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Sheetflow fluvial processes in a rapidly subsiding basin, Altiplano plateau, Bolivia

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ABSTRACT

Although facies models of braided, meandering and anastomosing rivers have provided the cornerstones of fluvial sedimentology for several decades, the depositional processes and external controls on sheetflow fluvial systems remain poorly understood. Sheetflow fluvial systems represent a volumetrically significant part of the non-marine sedimentary record and documented here are the lithofacies, depositional processes and possible roles of rapid subsidence and arid climate in generating a sheetflow-dominated fluvial system in the Cenozoic hinterland of the central Andes. A 6500 m thick succession comprising the Late Eocene–Oligocene Potoco Formation is exposed continuously for >100 km along the eastern limb of the Corque syncline in the high Altiplano plateau of Bolivia. Fluvial sandstone and mudstone units were deposited over an extensive region (>10 000 km^2) with remarkably few incised channels or stacked-channel complexes. The Potoco succession provides an exceptional example of rapid production of accommodation sustained over a prolonged period of time in a non-marine setting (>0·45 mm $year^{-1}$ for 14 Myr). The lower ≈4000 m of the succession coarsens upward and consists of fine-grained to medium-grained sandstone, mudstone and gypsum deposits with palaeocurrent indicators demonstrating eastward transport. The upper 2500 m also coarsens upward, but contains mostly fine-grained to medium-grained sandstone that exhibits westward palaeoflow. Three facies associations were identified from the Potoco Formation and are interpreted to represent different depositional environments in a sheetflow-dominated system. (i) Playa lake deposits confined to the lower 750 m are composed of interbedded gypsum, gypsiferous mudstone and sandstone. (ii) Floodplain deposits occur throughout the succession and include laterally extensive (>200 m) laminated to massive mudstone and horizontally stratified and ripple cross-stratified sandstone. Pedogenic alteration and root casts are common. (iii) Poorly confined channel and unconfined sheet sandstone deposits include laterally continuous beds (50 to >200 m) that are defined primarily by horizontally stratified and ripple cross-stratified sandstone encased in mudstone-rich floodplain deposits. The ubiquitous thin-sheet geometry and spatial distribution of individual facies within channel sandstone and floodplain deposits suggest that confined to unconfined, episodic (flash) flood events were the primary mode of deposition. The laterally extensive deposition and possible distributary nature of this sheetflow-dominated system are attributed to fluvial fan conditions in an arid to semi-arid,

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possibly seasonal, environment. High rates of sediment accumulation and tectonic subsidence during early Andean orogenesis may have favoured the development and long-term maintenance of a sheetflow system rather than a braided, meandering or anastomosing fluvial style. It is suggested here that rapidly produced accommodation space and a relatively arid, seasonal climate are critical conditions promoting the generation of sheetflow-dominated fluvial systems.

Keywords Altiplano, Andes, arid climate, sheetflow, subsidence, terminal fan.

INTRODUCTION

Study of fluvial systems commonly involves assignment of depositional style to one of three end-member models: braided, meandering or anastomosing rivers. In modern environments, such systems can be distinguished by comparing their plan-view morphology, channel migration pattern, sedimentary load and geometry and distribution of architectural elements and lithofacies in channels and floodplains regions. Modern settings also permit direct observation of the tectonic, climatic and eustatic influences on fluvial style. Quantitative models and controlled experiments further suggest that rivers developing under particular conditions of slope, discharge, sediment load and grain size will follow relatively predictable patterns of channel morphology, element geometry and lithofacies distribution (Bridge, 1985, 1993; Paola, 2000; Heller *et al.*, 2001). Hence, accurate interpretation of ancient fluvial systems is achieved by documenting the diversity, distribution and geometry of lithofacies and bar elements (Miall, 1977, 1985).

Each type of fluvial model has an established set of criteria distinguishing its morphology and facies distribution. Indicators of meandering streams include stratigraphic evidence of point-bar migration in a single sinuous channel and lateral channel migration across fine-grained floodplain regions (Allen, 1965; Davies, 1966). Evidence of systematic channel migration is provided by lateral-accretion surfaces and epsilon cross-bedding. In contrast, braided rivers exhibit bifurcating channel networks with numerous unstable channels and in-channel bars (Smith, 1970; Cant & Walker, 1976a,b; Hein & Walker, 1977). Diagnostic stratigraphic indicators of braided-stream deposition include multiple channel and bar elements exhibiting lateral and downslope accretion; these are rarely preserved in their entirety due to erosional scour of overlying channel deposits. Significant floodplain deposits are often considered rare in braided river deposits due to frequent lateral reworking (Miall, 1977, 1978, 1985). Anastomosing rivers are identified by intersecting, relatively straight, stable channels generally confined within a mud-dominated floodplain (Smith & Smith, 1980; Rust, 1981; Smith, 1986; Eberth & Miall, 1991; Gibling *et al.*, 1998). Anastomosing channel deposits rarely contain lateral bar elements or evidence of channel migration by lateral accretion. As a result of these generalizations, most sedimentological interpretations of large, long-lived river systems and their depositional products are restricted to one of the three end-member models. However, additional fluvial styles, particularly those responsible for depositing thick successions in aggrading systems, may be distinct from these end members.

A system that deviates from the traditional classification scheme is a sheetflow-dominated fluvial system. Deposits of this system exhibit laterally extensive, non-erosional sand sheets that may be interbedded with mudstone but lack the well-developed lenticular channel and bar elements typical of braided, meandering and anastomosing fluvial systems. Deposition in such fluvial systems involves brief pulses of rapid sedimentation, primarily on unconfined (non-channelized) plains, but also locally in broad poorly confined channels (Bromley, 1991). As a rule, water discharge and sediment transport fluctuate drastically in these systems (Williams, 1971; Hogg, 1982) and sediment tends to aggrade rather than be distributed by lateral or downslope migration.

Although sheetflow-dominated processes are known best from alluvial-fan settings, in areas typically <75 km^2 (Whipple & Dunne, 1992; Blair & McPherson, 1994; Horton & Schmitt, 1996; Smith, 2000) and distributive fluvial-fan systems up to 100 km^2 (Mukerji, 1976; Friend, 1978; Parkash *et al.*, 1983; Tunbridge, 1984; Kelly & Olsen, 1993; Rhee & Chough, 1993), similar processes have also been documented for >100 to 100 000 km^2 fluvial megafans (Gohain & Parkash, 1990; Singh *et al.*, 1993; Stanistreet & McCarthy, 1993; DeCelles & Cavazza, 1999; Horton & DeCelles, 2001; Leier *et al.*, 2005). The term 'terminal fan' has been used to described a fan setting where water infiltrates and evaporates before flowing out of the system and, although not scale dependent, these systems have been reported primarily from fan settings that are typically <100 km^2 (Friend, 1978; Nichols, 1987; Kelly & Olsen, 1993; Newell *et al.*, 1999). Terminal fans are most common in internally drained, hydrologically closed basins, as dictated by tectonic and climatic conditions. Terminal fans typically exhibit proximal well-defined channels, medial distributary channels that pass downslope into an unconfined region, and a distal zone defined by playa lake and aeolian environments (Kelly & Olsen, 1993). Downslope transitions in depositional processes, defined from existing terminal fan models, include confined flow in a proximal braidplain environment characterized by a network of bifurcating distributary channels. True sheetflood conditions are restricted to areas downslope of confined channels, typically occurring in the more distal reaches of the fan, where flow is unconfined.

This study summarizes the sedimentology of an extensive, long-lived fluvial system dominated by sheetflow processes and explores possible controls on its origin. A 6·5 km thick succession of principally sandstone and mudstone (Potoco Formation) was deposited over a large region (>10 000 km^2) of the Altiplano plateau in the central Andes of Bolivia (Fig. 1), providing an uninterrupted record of Late Eocene to Oligocene sedimentation. The thickness and lateral extent of these deposits suggest that unconfined sheetflow processes persisted both spatially and temporally during the middle Cenozoic and played a crucial role in the depositional history of the Altiplano basin. Also unique to these deposits are the occurrence of laterally extensive channel elements that have very little evidence of lateral migration or reworking, potentially suggesting that aggradational sedimentary processes active in downslope unconfined regions were also active in upstream confined channels. Channel deposits are bounded by fine-grained floodplain material throughout the succession and there is little evidence to suggest connectivity or amalgamation. This field investigation focuses on the

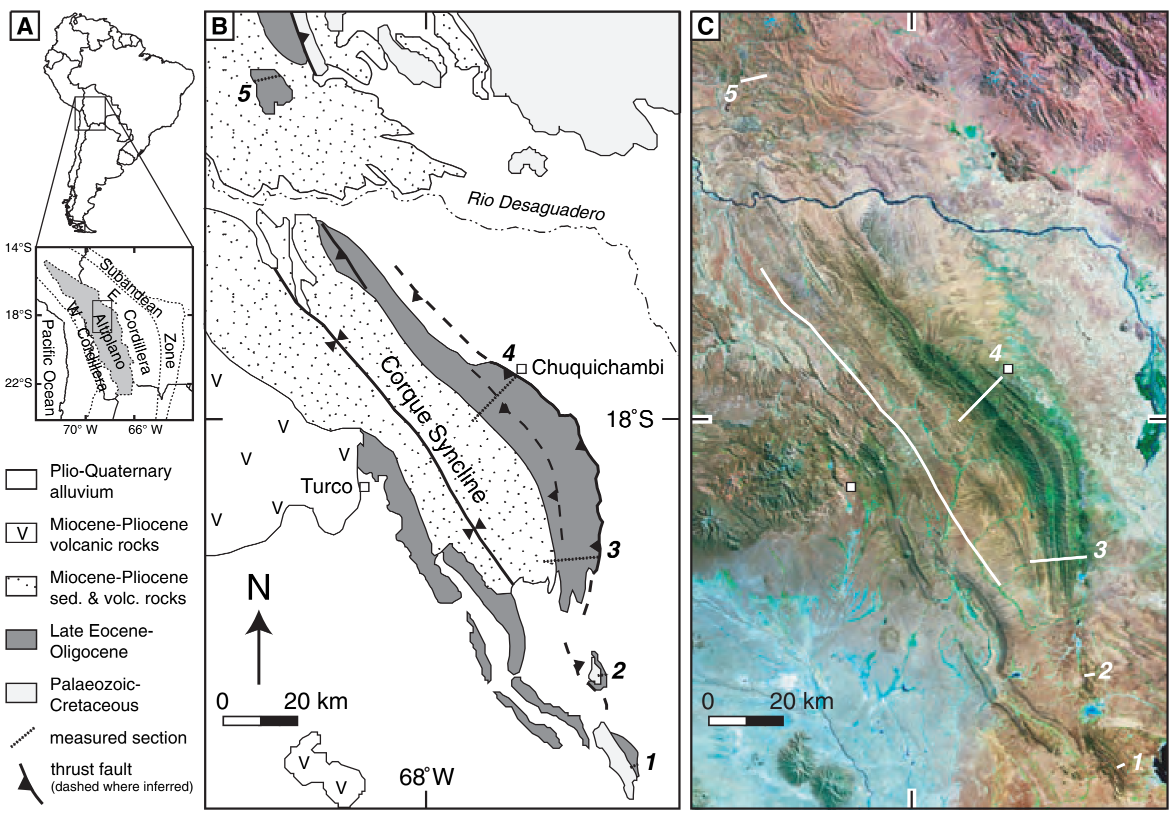

Fig. 1. (A) Regional geological setting of Altiplano plateau in central Andes of Bolivia. (B) Simplified geological map of Corque syncline study area (modified from Geobol, 1995, 1996; Marsh *et al.*, 1992). (C) Landsat image corresponding to area in Fig. 1B. Localities 1 to 5 represent measured stratigraphic sections.

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lithofacies and channel elements of a potential large-scale distributary system dominated by aggradation. Based on what is known about the climatic conditions and tectonic history of the central Andes during the Cenozoic, consideration is given to the possible role of external controls in maintaining widespread distributary sheetflow conditions and prolonged vertical aggradation in the Altiplano basin during Late Eocene–Oligocene time.

GEOLOGICAL SETTING

The Altiplano plateau in the hinterland of the central Andes is flanked to the west by Neogene arc-related volcanic rocks of the Western Cordillera and to the east by deformed Palaeozoic rocks of the Eastern Cordillera (Fig. 1). The low-relief plateau at 3·8 km average elevation contains Pliocene-Quaternary alluvium and north–south trending structures exposing mainly Cenozoic non-marine sedimentary fill of the Altiplano basin. The Corque syncline (Fig. 1) is one of the largest structures in the plateau and contains one of the thickest, most complete non-marine successions in South America. Fluvial strata of the Late Eocene–Oligocene Potoco Formation, the focus of this investigation, are well exposed throughout the region, particularly along a stratigraphic section displaying basal outcrops near Chuquichambi village (Fig. 1).

The tectonic setting of the Altiplano during deposition of the Potoco Formation is a subject of debate. Despite a lack of demonstrated normal faults, some authors suggest a phase of Cenozoic extension in the central Altiplano (e.g. Rochat *et al.*, 1998). However, the records of shortening and exhumation in regions to the west suggest a retro-arc foreland basin setting in the Altiplano region during Palaeogene deposition of the Potoco Formation (Horton *et al.*, 2001; Mpodozis *et al.*, 2005). In general, east–west shortening throughout the Cenozoic -induced crustal thickening, surface uplift and north–south-trending fold-thrust structures in the central Andes of Bolivia (McQuarrie, 2002; McQuarrie *et al.*, 2005).

Late Cenozoic motion along an east-directed thrust fault that defines the eastern margin of the Corque syncline has exposed a thick section of Late Eocene through Pliocene strata (Fig. 1). Previous investigators have mapped an additional smaller thrust fault within the eastern limb of the Corque syncline (Fig. 1; Geobol, 1995; Lamb & Hoke, 1997). However, palynological and volcanic tuff ages from multiple samples throughout the eastern limb demonstrate that the Potoco is progressively younger upsection from east to west (Horton *et al.*, 2001), suggesting no significant stratigraphic repetition across the smaller fault. These findings are consistent with bedding-parallel slip along this smaller fault, a potential result of flexural slip accommodated along the eastern limb during large-scale folding of the Corque syncline. Accordingly, the succession is regarded as a continuous section preserving a complete record of Late Eocene to Oligocene sedimentation.

STRATIGRAPHY

The Potoco Formation directly overlies a 20 to 100 m thick zone of palaeosols which, in turn, overlies a succession of Cretaceous-Palaeocene distal fluvial, lacustrine and shallow-marine rocks (Sempere *et al.*, 1997; Horton *et al.*, 2001) (Fig. 2). Available age constraints suggest that the

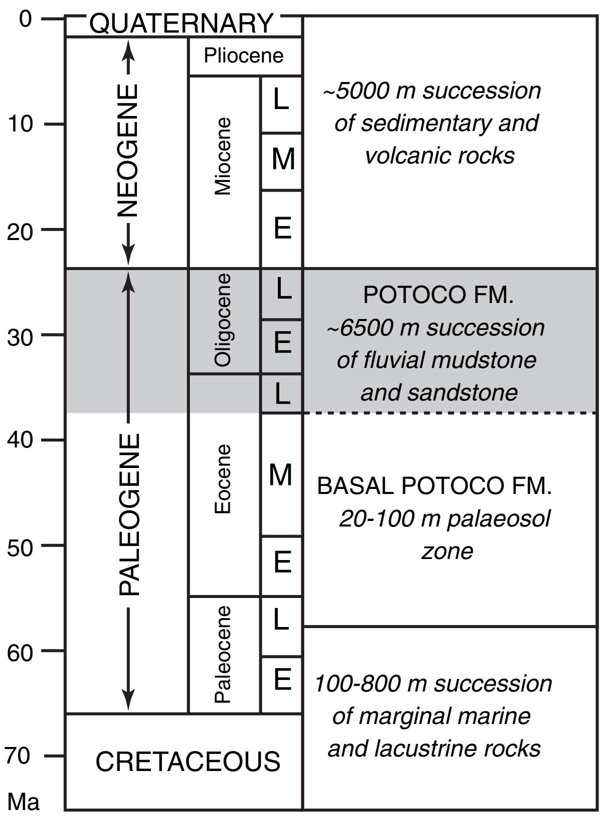

Fig. 2. Chronostratigraphy of Corque syncline region, central Altiplano plateau. Shading denotes the Late Eocene–Oligocene portion of the Potoco Formation, the focus of this study. This stratigraphic interval is underlain by a diagnostic Palaeocene–Eocene palaeosol zone and overlain by a thick Neogene volcaniclastic succession (after Horton *et al.*, 2001).

palaeosol zone at the base of the Potoco Formation represents about 15 to 20 million years of severely limited sediment accumulation during mid-Palaeocene to Middle Eocene time (Horton *et al.*, 2001). The main body of the Potoco is comprised of up to 6·5 km of non-marine sedimentary rocks that were deposited over some 14 Myr, from *ca.* 37 Ma to 23 Ma. Overlying the Potoco Formation is a thick succession (up to 6000 m thick) of Miocene–Pliocene sedimentary and volcanic rocks.

The thickest, most continuous exposure of the Potoco Formation occurs along the eastern limb of the Corque syncline near Chuquichambi (Fig. 1), but several additional localities offer partial exposure. Cretaceous–Eocene sedimentary rocks are exposed in two small anticlines south of the Corque syncline near Andamarca and San Pedro; similarly, Late Eocene–Oligocene strata are exposed north of the syncline near Corocoro (Fig. 1). The western limb of the Corque syncline is best exposed near Turco and contains coarser-grained deposits sourced from the west (Horton *et al.*, 2001, 2002); complete exposure, however, is precluded by unconformably overlying Miocene–Pliocene volcanic rocks (Fig. 1). Although these additional localities do not afford complete exposure, they help constrain the spatial scale of Potoco depositional systems and provide insight into lateral and vertical facies shifts.

Stratigraphic sections were measured at five localities: Andamarca, San Pedro, Corque, Chuquichambi and Corocoro (Fig. 3). Lithostratigraphic correlations are made on the basis of vertical facies changes, notably: (i) the transition from Late Cretaceous-Palaeocene fluvio-lacustrine and shallow-marine strata to Palaeocene-Eocene palaeosols; and (ii) the upward transition from these palaeosols to Late Eocene fluvial strata of the lowermost Potoco Formation. In some localities, an important correlation can be made utilizing the gypsum-rich Chuquichambi member of the lower Potoco Formation, a unit limited to the central Altiplano (Fig. 3).

Palaeocurrent data collected throughout the Potoco Formation include over 2200 indicators measured at some 215 sites (Fig. 3). Average trough axes were calculated for each locality from measured trough limbs (method I of DeCelles *et al.*, 1983). Additional palaeocurrent data come from asymmetric current ripple marks and bidirectional indicators measured from parting lineations and symmetric wave ripple marks. Overall, palaeoflow data indicate east-directed sediment dispersal for the lower 4000 m of the succession and westward dispersal for the overlying 2500 m (Fig. 3), indicating a reversal in palaeoflow within the Potoco Formation (Horton *et al.*, 2001). Sandstone compositional trends for the Potoco Formation support these findings, demonstrating a possible thrust-belt and magmatic-arc source to the west (Western Cordillera) for the lower section, and an eastern Palaeozoic clastic source (Eastern Cordillera) for the overlying section (Horton *et al.*, 2002).

FACIES ASSOCIATIONS

The sedimentology of the Late Eocene–Oligocene portion of the Potoco Formation was documented in >12 km of measured stratigraphic sections from five locations in the Corque syncline region (Fig. 3). Two upward-coarsening sequences are identified for the thickest succession, superbly exposed near Chuquichambi (Fig. 4A). The lower, *ca.* 4000 m thick sequence of westerly sourced deposits coarsens upward from gypsum, mudstone and fine-grained sandstone to interbedded fine-grained to medium-grained sandstone and mudstone. The overlying *ca.* 2500 m of easterly sourced facies coarsen upward from fine-grained sandstone and mudstone to medium-grained sandstone and interbedded mudstone. Mudstone is most abundant near the base of both sequences and decreases upsection (Fig. 3). The lower 750 m of the Chuquichambi measured section is made up of primarily tabular and laterally extensive sandstone bodies interbedded with mudstone and gypsum deposits (Fig. 4B). As stated above, this section is presented within the context of five measured sections that have continuous vertical exposure. The lateral extent of architectural elements was documented where possible by tracing deposits along-strike to the point where they pinch out. In most cases, lateral extents were documented normal to palaeoflow and are representative of width. Where three-dimensional outcrop exposures are available (modern drainages normal to bedding in Fig. 4A), lateral extent was documented parallel and normal to palaeoflow and is representative of width and length. Fine-grained tabular sandstone bodies in the lower 2000 m of the section are typically <2 m thick and extend laterally (width and length) for >200 m. The remainder of overlying fine-grained to medium-grained sandstone deposits are composed predominantly of more lenticular sandstone units >2 m thick that extend laterally for <150 m (primarily length). No evi-

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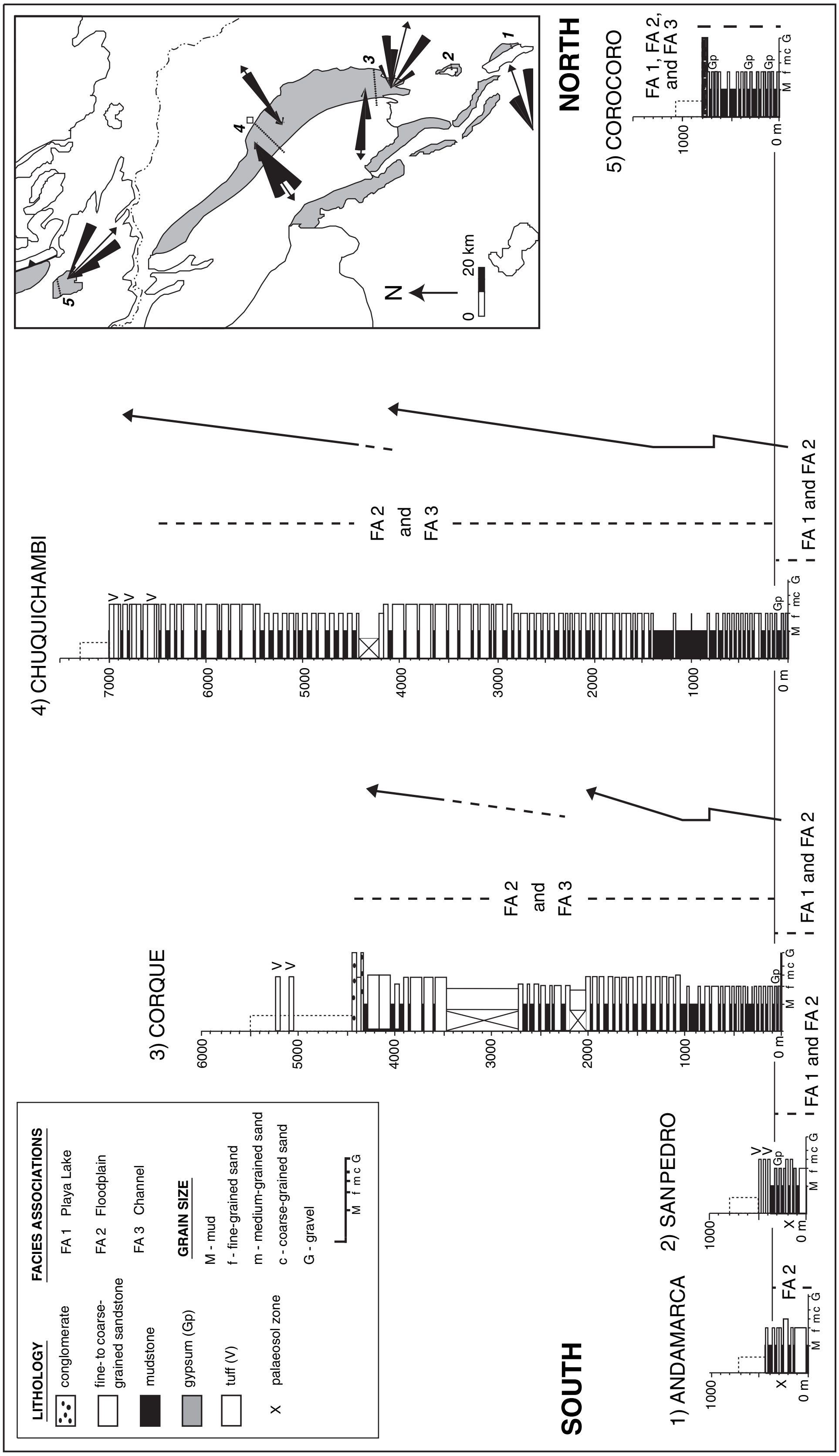

Fig. 3. Measured stratigraphic sections summarizing the basic lithology, grain-size trends and distribution of three facies associations (FA) of the Late Eocene–Oligocene Potoco Formation. FA 1 (playa lake) occurs in the lowermost Potoco; FA 2 (floodplain) and FA 3 (channel) occur throughout the Potoco succession. Two separate coarsening-upward sequences are identified in Sections 3 (Corque) and 4 (Chuquichambi). The lower sequence corresponds to east-directed palaeoflow; the upper sequence corresponds to west-directed palaeoflow. Rose diagrams in inset map (compare with Fig. 1B) depict palaeocurrent trends.

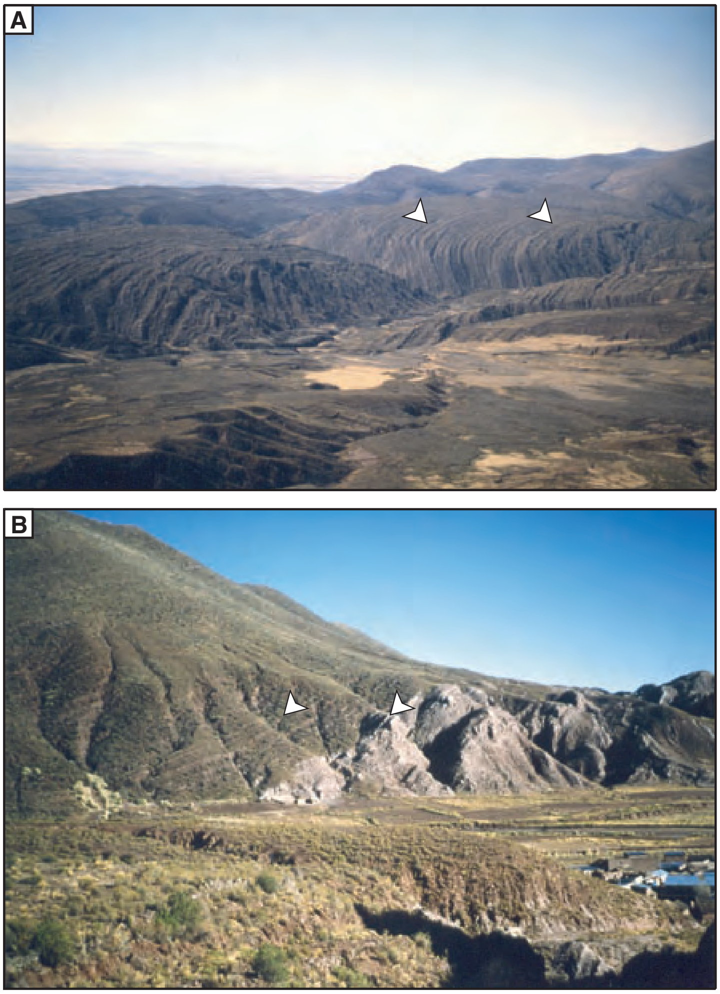

Fig. 4. Representative photographs of lower Potoco Formation. (A) View to south-east of lower ≈3000 m of Potoco Formation (Section 3, arrows denote ≈750 m stratigraphic thickness). (B) View to north of sharp contact (arrow) between basal white gypsum (Chuquichambi member) to the right and an overlying section of thin-bedded mudstone and sandstone of the lower Potoco Formation to the left (Section 3, arrows denote ≈100 m stratigraphic thickness).

dence was found that suggested a punctuated change from relatively thin tabular units in contrast to thick lenticular units. All sandstone bodies typically are encased within laminated, massive and aggregated mudstone deposits.

Nine separate sedimentary facies were identified (Table 1) and the distribution of these facies within the succession led to the identification of three facies associations attributed to deposition in playa lake, floodplain and unconfined sheet and poorly confined channel environments of a sheetflow-dominated fluvial system. The sedimentological descriptions and interpretations of facies associations and depositional systems are summarized in Table 2 and discussed in detail below.

Facies Association 1

The lower 750 m of the Potoco Formation consists primarily of tabular sheets of interbedded greenish violet/grey, fine-grained, gypsiferous sandstone, mudstone and massive, structureless beds of translucent to white gypsum of Facies Association 1 (Fig. 5).

Description

Individual beds exhibit non-erosive basal contacts, are laterally extensive for >200 m, and are typically interbedded with red mudstone. Continuous intervals of red mudstone and gypsum-bearing strata range from 10 to 350 m thick, as observed in the Chuquichambi measured section (Section 4), and are interbedded throughout the other measured sections (Figs 3, 4 and 5A). Gypsum layers are typically <2 m thick and are commonly encased within massive aggregated mudstone (Figs 5B and 6). Gypsum crystals are randomly oriented and exhibit an elongate geometry. Translucent crystals have been documented to be 8 cm long. Individual beds in Facies Association 1 are generally 0·01 to 0·20 m thick, fine upward, and contain horizontally stratified and ripple cross-stratified sandstone, massive, structureless sandstone and finely laminated to massive mudstone (Figs 5B,C and 6); all of these

Table 1. Summary of facies classifications and interpretations for the Potoco Formation, utilizing facies codes from Miall (1977).

Facies code	*Sedimentary structures and facies*	*Interpretation*
Sm	***Massive-structureless.*** Fine-grained sandstone; no grading or stratification	Sediment gravity flow; near-surface turbidity currents in fluid flows
Sh	*Horizontal stratification.* Fine-grained to medium-grained sandstone; no grading; flat parallel lamination; parting lineations common on bedding plane	Deposition under upper plane-bed flow conditions (critical flow) when associated with parting lineations; no occurrence of parting lineations (sub-critical flow)
Sr	***Ripple cross-stratification.*** Fine-grained to medium-grained sandstone; no grading; symmetric and asymmetric geometry; stoss and lee side preservation common with asymmetric ripples	Sedimentation during migration of current (asymmetric) and wave (symmetric) ripples; lower flow regime conditions; climbing ripple formation during periods of rapid sediment accumulation
St	***Trough cross-stratification.*** Fine-grained to medium-grained sandstone; no grading; beds containing trough sets that are <0·5 m thick; mudstone rip-up-clasts are common near base of troughs	Migration of 3D dunes in shallow water; traction processes during lower flow regime conditions
Sl	***Low-angle cross-stratification.*** Fine-grained to medium-grained sandstone; no grading; cross-stratification dips <10° with respect to bedding; beds containing low-angle stratification are <0·5 m thick	Migration of small-scale 3D bar and/or plane-bed macroforms; deposition on sloped surface; migration in shallow water
Fl	***Fine lamination.*** Mudstone; flat parallel lamination; secondary structures included desiccation cracks and bioturbation	Suspension fallout/weak traction; low flow regime; waning flow conditions
Fm	***Massive (poorly laminated).*** Mudstone; faint parallel lamination occurs but is rare; secondary structures included desiccation cracks and bioturbation	Suspension fallout; deposition during lower flow regime conditions; waning flow and fallout in standing water
Fr	***Massive (root traces).*** Mudstone; massive appearance; vertically oriented root casts (normal to bedding); calcite replacement; individual root casts are <10 mm long	Soil development and vegetation of mud deposits; arid–semi-arid environment resulting in root replacement by calcite
P	***Pedogenic carbonate.*** Mudstone and claystone; massive aggregated mudstone with thin clay-skin coating; mudstone nodules are typically <4 cm in diameter; calcareous and calcite veins are common (<0·3 cm thick)	Soil development of mud deposits resulting from infiltration, leaching and carbonate precipitation; arid–semi-arid environment

Table 2. Summary or descriptions and interpretations of facies associations for the Potoco formation.

Facies Association 1 (FA 1) Tabular, laterally extensive (>200 m) deposits of interbedded green-purple/grey sandstone, mudstone and gypsum; deposits are 0·25 to 2 m thick; individual beds are 0·01 to 0·20 m thick and fine-upward; non-erosive contacts at base of beds	***Playa Lake*** Shallow, ephemeral lakes in topographically low regions of the floodplain; lake formation and facies distribution is likely due to: (i) abandoned flood events resulting in standing water; followed by (ii) sediment suspension plumes and near-surface turbidity flow in standing water; and (iii) eventual lake water evaporation
(A) Sandstone. Horizontally stratified (Sh), ripple cross-stratified (Sr) and massive, structureless (Sm) fine-grained sandstone; symmetric and asymmetric ripple geometries are common; gypsum and carbonate cement are most common	(A) Flood events/sediment gravity flows. Sh and Sr due to deposition/migration during flood events; Sm due to small-scale sediment gravity flows in lakes related to later flow into standing water; oscillation ripples from sediment reworking during wind/wave action
(B) Mudstone. Extensive laminated and massive mudstone (Fl and Fm); gypsum and carbonate cement	(B) Suspension fallout (lake). Fl and Fm resulted from fallout of fine-grained material after flood events and sediment gravity flows
(C) Gypsum. Beds of translucent and opaque gypsum crystals; also massive gypsum beds with no visible crystal structure	(C) Evaporites. Precipitation of gypsum, carbonate and lake salts resulting from evaporation of standing lake water
Facies Association 2 (FA 2) Tabular, laterally extensive (>200 m) deposits of interbedded light red sandstone and dark red mudstone; deposits are 0·01 to 200 m thick; non-erosive contacts at base of beds	***Floodplain*** Deposition of mud and sand during extensive, un-confined sheet flooding in floodplain regions; pedogenic alteration occurred after flood events during periods of sub-aerial exposure of mudstone deposits
(A) Aggregated mudrock. Extensive 0·10 to 2 m thick deposits contain no primary sedimentary structures; mudstone is made up of peds (P) or aggregates (<0·04 m in diameter) that exhibit clay-skin coatings and slickenlined surfaces; root traces; calcareous	(A) Pedogenic alteration. Soil formation and vegetation in floodplain regions resulting from sub-aerial exposure of floodplain mudstone; calcareous deposits suggest semi-arid to arid climate conditions may have prevented complete leaching of floodplain carbonate
(B) Mudstone. Extensive laminated and massive mudstone (Fl and Fm); beds are 0·01 to 0·15 m thick; desiccation cracks occur and bioturbation structures are common	(B) Suspension fallout (floodplain). Fine-grained mudstone floodplain deposits; Fl and Fm from fallout during the waning flood stage
(C) Sandstone. Light red fine-grained to medium-grained sandstone sheets characterized by abundant horizontal stratification (Sh) and ripple cross-stratification (Sr); beds are <0·75 m thick (0·05 to 0·60 m thick); bioturbation structures occur locally	C) Splay. Sandstone deposition by overbank crevasse splays and distal down-slope splays; deposition and migration of sandy bedforms (Sh and Sr) in sand sheets during unconfined flood stage conditions
Facies Association 3 (FA 3) Lenticular and tabular sandstone bodies; Lenticular units are laterally extensive for 50 to 150 m and exhibit width-to-thickness ratios of >25:1; deposits are typically 2·0 to 3·0 m thick; erosional contacts and mudstone rip-up clasts are common; commonly draped with thin beds of (<0·01 m thick) of laminated mudstone; Tabular units extend laterally for >200 m and exhibit width-to-thickness ratios of >100:1; beds are typically <2·0 m thick (0·75 to 2·0 m thick); non-erosional basal contacts	***Channels AND Sheets*** Ephemeral flow in poorly confined channels and unconfined sheets; deposition and migration of sand occurred during maximum flow; mudstone fallout occurred during waning stages of flow; sediment migration in channels and sheets occurred on a bedform scale; only very rare migration on the bar scale is evident in channel deposits; individual channel scour-and-fill events resulted from either single or multiple depositional events
(A) Sandstone. Fine-grained to medium-grained sandstone bodies are made up dominantly horizontally stratified (Sh) and ripple cross-stratified sandstone (Sr); occurrences of trough-cross-stratification (St) are sporadic and low-angle cross-stratification (SI) is very rare	(A) Channel and sheet, poorly confined channel and unconfined sheet deposits; unconfined flow represents deposition by proximal terminal splays; migration dominated by small-scale bedform migration (Sh and Sr) with rare dune migration (St) and very rare bar migration (SI); Channels and sheets were broad, extensive and isolated within floodplain deposits
(B) Mudstone. Thin deposits of massive Mudstone (Fm) commonly occur on the top of sandstone deposits	(B) Mudstone. Laminated mudstone (Fm) was deposited in standing pools of water during terminal flood conditions

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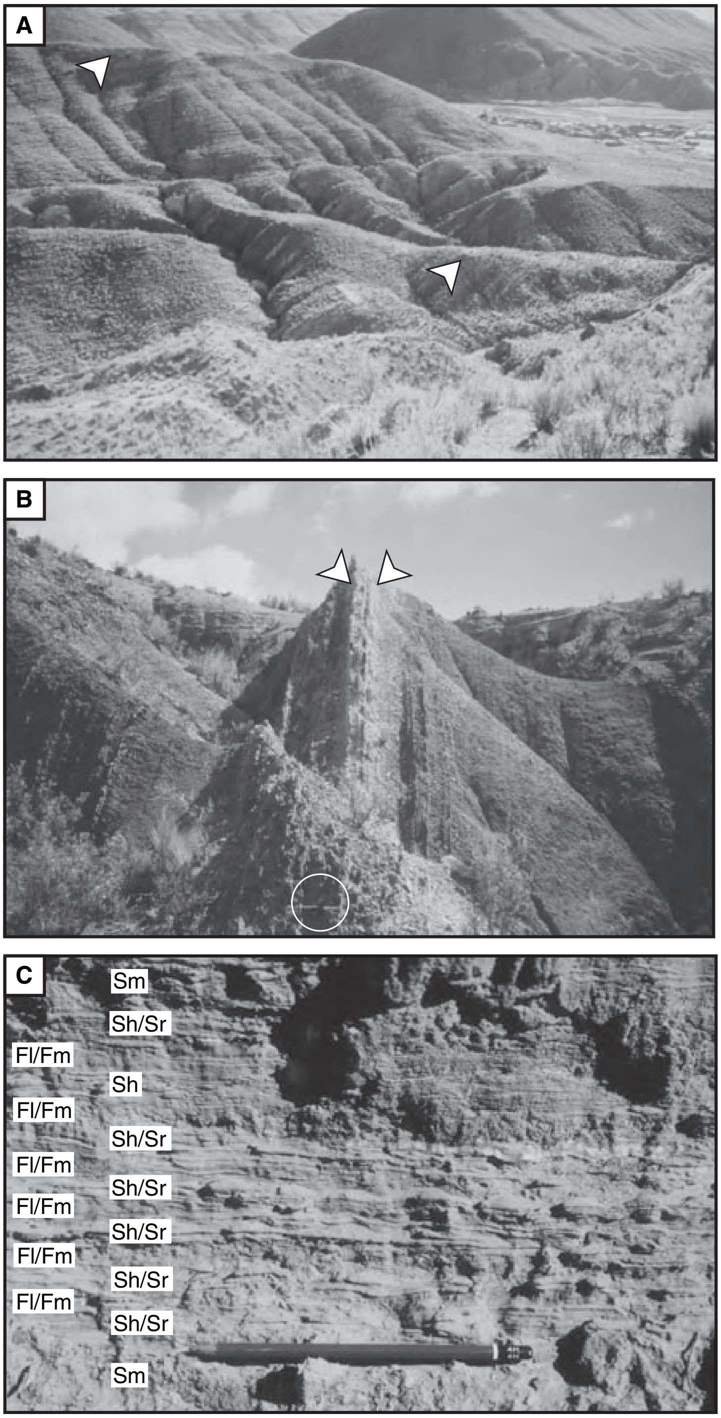

Fig. 5. Facies Association 1 (playa lake). (A) Laterally extensive gypsum-bearing deposits of FA 1 interbedded with mudstone and sandstone of FA 2 (floodplain), near the base of Section 4 (Chuquichambi). Arrows denote ≈150 m stratigraphic thickness. (B) A single white gypsum-bearing unit of FA 1 (arrows denote 0·25 m thickness) encased in dark mudstone of FA 2. Hammer (0·3 m long) near base of photo for scale. (C) Typical section of gypsum-bearing sandstone and mudstone deposits that make up FA 1, including horizontally stratified (Sr) and ripple cross-stratified sandstone (Sr), and massive, structureless sandstone (Sm). Individual beds are 0·01 to 0·03 m thick. Pencil (0·15 m long) for scale.

beds contain variable amounts of gypsum in their matrix. A typical vertical distribution of facies in tabular sandstone sheets includes horizontally stratified sandstone at the base, overlain successively by ripple cross-stratified, horizontally stratified and massive, structureless sandstone, then laminated and massive mudstone, and finally gypsum (Figs 5C and 6). Symmetric and asymmetric ripple structures, laminated mudstone and gypsum are most common near the top of gypsum-bearing sandstone and mudstone sheets. Overall, strata in Facies Association 1 can be recognized by: (i) the presence of fine-grained, gypsum-bearing lithologies; (ii) the thin, laterally extensive nature of individual beds; and (iii) the common vertical pattern of sandstone overlain by mudstone, overlain in turn by gypsum (Fig. 6).

Interpretation

Gypsum-bearing deposits of Facies Association 1 are interpreted to be the result of clastic deposition and evaporite precipitation in shallow playa lake environments located in topographically low areas of a floodplain. The distribution of gypsum deposits within red mudstone throughout the lower Potoco may be attributed to episodic depositional patterns that regularly involved initial flooding, waning flow and growth of shallow, extensive (>200 m in length) lakes, subsequent evaporation and saline-lake conditions, followed by evaporative precipitation of saline minerals and complete lake desiccation. Distal sheetflow processes are invoked for the origination of lakes and are the primary process by which standing water comes to be in floodplain regions. Subsequent flow events in standing water probably resulted in deposition by near-surface turbidity currents and sediment suspension plumes. Gypsum precipitation is interpreted to be independent of sheetflow processes and occurred as an evaporative process after lake formation.

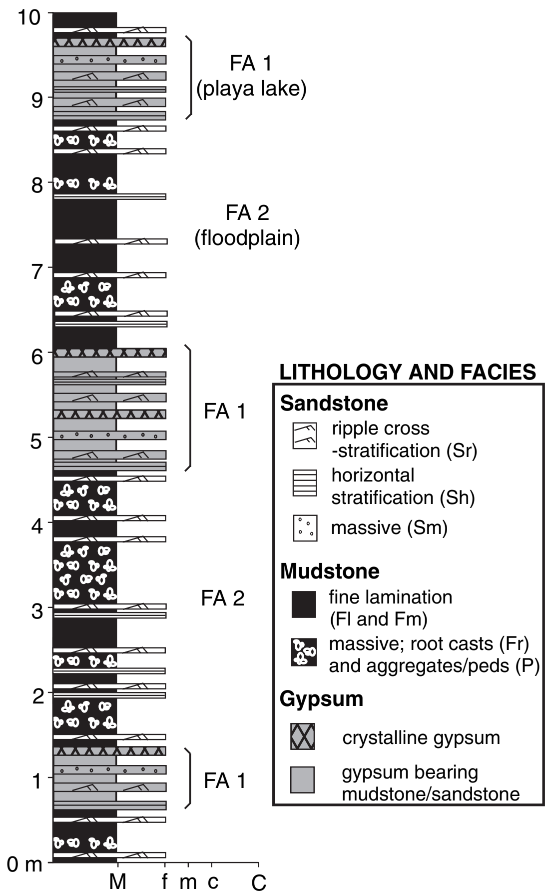

Fig. 6. Detailed measured section of 10 m of interbedded FA 1 (playa lake) and FA 2 (floodplain) from the lower Potoco Formation. Note interbedded units of gypsum-bearing mudstone, fine-grained sandstone and massive, crystalline beds of gypsum (0·01 to 0·20 m bed thicknesses). Sandstones are generally horizontally stratified and ripple cross-stratified (Sh and Sr) or massive (Sm).

The majority of these deposits appears to be the result of an initial flood event in which flow was characterized by lower plane-bed flow and current-ripple migration during waning flow (Froude number <1). Initial flood events were probably followed by multiple subsequent episodes of discharge in shallow lakes that resulted in sediment deposition and migration by shallow currents and suspension. The common vertical distribution of horizontally stratified and ripple cross-stratified sandstone facies is interpreted to have resulted from initial traction and current-ripple migration during sheetflow events. Laminated and massive mudstones and massive, structureless sandstone are attributed to late-stage suspension fallout following initial flooding and subsequent near-surface turbidity currents respectively (Ghibaudo, 1992). Although the preservation of complete Bouma sequence turbidite facies may be expected in these deposits, only massive, structureless sandstone beds are preserved from near-surface turbid flow. This is the only facies association that contains massive, structureless sandstone beds and, based on its occurrence with laminated and massive mudstone in lake deposits, these occurrences are interpreted to reflect near-surface turbidity currents in shallow ponds or lakes (Lowe, 1982). The occurrence of asymmetric ripple forms at the top of gypsum-bearing deposits is probably the result of flow during wave-driven traction associated with discharge and shallow currents during subsequent flood events (e.g. Weirich, 1989; Horton & Schmitt, 1996; Mohrig *et al.*, 1998). Symmetric ripples are interpreted to reflect sediment reworking resulting from wind-induced current oscillations in standing water. Precipitation of gypsum occurred as a result of lake water evaporation and saturation (Lowenstein & Hardie, 1985). The evaporation of surface water, precipitation of saline minerals and overall episodic depositional patterns recorded within the lower Potoco Formation suggest semi-arid to arid climate conditions during deposition, typified by ephemeral flooding events followed by periods of non-deposition and desiccation (McKee, 1967; Picard & High, 1973; Tunbridge, 1984; Bull, 1997; Daniels, 2003). The tabular sheet geometry and laterally continuous nature of beds together with the fine-grained lithology and abundance of horizontally stratified sandstone and laminated mudstone further suggest deposition during low-flow events, or in standing water (e.g. Miall, 1996; Bridge, 2003). On the basis of the lateral extent of individual beds, lack of basal erosional scour and overall fine-grained lithology, these strata are interpreted to represent: (i) initial deposition during the waning terminal stages of unconfined sheetflow; followed by (ii) subsequent flow events into lakes forcing small-scale, shallow turbidity flow and sediment plumes; and finally (iii) evaporation and precipitation in shallow playa lakes.

Facies Association 2

Laterally extensive red mudstone occurs throughout the measured sections and is commonly associated with isolated tabular sheets of sandstone in Facies Association 2 (Fig. 7).

Description

Sandstone and mudstone deposits are typically <4 m thick, but may be up to 200 m thick. Mudstone beds are 0·01 to 2·0 m thick, sandstone sheets are typically <0·75 m thick, and both may extend laterally for >200 m. Individual beds have even thicknesses with non-erosive basal contacts (Fig. 7A). The majority of mudstone deposits are massive, >0·05 m thick, and contain spheroidal mudstone aggregates (peds) coated by clay skins and exhibiting slickenlined surfaces (Fig. 7B). Peds are typically <0·05 m in diameter and occur throughout mudstone deposits, but are not organized sufficiently to form discrete horizons. Most aggregated mudstone deposits are moderately calcareous and accompany rare gypsum and calcite veins that are present locally. Root traces are common near the top of mudstone and sandstone beds (Fig. 7C). Laminated mudstone occurs throughout Facies Association 2 in thin (<0·05 m thick) sheets that drape massive mudstone and sandstone deposits (Fig. 7D). Desiccation cracks and occurrences of horizontal and vertical burrow structures occur throughout the sections but are not abundant. Sandstone deposits contain horizontal stratification and ripple cross-stratification and are directly overlain by laminated or aggregated mudstone (Fig. 7D). Figure 8 shows a detailed measured stratigraphic section of a 10 m interval of mudstone and sandstone deposits of Facies Association 2.

Interpretation

Mudstone and subordinate sandstone of Facies Association 2 are interpreted to represent floodplain deposits associated with: (i) overbank flooding resulting from unconfined flow originating from overtopped channels when they occur adjacent to lenticular sandbodies; or (ii) downslope, unconfined sedimentation associated with terminal flooding stages. In both cases, sedimentation was followed by a period of non-deposition and sub-aerial exposure. Sandstone is interpreted as the products of poorly developed traction currents during the waning stages of flood events (Froude number <1). The tabular, even-bedding of horizontally stratified and ripple cross-stratified sandstone sheets and overlying laminated mudstone may suggest crevasse-splay or terminal-splay deposition as a result of distal, waning flow (Miall, 1996) during the final phase of splay abandonment (Ghosh, 1987). Levée deposits and erosive bases would be expected to occur in the more proximal parts of splay deposits, however, neither was observed. This absence could be due either to the lack of well-defined levées and the erosive nature of splays in this system, or simply that the documentation comes from more distal portions of the floodplain. For mudstone facies, the dominantly aggregated texture and occurrence of root traces suggest that floodplain regions underwent periods of non-deposition and subsequent oxidation and pedogenic alteration, accompanied by plant development (Bown & Kraus, 1987; Retallack, 1988; Daniels, 2003). Slickensided surfaces on palaeosol peds are interpreted to have formed by shrinking and swelling of clay material associated with episodic water infiltration and evaporation. Although deposits are mildly calcareous, the lack of significant amounts of carbonate material suggests that partial leaching may have occurred as a result of moderately well-drained conditions throughout the floodplain (Mack *et al.*, 1993) and/or limited amounts of carbonate in the source area. Occurrences of peds, root traces, desiccation cracks and

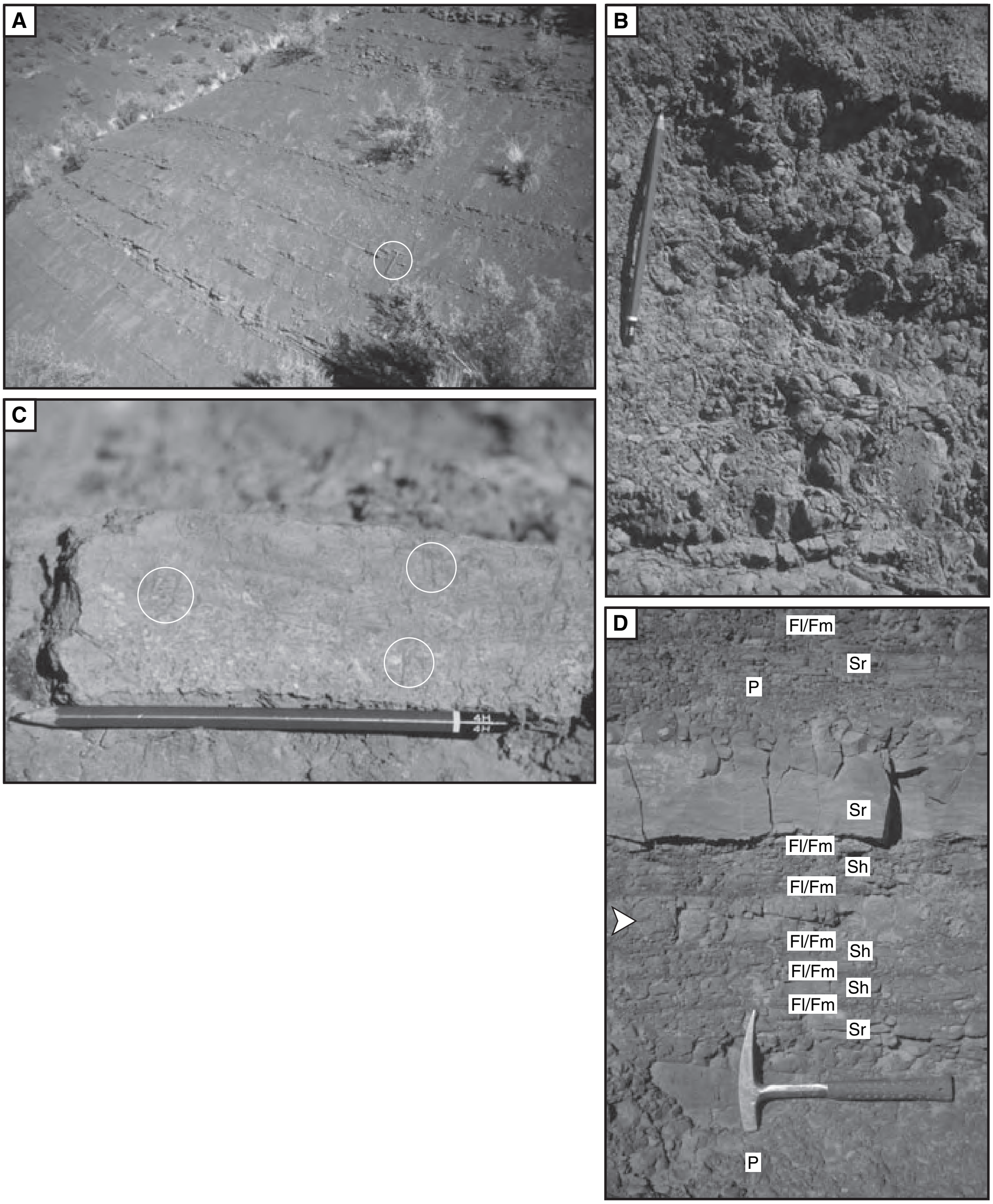

Fig. 7. Facies Association 2 (floodplain). (A) Tabular, laterally extensive deposits of less-resistant mudstone and more-resistant siltstone and fine-grained sandstone (<0·1 m thick). Hammer (0·3 m long) for scale. (B) Massive deposits of aggregated mudstone and claystone with spherical nodules (typically <0·04 m in diameter). Pencil (0·15 m long) for scale. (C) Thin bed (≈0·10 m thick) of massive mudstone with root casts (circles) typically <0·03 m long. Pencil (0·15 m long) for scale. (D) Laminated and massive mudstone (Fl and Fm) with interbedded horizontally stratified and ripple cross-stratified, fine-grained sandstone (Sh and Sr). Sandstone units are commonly encased in aggregated mudstone (P). The thick sandstone (≈0·20 m thick) in upper half of photo grades from a ripple cross-stratified lithofacies into massive aggregated mudstone. Hammer (0·3 m long) for scale.

burrows are indicative of a floodplain region that is well-drained and sub-aerially exposed (Deluca & Eriksson, 1989; McCarthy *et al.*, 1997; Retallack, 1997; Mack *et al.*, 2003). An abundance of altered floodplain material suggests sub-aerial exposure was common, however, the lack of well-developed nodular horizons or calcretes suggests palaeosols were not well-developed, potentially indicative of a floodplain characterized by repetitive cycles of sediment aggradation

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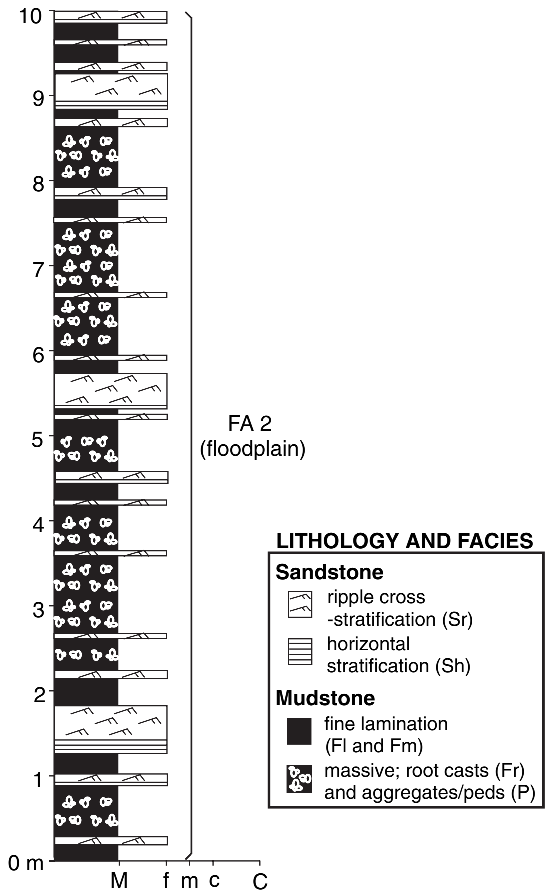

Fig. 8. Detailed measured section of 10 m of interbedded sandstone and mudstone of FA 2 (floodplain). Mudstone intervals are typically thicker (up to 2 m) than sandstone deposits (<0·6 m). Most mudstones exhibit a massive, aggregated texture with common occurrences of root casts, mudcracks and bioturbation. Sandstone beds are tabular and horizontally stratified and ripple cross-stratified (Sh and Sr) with non-erosional basal contacts.

followed by periodic, short-lived sub-aerial exposure (Gile *et al.*, 1966; Bridge, 2003). The laminated and massive mudstone deposits, that lack evidence for pedogenic alteration, are interpreted to be the result of weak traction currents and suspension fallout during waning flow of overbank or downslope flooding events. These mudstones were overlain by subsequent flood material in sufficiently rapid fashion to prevent pedogenic alteration.

Facies Association 3

Tabular and lenticular sandstone bodies of Facies Association 3 occur throughout most measured sections and are composed of fine-grained to medium-grained sandstone (Fig. 9).

Description

Deposits range from 0·75 to 3 m thick and extend laterally for 50 to 200 m. Horizontally stratified and ripple cross-stratified sandstone is abundant throughout the sandstone bodies and often occurs locally with parting lineations and climbing ripple structures respectively. Trough cross-stratification occurs locally and low-angle cross-stratification and epsilon cross-bedding are isolated and rare. Both tabular and lenticular sandstone bodies have sharp contacts with underlying and overlying mudstone deposits of Facies Association 2. Width-to-thickness ratios are consistently greater than 100:1 for individual tabular sandstone bodies and greater than 25:1 for lenticular sandstone bodies.

Two distinct types of sandstone bodies have been identified in Facies Association 3 and can be distinguished by their thickness, lateral extent, basal erosional features, mean grain size and facies distribution. The first set of sandstone bodies occurs throughout the lower 2000 m of the Potoco Formation and consists of thin (<2 m thick), laterally extensive (>150 m) sheets (Fig. 9A). The base of each sandstone body is characterized by non-erosional basal contacts with underlying deposits, commonly aggregated mudstone of Facies Association 2 (Fig. 9A). These sandstone bodies are principally composed of an individual sheet containing interbedded horizontally stratified and ripple cross-stratified fine-grained sandstone; ripple cross-stratification is most common near the upper parts of sandstone sheets (Fig. 9B). Near the base of sandstone sheets, horizontally stratified beds are most common with rare occurrences of trough cross-stratified sandstone. The ripple cross-stratified facies at the top of individual sandstone bodies is typically draped by one or more thin beds (<0·01 m thick) of laminated mudstone. Distorted and convoluted sandstone beds are common throughout these deposits (Fig. 9C).

The second set of sandstone bodies in Facies Association 3 constitutes the remainder of sandstone deposits >2 m thick that occur above the lower 2000 m of the Potoco Formation. These deposits have lenticular geometries with channels exhibiting a single basal erosional scour surface (Fig. 9D). Lenticular sandstone bodies commonly contain mudstone rip-up clasts and have erosional basal contacts with underlying laminated, massive and aggregated mudstone deposits of Facies Association 2. Individual sandstone bodies are invariably encased within mudstone deposits of Facies Association 2

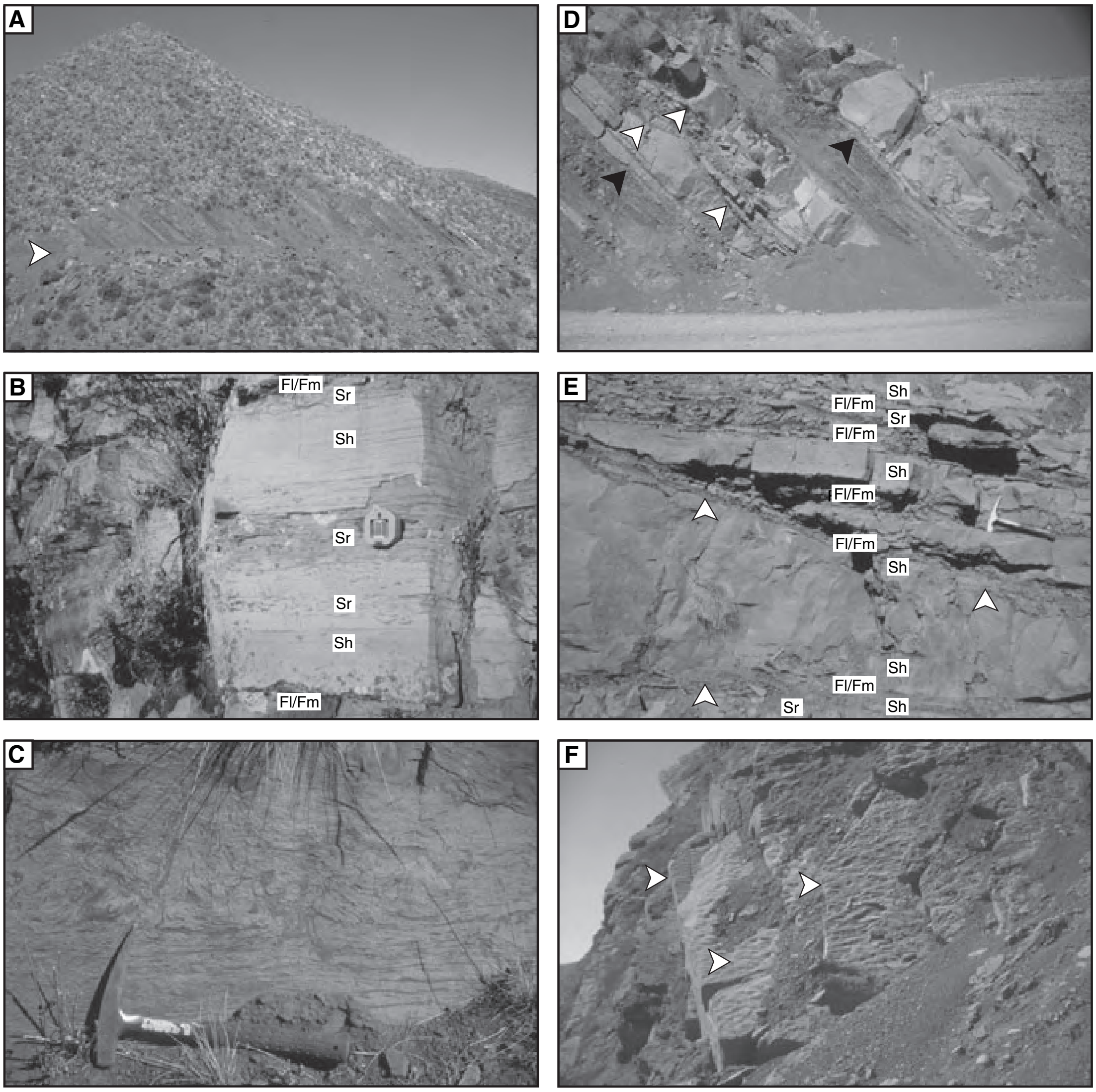

Fig. 9. Facies Association 3 (channel). (A) Representative section of resistant ledges of channel sandstone of FA 3 interbedded with less-resistant mudstone and sandstone of FA 2. Road (arrow) for scale. (B) Interbedded horizontally stratified and ripple cross-stratified sandstone (Sh and Sr) in a single channel sandstone. Ripples are commonly draped by laminated or massive mudstone (Fl or Fm). Mudstone rip-up clasts near base are associated with rare local erosional surfaces. Compass (0·07 m) for scale. (C) Convolute, distorted beds overlying ripple cross-stratified beds, a common feature in channel sandstones. Hammer (0·3 m long) for scale. (D) Two lenticular channel sandstone units (each ≈2 m thick) displaying different facies patterns. The lower sandstone body to left is characterized by a basal erosional scour surface (black arrow) and contains sandstone (0·15 to 0·5 m thick) and interbedded thin (<0·06 m thick) mudstone. Multiple internal scour surfaces (white arrows) occur throughout. The upper sandstone body to the right represents a continuous interval of sandstone above a basal erosional scour surface (black arrow). Both sandstone bodies are encased in fine-grained deposits of FA 2 (floodplain). Road in foreground for scale. (E) Interbedded sandstone and mudstone within a single channel sandstone body. Sandstone beds contain dominantly horizontal stratification (Sh) grading into ripple cross-stratification (Sr) near the top of individual units. An internal scour surface (arrows) can be traced from the upper left to middle right portion of the photo. Laminated and massive mudstone (Fl and Fm) drape the inclined scour surface. The overlying sandstone and mudstone units onlap the scour surface. Hammer (0·3 m long) for scale. (F) Ripple marks on the top of three separate sandstone beds (arrows). Ripple geometry is asymmetric with rare symmetric forms. Hammer (0·3 m long) for scale.

(Fig. 9D). Lenticular sandstone bodies are composed of a single isolated sandstone body or a series of sandstone bodies (complex) bounded above and below by thin (<0·10 m thick) deposits of laminated and massive mudstone (Fig. 9D). Multiple stacked sandstone bodies (complexes) are composed primarily of horizontally stratified and ripple cross-stratified, fine-grained to medium-grained sandstone (Fig. 9E). Most sandstone bodies are completely preserved, but the tops of some sheets exhibit erosional scours surfaces (Fig. 9E). More commonly, the tops of sandstone bodies are defined by ripple cross-stratified sandstone characterized by straight-crested, undulatory or lingoid ripples (Fig. 9F) that are draped by thin (<0·10 m thick) laminated and massive mudstone deposits. A detailed measured stratigraphic section of a 10 m interval of Facies Association 3 is summarized in Fig. 10.

Interpretation

Tabular and lenticular sandstone bodies of Facies Association 3 are interpreted to be the result of rapid flood deposition in laterally extensive, unconfined sheets and poorly confined fluvial channels. Tabular sandstone sheets are interpreted to represent deposition associated with unconfined flow just downslope of confined channels. In this respect, sheets are interpreted as downslope terminal splays. The abundance of laterally extensive sandstone units consisting of horizontally stratified and ripple cross-stratified sandstone, parting lineations and sets of climbing ripples, combined with rare occurrences of trough cross-stratification, low-angle and epsilon cross-stratification suggests that flow events were short-lived and of high intensity (Tunbridge, 1984) and, at times, bedload dominated. Interbedded horizontally stratified and ripple cross-stratified sandstone may suggest oscillation between high-flow and low-flow conditions during a single depositional event. The occurrence of ripple cross-stratified sandstone at the top of both tabular and lenticular sandstone bodies is a common product of waning flow velocity associated with flow termination or channel abandonment (Smith *et al.*, 1989; Miall, 1996). Sediment transport in channels was accomplished primarily by the initial downslope migration of plane beds (Froude number ≥ 1) and subsequent lateral and downslope migration at the scale of three-dimensional dunes and ripple trains (Froude number

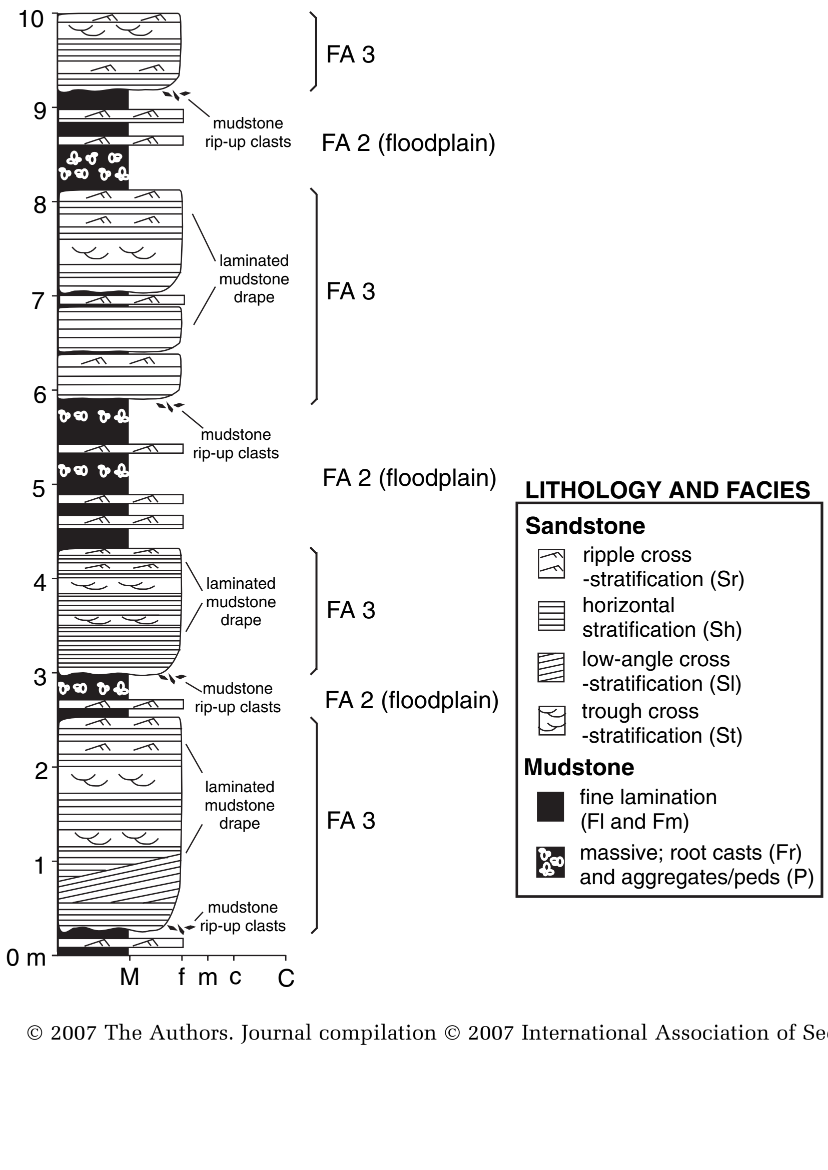

Fig. 10. Detailed measured section of 10 m of interbedded sandstone of FA 3 and mudstone and sandstone of FA 2. Sandstone packages are characterized by two types of stacking patterns, including continuous beds containing horizontally stratified and ripple and trough cross-stratified sandstone (for example, 3 to 4·25 m level) and interbedded sandstone and mudstone (for example, 6 to 8·0 m level). Note basal occurrence of mudstone rip-up clasts and basal erosional scours for many sandstone bodies. All sandstone packages are bounded by fine-grained deposits of FA 2.

<1) rather than bars and bar complexes. Sporadic occurrences of low-angle cross-stratification and large-scale cross-bedding, in addition to rare occurrences of convex-up bar geometries in channel deposits, suggest that lateral or downslope transport of bar macroforms was not an important mechanism of sediment migration. Distorted bedding is attributed to dewatering as a result of rapid deposition on a saturated substrate (Postma, 1983). The occurrence of climbing-ripple structures supports an interpretation of rapid deposition during conditions of sustained bedload transport.

The majority of unconfined deposits appears to be the result of a single flood event in which flow was characterized by initial upper plane-bed conditions characterized by traction transport during peak flood conditions, followed by three-dimensional dune migration and current-ripple migration during waning flood flow. In contrast, the poorly confined lenticular channel deposits are the result of either single or multiple flood events in which channels scoured a single broad erosional surface in underlying mudstone deposits. Deposition, involving stacked sandstone deposits in channels, was characterized by initial basal scour and subsequent scour and fill events that occurred within the confines of an initial broad channel, ultimately resulting in nearly complete preservation of multiple sandstone units. Mudstone drapes interbedded with tabular sheets in channel sandstone bodies imply that, in addition to recurring episodes of scour and fill during peak flood conditions, there were multiple episodes of suspension fallout during waning flood flow. The lack of abundant trough cross-stratification and bar elements, together with the conspicuous lack of planar cross-stratification indicative of simple bars (Todd, 1996; Bridge, 2003), suggests minimal lateral migration of channel elements. Based on the tabular to slightly lenticular, thin-sheet geometry of these deposits, and the vertical distribution of horizontally stratified and ripple cross-stratified sandstone with thin drapes of mudstone, unconfined to poorly confined sheetflow conditions, are interpreted to be responsible for laterally extensive channels throughout Facies Association 3.

Both the tabular (sheet) and lenticular (channel) deposits are always encased within fine-grained floodplain material with little to no evidence of amalgamation of sandstone units. The channel sandstone is interpreted to be bounded by overbank floodplain deposits, whereas tabular sheet sandstone is bounded by terminal downslope floodplain deposits. In general, crevasse splay deposits adjacent to channel sandstone units are typically <0·75 m thick, whereas unconfined sheet deposits are typically <2 m thick (0·75 to 2·0 m thick). However, given the difficulty in identifying the exact transition from channelized to unconfined flow, distinguishing between overbank crevasse splay deposits and downslope terminal splays can be difficult. In the context of measured sections, the majority of fine-grained deposits and sheet sandstone units <0·75 m thick in the lower Potoco Formation are interpreted to represent terminal floodplain deposits associated with the most distal portion of the system.

Depositional processes

The thick Potoco Formation in the Corque syncline region is interpreted to be the result of poorly confined channels that change downslope into laterally extensive, unconfined sheetflows (Fig. 11). This fluvial system was characterized by episodic, short-lived depositional events in three environments: (i) playa lakes; (ii) overbank and downslope terminal floodplain regions; and (iii) unconfined sheets and poorly confined channels. Confined channel flow and unconfined sheetflow were marked by rapid deposition of sandstone deposits from bedload during single and multiple flood events within poorly defined channels and unconfined floodplain and playa settings. Periods of peak discharge in channels were responsible for flooding in overbank floodplain environments (McKee, 1967; Williams, 1970) and occasional standing water in shallow lakes. The episodic or 'flashy' nature of this system ultimately resulted in: (i) temporary termination of flow and subsequent evaporative precipitation of gypsum in playa lakes; and (ii) infiltration, pedogenesis and vegetative growth in floodplain regions. Late-stage waning flow commonly resulted in suspension fallout of mud directly above coarser channel deposits (Williams, 1970; Picard & High, 1973). Periods of channel abandonment during lowered flow conditions probably corresponded to evaporative episodes in playa lakes and pedogenic alteration of fine-grained material exposed in floodplain areas.

No evidence exists that suggests a punctuated, upsection change from relatively thin tabular units compared with thick lenticular units, indicating a gradual downslope transition between confined flow in channels to unconfined flow in sheets (Fig. 11). Similarly, given the facies

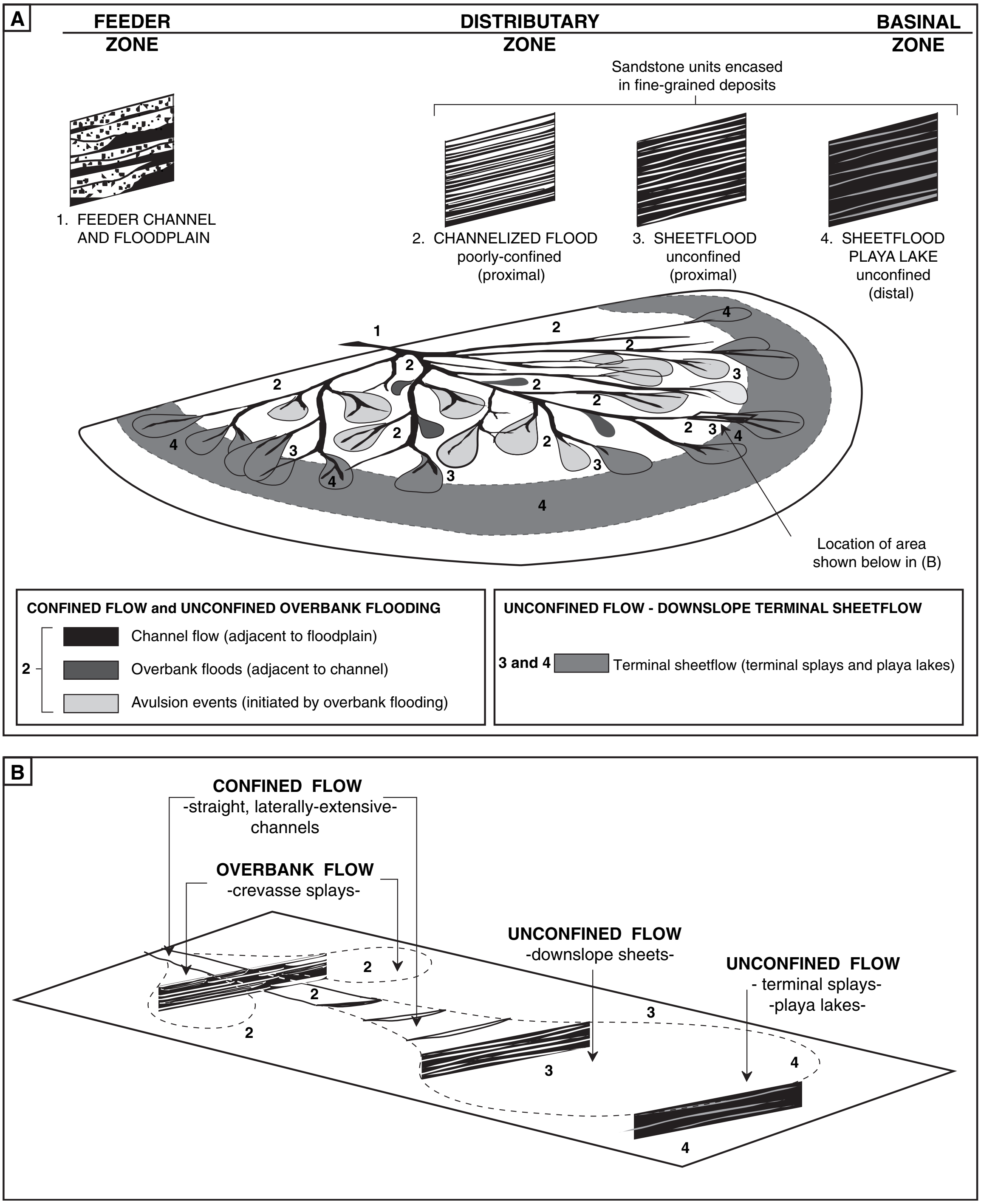

Fig. 11. Schematic depositional model of sheetflow-dominated, distributary fluvial processes for the Late Eocene–Oligocene Potoco Formation. (A) Distributary terminal fan model that highlights confined flow in channels and unconfined flow in overbank environments (Distributary Zone 2) and unconfined terminal sheetflow downslope of channels (Distributary Zone and Basinal Zone 3 and 4). Feeder Zone, Distributary Zone and Basinal Zone terminology from Kelly & Olsen (1993). Note that, in this model, channel relocation is accomplished by avulsion events associated with overbank flooding rather than lateral migration of channels. Overall, deposits become finer grained and exhibit more tabular geometries farther from the source due to water infiltration and evaporative loss. (B) Detailed schematic of the downslope transition from confined flow to unconfined flow. Confined portions of this system are characterized by poorly confined channels and unconfined overbank deposits where downslope unconfined regions are characterized by unconfined terminal splay deposits and subsequent playa lake formation.

homogeneity and similar stacking patterns between sheet and channel deposits, it seems evident that the confined and unconfined portions of this system behaved similarly with only a slight initial decrease in flow strength as the flow became unconfined downslope. Confined channels have a range of widths from 50 to 150 m, whereas unconfined sheets can be laterally extensive for >200 m, potentially indicative of a downslope maximum difference in channel width of up to 150 m.

Examples of ephemeral sheetflow-dominated streams in semi-arid regions include modern streams adjacent to the Ethiopian Highlands in north-eastern Africa (Abdullatif, 1989), the southern Karoo region of South Africa (Stear, 1985), central Australia (Williams, 1971) and in south-western USA. Consistent in modern examples is the pervasive occurrence of parallel lamination associated with flood conditions in channel and unconfined sheet environments and formation of ripples during waning stages of flow. Ancient examples of sheetflow-dominated systems include the Jurassic Kayenta Formation of western Colorado (Bromley, 1991; North & Taylor, 1996) and the middle sandstone member of the Triassic Chinle Formation in New Mexico (Deluca & Eriksson, 1989). Notable ancient sheetflow examples have also been described from Devonian strata throughout Europe and include the Shrinkle Sandstone in Whales, the Munster Basin in south-west Ireland, and the Trentishoe Formation of north Devon (Tunbridge, 1981; Kelly & Olsen, 1993; Marshall, 2000).

Due to rapid, short-lived depositional events in laterally extensive bedload channels, the majority of channel-fill deposits were preserved in their original tabular sheet geometry rather than reworked laterally or downslope by channel bar complexes. Individual channels in this system were relatively stationary, remaining fixed in one location during initial scouring and subsequent scour and fill events; lateral migration across floodplain regions was limited. Channel relocation occurred only after the initial broad basal scour had been filled. Such immobility suggests that channel relocation to other parts of the floodplain occurred primarily by rapid avulsion events (e.g. Mack & Leeder, 1998; Slingerland & Smith, 2004), rather than by continuous lateral migration and accompanying floodplain erosion. The combination of this avulsive pattern of channel relocation and ephemeral (flash-flood) fluvial style resulted in the preservation of significant amounts of fine-grained floodplain material.

ALTIPLANO DEPOSITIONAL HISTORY

A sheetflow-dominated fluvial style was responsible for depositing up to 6500 m of sediment in the thickest part of the Altiplano basin, resulting in a long-term average sediment accumulation rate >450 m Myr^{-1} for the Potoco Formation. This value represents a minimum accumulation rate using a maximum duration of 14 Myr during Late Eocene to Oligocene time and considering compaction of mud and sand beneath *ca.* 6000 m of sediment (Sclater & Christie, 1980). This rate is near the upper limit of previously documented accumulation rates for foreland basins (Jordan, 1995; Brozovic & Burbank, 2000), but those estimates are generally reported over shorter (several million-year) time frames.

Unique to the Altiplano basin is the large regional extent of the sheetflow-dominated fluvial style. Both westerly and easterly sourced deposits of Late Eocene to Oligocene age in the Corque syncline exhibit continuous exposure along the strike over a distance >100 km (Fig. 1).

Correlation of the lower Potoco Formation in the eastern limb of the syncline with coarse-grained strata in the western limb indicates that the westerly sourced depositional system had a minimum original down-dip extent >70 to 80 km, from a proximal zone in the west to a distal zone in the east (Horton *et al.*, 2001). It is difficult to estimate the scale of the easterly sourced deposits of the upper Potoco Formation due to significant Neogene-Quaternary cover east of the Corque syncline (Fig. 1); nevertheless, based on the preserved eastern limb, this depositional system exhibited a minimum original down-dip extent >30 to 35 km. Whereas the lower Potoco can be correlated throughout the study area over roughly >10 000 km^2, the minimum estimate derived from continuous aerial exposure of upper Potoco is >5000 km^2.

Both upward-coarsening successions in the Potoco Formation display upsection reductions in floodplain strata accompanied by increased thickness and lenticularity of channel deposits. Palaeocurrent data indicate that the lower Potoco Formation was generally derived from the west and the upper Potoco Formation from the east (Fig. 3), transverse to the flanking Western Cordillera and Eastern Cordillera respectively. Palaeocurrent data from the lower 4000 m (Fig. 3) reveal a radial pattern of sediment distribution, with east–south-east-directed flow for the Corque locality (Section 3) and north-east-directed flow for the Chuquichambi locality (Section 4). The coarsening-upward trends, upsection thickening of channel deposits and radial flow pattern of the lower Potoco Formation are attributed to eastward progradation of an extensive sheetflow-dominated distributary fluvial system related to a zone of initial Andean shortening west of the Altiplano plateau (Horton *et al.*, 2001, 2002). Similarly, upward coarsening and thickening of the overlying Potoco Formation is attributed to a subsequent progradation episode; however, this second sheetflow-dominated system was sourced from the east, in response to westward advance of a backthrust belt in the Eastern Cordillera (Sempere *et al.*, 1990; McQuarrie & DeCelles, 2001; Horton *et al.*, 2002; McQuarrie *et al.*, 2005). Despite the dramatic reversal in palaeoflow directions, the homogeneity of Potoco deposits throughout the thickest succession and across a broad region suggests that external factors controlling sheetflow-dominated fluvial style and extent were regionally pervasive throughout Late Eocene to Oligocene filling of the Altiplano basin.

The thickness and lateral extent of Potoco facies associations suggest that sheetflow-dominated fluvial processes in the central Altiplano basin occurred over a considerably larger spatial scale than debris-flow and sheetflow-dominated alluvial fans (e.g. Blair & McPherson, 1994). Moreover, the abundance of fine-grained floodplain material, a characteristic not ascribed to typical alluvial fans, together with the regional extent of these deposits, suggests this depositional system was more analogous to large-scale (100 to 100 000 km^2) ephemeral fluvial systems with distributary drainage patterns. Upward coarsening trends, radial palaeoflow and geometry and distribution of Potoco facies may be attributed to deposition in a medial to distal distributary region of a large-scale terminal fan (Fig. 11). This sheetflow-dominated fluvial style is strikingly similar to ephemeral and poorly confined depositional processes described for terminal fans in closed sedimentary basins (Kelly & Olsen, 1993), but with a few noted exceptions: (i) the large volume of fine-grained floodplain strata preserved throughout much of the distributary regions of the fan; and (ii) the lack of any consistent connectivity between lenticular or tabular sandstone units. This study documents an overall upsection decrease in fine-grained strata and an increase in thickness and occurrence of lenticular sandstone units is documented (Fig. 3). Within the context of a prograding terminal fan model, these trends imply a greater propensity for channel amalgamation from distal to more proximal parts of the system; however, evidence for stacked channel networks is largely absent from the Potoco Formation. Accordingly, the exposed portions of the Potoco Formation in the Corque syncline are interpreted to represent the remnants of two terminal fluvial fans where deposition was driven by ephemeral poorly confined flow and unconfined sheetflow conditions in the absence of any well-developed braidplain channel network.

DISCUSSION

Facies associations of the Potoco Formation provide an ancient example of sheetflow-dominated fluvial systems characterized by episodic depositional events.

Identifying sheetflow fluvial systems

On the basis of observed facies, diagnostic criteria for identifying sheetflows in the rock record include the recognition of thin (<4 m thick), tabular-to-lenticular sandstone bodies associated with non-erosional to slightly erosional basal contacts. The laterally continuous channel sandstone bodies are composed primarily of horizontally stratified and ripple cross-stratified sandstone, typical of deposits in ephemeral streams (McKee, 1967; Williams, 1971; Frostick & Reid, 1977). Sheetflow deposition is generally dictated by ephemeral high-energy flood events (Schumm, 1961; McKee, 1967; Rahn, 1967; Glennie, 1970; Williams, 1970, 1971). Playa lake evaporites and channel deposits interbedded with pedogenically altered floodplain material attest to the ephemeral nature of the system. Mudstone drapes within some channel sandstone further indicate deposition of fine-grained material during waning flood stages.

The thin, even geometry and laterally extensive distribution of channel deposits would be typical of braided river systems, yet the distribution of facies indicative of deposition in fixed channels suggests that channel filling occurred *in situ*, isolated in a single part of the floodplain. In other words, channels remained stationary until completely filled by single or multiple flood events, and only then avulsed to an adjacent part of the floodplain, a quality reminiscent of strongly confined channels in anastomosing rivers. However, the lateral extent, high width-to-thickness ratios and poorly defined nature of channels, eliminate an anastomosed style as the primary depositional system. It could also be argued that isolated channels encased in floodplain deposits are indicative of meandering depositional systems but the bar macroforms and epsilon cross-bedding diagnostic of lateral channel migration that typify meandering systems are rare in these deposits. The increased occurrence of channel deposits and decreased floodplain strata in the upper Potoco Formation suggest that the system may have been evolving towards an extensive sand-dominated braided system. However, the occurrence of pervasive horizontally stratified and ripple cross-stratified sandstone and rare epsilon cross-bedding are indicative of the isolated nature of channels throughout these deposits, suggesting that if these strata are to be interpreted as the result of a braided fluvial style, the basic component of bar migration used to identify braided rivers in ancient deposits and modern settings is starkly absent. These findings suggest that the sheetflow-dominated fluvial style responsible for these deposits retains minor components of the meandering, braided and anastomosing fluvial styles but, as a whole, is fundamentally distinct from these classic depositional models.

External controls on fluvial style

Numerous studies have explored the external controls on alluvial architecture through modelling (Allen, 1978; Leeder, 1978; Bridge & Leeder, 1979; Alexander & Leeder, 1987; Mackey & Bridge, 1995), field studies (Alexander *et al.*, 1994; Leeder *et al.*, 1996a,b; Peakall, 1998; Mack & Madoff, 2005) and within a sequence stratigraphic framework (Shanley & McCabe, 1991, 1993; Holbrook & Schumm, 1999; Schumm *et al.*, 2000; Holbrook, 2001). Alluvial architecture is affected most by changes in base level, sediment supply and subsidence. Recent experiments by Hickson *et al.* (2005) have shown that forced facies migrations are largely responsible for controlling stacking patterns and architecture. Although forced migration of facies is ultimately driven by external controls, such experiments reveal the difficulty that arises in isolating and observing specific allogenic controls and their effect on deposition.

Given the large thickness and spatial extent of the Potoco Formation and its distinction from more standard fluvial facies models, an attempt is made to delimit the first-order external (allogenic) controls, including eustatic and other fluctuations in base level, climatic effects on sediment supply, and tectonic conditions affecting subsidence that may influence the generation of a sheetflow-dominated fluvial style over such large temporal and spatial scales.

Eustasy

The overall ephemeral nature of sedimentation, presence of evaporite facies and documented dual sediment source areas on the opposing (eastern and western) flanks of the basin suggest that the sheetflow-dominated fluvial system was internally drained and unaffected by variations in eustatic sea-level variations. The terminal nature of this system, together with the lack of evidence for any axial or trunk drainage system that would link this system to base level, suggests that the fluvial style responsible for these strata entirely was unaffected by fluctuations in sea-level. Furthermore, regional stratigraphic considerations for provinces to the west (e.g. Mpodozis *et al.*, 2005) and to the east (e.g. DeCelles & Horton, 2003) suggest that the Potoco depositional system was confined by topographic barriers related to Early Cenozoic to mid-Cenozoic shortening. Therefore, the closed drainage system observed on the modern surface of the Altiplano plateau may have prevailed since Late Eocene time, with deposition unaffected by specific base level conditions and fluctuations through time.

Climate

Significant fine-grained floodplain material is present in the Potoco Formation. Aggregate soil textures and preserved root traces suggest that these deposits were exposed sub-aerially and underwent initial stages of pedogenic alteration (Bown & Kraus, 1987; Daniels, 2003). Although palaeosols in the study area are weakly developed, their frequent occurrence throughout measured sections is suggestive of episodic deposition, consistent with seasonal climatic conditions. The occurrence of slickensided surfaces on palaeosol peds in floodplain deposits, together with reoccurring thin laminated and massive mudstone drapes in channel fill, are strong lines of evidence for seasonality of precipitation and cyclicity of flood events (e.g. Mack *et al.*, 2003). Episodic sedimentation is a common feature of semi-arid to arid climates where sporadic rainfall combined with sparse vegetation leads to rapid pulses of run-off and sedimentation (Schumm, 1968; Bull, 1997). Arid conditions and rapid sedimentation events have been proposed for similar deposits in other ancient fluvial systems (Glennie, 1972;

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Middleton & Blakey, 1983; George & Berry, 1993; Herries, 1993; Trewin, 1993). Short-lived, ephemeral flood events promoted preservation of horizontally stratified and ripple cross-stratified sandstone sheets and inhibited the development and migration of sediment within longer-lived channel bars. Large fluctuations in discharge may be responsible for the poor development of incised channels and may ultimately promote the rapid avulsive pattern of channel relocation. Episodic flood events accompanied by an increase in overall discharge may indicate rapid aggradation of channels and subsequent avulsion (Wells & Dorr, 1987; Bryant *et al.*, 1995; Jones & Schumm, 1999). Although sediment supply and discharge would be expected to be punctuated, the homogeneity of deposits with respect to the thickness, stacking patterns and facies distribution in sandstone bodies throughout the succession suggests that the magnitude, discharge and sediment supply during successive events did not fluctuate significantly through time. Potential links have been shown to exist between cycles of seasonal precipitation and the development of modern fluvial megafans adjacent to active mountain belts (Leier *et al.*, 2005). Given the distribution of facies throughout the Potoco Formation, it seems probable that seasonal, arid to semi-arid climate conditions persisted in the Altiplano basin during Late Eocene to Oligocene time and were influential in controlling the style of sediment accumulation by inducing episodic but homogeneous depositional events in an ephemeral system over an extended period of time.

Tectonics

Given the absence of significant fluctuations in base level and long-term sediment supply, the following section focuses on the possible effects of subsidence on the depositional system. Although experiments highlight the difficulty in isolating the effects of subsidence on alluvial architecture, it has been suggested that if subsidence occurs faster than a fluvial system can adjust, a river is likely to adjust by the deposition of floodplain material, including sheet sands (Hickson *et al.*, 2005). A brief review is given to the distribution of fine-grained facies and stacking patterns of sandstone units throughout the succession are considered to explore the possible effect of subsidence on depositional patterns.

Significant volumes of fine-grained floodplain material are not incorporated within braided stream facies models, primarily due to their absence in modern settings (Moody-Stuart, 1966; Cant & Walker, 1976a,b; Miall, 1977; Walker & Cant, 1984). However, a number of ancient braided systems contain significant amounts of preserved floodplain material complementing the coarse-grained channel fill (Raynolds, 1980; Desloges & Church, 1987; Mack & Seager, 1990; Bentham *et al.*, 1993). One proposed explanation for enhanced floodplain preservation is sediment accumulation during rapid regional subsidence over extended periods of time (Bentham *et al.*, 1993). Deposition during rapid subsidence requires that active channels aggrade vertically to keep pace with basin subsidence, resulting in the isolation of channel deposits within floodplains and the suppression of significant channel migration (Kraus & Middleton, 1987; Schuster & Steidtmann, 1987). Similarly, non-erosional sandstone sheet geometries in sheetflow-dominated systems may also be diagnostic of high subsidence rates (Friend, 1978). Relocation of channels under these conditions will probably occur by avulsion events, rather than by continuous lateral channel migration (Bentham *et al.*, 1993). The result most probably would involve the rapid aggradation of sediment within channels and relocation of channels by punctuated avulsion. Punctuated channel relocation coupled with a low avulsion frequency during flow events would be conducive to the preservation of floodplain material.

Many studies have used numerical models to test the controls of subsidence on alluvial architecture (Allen, 1978; Bridge & Leeder, 1979; Bridge & Mackey 1993; Bryant *et al.*, 1995; Mackey & Bridge, 1995; Heller & Paola, 1996). Bridge & Leeder (1979) suggest that floodplain material is more likely to be preserved between channel avulsion events during periods of rapid subsidence, in contrast to periods of lower subsidence where floodplain material is removed during more frequent channel avulsion and migration. Similarly, with decreased subsidence, an increase in amalgamated channel deposits is expected; rapid subsidence would produce less channel connectivity.

In the case of the Potoco Formation, a sheetflow-dominated fluvial style was responsible for deposition of up to 6·5 km of sediment during Late Eocene to Oligocene time, yielding a long-term average sediment accumulation rate, corrected for compaction, of greater than 450 m Myr^{-1} (0·45 mm $year^{-1}$). This value represents a minimum accumulation rate over ≈14 Myr during the Late Eocene to Oligocene time. This rate is near the upper limit of documented sediment accumulation rates over several million-year time frames in foreland basins (Jordan, 1995; Brozovic & Burbank, 2000), suggesting that the rapid subsidence necessary to accommodate the thick Potoco succession may have been partially responsible for driving avulsive channel relocation and limiting scour of previously deposited sediment.

CONCLUSIONS

1 Sheetflow fluvial processes dominated the 6500 m thick succession of the Late Eocene to Oligocene Potoco Formation in the Altiplano basin. Deposition occurred in three sub-environments, represented by the playa lake, floodplain and poorly confined channel and unconfined sheet facies associations. Channel and sheet deposits are laterally continuous for 50 to 200 m and exhibit little evidence of amalgamation or connectivity. Although individual facies characteristics of the sheetflow-dominated Potoco Formation are similar to selected components of classic braided, anastomosing and meandering fluvial systems, the overall thickness and long-term influence this system had during the deposition of the Potoco Formation suggests that it is fundamentally distinct from these three end-members and recognizable in the stratigraphic record.

2 Widespread exposure of the Potoco Formation in the Corque syncline allows regional stratigraphic correlation, suggesting an original depositional system of large regional extent (>10 000 km^2). Whereas palaeocurrent indicators in the lower 4000 m show eastward palaeoflow in a radial pattern, the upper 2500 m exhibits westward palaeoflow. Despite this palaeoflow reversal, facies are remarkably similar throughout the succession, and both the lower and upper sections show consistent upward coarsening. These features are attributed to the evolution of two separate terminal fluvial fans in a closed drainage setting. The fans were derived from transverse drainage systems during uplift of the early Andean orogen, to the west and east.

3 Available age constraints suggest that the 6500 m thick Potoco Formation was deposited over a 14 Myr period during Late Eocene to Oligocene time. Decompacted sediment accumulation rates exceed 450 m Myr^{-1}, comparable with the most rapid rates recorded in foreland basins.

4 An episodic nature of sheetflow sedimentation in the Potoco depositional system is revealed by sharp contacts between variable lithofacies and minor palaeosol development with root traces. These depositional patterns are consistent with ephemeral drainage in a seasonal, arid to semi-arid climate.

5 On the basis of the Potoco depositional system, it is concluded that rapid subsidence and a seasonal climate may be one set of necessary conditions for the long-term evolution of a sheetflow-dominated fluvial systems.

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