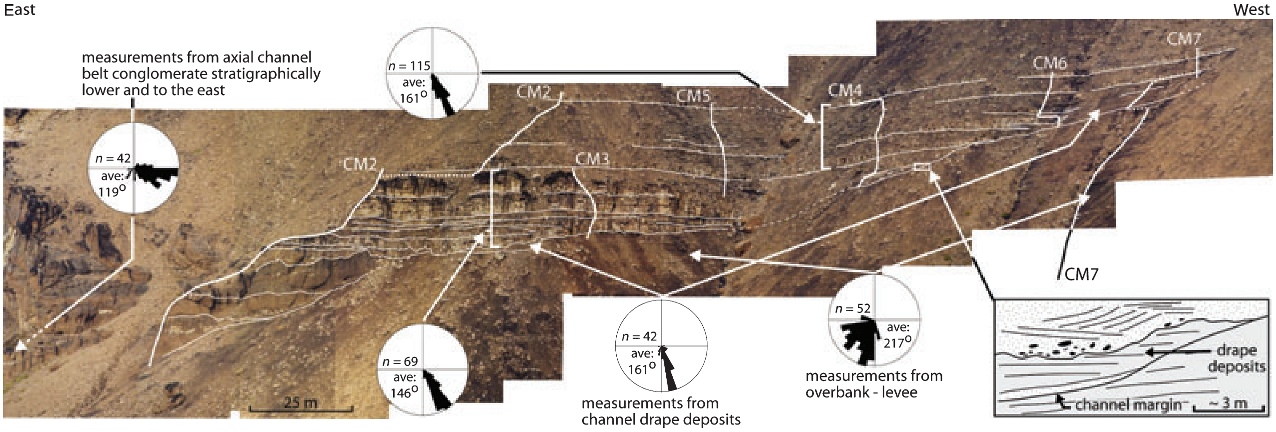

Fig. 11. Close up of channel margin at Cerro Mocho (see Fig. 10A for location) showing the divergent mean palaeocurrent measurement vectors from within the channel belt and in laterally equivalent overbank deposits. A fine-grained layer is present draping, and locally on lapping the channel margin in this location, as illustrated in the inset at the lower right.

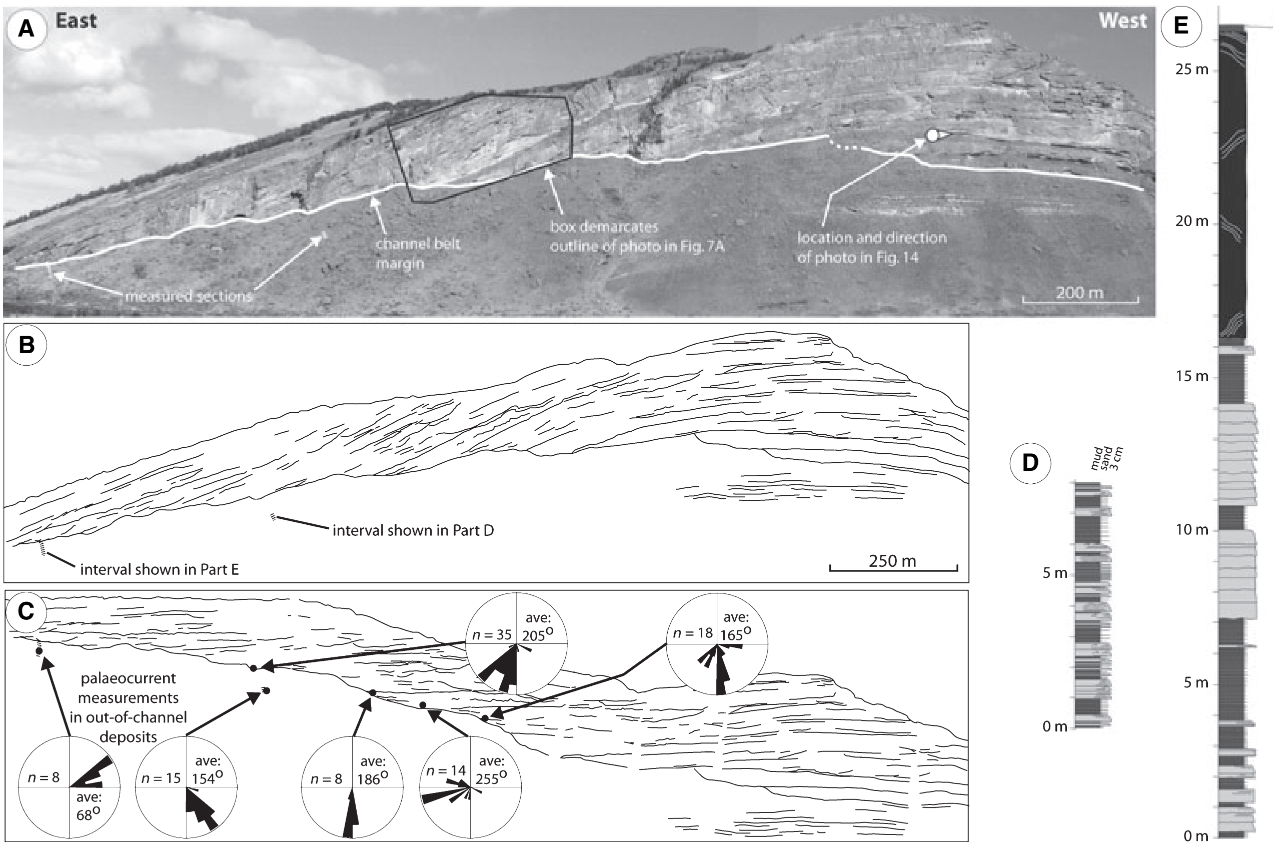

Fig. 12. Photomosaic (A) and line drawing trace (B) of the channel margin exposed on the north face of Cerro Benitez (see Fig. 1B for location), characterised by monoclinally (northward) dipping strata. Palaeoflow was into the plane of the outcrop. The base of the conglomeratic cliff corresponds to the margin of the channel belt, as evidenced by the presence of fine-grained strata in underlying beds (measured section locations shown in parts A and B; measured sections shown in parts D and E). (C) Palinspastically restored margin from parts A and B, with rose diagrams showing palaeocurrent vectors in channel conglomerate (IV_3) and in equivalent overbank units of IV_5.

(Manley *et al.*, 1997). Upward-fining and bed-thinning successions in the Cerro Toro Formation have not yet been observed (Figs 10C & 12D). The authors interpret that this is due to the fact that the channel belt was stable, unable to avulse because of confinement in the foredeep axis. An upward fining succession of levée deposits in such a setting would be difficult to discern, as it would be observable over 100 m or more, representing the initial establishment of the channel belt levée and its slow overall increase in relief. The extensive outcrop of IV_5 at Cerro Mocho may offer the opportunity to observe such an upward fining succession, but the potentially subtle trend has yet to be observed; a more rigorous analysis is necessary to establish its presence or absence.

Common slumped beds (Fig. 5E) and soft sediment deformation (Fig. 5C) indicate that deposits of IV_5 were deposited on a slope, and are consistent with a levée interpretation for associated strata (Morris & Busby-Spera, 1990). Slump fold axes are predominantly oriented north–south, indicating that mass wasting occurred on slopes oriented parallel to the channel belt (e.g. levée). Because of the fact that overturned beds are typically not traceable to their point of attachment to underlying beds, however, the slump direction cannot be unequivocally determined in most cases.

Evidence that the fine-grained deposits of IV_5 were not highly consolidated during channel incision and sedimentation also supports the notion that channel deposits (IV_1 to IV_4) were not emplaced within a deep, erosional conduit. A stepped channel margin (Figs 10A and 13A), injection of coarse-grained channel material into adjacent out-of-channel units (Fig. 13B) and an undulous channel margin contact (Fig. 5D) indicate that the out-of-channel deposits were (relatively) poorly indurated during the emplacement of channel fill. These observations, along with those discussed above, are suggestive that the deposits of IV_5 accumulated on a levée. Furthermore, the presence of climbing ripples in deposits of IV_5, indicating high sediment fall-out from low-density turbidity currents, is common in levée environments where flows become unconfined as they spill over channel banks.

Thin-bedded sandstone and siltstone of IV_5 is notably tabular over at least hundreds of metres, typical of levée sequences. In contrast, beds 20 to 150 cm thick in this architectural element are coarser (up to medium-grained) and lenticular (Fig. 13C). These beds can be isolated and lenticular over 10 to 20 m (Fig. 13C), or part of channelform bodies hundreds of metres wide and tens of metres thick (Fig. 13D). Isolated beds are observed in close proximity to the channel margin, and may represent the fill of focused overbank flows that eroded and subsequently filled scours in the area (cf. Hickson & Lowe, 2002). Winn & Dott (1979) and Beaubouef (2004) interpreted similar beds at the Silla Syncline as crevasse-splay deposits. The larger channelform bodies are characterized by a significant fine-grained drape deposit overlain by on lapping thick-bedded sandstone units (Fig. 13D and E); the features are exclusively observed a significant distance (>1 km) from laterally equivalent axial channel conglomerate (Fig. 10A). Measurement of flute casts in these bodies at Cerro Mocho indicates that palaeoflow was nearly due south, more similar to the mean flow in the axial channel belt than that indicated in proximal out-of-channel deposits of IV_5 (Fig. 11); this is consistent with observations made in distal levée deposits by Hickson & Lowe (2002). It is probable that these features represent crevasse-splay or distributary channels (or scours), eroded and filled by focused overbank flow on the levée (cf. Normark *et al.*, 1979).

DISCUSSION

Channel–levée complex: architectural considerations

Channel belt fill morphology

Of the five major mountain peaks in the Cordillera Manual Señoret, Cerro Castillo, Cerro Mocho and Cerro Benitez (Fig. 1B) are characterized by the thickest preserved intervals of the Lago Sofia Member. The top of the coarse-grained interval is best observed at Cerro Benitez, and in eastward-dipping strata preserved at the eastern end of Cerro Mocho at Ventana Creek (Fig. 1B). The total thickness of the main Lago Sofia Member is 390 to 440 m. Channel belt fill is highly asymmetric, as evidenced from the gradual (stepped) thinning of the Lago Sofia Member from 390 m at its eastern margin (Ventana Creek; Fig. 6) to its western pinch-out at Cerro Mocho (Figs 10 & 11). The width of the channel belt varies, as discussed, but is in the order of 4 to 8 km (Fig. 9). The relief on individual steps associated with the margin (Fig. 10A), gives an indication of the stratigraphic thickness associated with the fill of an individual channel belt layer, or fourth-order architectural element (up to 60 to 100 m typically), and allows for the estimation of channel aspect ratio. Particularly high aspect ratios of 40 to 130 for the Cerro Toro Formation channel belt are consistent with observations of other major trunk channels or channel belts associated with coarse-grained fill

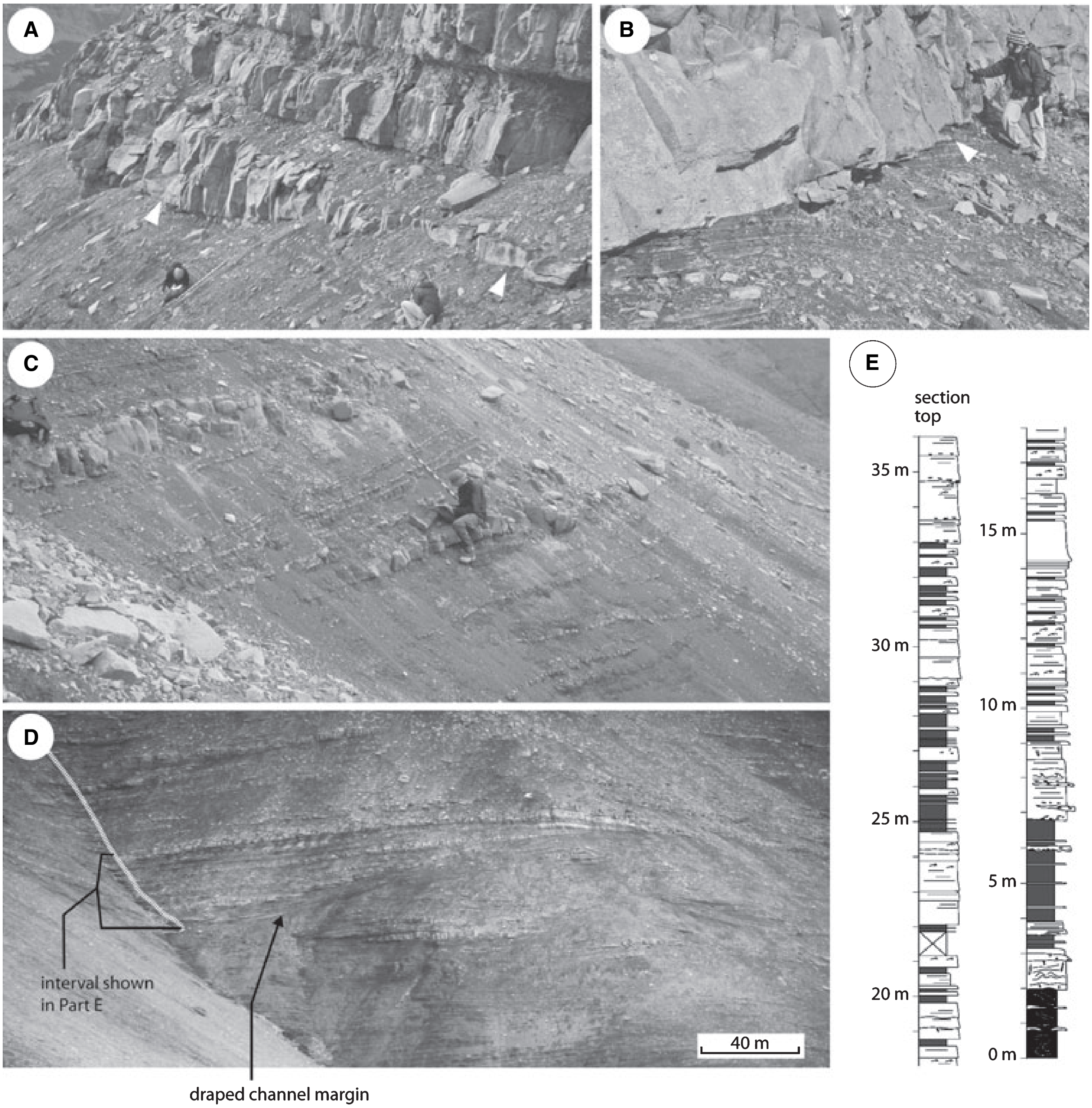

Fig. 13. Characteristics of channel margin and overbank deposits (IV_5) at Cerro Mocho. (A) Stepped channel margin (indicated by arrows); person at right is sitting on thin-bedded units that are in a laterally equivalent position to the thick-bedded channel sandstone present just above person at left (indicated by arrow on the left). Note 1·5 m long staff for scale. (B) Incisional channel margin contact with arrow pointing to sandstone injection into fine-grained overbank deposits. Person for scale is 175 cm tall. (C) Lenticular sandstone bed in fine-grained overbank succession (IV_5). Note staff with 10 cm long divisions for scale. (D) Channelform element associated with IV_5 characterised by basal drape and lenticular beds that onlap the margins of the feature. (E) The measured section through this channelform body shows that fine-grained slumped units characterize the base of the channel, and overlying sandstone beds are present in amalgamated and non-amalgamated packages. The legend for features in the measured section is shown in Fig. 6.

in the rock record (75 to 100, Eschard *et al.*, 2003; 50 to 80, De Ruig & Hubbard, 2006) and in modern settings (50, Kenyon *et al.*, 1995; *ca* 100, Klaucke *et al.*, 1998). The sinuosity of the channel belt in the study area (Fig. 9) is very low (1·06), again consistent with other major trunk channel systems (Klaucke *et al.*, 1998; De Ruig & Hubbard, 2006).

Inner levées

Inner levées, which form within the confines of large channel or channel belt conduits, have been demonstrated to be important depositional elements in many deep-water depositional systems (Hubscher *et al.*, 1997; Deptuck *et al.*, 2003). The features record flows associated with underfit channels; these underfit systems are contained within much larger conduits, whose original morphology was shaped by considerably larger flows. Evidence for the development of inner levées within the axial channel belt is interpreted locally near the base of the Lago Sofia Member at Cerro Benitez (Fig. 14). In this locality, a stepped channel margin profile bounding conglomeratic units, and interbedded sandstone and mudstone overbank units (inner levée deposits) are preserved; subsequent erosion within the channel belt was significant, as inner levée units cannot be traced laterally for greater than 25 to 50 m. The overbank sandstone beds are 10 to 50 cm thick on average, upper fine-grained to lower medium-grained, are massive with normally graded tops (horizontal laminations present locally), contain rare mudstone clasts and moderately abundant trace fossils (*Ophiomorpha* and *Palaeophycus*), and have sharp or loaded basal contacts. The mudstone interlayers are associated with thin silty beds characterized by ripples that indicate variable flow directions. An important criterion for inner levée deposit recognition is their presence within the confines of the coarse-grained channel belt fill; the deposits do not lie directly adjacent to levée deposits associated with the channel belt as a whole (i.e. the fine-grained member of the Cerro Toro Formation present lateral to the conglomeratic Lago Sofia Member). The coarseness, thickness and internal architecture of sandstone beds suggest that the relief on inner levées was not nearly as developed as that of the levées of IV_5 (Fig. 5D). Preservation of these inner levée deposits is not widespread, therefore, it is not possible to discern whether the features were rarely formed within the channel belt, or just associated with poor preservation potential due to intra-channel belt erosion.

Palaeogeographic reconstruction and the effect of basin confinement on the depositional system

It is well-established that the complicated architecture of foreland basins can impart a significant influence on the deep-water depositional systems that form within them (Ricci Lucchi, 1985; Mutti *et al.*, 1999; Kneller & McCaffrey, 1999; De Ruig & Hubbard, 2006). Interpreting the narrowing of the channel belt in the study area (Fig. 9) is not straightforward given the outcrop data available, although it seems probable that processes active along the western basin margin played an important role in constricting flow within the depositional system; the authors speculate that the differential eastward propagation of the active Andean fold-thrust belt significantly influenced channel belt behaviour, consistent with the interpretation by Wilson (1991) that the position of the western margin of the Magallanes basin was closely tied to the position of the Andean fold-thrust belt.

Based on interpretations from the present study, as well as the studies of recent researchers, a revised palaeogeographic reconstruction of the Magallanes basin during the time period when the middle part of the Lago Sofia Member was deposited is presented in Fig. 15. To account for deposition of the Cerro Toro Formation, Winn &

Fig. 14. The stepped channel margin present at the base of the Lago Sofia Member on the North Face of Cerro Benitez, with laterally equivalent inner levée deposits in the foreground at the left. Staff is 1·5 m long. See Fig. 12A for location.

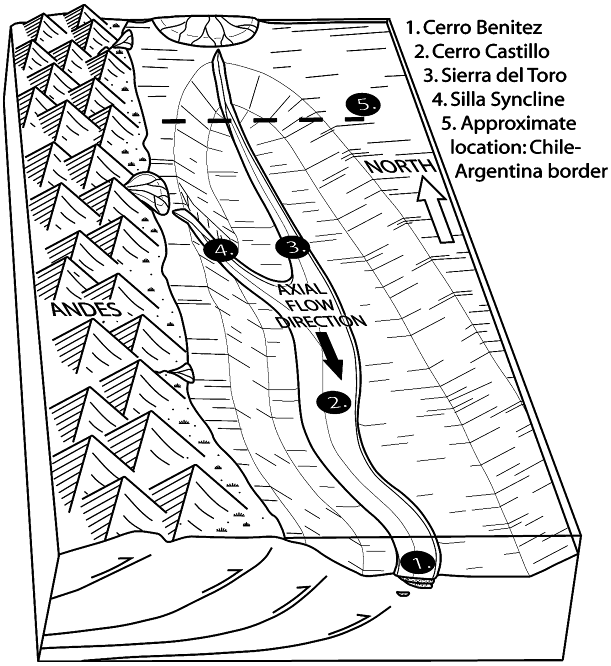

Fig. 15. Palaeogeographic reconstruction of the Magallanes basin during deposition of the middle part of the Lago Sofia Member (not to scale). Various outcrop and geographic localities are indicated. The axial channel belt was fed coarse-grained sediment from a delta to the north, and from conduits sourcing material directly from an Andean catchment area along the western margin of the basin. Outcrop observations and interpretations that have been incorporated into the diagram from this study (and from the study of Crane, 2004, Beaubouef, 2004 and Hubbard *et al.*, 2007a), include the presence of two tributaries in the north, the narrowing of the channel belt towards the south, and the sinuosity of the channel belt between Cerro Benitez and Cerro Castillo.

Dott (1979) envisioned a north- to south-oriented elongate submarine fan in the Magallanes basin, fed from a canyon-channel system that originated from the fold-thrust belt to the west, taking a sharp bend towards the south as it encountered the basin axis. Based on mapping of Upper Cretaceous non-marine strata to the north of the study area in Argentina, however, the deep Magallanes basin is also interpreted to have been delta-fed, from an axial fluvial depositional system (Fig. 15; Macellari *et al.*, 1989). Crane & Lowe (2001) and Crane (2004) have speculated that the channellized deposits of the Cerro Toro Formation at the Silla Syncline represent a conduit that fed the axial channel belt from the west (Fig. 15). Based on extensive faulting in strata to the east of the syncline, the authors considered a piggy-back setting for this conduit (Crane, 2004). Notably in the Silla Syncline area, coarse-grained units (conglomerate and sandstone) are present in a series of offset channelform sedimentary bodies separated by continuous mudstone layers (Beaubouef, 2004; Crane, 2004). Beaubouef (2004) recognizes numerous 'channel complexes' within each of the lenticular sedimentary bodies (channel complex sets). Conglomeratic deposition in the assumed basin axis proper (cf. Winn & Dott, 1979), is recorded by outcrops present at the eastern part of Sierra del Toro, and in the Cordillera Manual Señoret; patchy outcrops to the north of Sierra del Toro, and a thick succession of coarse-grained material at Cerro Rotonda, south of Puerto Natales, are also attributed to deposition in the basin axial channel belt (Fig. 1A). The stratal hierarchy used by Beaubouef (2004) is not easily defined in the Cordillera Manuel Señoret because of the amalgamation of channel complexes throughout the entire Lago Sofia Member. The fourth-order architectural elements as defined in this paper are conceptually equivalent to the channel complexes of Beaubouef (2004), although generally much wider (4 to 8 km in the study area vs. 500 m to 1·5 km at Silla Syncline). Although a series of distinct channel complex sets are recognized at the Silla Syncline, because of the amalgamation of units at the Cordillera Manuel Señoret, the entire stratigraphic succession of coarse-grained units is delineated as one immense channel complex set (fifth-order element). Stratigraphic correlations in the Cerro Toro Formation between the Silla Syncline and the Cordillera Manuel Señoret are a focus of a Stanford University group currently researching at Sierra del Toro (Bernhardt *et al.*, 2007), and may shed insight into the equivalency of units (i.e. channellized bodies) across the region. As discussed, the sinuous planform architecture of the axial channel belt between Cerro Castillo and Cerro Benitez is delineated based on outcrop distribution and palaeocurrent measurements (Fig. 9). A terminal sandy lobe has not yet been identified down-system of the channel deposits examined in this study; however, the Cerro Toro Formation (and equivalent units) further south have been understudied due in large part to inaccessibility.

The authors attribute major gravity flow initiation in the basin to delta front failure, on deltas fed from high-discharge rivers sourced from a mountainous Andean catchment area (cf. Normark & Piper, 1991). Well-developed traction structures, including 4 m high dunes, were formed through sustained gravity flow currents, perhaps originating from hyperpycnal flow generated in conduits dominated by fluvial systems characterized by high concentration of suspended sediment (Normark & Piper, 1991; Mulder & Syvitski, 1995), or by retrogressive slope failure (Hughes Clarke *et al.*, 1990). Gravelly traction structures, along with the paucity of sandstone and mudstone within channel belt deposits in the study area, indicate that a significant amount of sediment bypassed the area. Evidence of bypass associated with finer-grained, turbidity current tail deposits (Grecula *et al.*, 2003) are rarely observed in the axial channel belt, although their preservation potential in this depositional system is intuitively low. In support of this, a fine-grained drape overlying the channel belt basal scour is only preserved when overlain by sandstone beds at the margin of the channel belt (Fig. 11).

In modern passive margin settings, where large-scale channel–levée complexes have been studied in great detail (e.g. the Amazon Fan), understanding of the systematic downstream evolution of these depositional systems has developed based on a series of key observations. These include: (i) channel cross-sectional area decreases downstream (Flood & Damuth, 1987); (ii) channel slope decreases nearly uniformly downstream, associated with a decrease in channel sinuosity (Flood & Damuth, 1987); and (iii) the levée height decrease downstream corresponds to a coarsening of levée deposits (Hiscott *et al.*, 1997; Manley *et al.*, 1997). These characteristics from passive margins differ from those of a confined system such as the Magallanes basin. Changes in channel slope may periodically be non-uniform because of tectonic influences on the sea floor or basin margins (Fig. 9; De Ruig & Hubbard, 2006). Furthermore, input from conduits along the length of the channel belt complex (e.g. conglomeratic deposits of the Cerro Toro Formation at the Silla Syncline; Crane & Lowe, 2001) may significantly change the magnitude and composition of gravity flows that pass through, and subsequently form, the depositional system at various points along its length. Systematic downstream changes in channel behaviour and resultant sedimentary deposit characteristics, like those observed on the Amazon Fan (Flood & Damuth, 1987; Hiscott *et al.*, 1997) may not be expected in a confined, tectonically active setting like a foredeep.

Applications of study to hydrocarbon exploration

Deposits of large-scale deep-water channels in the sub-surface represent a common hydrocarbon reservoir target (Reeckmann *et al.*, 2003; Samuel *et al.*, 2003). Consequently, analogues from high-resolution seismic data sets (Kolla *et al.*, 2001; Abreu *et al.*, 2003; Deptuck *et al.*, 2003) and outcrops (Cronin *et al.*, 1998; McCaffrey *et al.*, 2002; Beaubouef, 2004) are commonly examined in order to better understand the stratigraphic architecture of channellized strata, and ultimately improve exploration success and exploitation strategies in similar deposits.

An exceptional sub-surface analogue to the axial channel belt complex in the Cerro Toro Formation is present in Oligocene–Miocene strata of the Austrian Molasse foreland basin (Fig. 16; Hubbard *et al.*, 2005). The Austrian depositional system is characterized by a low sinuosity axial channel belt 3 to 6 km in width (Fig. 16A), dominated by coarse-grained (sandstone and conglomerate) fill (De Ruig & Hubbard, 2006); thick successions of fine-grained units that surround the axial channel belt deposits accumulated, in part, in a levée environment (Fig. 16B), with additional input from the foredeep margins. An outcrop showing a cross-section of the entire (5 to 8 km wide) channel belt in the Cerro Toro Formation is not readily observed; therefore, the three-dimensionally imaged Austrian channel offers important insight into the architecture of the channel belt in the Cerro Toro Formation. The feature in the sub-surface of Upper Austria is asymmetric (Fig. 16A) and, as in the Cerro Toro Formation, the architecture of the Austrian channel belt and overbank sediment was strongly influenced by the margins of the narrow foredeep (De Ruig & Hubbard, 2006; Hubbard *et al*, 2008). Various elements of the Cerro Toro Formation are potentially analogous to reservoir deposits in the petroliferous Austrian Molasse basin, including those associated with deposits of the channel thalweg and margin, and overbank-distributary channels.

CONCLUSIONS

The Upper Cretaceous Cerro Toro Formation in the Cordillera Manuel Señoret was deposited in a 4 to 8 km wide deep-water channel belt with transport southward along the axis of the Magallanes basin foredeep. Exceptional outcrop exposures, including those of the channel margin in several localities, permit an interpretation of the genetic relationship between channel and out-of-channel deposits. Five fourth-order architectural elements characterize the sequence of strata in the

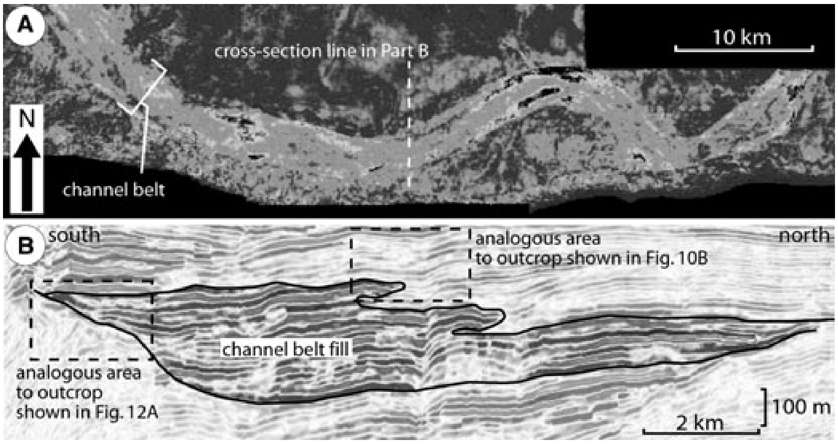

Fig. 16. Seismic characterization of Oligocene–Miocene strata from the Molasse basin of Austria (modified from De Ruig & Hubbard, 2006). (A) Plan view amplitude map showing a sinuous basin axial channel belt (characterized by bright amplitudes) surrounded by constructional, fine-grained overbank deposits (associated with darker amplitudes). (B) Seismic cross-section of the basin axial channel belt with outlined coarse-grained fill laterally juxtaposed against dimmer, finer-grained levée–overbank deposits (palaeoflow was out of the plane). The channel belt is 3 to 6 km wide and the channel fill succession in part B is *ca* 250 m thick. Like the channel belt in the Cerro Toro Formation, the fill is coarse grained (conglomeratic) and characterised by asymmetry. The two outlined boxes in part B are considered analogous to outcrop panels presented in Figs 12A and 10B.

Cerro Toro Formation. IV_1, relatively tabular layers of predominantly sandy matrix conglomerate 40 to 80 m thick is interbedded with IV_2, similarly tabular and thick layers of mostly muddy matrix conglomerate; these fourth-order elements were deposited in the axial channel belt in the northern part of the study area. More randomly distributed conglomeratic units with extensive erosional incision (IV_3) characterize the channel belt fill in the southern reaches of the study area. Successions of thick-bedded sandstone tens of metres in thickness, IV_4, are present locally within the channel belt, most notably at the top of the conglomeratic member of the Cerro Toro Formation and in channel bodies at the margins of the channel belt. Fine-grained levée-overbank units constitute IV_5.

A mapped downstream constriction of the channel system corresponds with a shift from tabular beds of IV_1 and IV_2 to more erosive and lenticular beds of IV_3. The axial channel complex is characterized by a sinuous planform architecture, as delineated from outcrop distribution and extensive palaeocurrent measurements. This architecture was affected by the tectonically influenced western basin margin slope.

The coarse-grained, gravel-dominated channel belt was associated with constructional overbank deposits consisting of interbedded sandstone and mudstone deposits (IV_5). Evidence that the fine-grained deposits accumulated on a levée to the axial channel belt (and that they do not represent older, genetically unrelated units) includes: (i) palaeocurrent measurements indicate that overbank flow diverged 50° to 100° from the mean flow direction in the channel belt; (ii) overbank sandstone beds thin laterally, away from the contact with coarse-grained channel belt deposits; (iii) sedimentological observations, including a stepped channel margin profile and lateral injection of channel material into adjacent overbank units, suggests that the fine-grained out-of-channel beds were not highly indurated when they were incised by channel belt processes; and (iv) presence of slumped units (associated with levée topography), and sandstone beds that show evidence of high sediment fall-out (attributed to flow unconfinement as it overspills the channel). Channelform bodies associated with overbank strata represent scours or distributary channels, formed and filled by overbank flow.

A systematic downstream change in channel character has been observed from large-scale channels from modern passive margins (e.g. the Amazon fan). It is apparent from observations of the Cerro Toro Formation in the tectonically active, confined Magallanes basin setting, that downstream changes in channel architecture and deposits are complicated by various factors. Local influences on channel behaviour, including: (i) variability in basin width and effects from lateral margin slopes; and (ii) the presence of multiple sediment sources or conduits along the length of the channel system, complicate the proximal–distal relationships that have been documented from large channel systems in passive margin settings.

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