HIGH RESOLUTION STRATIGRAPHY AND GRAVITY FLOW DEPOSITS IN THE LOS MOLLES FORMATION (CUYO GROUP - JURASSIC) AT LA JARDINERA REGION, NEUQUÉN BASIN

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ABSTRACT

The Pliensbachian to Early Callovian Cuyo Group in the Arroyo La Jardinera area reflects a shelf-slope-basin plain physiography. A major unconformity defines the onset of a thick turbidite succession and represents a 2nd order sequence boundary. The older 2nd order depositional sequence comprises the base of Los Molles Formation and includes a transgressive-regressive cycle ascribed to basin plain and slope rise strata. The younger one, which includes the rest of the Cuyo Group, consists of a regressive succession punctuated by several abrupt shifts of physiographic elements (3rd order sequence boundaries). The 3rd order depositional sequences include Aalenian slope rise and slope deposits in the Los Molles Formation, Early Bajocian shelfal facies at the transition of the Los Molles and Lajas formations, and Middle to Late Bajocian inner shelf to nearshore strata in the Lajas Formation that are overlain by Bathonian alluvial deposits of the Challacó Formation. Higher frequency cycles punctuate the succession and have controlled the origin, deposition and abandonment of the architectural elements. Facies and architectural elements analyses indicate that gravity flow deposits in the Los Molles Formation fit in a submarine ramp model. The three identified gravity flow (GF) types have been related to 4th order relative sea-level falls. The GF1 was ascribed to hyperpycnal flows produced during 4th order early lowstand, coeval to fluvial incision on the shelf, which were ignited in the slope and produced depletive depositional pulses with a fluvial compositional signature. The GF1 system includes relatively small channels in the slope, well-developed lobes in the slope rise and proximal basin plain, and lobe fringes in the basin plain. The GF2 strata were ascribed to hyperpycnal flows influenced by an oscillatory component and related to the 4th order late lowstand systems tract that also includes the incised channels fill. They are characterized in the slope by widespread, undulating and laminated sandstone and heterolithic facies, which include low relief scours at their central portions. They represent more diluted and finer-grained density flows relative to the GF1. The GF3, also associated with the 4th order lowstand wedge, comprises mass and debris flow deposits in the slope and slope rise that represent classical, short-lived surges caused by slope failures on relatively steep slopes. The 4th order transgressive and highstand systems tracts led to the abandonment of the turbidite stages and widespread mud deposition.

Key words: *Neuquén basin, Jurassic, Turbidite, Hyperpycnal flow, Gravity flow.*

RESUMEN: *Estratigrafía de alta resolución de depósitos de flujos gravitacionales de la Formación Los Molles (Grupo Cuyo - Jurásico) en la región de La Jardinera, cuenca Neuquina.* El Grupo Cuyo en el área del arroyo La Jardinera (Pliensbachiano a Caloviano Temprano) refleja una fisiografía de cuenca de plataforma y talud. Una discordancia de orden mayor define la culminación de una espesa sucesión de turbiditas y representa un límite de secuencia de 2do orden. La más antigua secuencia de 2do orden comprende el tramo basal de la Formación Los Molles e incluye un ciclo transgresivo-regresivo asignado a estratos de base de talud y fondo de cuenca. La secuencia más joven, que incluye el resto del Grupo Cuyo, consiste de una sucesión regresiva puntuada por varios desplazamientos abruptos de elementos fisiográficos (límites de secuencia de 3er orden). Las secuencias depositacionales de 3er orden incluyen depósitos de talud y de base de talud del Aaleniano de la Formación Los Molles, facies de plataforma del Bajociano Temprano en la transición entre las formaciones Los Molles y Lajas, y sedimentitas de plataforma interna a *nearshore* del Bajociano medio a tardío de la Formación Lajas, que es a su vez cubierta por depósitos del Bathoniano aluvial de la Formación Challacó. Ciclos de más alta frecuencia alternan en la sucesión y han controlado el origen, depositación y abandono de los elementos arquitecturales. Análisis de facies y de elementos arquitecturales indican que los depósitos gravitatorios densos de la Formación Los Molles encuadran en un modelo de rampa submarina. Los tres tipos de flujos gravitacionales (GF) han sido relacionados a caídas del nivel del mar de 4to orden. Los GF1 fueron asignados a flujos hiperpícnicos producidos durante un cortejo temprano de mar bajo de 4to orden, coevo con incisión fluvial en la plataforma, que evolucionaran a flujos turbidíticos en el talud, produciendo cargas de pulsos depositacionales cuya signatura composicional es fluvial. El sistema de GF1 incluye canales relativamente pequeños sobre el talud, lóbulos bien desarrollados en la base del talud y la planicie de fondo de cuenca proximales, así como lóbulos adventicios en la planicie del fondo de cuenca. Los estratos GF2 fueron asignados a flujos hiperpícnicos influenciados por un componente oscilatorio y relacionados a cortejos tardíos de mar bajo de 4[to] orden, que también incluyen relleno de canales incididos. Ellos están caracterizados en el talud por areniscas onduladas y laminadas ampliamente distribuidas y facies heterolíticas, que incluyen *scours* de bajo relieve en sus porciones centrales. Ellos representan flujos densos más diluidos y de grano más fino con respecto a los GF1. Los GF3, también asociados con cuñas de mar bajo de 4[to] orden, comprenden depósitos de flujos en masa y *debris* de talud y de base de talud, que representan clásicos *surges* de corta duración causados por debilidades en taludes relativamente abruptos. Los cortejos transgresivos y de mar alto de 4[to] orden llevaron al abandono de la etapa turbidítica y extensiva depositación de fango.

Palabras claves: *Cuenca Neuquina, Jurásico, Turbidita, Flujo hiperpícnico, Flujo gravitatorio.*

INTRODUCTION

This paper outlines some results of a study on turbidites of the Los Molles Formation (Cuyo Group) in the La Jardinera area, south-western portion of the Neuquén basin. In this region, the Cuyo Group rests in unconformity (Rioatuelican) upon metamorphic breccias ascribed to the Colohuincul Formation (Upper Proterozoic). The base of the Cuyo Group in the area belongs to the Pliensbachian Sierra Chacaicó Formation whereas the Los Molles and Lajas formations are represented by Toarcian to Bajocian marine strata.

One of the main goals of the research was to test the potential association of a well exposed turbidite succession, which crops out near the bridge over the La Jardinera creek along National Route 46, with fluvial discharge as a direct link of these turbidite strata to catastrophic fluvial floods was formerly proposed (Mutti *et al.* 1994). In our view, a broader analysis of the geological record through photostratigraphy (*sensu* Sgavetti 1991 and Sgavetti et al. 1995) added by the description of nearby sections would be useful to test this model.

Therefore, 3D views of high resolution Ikonos satellite images were primarily used to delineate stratigraphic surfaces that represent either conformable bed sets boundaries or unconformities. In addition, these images were employed to discriminate photofacies and to perform geometrical analysis of some architectural elements. Vertical sections were described to identify facies, facies associations, architectural elements (after Miall 1985 adapted to marine deposits) and key stratigraphic surfaces, hence tying indirect (*e.g.* spectral images) to direct (*e.g.* lithology) data. In this way, image mapping of major bedding surfaces has allowed constraining contemporaneous facies, facies associations and architectural elements.

At last, some information about terminology. The term *tabular* was used to describe widespread, parallel-sided beds; *laterally extensive* to less continuous, non tabular strata that still present a high width / height (w/h) ratio; and *lenticular* to beds with a low w/h ratio. The word *undulating* was applied to sedimentary bodies with repetitive trend of thickness change that follows a wavy trend. In terms of facies codes, the initial uppercase letters G, S, H and F indicate gravelly, sandy, heterolithic and fine-grained deposits; FC and FS point to fine-grained claystone and siltstone; HF and HSF designate heterolithic deposits composed of siltstone / claystone and sandstone / mudstone; and DF specifies debris flows. The lowercase letters signify massive (m); normal- (g) or inverse (i) grading; low-angle (l), trough (t) or hummocky (hcs) cross-stratification; horizontal (h) and ripple cross (r) lamination; traction carpets (tc); bioclast-rich (bio); mud drape (d); reactivation surface (rs); wave-reworked (twr) and wave-produced (tw) trough cross-bedding; wave ripple cross lamination (wr); wave-related planar lamination (hw); and wave-ripples (Sw). The letters between brackets indicate coarse- to very coarse-grained (Sc) and/or very fine- to medium-grained (Sf) sandy matrix of paraconglomerates.

REGIONAL SETTING

The Neuquén basin is located in central western Argentina and eastern Chile between latitudes 31° and 41° S. It occurs in Argentine territory in the provinces of Neuquén, from which it takes its name, Mendoza, Río Negro and La Pampa (Fig. 1). It extends northwards along the axis of the Andean Cordillera up to 31° S (San Juan province), where it is called the Aconcagua basin. Between 34° and 37° S it is restricted to the cordilleran belt as a narrow N-S elongated strip. Southwards from 37° S it broadens eastwards, into the extra-Andean domain, where it is known as the Neuquén embayment. Displaying a triangular shape, the Neuquén basin covers more than 160.000 km^2 and extends up to 700 km in a north-south direction (Zavala 1993). Besides the Andean chain to the west, the basin is also bounded by two large cratonic blocks, the Pampeano-Sierra Pintada massif to the northeast and the North Patagonian massif to the southeast. The infill of the Neuquén basin (Fig. 2) exceeds 7000 m of marine and continental strata (epiclastics, carbonates, evaporites and pyroclastics) that range from Late Triassic to Paleocene in age (Ramos 1998).

In Late Triassic times, central western Argentina and eastern Chile underwent an extensional tectonic process, linked to

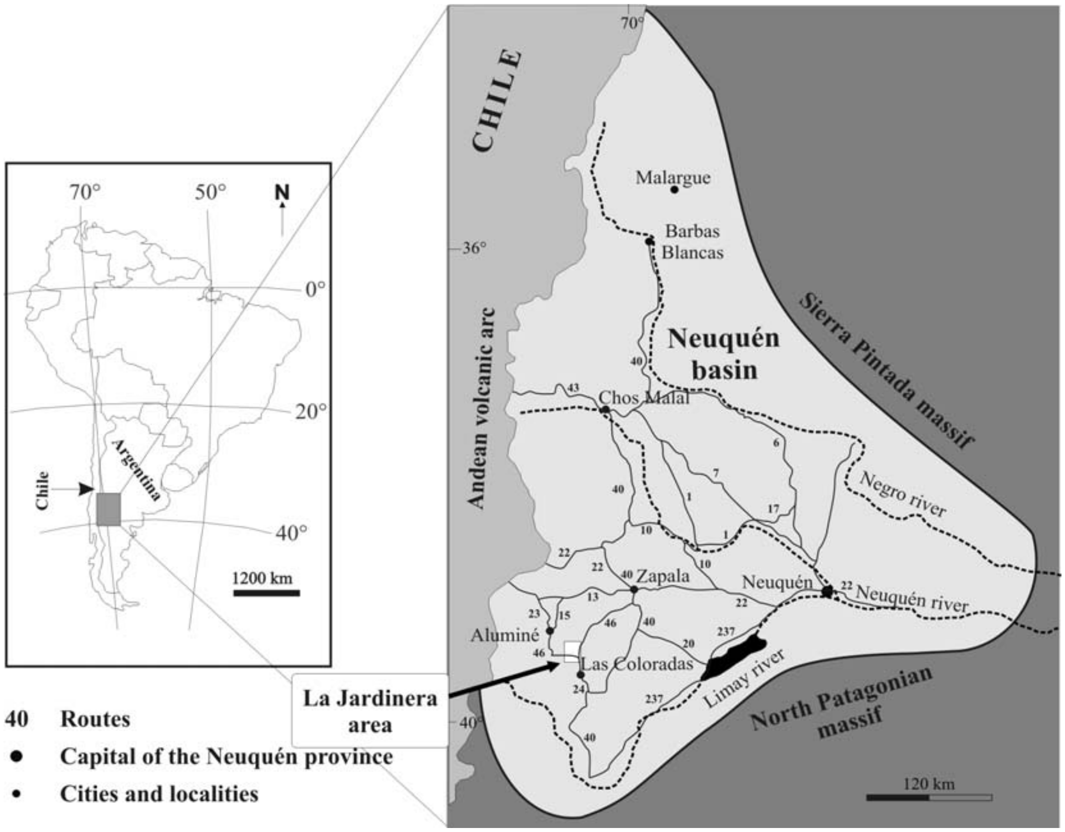

Figure 1: Location of the Neuquén basin in South America, with indication of the main localities and the study area of La Jardinera region.

the existence of an arc/trench system along the western margin of the South American Plate (Legarreta and Uliana 1991, Gulisano and Gutiérrez Pleimling 1994). As result, a series of fault bounded depressions began to form during a rifting process with their orientation being controlled by structural features of the underlying sialic substrate. Therefore, Late Triassic sedimentation was confined to isolated depressions filled with nonmarine facies with a strong influence of pyroclastic and volcanic materials and large lateral changes of thickness (Gulisano and Gutiérrez Pleimling 1994), which are known as the "Precuyo" Group (Lapa Formation in southern Neuquén). These depocenters, located to the east of the arc trench system, became progressively unified, to ultimately merge into an extensive area of marine sedimentation during the Pliensbachian, which was located between the volcanic arc to the west and the South American foreland to the east (Vicente 2005).

From the Early Jurassic to part of the Middle Jurassic, the deposition was strongly controlled by tectonics; a phenomenon that gradually diminished to give way to a regional subsidence stage that lasted from the Middle Jurassic until the Early Paleogene (Ramos 1998). Although most of the Neuquén basin has maintained an almost continuous subsidence rate, local episodes of elevation, folding, erosion and synsedimentary tectonics were recorded (Vergani 2005). Therefore, the sedimentation styles and the stratigraphic column record these episodes of structural inversion and related unconformities, the more important one being responsible for the development of the Huincul Arch, a large east-west transcurrent fault zone located in the southern portion of the basin and related to extensional stresses caused by the Gondwana break-up and the Atlantic ocean opening (Vergani *et al.* 1995). A number of transgressions and regressions mainly driven by eustatic sea level changes took place before the progressive Andean chain growth cut off any oceanic influence into the basin (Legarreta and Gulisano 1989). From the Miocene, an increase on Andean tectonic activity made the Neuquén basin evolution still more complex.

PALEOPHYSIOGRAPHIC ELEMENTS

Based on the analysis of facies, facies associations and architectural elements, the Los Molles and Lajas formations were assigned to four paleophysiographic elements, herein understood as genetic units larger than architectural elements and analogous to modern physiographic features of many marine basins. The identified paleophysiographic elements include the slope rise to basin plain and the slope in the Los Molles Formation, the mid to outer shelf (including the shelf margin) in the transition between the Los Molles and Lajas formations, and the inner shelf to nearshore in the Lajas Formation (Figs 3 and 4). These physiographic elements were further subdivided into smaller-scale, architectural ele-

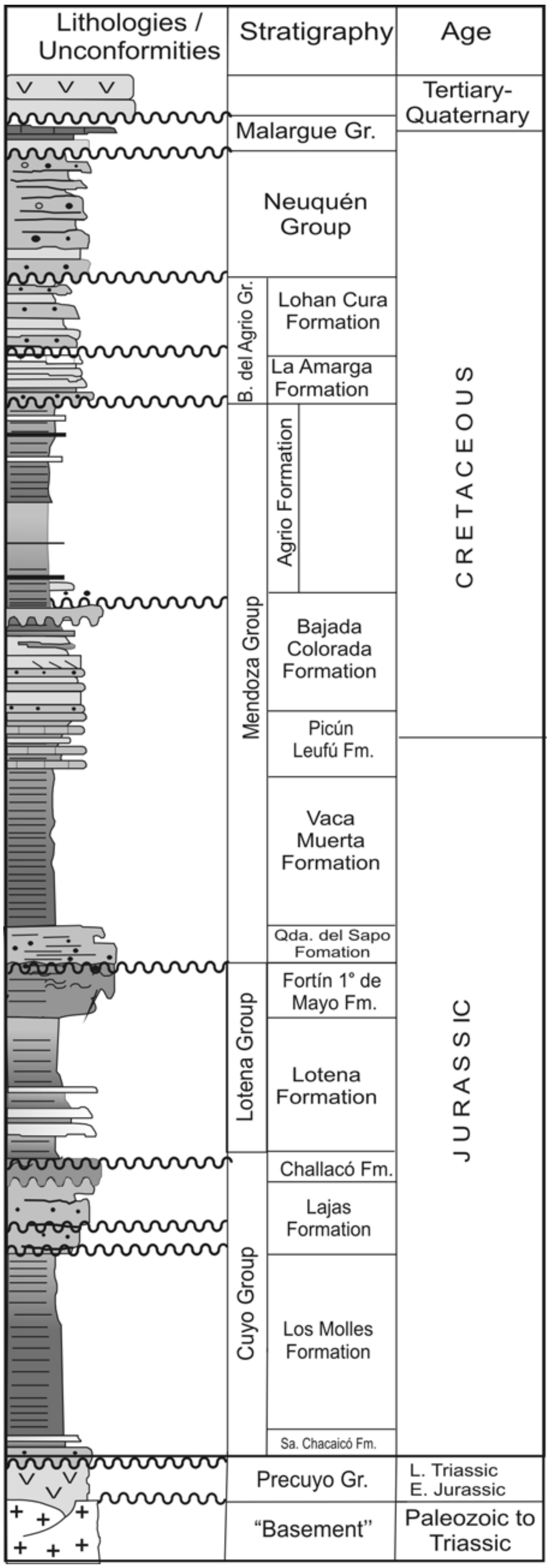

Figure 2: Regional stratigraphic column for the southern and central part of the Neuquén basin (after Leanza and Hugo 1997).

ments that constitute them and present distinctive geometries and specific facies associations. The fluvial deposits of the Challacó Formation were not described, but used as a stratigraphic marker to define the upper limit of the studied interval. Abundant fine grained deposits and sandy turbidite lobe strata as well as the dominance of planktonic (radiolarian) specimens among the microfauna comprise the main features of the slope rise to basin plain. The distinction between slope rise and basin plain was based on the exclusive occurrence of slumped beds in the slope rise setting. Similar faunal content and slumped beds, but usually associated with slide deposits and turbidite channels encased by muddy interchannel and overbank facies characterize the slope realm. A shallow marine assemblage, shoreface and shallow marine deposits scoured by fluvial incised channels characterize the mid to outer shelf scenario. Similar features but in a dominantly sandy interval set apart the inner shelf / nearshore paleophysiographic element.

Pebbles and cobbles composition suggests a volcanic source area for the Los Molles Formation whereas abundant siliceous grains are dominant in the Lajas Formation. Intraclasts (abundant mud clasts and plant debris, common wood pieces and minor bioclasts) and rarer metamorphic clasts complete the spectrum of large clasts in the studied area.

The basin plain and turbidite lobe deposits, which comprise most of the lower and middle portions of the Los Molles Formation, respectively, and the turbidite and incised fluvial channels, which are correspondingly associated with widespread fine-grained facies of the slope and mid to outer shelf, are equivalent to tripartite subdivisions of the Los Molles Formation proposed from subsurface data (Gómez Omil *et al.* 2002, Verzi *et al.* 2005).

SEQUENCE STRATIGRAPHY

In southern Neuquén basin the Cuyo Group spans from the Pliensbachian to the Early Callovian (Leanza 1992) and its most important units regarding the La Jardinera region are the Sierra Chacaicó,

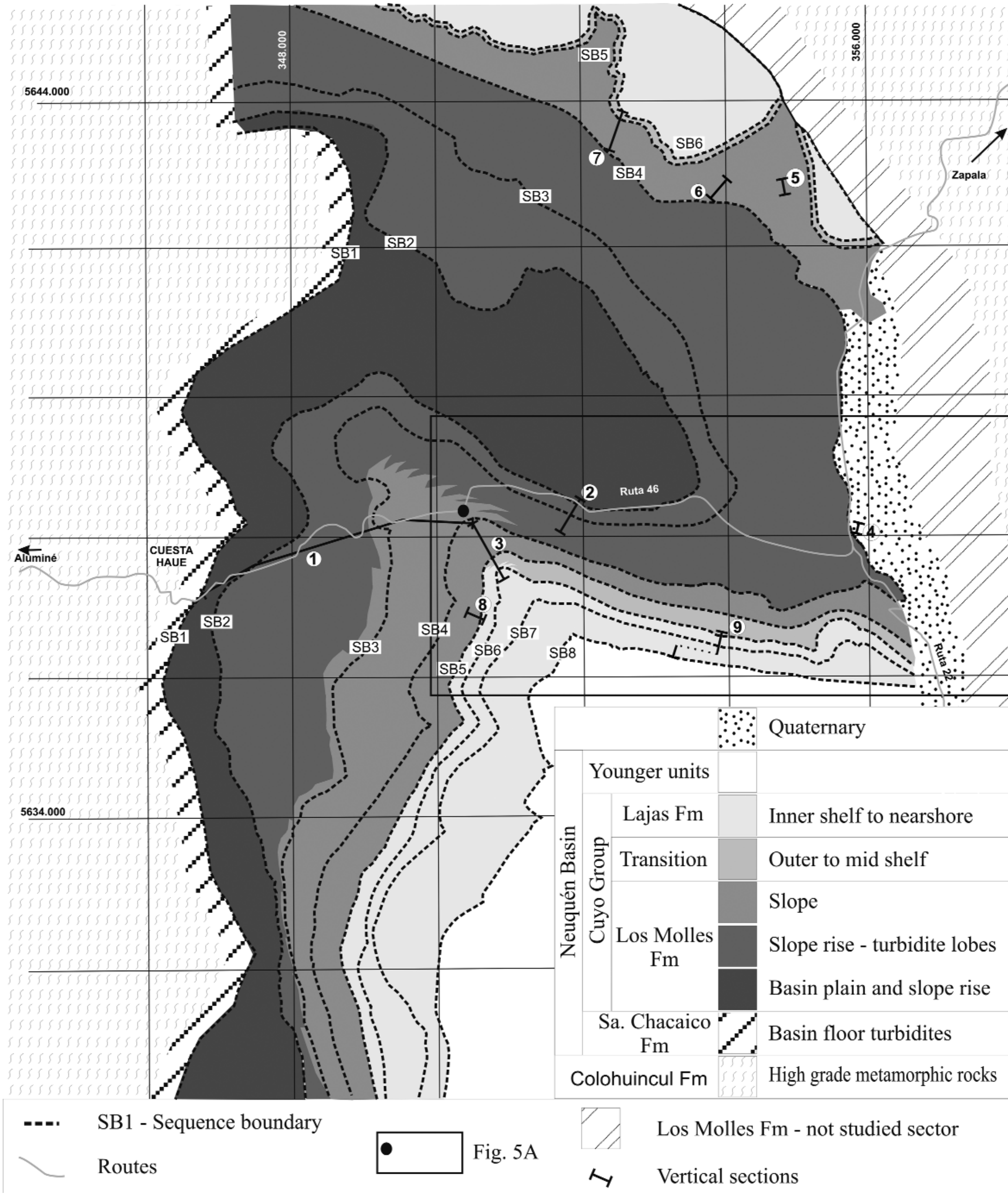

Figure 3: Simplified version of the photostratigraphic map presenting the main geological units and the paleophysiographic elements and sequence boundaries of the Los Molles and Lajas Formations.

Los Molles, Lajas, and Challacó formations (see Leanza and Hugo 1997, Cucchi and Leanza 2006). In the study region (Fig. 4) the Cuyo Group unconformably overlies metamorphic breccias of the Colohuincul Formation (sequence boun-

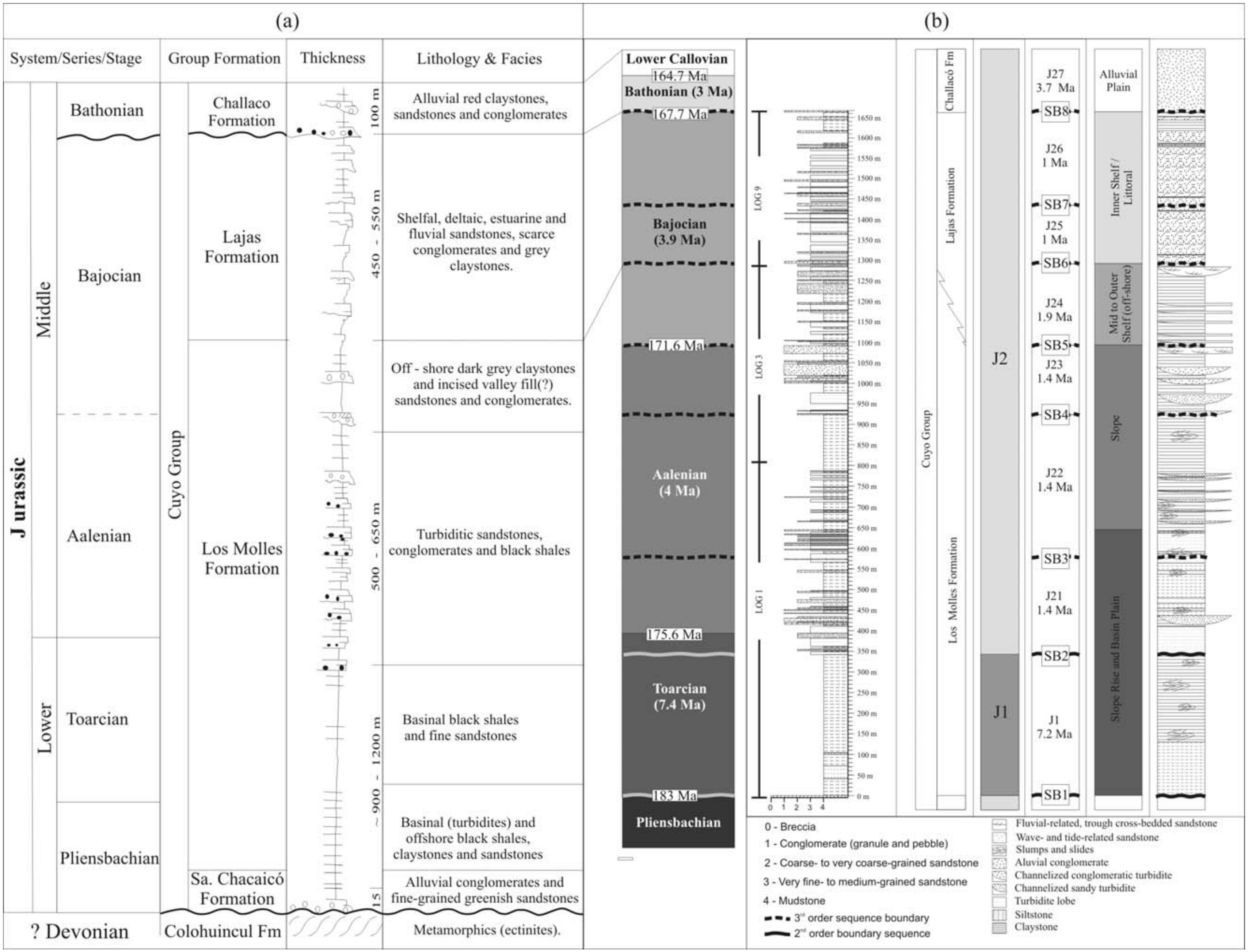

Figure 4: a) Stratigraphic chart of the Arroyo La Jardinera and Fortín 1º de Mayo area (Gulisano and Gutiérrez Pleimling 1995); and b) simplified, composite vertical section of the area (this paper). Stages obtained from correlation to Gulisano and Gutiérrez Pleimling (1995) chart and absolute ages from Gradstein *et al.* (2004) chart.

dary 1 - SB1) with 15 m of alluvial conglomerate, thin bedded yellowish to greenish turbidite sandstone and volcanic breccias of the Sierra Chacaicó Formation. The basal deposits of the Los Molles Formation then onlap this lower unit (SB2). Above this major sequence boundary, a thick marine succession was deposited and is recorded in the region by about 1110m of deep-marine strata (Los Molles Formation) and around 550m of shallow-marine facies (Lajas Formation). Finally, this marine interval is unconformably overlain (SB8) by the alluvial facies of the Challacó Formation.

Two 2nd order depositional sequences spanning 7.2 (J1) and 11.8 (J2) Ma were identified. Time frame (stages) was derived from the correlation of the stratigraphic chart of Gulisano and Gutiérrez Pleimling (1994) with the composite section (Fig. 4) whereas absolute stage ages were taken from Gradstein *et al.* (2004) time scale. These two 2nd order depositional are bounded by a major key stratigraphic surface (SB2) that delineates the abrupt deposition of a relatively thick (up to 400m thick), sandy turbidite succession (base of J2) over fine-grained, deep water marine deposits (J1). It seems that SB2 corresponds to the limit between the Lower Section and the Cutral-Có Member of the Los Molles Formation (Gómez Omil *et al.* 2002), the Lower and the Middle Los Molles Formation (Verzi *et al.* 2005) and the late rift phase and the post-rift phases (Vergani 2005). In addition, an eustatic sea-level fall near the Toarcian - Aalenian boundary, the estimated age of SB2, is shown in most of the published Jurassic sea-level curves (*e.g.* Vail and Todd 1981, Vail *et al.* 1977, 1984, Haq *et al.* 1987, 1988, Hallam 1988) hence suggesting an eustatic control on SB2 origin.

The J1 sequence (base of the Los Molles Formation) rests on onlap above SB1. It includes a T-R cycle characterized by fine-grained, poorly developed lobe and lobe fringe turbidites at the base (slope rise) successively overlain by muddy deposits (basin plain) and then by thin-bedded, fine-grained slumped beds (slope rise). The transition from slope rise to basin plain records the trangressive phase and the shift from basin plain to slope rise registers the regressive stage.

The J2 sequence rests on SB2 and comprises the middle and upper parts of the Los Molles Formation as well as the Lajas and Challacó formations. It shows an overall shallowing-upward trend punctuated by abrupt facies shifts ascribed to 3rd order relative sea-level changes that produce sharp, unconformable boundaries of shallower facies over deeper deposits. As a result, J2 was further subdivided into seven 3rd order depositional sequences (J21 to J27, Fig. 4).

Aalenian J21, J22 and J23 sequences (Los Molles Formation) include slope rise and slope strata and their bounding unconformities (SB3 and SB4) represent successive, abrupt superimpositions of slope over slope rise deposits. Early Bajocian J24 is mostly composed of shelfal facies including sandy strata (inner shelf to nearshore) similar to those of the Lajas Formation to fine-grained facies (mid to outer shelf) comparable to those of the Los Molles Formation. J24 represents the transition between the Los Molles and Lajas formations and its basal boundary (SB5) is defined by an abrupt shift from slope to shelf facies and includes significant fluvial incision on the shelf margin. Middle to Late Bajocian J25 and J26 encompass inner to nearshore, mostly sandy deposits of the Lajas Formation. Their lower boundary (SB6) corresponds to a sharp limit between muddy offshore (below) and sandy inner shelf / nearshore (above) facies. The limit between J25 and J26 (SB7) is defined by an abrupt increase in grain size (forced regression) that bounds two deepening, fining-upward shallow marine successions.

Sequence boundary 8 stands for the abrupt onset of an alluvial plain (Challacó Formation) over a shallow marine setting (Lajas Formation) at the Bajocian/Bathonian boundary. However, the description of this alluvial system (J27) is beyond the scope of this paper.

Sequences J1 to J27 are comparable to previously proposed schemes as follows: J1 to C3 (Legarreta and Gulisano 1989); J21 - J24 to C4 (Legarreta and Gulisano 1989) and JC4 (Zavala 1993); J25 - J26 to C5 (Legarreta and Gulisano 1989) and JC5 (Zavala 1993); and J27 to C6 (Legarreta and Gulisano 1989) and JC6 (Zavala 1993).

From both satellite image interpretation and field work, it was possible to realize that higher frequency (at least 4th order) sequence boundaries punctuate the entire succession and are related to the origin, deposition and abandonment of individual architectural elements whereas 3rd order sequence boundaries are associated with major shifts that affect entire physiographic elements. Lastly, the 2nd order sequence boundary (SB2) is associated with the largest volume (hundreds of meters thick and tens of kilometres long) of turbidite deposits present in the studied interval.

FACIES ASSOCIATIONS AND ARCHITECTURAL ELEMENTS

Basin plain and slope rise

Turbidite lobe: This architectural element (Figs 5 and 6) comprises around 101 m thick and more than 101 km long, tabular sandstone bed sets, at times including minor mudstone thin beds, interlayered with 5 to 10 m thick and more than 101 km long, dominantly muddy deposits. Sandstone beds range from 0.1 to 0.8 m thick and are laterally extensive, at times with an undulating geometry. Abundant mud clasts and plant debris, common tool and flute casts and scattered ammonites, vitrain layers and pelecypods are present. Fifteen paleocurrent readings on groove and flute marks, climbing ripples and rare small to medium-scale, tangential cross bedding show a mean vector oriented to ESE (102º).

The turbidite lobes consist of laterally-extensive beds of massive (Sm) or normally-graded (Sg), fine to very coarse

TABLE 1: Facies association and architectural elements.

Physiography	Architectural Elements		Main Facies	Minor Facies
Basin plain and slope rise	turbidite lobe		Sm Sg Sl	Gmg, Gm(Sc), Sh Shcs, St, Stc, FCm, FSm.
	turbidite lobe fringe		Sm HSF FSm HF	Sh, Sl, FCm.
	muddy plain		FSm FCl	Sr, Sm.
	muddy slope rise		FCl FCm FSm	Sm.
	turbidite channel		Gmg	Gm (Sc), Sm.
	deformational elements		Slump Debris Flow	Slide
Slope	turbidite channels		Gm(Sc, Sf) Sm	Gm, Gmg, Smg, Sh, Smi, Stc, Stw, St, FCl.
	channel-overbank	channel	Gm (Sc)	Sm, Smg, Sh.
		overbank	Shcs Shcslike HSF	Sl, Sm, Sh, Sr, FSm.
	muddy slope		FCl FSm HF HSF	Sm, Sr, Shcs, Sbio, Shcslike, Sh, FCm.
	deformational elements		Slide Slump	Debris Flow, Fluidization.
Middle to outer shelf (offshore)	incised channels		Gt St	Gm, Sh, Std, Srd
	delta front / shoreface	proximal / upper	St Stsr Std Srd Shcs	Gm, Stw, Sr, Sm, Sl, Sw, Srw, Sh, HSF.
		distal / lower	Sh Shcslike Sr Shcs	Gl, Srd, Sm, Sbio, Sl, Smg, FSm
	prodelta		FSm	HSF
	muddy outer shelf		FSm FCl	Sh, Sr, Stw, Sm, Sbio.
	transgressive lags		Gbio Sbio	
Inner shelf to nearshore	incised channels		Gm St	
	upper shoreface	gravelly	Gm	Gt, Gbio.
		sandy	Stwr	Shcs, Stw, Sbio, Sh, Shw, Sm, FCl, FSm.
	lower shoreface		Shcs Shw FSm	Srw, Sh, Sm, Sbio, FSm, FCl.
	estuary-lagoon		St FSm	Std, Shw, Sbio.

Light-, medium- and dark-grey for grouping gravelly, sandy and muddy facies, respectively.

sandstone with floating granules and small pebbles and undulating, medium- to coarse-grained sandstone bodies with low-angle cross-stratified sets (Sl). Minor facies are presented in Table 1.

This facies association was ascribed to recurrent, unconfined turbidity currents flowing ESE and assigned to two types of gravity flows (GF). The first type (GF1) is seen as sandy turbidity currents with deposition taking place due to frictional freezing (Sm) or individual settling (Sg), sometimes with incipient traction (Stc, Sh and St). Minor debris flows (Gm (Sc)) and gravelly turbidity currents (Gmg) complete the spectrum of sedimentary processes. The thin nature of the strata, well-defined limits and regular presence of normal grading suggest surge type flows whereas the abundant plant debris indicates a nearby fluvial source. The second type (GF2) is related to low-density, sandy turbidity currents with an oscillatory component (combined flow) producing low-angle (Sl) and hummocky (SHCS) cross-stratified sandstones. Fine grained deposits (FCm and

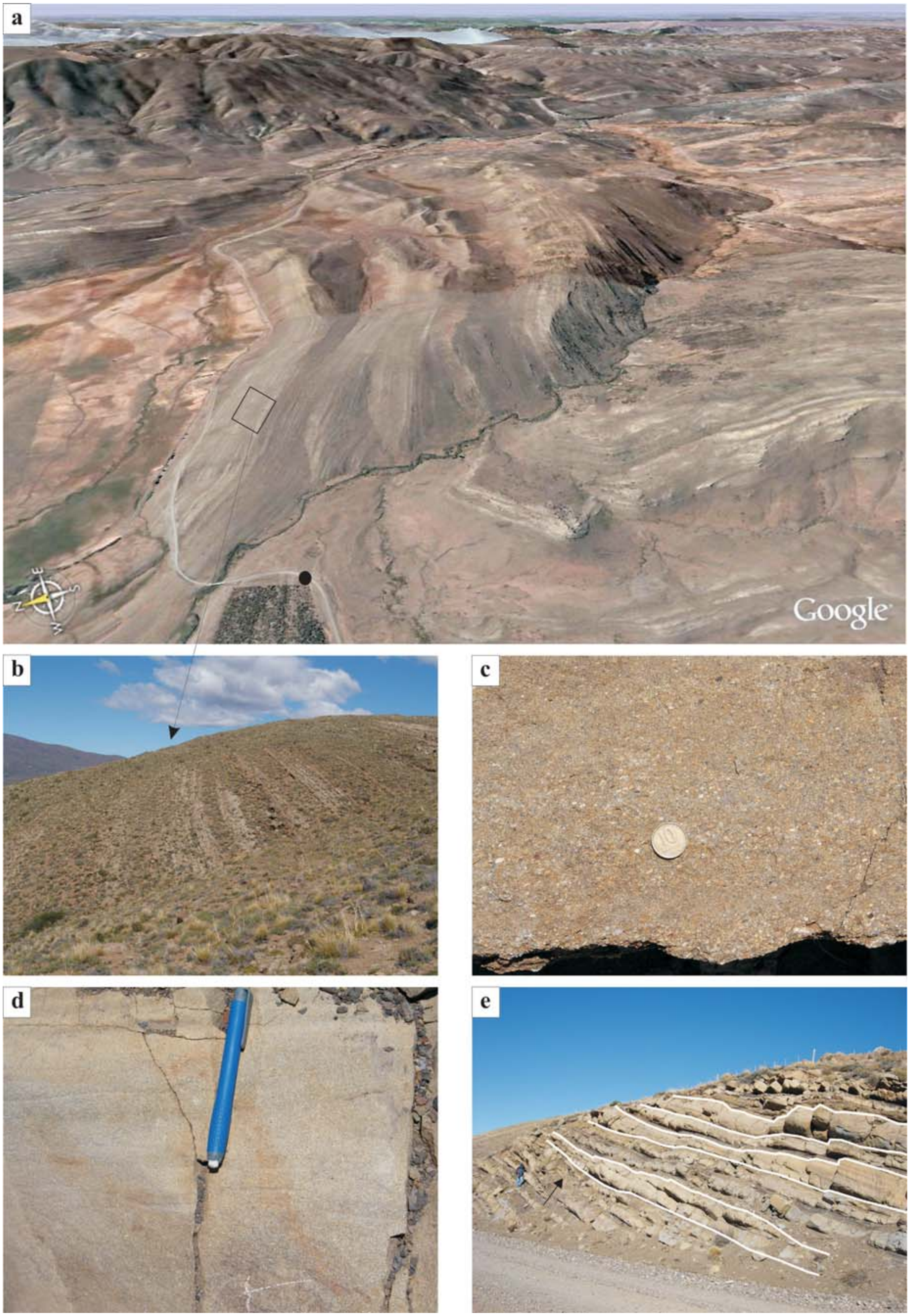

Figure 5: Basin Plain and Slope Rise (turbidite lobe): a) Satellite image view towards the E (for location and scale see rectangle in Fig. 3 and arrows in both figures point to the same point) and b) field view (rectangle in Fig. 5a) to highlight the sheet-like geometry of turbidite lobe bed sets. These beds are mostly composed of c) very coarse- to d) medium-grained, massive and laterally-extensive sandstone (Sm) beds (GF1 deposits) and e) undulating, low-angle cross-stratified sandstone (Sl) strata (GF2 deposits - two examples highlighted by white lines). Notice also the presence of slumped beds (GF3 - black arrow).

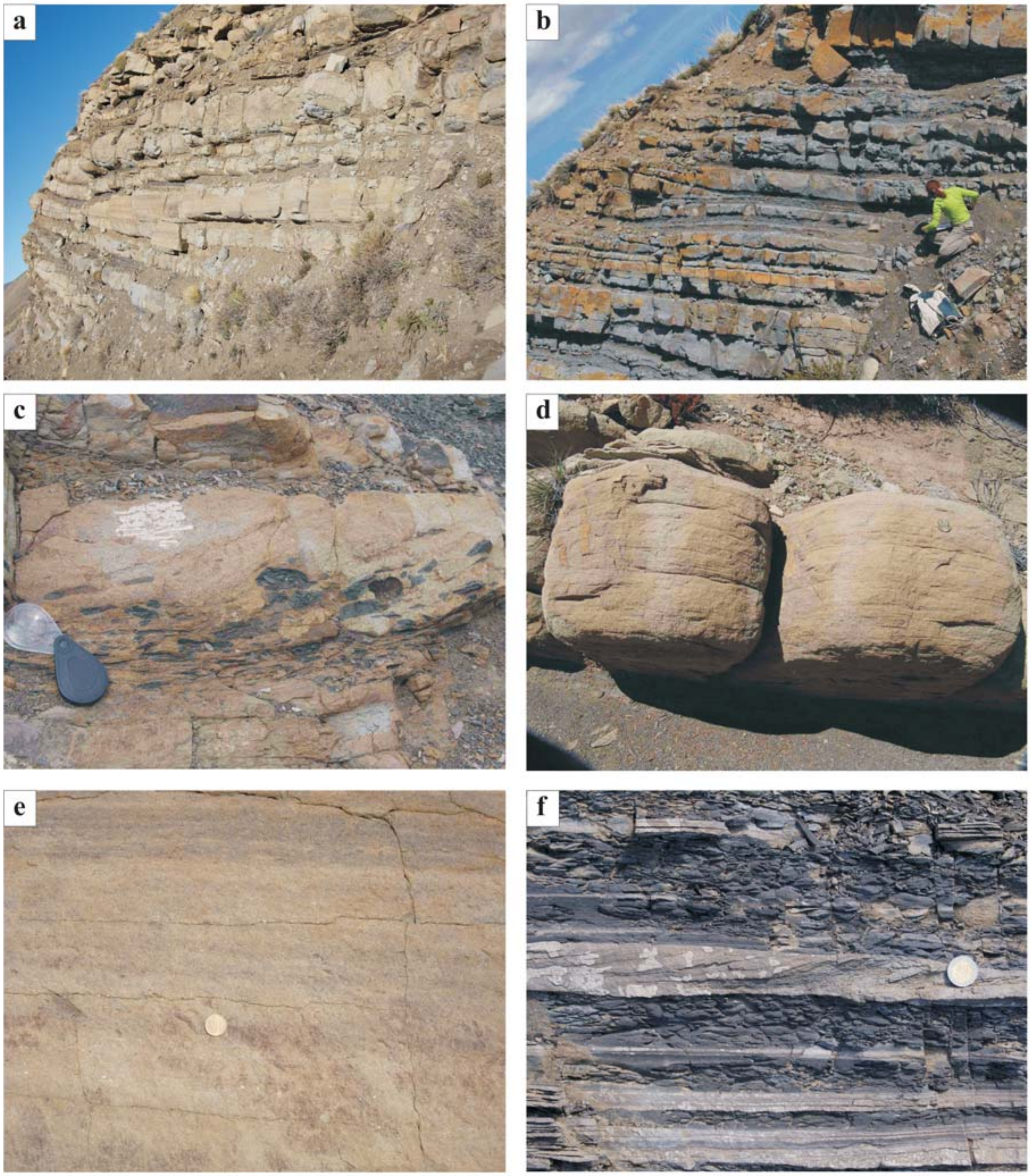

Figure 6: Basin Plain and Slope Rise (turbidite lobe): a, b) undulating geometry and internal low-angle cross-stratification of medium- to coarse-grained sandstone (Sl and SHCSlike); c) trough cross-bedded, coarse-grained sandstone (St); d) plane bedded, medium-grained sandstone (Sh) e) sometimes with traction carpets (Stc); and f) heterolithic facies of very fine-grained sandstone with climbing cross- and plane lamination interfingering with muddy intervals related to lobe abandonment phases.

FSm) represent the settling of mud and pelagic sediments during shorter (thin mudstone beds within sandstone bed sets) or longer (thick mudstone beds between sandstone bed sets) depositional episodes.

Turbidite lobe fringe: This architectural element (Fig. 7) comprises around 10^1 m thick and more than 10^1 km long, tabular and usually thin-bedded mudstone and sandstone. Bed thickness typically ranges from 0.5 to 10 cm, exceptionally tens of centimetres in some sandstone beds. Profuse, millimetre-scale plant debris and mud chips as well as scattered small trunks, bivalves, ammonites, ostreids and vitrain layers are present. Nine paleocurrent readings on current ripples show a mean transport vector towards E (97º).

Turbidite lobe fringes consist of tabular bodies of thin-bedded heterolithic strata (HSF and HF), dark grey massive siltstone (FSm) and laterally extensive beds of massive sandstone with rare flame structures (Sm). Minor facies are shown in Table 1.

This facies association represents mud and pelagic sediments settling down in a low energy, suboxic environment (FSm and FCm) occasionally affected by distal, low (Sh, HSF and HF) to high-concentration (Sm) turbidity currents (GF1) and minor low-density combined flows (Sl)

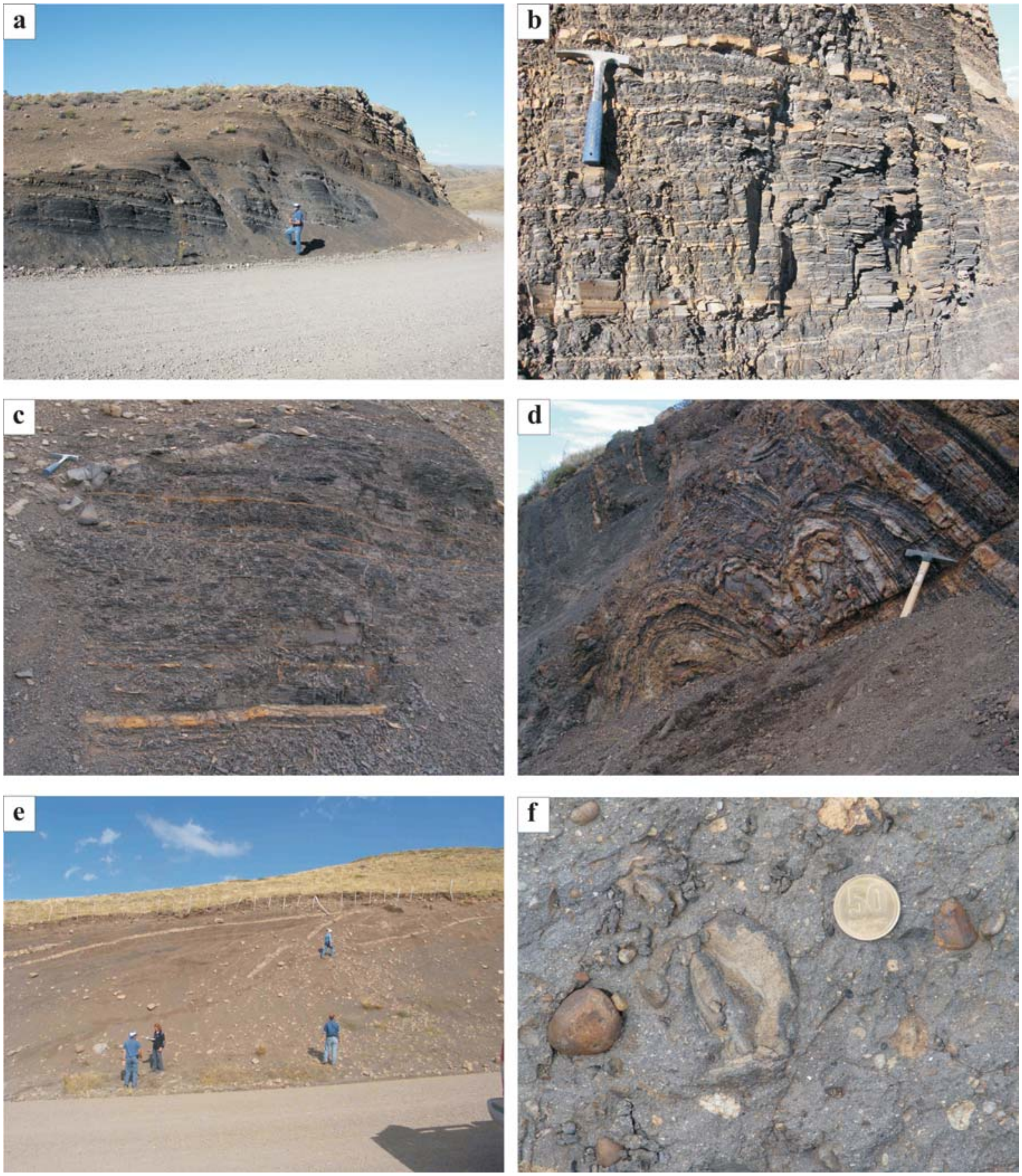

Figure 7: Basin Plain and Slope Rise (fan fringe, muddy slope rise and deformational features) - (a to c) undisturbed, muddy (FCl, FCm, FSm) and heterolithic (HSF) deposits; and (d to f) deformed, muddy and heterolithic facies resulting in slumped beds and debris flow deposits ascribed to type 3 gravity flows.

related to GF2.

Muddy plain: This architectural element (101 to 102 km long) is characterized by tabular beds of mudstone (with bivalves and ammonites) and rare sandstone. Mean paleocurrent, estimated from 14 readings on current ripples, point towards NE (48º). The muddy plain is composed of tabular bodies of massive, dark grey to black siltstone (FSm) and black shale (FCl). Minor facies are presented in Table 1.

This facies association points to stagnant areas characterized by the settling of mud and pelagic sediments (FSm and FCl) intermittently influenced by high- (Sm) to low-density (Sr) turbidity currents (GF1).

Muddy slope rise: Similar to the muddy plain, the muddy slope rise (Fig. 7) is also characterized by mudstones, which include bivalves, ostreids and ammonites. Only two paleocurrent readings on current ripples give a rough estimative of sedimentary transport towards ESE (110º). It consists of tabular bodies of dark grey shale (FCl), claystone (FCm) and siltstone (FSm) whereas massive sandstones (Sm) occur as a minor component.

This facies association was also related to stagnant conditions and settling of mud and pelagic sediments (FCl, FCm and FSm) sporadically modified by high-density (Sm) turbidity currents (GF1). However, differing from the previous element, the muddy slope rise was involved in recurrent mass gravity flows, mostly slumps.

Turbidite channel: This architectural element, rare within the slope rise realm, comprises up to 20 m thick bodies formed by amalgamated lenses of clast-supported, normally-graded conglomerate (Gmg). Mud clasts are frequent and minor facies are shown in Table 1.

Channel fill was related to confined, gravelly (Gmg) to sandy (Sm), high density turbidity currents and minor hyperconcentrated flows (Gm (Sc)), both related to GF1.

Deformational elements: They encompass poorly deformed (slides), folded (slumps) and disrupted (debris flow) muddy and thinly-bedded heterolithic strata (Fig. 7) derived from the muddy slope rise and form the third type of gravity flow identified in the area (GF3).

Slope

Turbidite channels: This architectural element is defined by either isolated or partially amalgamated lenses (3 to 25 m thick and 30 to 400 m wide) of conglomerate and sandstone with abundant mud clasts, plant debris and trunk pieces and encased within muddy slope deposits with bivalves (Figs 8 and 9). A total of 28 measurements on flute casts indicate a mean transport vector towards NE (60º).

It is composed of thick lenses of massive sandstone with scattered granules to small cobbles and mud clasts, at times with a faint planar lamination emphasized by millimetre-scale plant debris at the beds top (Sm), and matrix-supported conglomerate with granule to cobbles dispersed in a sandy matrix (Gm(Sc, Sf)). Minor facies are presented in Table 1.

This facies association represents high density, sandy (Sm) and gravelly (Gm (Sc, Sf)) confined turbidite currents flowing north-eastwards and depositing their load by frictional freezing. Abundant mud clasts and flute casts highlight the erosional and turbulent nature of the flows. Channel fill is usually sandier near the slope rise and gravelly towards the shelf margin. Less often, channelled turbidites represent more diluted, turbulent (Smg and Gmg) and tractive (Gm, St, Sh and Stc) flows, or grain collision processes (Smi). This facies association was related to GF1 although a few evidence of oscillatory flow (Stw) suggests a minor influence of GF2.

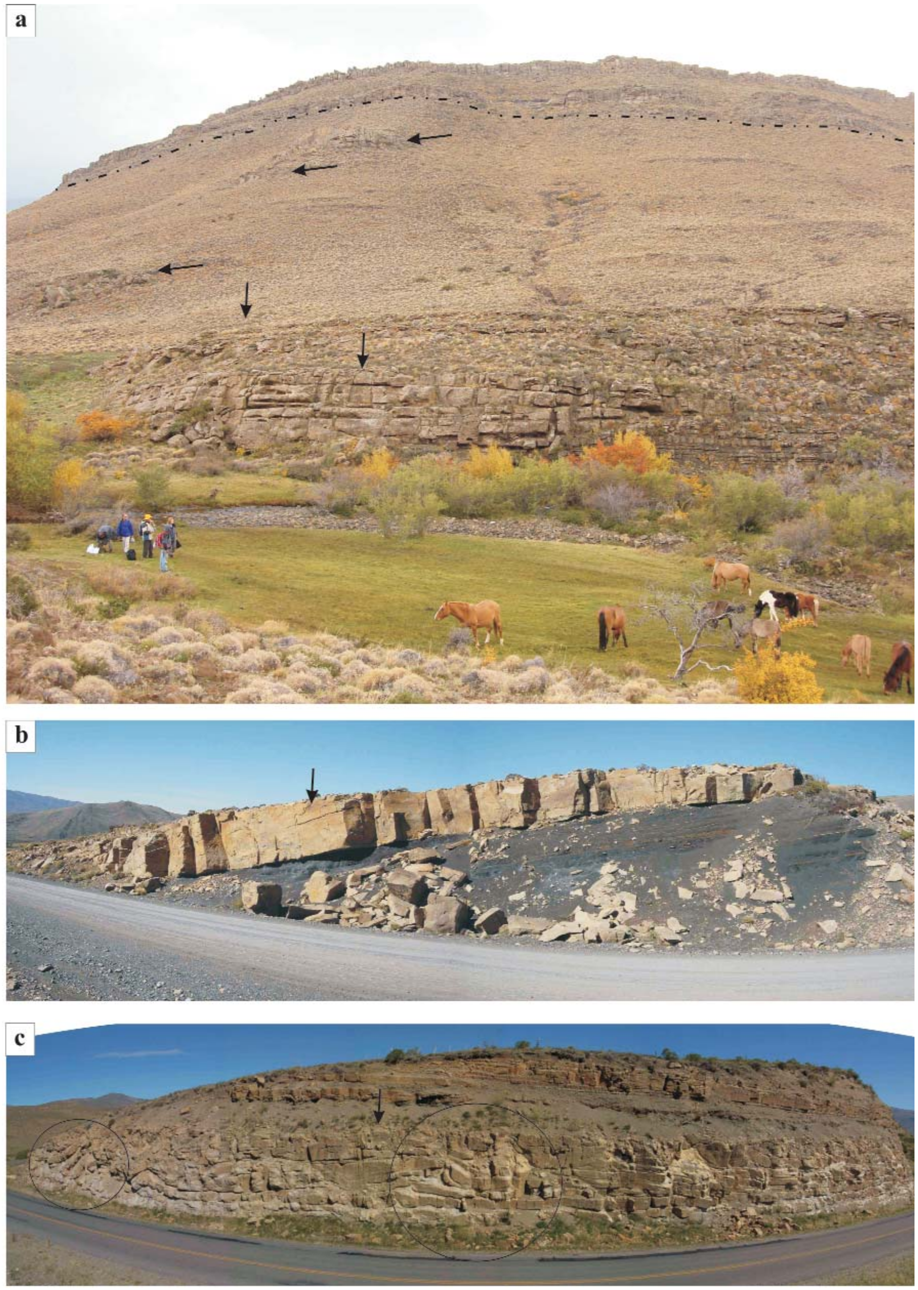

Figure 8: Slope (turbidite channels related to type 1 gravity flows): a) Channels deposits (arrows) surrounded by mostly muddy slope facies and overlain by shelf margin facies (above dotted line); and b) and c) sandy turbidite channels (arrows) with occasional fluidization structures (circles in c).

Channel-Overbank: This architectural element (Fig.10) comprises lenticular axial bodies (up to 3 m thick and 10 m wide) that pass towards both sides into laterally-extensive (0.5 to 1 m thick and up to 120 m wide), undulating, sandy to heterolithic deposits. Abundant plant debris, trunk pieces (Fig. 10g) and sparse thin vitrain layers suggest a nearby fluvial sour-

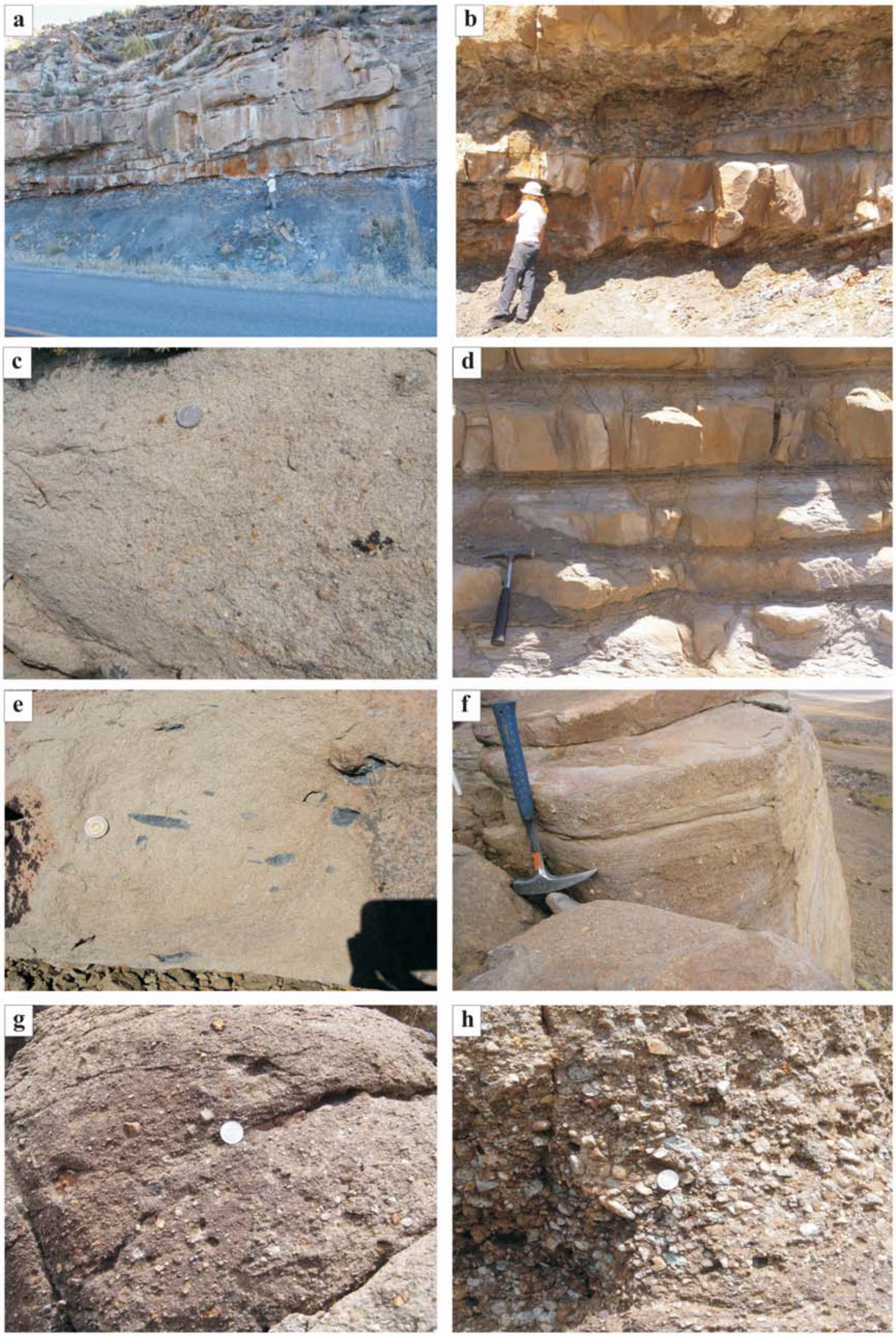

Figure 9: Slope (turbidite channel deposits of GF1): a) partially scoured, amalgamated lenses of b, c) coarse- and d, e) fine-grained, massive sandstone (Sm) with e) abundant rip-up clasts, sometimes presenting f) normal grading and a faint planar lamination, usually on top of the massive sand beds; g) matrix- and (h) clast-supported conglomerates (Gm (Sc) and Gm, respectively).

ce whereas bivalves and ammonites indicate a marine setting. Four paleocurrent readings on flute casts point to a mean transport vector towards northeast (55º).

a) Channel: The channel-fill consists of up to 0.4 m thick lenses of matrix-sup-

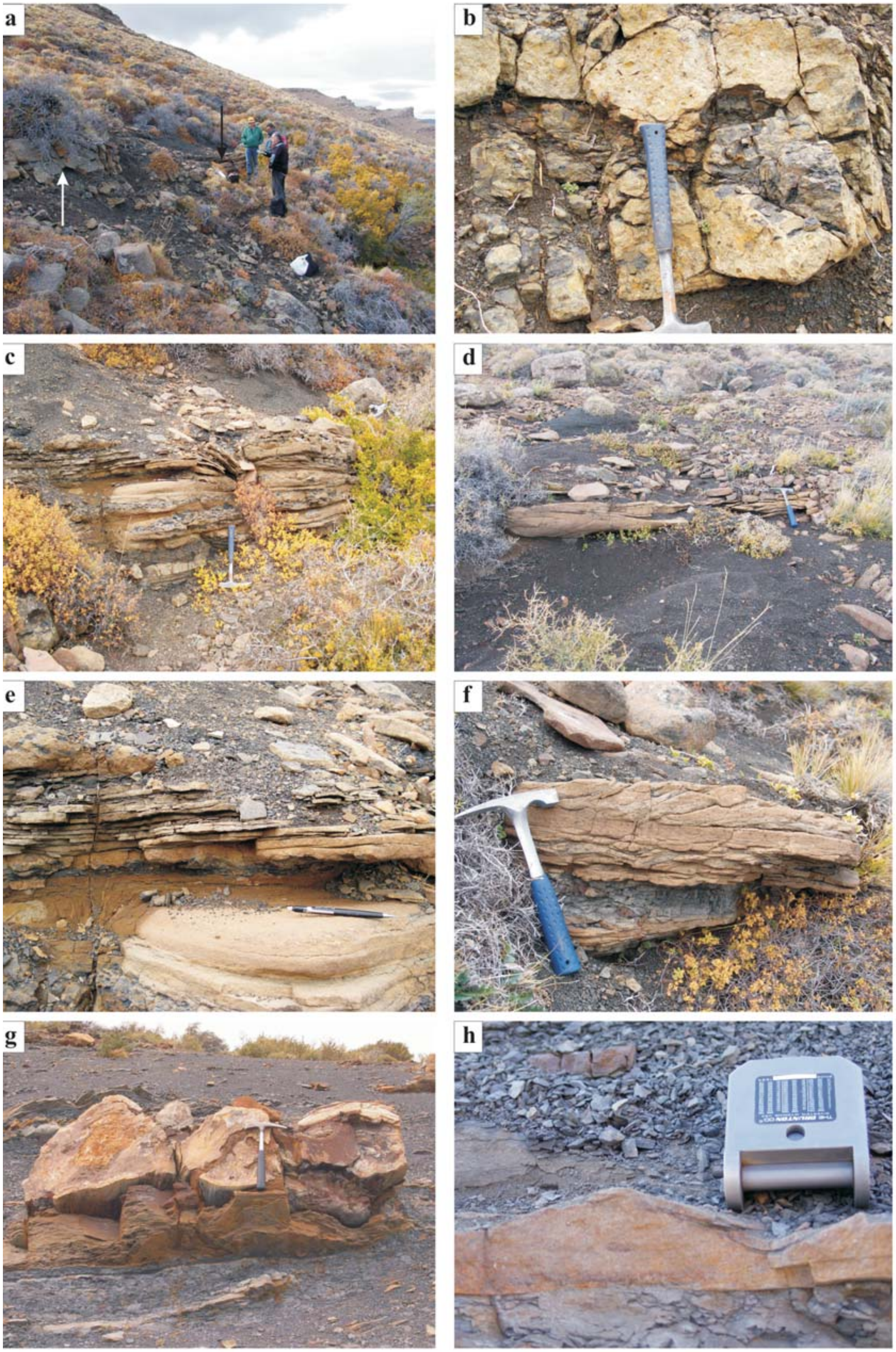

Figure 10: Slope (turbidite channel and overbank deposits of GF2): a) general view of channel (white arrow) encased in overbank (black arrow) strata; b) Channel filled with matrix-supported conglomerate (Gm(Sc) and c, d and e) lateral, undulating, massive (Sm) and hummocky cross-stratified (SHCS) sandstone, at times displaying f) cross-bedding on HCS bedding surfaces; g) large wood piece and h) unidirectional, cross laminated sandstone with symmetrical ripple morphology (Sr), both linked to heterolithic overbank deposits.

ported conglomerate with coarse-grained sandy matrix (Gm (Sc)) and abundant mud clasts. Minor facies are shown in Table 1.

This facies association was related to slightly confined, gravelly (Gm (Sc)) to

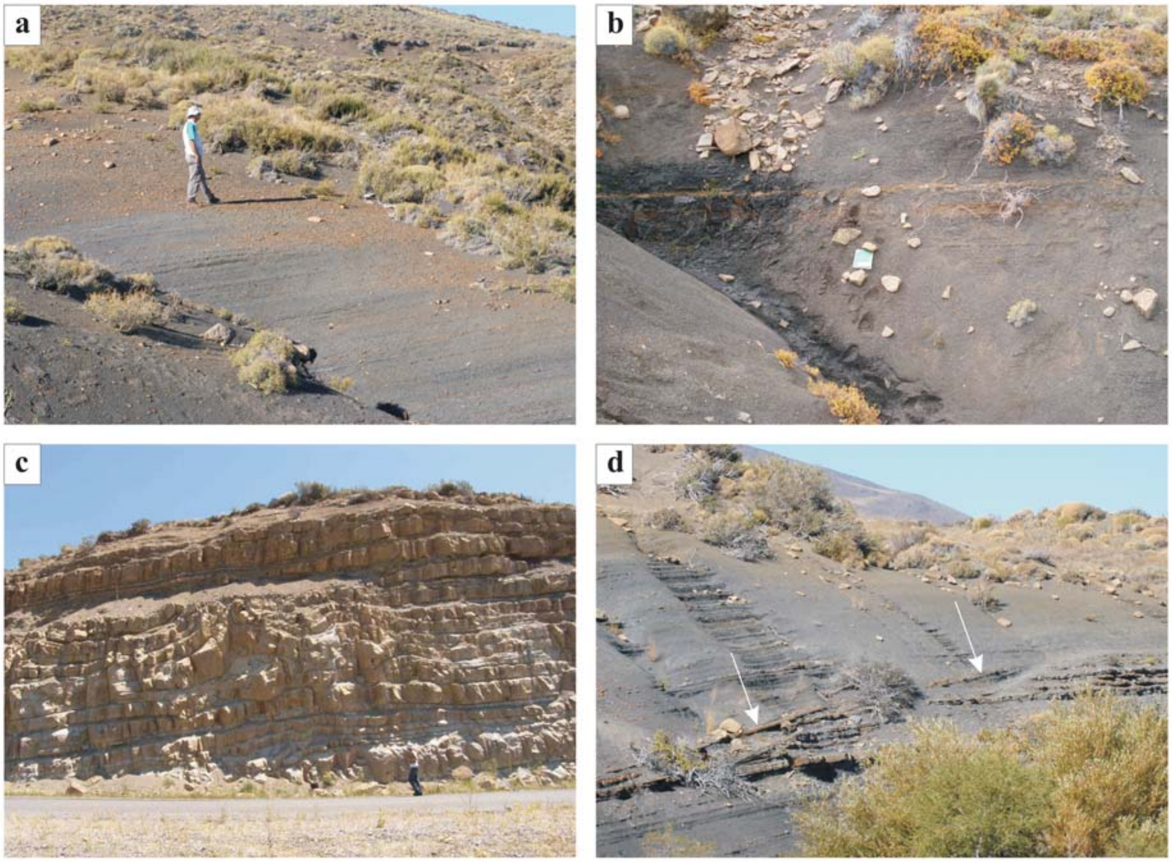

Figure 11: Slope (muddy slope and deformational elements): a, b) undisturbed, fine-grained strata (HSF, HF, FCl and FSm), c) deformed, sandy (fluidized channel deposits) and d) heterolithic slope deposits (slide - see arrows).

sandy (Sm) high-density turbidity currents deposited by frictional freezing. The turbulent nature of the parental flow is deduced from the abundance of rip up clasts and flute casts. Occasional increase in turbulence during transport is suggested by normal grading (Smg) and evidence of traction (Sh). Its close relationship with overbank deposits that present evidence of oscillatory flows point to combined flows (GF2).

b) Overbank: It comprises fine-grained, amalgamated undulating sandstone beds with well- (SHCS) and poorly-defined (SHCSlike) hummocky cross stratification at times revealed by mud chips or plant debris rich layers. The sandy beds pass laterally into heterolithic, thin-bedded, tabular to undulating beds of fine-grained sandstone (Bouma cycles with planar lamination replaced by low-angle cross-stratification) interlayered with dark grey mudstone (HSF). Flute and load casts, flame structures, mud chips, plant debris and wood pieces are common and vitrain layers are rare. Minor facies are shown in Table 1.

This facies association represents proximal (sandy) to distal (heterolithic) overbank strata associated with high energy oscillatory flows, occasionally including unidirectional components (external undulating geometry, profuse mud clasts, SHCS, SHCSlike, Sl and Sr facies). Its close link to slightly confined, hyperconcentrated flow (channel deposits) suggests combined flows (FG2). Minor massive sandstone (Sm) represents the high density portion of the combined flows in the overbank areas. The heterolithic facies (HSF) dominate the distal overbank areas with sandstone beds representing episodic combined flows into an area usually dominated by muddy and pelagic deposits (FSm).

Muddy slope: This architectural element comprises muddy and heterolithic and minor sandy facies (Fig. 11). Abundant plant debris associated with marine fossils (bivalves and ammonites) suggests a marine setting influenced by fluvial discharge. Paleocurrent mean vector from 23 readings on current ripples indicates a sedimentary transport towards ENE (69º).

It is composed of dark grey, tabular beds of shale (FCl), massive siltstone (FSm), thin-bedded, heterolithic mudstone (HF) and mudstone interlayered with sandstone (HSF). Minor facies are presented in Table 1.

This facies association represents the settling down of fine-grained terrigenous and pelagic sediments (FCl, FSm, HF and FCm) on a marine, low energy and suboxic setting intermittently subject to mass (slide and slumps) and distal overbank (HSF, Sm, Sr, SHCS, SHCSlike and Sh) flows. The profusion of plant fragments suggests a nearby fluvial input.

Deformational elements: Slide and slump deposits comprise around 5 m thick and more than 150 m long masses of downslope slipped strata. Slides are defined by sub parallel, slightly deformed beds

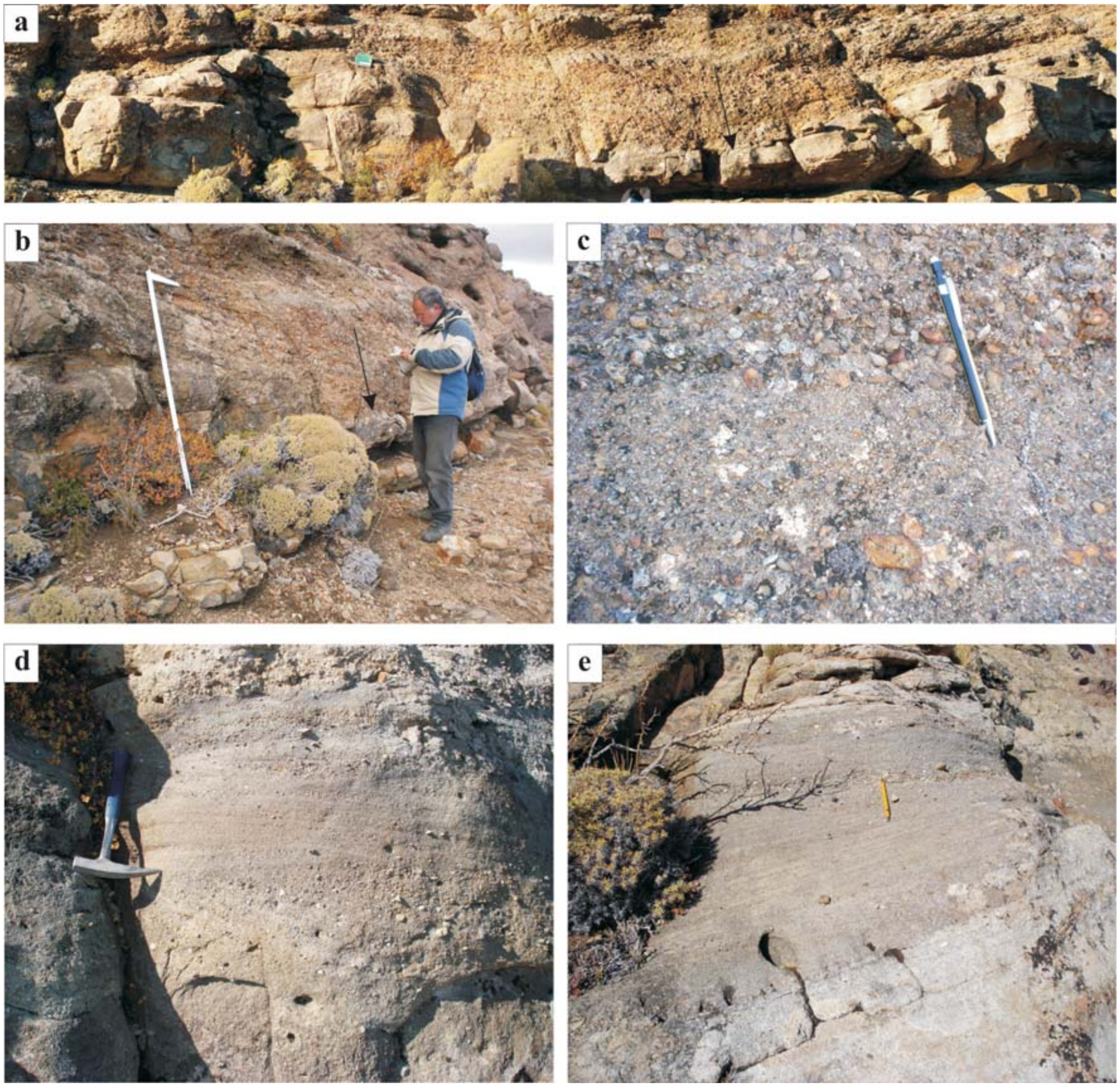

Figure 12: Outer to mid shelf (incised channels): a) General and b) detailed view of a fluvial incision (arrows) on upper shoreface facies (lowstand and falling-stage systems tracts, respectively). Notice some common incised channel fill facies such as a, b) trough cross-stratified (Gt) and c) massive, clast-supported conglomerate, and d) trough cross bedded (St) and e) plane bedded (Sh) sandstone.

bounded by uneven low-angle slip surfaces (dip < 10°) whereas slumps are discerned by folded, at times overturned strata. Debris flow strata consist of intraclasts, rare extraclasts and plant debris floating within a muddy sandstone matrix.

These slope-related deformational elements (GF3 - Fig. 11) represent the basinward displacement of a poorly distorted (slide), through intensely deformed (slump) to disrupt (debris flow) strata mostly derived from the muddy slope and overbank facies associations.

Another kind of post-depositional feature consists of slightly folded sandstone bed sets with large-scale fluid escape features (Fig. 11c). Considering their post-de-positional nature (deformation of entire bed sets rather than an internal bed feature) it seems reasonable to relate these processes to seismic triggering.

Mid to Outer Shelf (Offshore)

Incised channels: This architectural element includes either isolated or amalgamated lenses (2 to 10 m thick and 60 to 500 m wide) of stratified sandstones and conglomerates. These channel-fill facies are usually scoured into shoreface deposits (Fig. 12) and encased within muddy shelf deposits. Apart from common wood fragments and plant debris, no other fossils were found. Fifteen paleocurrent readings on trough cross stratification indicate an east-northeastwards (82º) paleoflow.

The incised channels fill consists of lenses of clast-supported conglomerate (Gt) and sandstone (St) with small to large-scale trough cross-bedding and abundant mud clasts. Minor facies are presented in Table 1.

This facies association points to confined currents flowing ENE and producing sand (St) and gravel (Gt) 3D dunes. Minor longitudinal gravel bars (Gm), upper flow regime plane beds (Sh) and tidal-influenced deposits (Std and Srd) complete the facies spectrum. The presence of wood fragments and plant debris and the lack of marine fossils suggest a fluvial origin. Considering that many channels cut down through coastal to offshore facies and their fill at times include a tidal signature, these features were interpreted as fluvial incision followed by a fluvial to estuarine fill.

Proximal delta front - upper shoreface: This architectural element includes unidirectional, tidal- and wave-related features (Fig. 13). The primacy of unidirectional flow deposits or wave/tidal related facies suggests either a delta front or an upper shoreface setting, respectively. Fourteen paleocurrent readings on trough cross-strata indicate transport towards ESE (110º).

This depositional setting is represented by sandstone beds with medium-scale trough cross-stratification (St), sigmoidal cross-bedding sets bounded by reactivation surfaces (Stsr), sigmoidal cross-stratification sets bounded by mud drapes (Std), cross-lamination with drape and flaser bedding (Srd) and hummocky cross stratification (SHCS). Scattered pebbles, mud clasts and wood fragments, and common plant debris are present. Minor facies are shown in Table 1.

This facies association represents widespread, unidirectional flows in a proximal delta front and producing subaqueous 3D dunes (St) and minor current ripples (Sr), plane-bed (Sh) and gravel bars (Gm). Reactivation surfaces, mud drapes and flaser bedding point to partial reworking by tidal currents (Stsr, Std and Srd). On the other hand, hummocky and rare low-angle cross-stratified sandstone suggest oscillatory flows, either related to wave action or combined flows. Wave driven flows (Stw and Srw) point to alongshore currents (upper shoreface). Fine-grained deposits (HSF) indicate periods of sedimentation below storm wave base whereas massive sandstone (Sm) point to episodic hyperpycnal, high density flows. Paleocurrent mean vector (110º) diverges from 28º to 50º respect the incised (82º) and turbidite (60º) channels, suggesting the reworking of mouth bar deposits by longshore currents. Sporadic combined or unidirectional hyperpycnal flows complete the spectrum of sedimentary processes in the proximal delta front / upper shoreface setting.

Distal delta front - lower shoreface: Like the preceding architectural element, this one also contains a mixture of facies related to oscillatory (tide or wave) and unidirectional flows. Bivalves, ammonites and plant debris are common and wood pieces rare.

It consists of sandstone with plane bedding (Sh), poorly- (SHCSlike) and well-defined (SHCS) hummocky cross-stratification, and climbing ripple cross-lamination (Sr). Minor facies are presented in Table 1.

This facies association, a combination of oscillatory (SHCS, SHCSlike, Gl and Sl) and unidirectional (Sr and Sh) flow deposits, is supposed to represent a lower shoreface to distal delta front depositional context. Considering the presence of massive (Sm) and normally graded sandstone (Smg), suggestive of hyperpycnal, high to low density underflows, it is possible that some facies would have been produced by combined flows (GF2) rather than merely by wave-related oscillatory flows. Low energy periods (FSm) and occasional tidal reworking (Srd) complete the spectrum of depositional processes.

Prodelta: This architectural element is composed of massive greyish siltstone (FSm) and minor thin-bedded, fine-grained sandstone (Bouma Tabc intervals) interlayered with greyish siltstone (HSF). This facies association represents the settling of fine-grained sediment on a usually low energy prodelta environment occasionally disturbed by distal hyperpycnal flows.

Muddy outer shelf: Like the preceding architectural element, this one is also comprises fine-grained strata. Small plant debris and bivalves are common. Two paleocurrent measurements on current ripples suggest transport towards NE (45º). It is composed of dark grey, massive siltstone (FSm) and claystone (FCl). Minor facies are presented in Table 1.

This facies association suggests a low energy, usually suboxic environment typified by the settling of clay, silt and plant debris from hypopycnal plumes (FSm and FCl). This environment was intermittently disturbed by high to low density, northeastwards hyperpycnal flows (Sh, Sr, Sm and Sbio) or by storm waves (Stw) striking the coastline at oblique angles (crestlines orientation about 110º / 280º).

Transgressive lags: This architectural element usually occurs just above the incised channel-fill deposits and it presents a mixed composition (Fig. 13). This facies association comprises clast supported conglomerates of granules and pebbles, bioclasts (bivalves and oysters) and plant debris (Gbio) and greenish, fine-grained sandstone with abundant bivalves (Sbio). The transgressive lags represent wave-ravinement residual deposits (high frequency transgressive surfaces) of basinal and external clasts above the incised channel fills.

Inner Shelf to Nearshore

Incised channels: This architectural element is characterized by traction-related sedimentary features associated with the infill of incised channels that down cut delta front/shoreface deposits. Five readings on trough cross bedding indicate transport of gravel and sand towards NE (40º). Channel fill consists of lenses of trough cross-bedded sandstone (St) and clast-supported conglomerate (Gm) with abundant mud clasts.

This facies association represents confined, unidirectional streams flowing NE and forming sandy 3D dunes (St) and gravelly longitudinal bars (Gm).

Upper shoreface: This element was further subdivided into two sub-elements that represent a shorter (gravelly upper shoreface) or larger (sandy upper shoreface) distances from the sediment source (incised channels). In both instances, bioclasts are an important component of the deposits. A large amount of paleocurrent measurements (109 readings) on cross bedding indicate a sense of transport towards SSE (168º). Both features

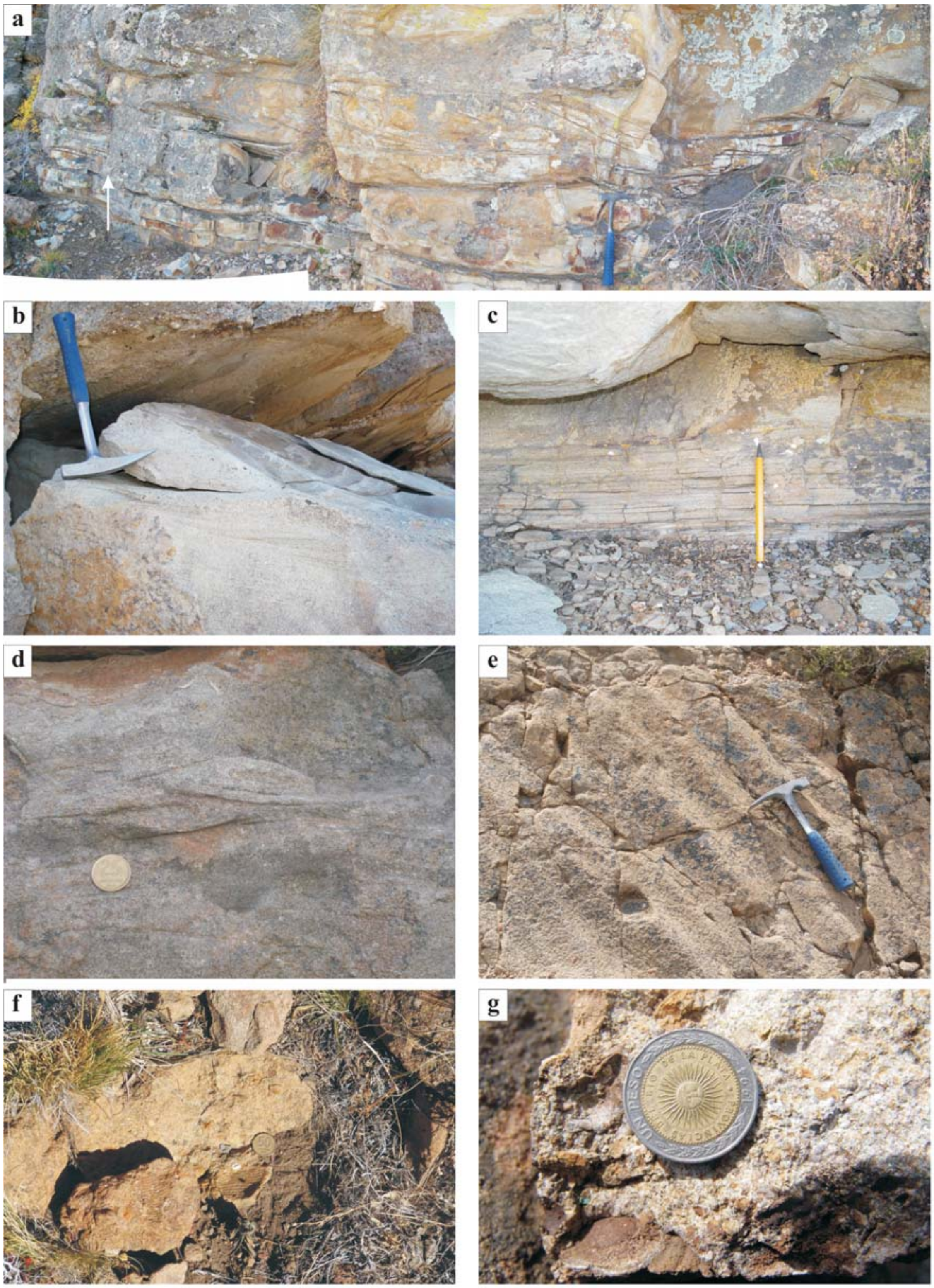

Figure 13: Outer to mid shelf (upper shoreface and transgressive lags): a) sigmoidal-shaped, large-scale cross-stratified sandstone (fine to medium-grained) with reactivation surfaces (Stsr) and mud drapes (Std); b) medium- to coarse-grained, trough cross-bedded sandstone (St); c) plane bedded sandstone (Sh); d) wave ripple cross laminated, fine-grained sandstone (Srw); e) plan view of wave ripples (Sw); and f, g) coarse-grained transgressive lags with abundant bioclasts that occur above some incised channels.

(paleocurrent trend and mixed composition) reinforce the interpretation of bedforms as a result of longshore currents flowing at nearly right angle relative to the flow direction in the incised and turbidite channels (mostly oriented towards ENE).

a) Gravelly upper shoreface: This sub-element represents gravel bars of mixed composition. It comprises lenses of massive, clast-supported conglomerate including mud clasts and scattered bivalves (Gm). Minor components include clast-supported conglomerate with medium-scale trough cross-bedding, large wood

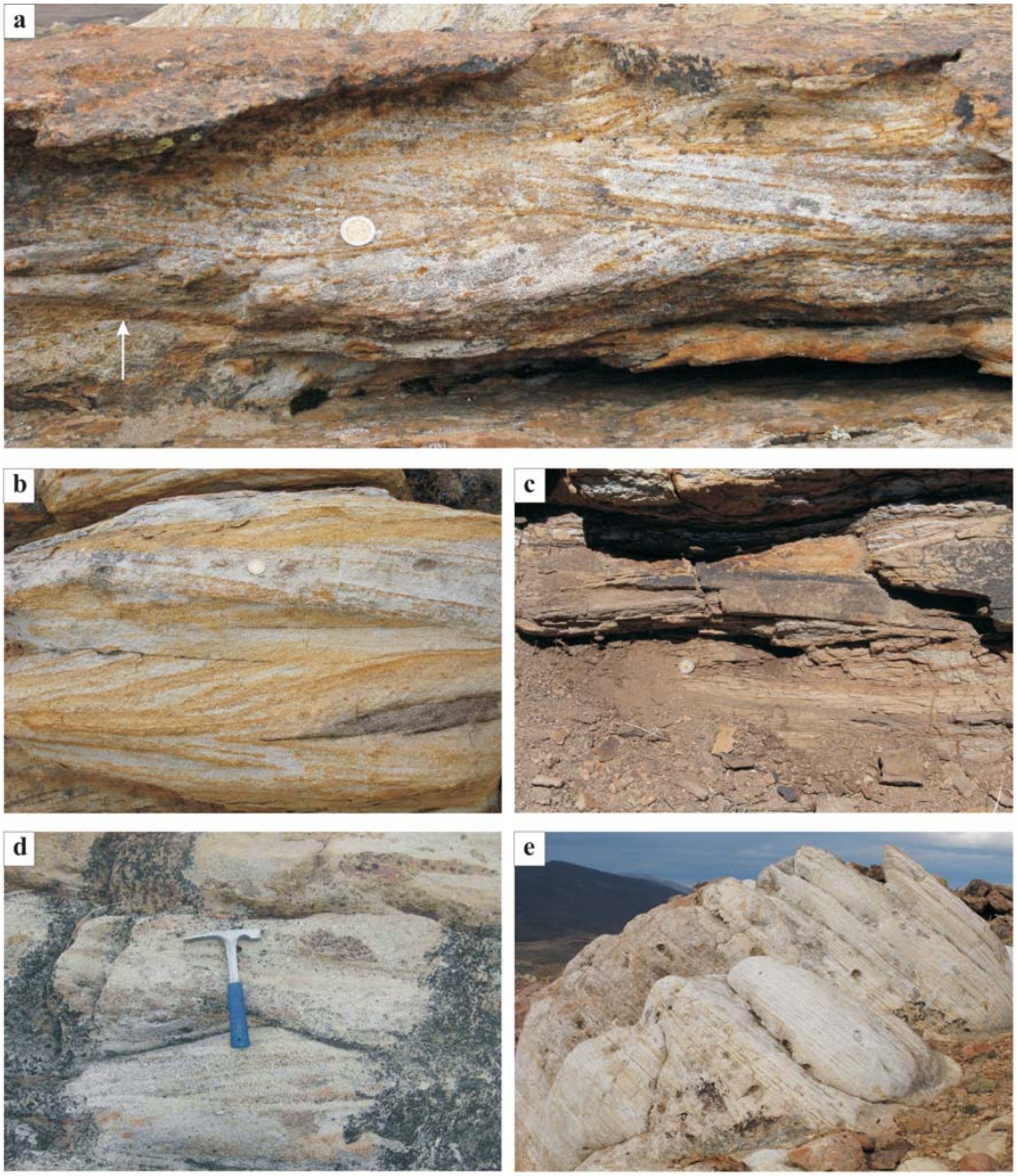

Figure 14: Nearshore to inner shelf (shoreface and foreshore): a, b) fine to medium-grained sandstone presenting bi-directional, wave induced trough cross-bedding (Stw); c) hummocky cross-stratified, medium-grained sandstone (SHCS); d) coarse-grained, trough cross bedded sandstone with convex-upward set geometry (Stwr); and e) plane-bedded, fine- to medium-grained sandstone (Sh) laterally associated with wave bedforms.

fragments and small bivalves (Gt) and clast-supported, bioclast-rich (bivalves, plant debris and wood pieces) conglomerate (Gbio).

This facies association was ascribed to unconfined flows producing nearshore gravel bars (Gm) and, secondly, 3D gravel dunes sometimes with large amount of bioclasts (Gbio). These gravel accumulations are closely related to incised channel conglomerates and interfinger with sandy upper shoreface facies. All together, these features suggest alongshore currents reworking fluvial deposits in an upper shoreface environment.

b) Sandy upper shoreface: This sub-element (Figs14 and 15) is characterized by wave-related facies, at times with abundant bioclasts (bivalves, belemnites), plant debris, wood fragments and mud clasts, interlayered with minor muddy deposits. Its main facies (Stwr) consists of trough cross-bedded sandstone with convex-upward or undulating set morphology (wave-reworked 3D dunes). Minor facies are presented in Table 1.

This facies association was ascribed to unidirectional, wave modified 3D dunes (Stwr) associated with other wave-related facies (Stw, Shw and SHCS). These interpretations point to an upper shoreface environment located in a more distal (relative to gravelly shoreface) setting in

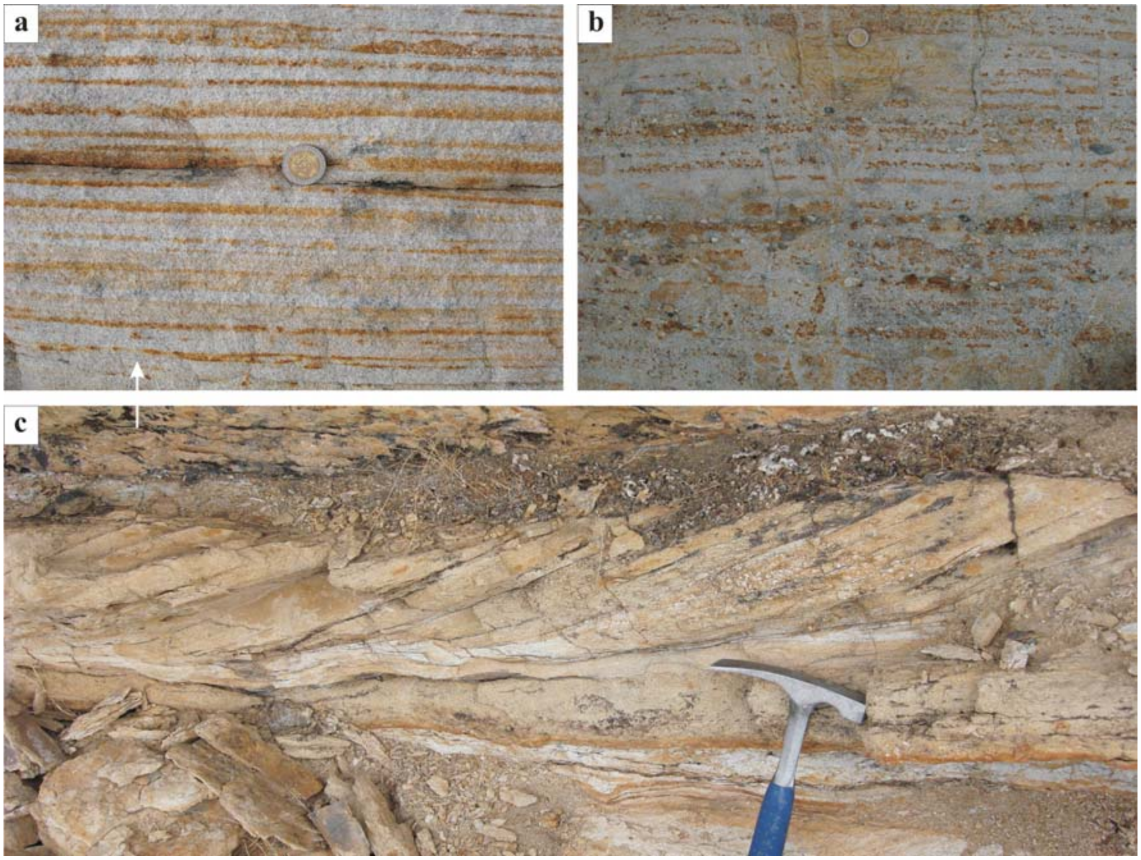

Figure 15: Nearshore to inner shelf (foreshore and tidal deposits): a, b) fine to very coarse-grained sandstone, eventually including granule to small pebble layers (Shw); and c) fine-grained sandstone with mud drapes along the trough cross strata (Std).

terms of sediment source distance (incised fluvial channels). Occasional, high-density hyperpycnal flows (Sm), sometimes with large amounts of bioclasts (Sbio), and the settling down of fine-grained sediments (FCl and FSm) complete the spectrum of processes operating in this depositional setting.

Lower shoreface: This architectural element consists of wave-related sandy deposits interlayered with mudstones with plant debris. It is composed of sandstone lenses with hummocky cross-stratification (SHCS) and wave-related planar lamination (Shw), and greenish, massive siltstones (FSm). Minor facies are shown in Table 1.

This facies association represents sand deposition associated with oscillatory flows (SHCS, Shw and Srw) in a lower shoreface environment. Occasional hyperpycnal flows (Sm, Sh), sometimes with large amount of bioclasts (Sbio), and mud settling (FSm and FCl) complete the range of operating sedimentary processes.

Estuary-lagoon: This architectural element is poorly constrained due to the small amount of available data. It is defined by lenses of trough cross-bedded sandstone (St) closely related to greenish massive siltstone with oysters (FSm). Minor facies are presented in Table 1.

This facies association (Fig.15) represents unidirectional flows forming 3D dunes (St), sometimes including tidal-related sedimentary features (Std), closely related to greenish, fine-grained lagoon sediments. It was ascribed to tidal deltas (St and Std) closely related to lagoons where fine-grained sedimentation was dominant (FSm). Foreshore (Shw) facies and oysters-rich layers complete the variety of facies.

DISCUSSION

Although the studied interval cannot be seen as an uninterrupted succession, as it can be subdivided into several unconformity-bounded units of distinct hierarchies, the entire interval includes physiographic elements and architectural elements that suggest a genetic link between them (Fig. 16). This statement is based on the following reasoning:

1) Each 3rd order depositional sequence shows a prevalence of some physiographic and architectural elements. Therefore, their vertical deepening- or shallowing-upwards trends suggest their possible genetic link. Besides, their lateral or proximal to distal arrangement within the same depositional sequence, as can be seen in satellite image and attested in the field, represents contemporary facies tracts that were used to confirm the hypothesis inferred from their vertical succession. Some examples of coeval elements include the slope rise and the basin plain in J1; turbidite channels (slope) and lobes (slope rise) in J21 and J22; incised and turbidite channels in J23, and the inner shelf/nearshore and the outer/mid shelf in J24;

2) There is a uniform sense of transport towards the basin depocentre (ENE) from the turbidite channels and lobes (Los Molles Formation) through the channels incised on shelf deposits (transition between the Los Molles and Lajas formations) to the fluvial facies (Challacó Formation). The distinct paleocurrent trend in the Lajas Formation (transport towards SSE) was assigned to different forming processes (basinwards fluvial and turbidite flows in opposition to parallel to the coastline longshore currents) rather than basinwide depocentre changes and drainage re-organization; and

3) Abundant plant debris, leaves, trunks and vitrain layers in both deep and shallow marine deposits suggest a regular link between marine (Los Molles and Lajas formations) and non-marine (Lajas and Challacó formations) processes. Small plant debris are abundant in the distal turbidites, whereas larger plant debris and wood pieces are usual in the more proximal settings. This piece of evidence suggests a connection between fluvial input and turbidite sedimentation.

Another theme that deserves attention is related to basin physiography. The existence of a slope between two gentle dipping areas (shelf and basin plain) seems to have enhanced the conditions to trigger gravity flows. This tripartite physiography is similar to that proposed by Romans *et al.* (2008), in both examples signifying an inherited feature from precursor basins that controlled the deposition of thick turbidite strata on a slope rise setting. In the Neuquén basin, it was credited to a not fully covered rift configuration (Legarreta and Uliana 1991, Gulisano and Gutiérrez Pleimling 1995, Ramos 1998, Gómez Omil *et al.* 2002, Vicente 2005, Verzi *et al.* 2005, Vergani 2005).

A further topic refers to the lack of a major bypass zone (canyon). The feeder system comprised multiple point sources (small incised channels) as well as the transference of sediments occurred through multiple, small submarine conduits (turbidite channels), in both cases

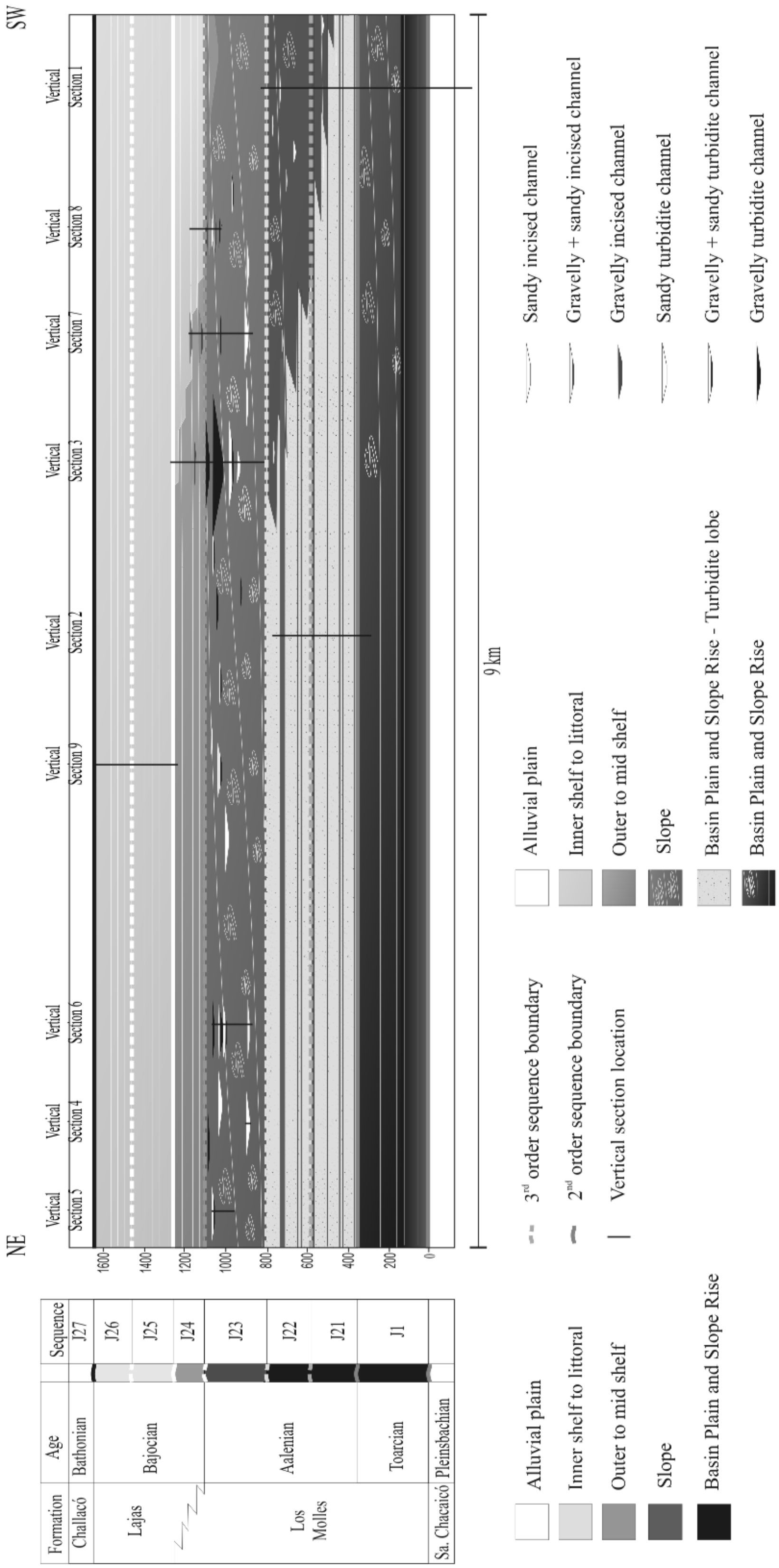

Figure 16: SW-NE oriented stratigraphic chart showing sequences boundaries, main physiographic and some architectural elements of the Los Molles/Lajas formations in the Arroyo La Jardinera area.

either as isolated elements or channel clusters. Therefore, the studied turbidite systems fit better in the submarine ramp model (Heller and Dickinson 1985). They include small, discrete or clustered turbidite channels that pass basinwards into sandy turbidite lobes (proximal ramp) dominated by high concentration turbidites and finally to heterolithic lobe fringes (distal ramp) dominated by low concentration turbidites. In addition, the primacy of muddy shelfal and slope strata relative to turbidite and incised channels fill indicates that the studied system also differs from those systems (debris aprons) linked to linear sediment sources (Stow and Mayall 2000).

The turbidite lobes are formed by tabular, widespread (tens of kilometres long) and relatively thin (10 to 15m thick) sandy bed sets interlayered with volumetrically similar muddy bed sets ascribed to abandonment phases. Similar features are also present in the slope and shelf deposits. In the former, gravelly to sandy bed sets represent successive events of turbidite channel fill that are later abandoned and covered by mudstone. In the latter, sandy and gravelly beds ascribed to incised channels, which scour falling-stage shoreface deposits, are partially reworked by waves and then encased by mudstone. All together, these features suggest turbidite systems linked to 4th order relative sea level changes with the following systems tracts:

1) Falling-stage systems tract: abrupt shift of facies characterized by sandy, shallow water deposits sharply superimposed on muddy, offshore strata;

2) Early lowstand systems tract: fluvial incision into shelfal to nearshore strata and submarine incision of turbidite channels into muddy slope facies. Deposition of gravelly and sandy confined turbidites in the upper and lower slope, respectively, and sandy (lobes) and heterolithic (lobes fringe) unconfined turbidites in the slope rise and basin plain. GF1 dominated by high-concentration turbidity currents represent this stage;

3) Late lowstand systems tract: fluvial (minor estuarine) fill of the incised channels, hence trapping most of the coarser-grained bedload on the shelf. Fine-grained sediments are accumulated in the slope (lowstand wedge) and, as a result of high sedimentation rates of a relatively steep slope, they were usually subject to slope failures and ensuing mass and sediment gravity flows (GF3). Only a minor part of the coarse-grained load, but smaller than in the preceding stage, was intermittently transferred as more diluted flows (GF2) into deeper water through poorly confined density flows. The GF2 deposits occur interlayered with lowstand wedge mudstones and also comprise part of the turbidite lobe deposits on the slope rise; and

4) Transgressive systems tracts: it begins with wave-ravinement of the top of some incised channels fill and subsequent deposition of few tens of meters thick mudstone strata that encase the incised channels (outer to mid shelf), turbidite channels (slope) and sandy lobes (slope rise and basin plain).

A last topic to be addressed is related to the trigger mechanism of the density flows. As formerly stated, several pieces of evidence suggest a genetic link between the turbidites of the Los Molles Formation and the incised channels at the transition of the Los Molles and Lajas formations. To properly address this subject, some criteria used to identify hyperpycnal flows are listed in Table 2 and

TABLE 2: Criteria used for hyperpycnal flow identification and their relation with this study.

Item	Criteria	Reference	Studied Interval
1	Physical connection between fluvial and turbidite channels at the shelf margin.	1	Yes, through small incised channels.
2	Alternating massive and stratified inter vals within a single bed.	1, 2, 3, 4, 5.	No. Massive, stratified, or massive with stratified top discrete beds.
3	Coarsening- and thickening-upward trend near the bed base and the rever se above.		No. Thin, discrete uniform or graded beds.
4	Abundant cut-and-fill features in a sin gle bed.		No. Absent.
5	Laterally irregular grain size changes		No. Absent
6	Sandy nature and abundant meter-scale beds	1, 3, 5, 6, 7, 8, 9.	No. Gravel and sand as discrete and relatively thin beds (less than 1m thick).
7	Systematically-accreted shelf margin with associated turbidites.	1.	Yes.
8	Abundant continental plant material (leaves, phytodetritus and coal fragments) in the turbi dites beds.	1, 9, 10.	Yes.
9	Turbidite beds with lamination outlined by phytodetritus.	11.	Yes, mainly for GF2.
10	Small amount of slump, slide and debris flow deposits.	1.	No. High proportion of mass and debris flow facies.
11	Down-current pinch-out of thick beds of sandy turbidite.	1	Yes, for GF2.
12	Rounded and aligned mud clasts.		Yes (usually aligned).
13	Siltstone and claystone graded couplets with syneresis cracks.	2	No, absent.
14	Low to moderate trace fossil diversity, low bioturbation intensity, normal size icnotaxa, lack of complex behavior strategies, suspen sion-feeding orga nisms.	12, 2	Yes, usually low trace fossil diversity and bioturbation intensity and lack of complex behavior strategy.

1. Plink-Björklund and Steel (2004); 2. Bhattacharya and MacEachern (2008); 3. Arcuri and Zavala (2008); 4. Bourget *et al.* (2008); 5. Vesely (2008); 6. Piper and Savoye (1993); 7. Mulder *et al.* (1998); 8. Kneller and Buckee (2000); 9. Mulder and Alexander (2001); 10. Johnson *et al.* (2001); 11. Zavala (2008); 12. Carmona *et al.* (2008).

examined in the next paragraphs.

In terms of the criteria here regarded as the more important ones in terms of hyperpycnal flow diagnosis (1 to 6 in Table 2) only one of them was positive. Although it indicates a physical connection between fluvial and turbidite elements, it does not necessarily mean a flow continuum. The next criteria (2 to 6), all missing in the analyzed interval, represent features to be expected in coarse-grained hyperpycnal flow deposits. The studied turbidite beds are relatively thin, discrete, massive or normally-graded, thus suggesting short-lived, depletive pulses. They lack basal coarsening- and thickening-upward trends, cut-and-fill features and laterally irregular grain size changes that evidence waxing flows or flow adjustments due to discharge fluctuations. This first analysis suggests density currents linked to fluvial sources but whose deposits suggest short-lived (surges) depletive turbidite flows.

On the other hand, considering other key criteria for hyperpycnal flow interpretation (7 to 11 in Table 2), all except one (item 10) are valid in the studied interval. Both shelf margin and slope were systematically-accreted in association with turbidites (7); continental-derived plant material (leaves, phytodetritus, pieces of trunks and vitrain layers) are abundant (8); in GF2 deposits, sandy beds with lamination defined by alternating grain- and phytodetritus-rich layers (9) are common; and rapid pinch-out of thick sandy turbidite beds due to flow uplifting, a result of the low density contrast between the sediment-rich, but fresh water underflow and the ambient water, is present (11). Therefore, GF2 strata display features comparable to hyperpycnal flow deposits (9 and 11) and all turbidite beds had some kind of link with fluvial sources (8). The only negative criteria (10) is related to the fact that mass gravity flows, whose evolution through mass disruption and flow dilution represents the most classical model for surge-type turbidite currents, were abundant in the slope and even in the slope rise in the study area. However, although their lack implies the action of other triggering mechanisms, their incidence does not inevitably preclude other mechanisms.

Among the remaining criteria (12 to 14), the first one indicates traction and/or laminar flow that can either be a product of turbidity or hyperpycnal flows. Low bioturbation intensity and trace fossil diversity are general characteristic of the marine Los Molles Formation in the studied area rather than a specific attribute of the turbidites. Consequently, this evidence seems to represent more perennial stressed conditions or some taphonomic control rather than an episodic environmental stress caused by intermittent fresh water underflows. The existence of syneresis cracks as an evidence of near bottom fresh water inflow is negative for the studied succession.

Therefore, the analysis of the aforementioned criteria suggests that the GF1 strata were partially associated with fluvial discharge. However, fluvial effluents seems to have been accelerated along the slope through substrate erosion (abundant mud clasts) and transformed into auto-suspended flows, i.e., the ignition of a parental hyperpycnal flow and the ensuing transformation into a surge type, depletive turbidity current that kept the fluvial composition signature. Conversely, GF2 strata include several features that are similar to those expected for hyperpycnal deposits. All three types of gravity flows were genetically independent, except as sediment source to mass remobilization (GF2 strata).

FINAL REMARKS

The entire turbidite succession represents a turbidite complex (sensu Mutti and Normark 1987) associated with a 2nd order relative sea-level oscillation and associated relative base level fall. The turbidite systems, in turn, were driven by 3rd order relative base-level fluctuations. Finally, the turbidite sub-stages, which comprise interlayered sandy and muddy bed sets (lobe areas) and channel scour /fill and abandonment (slope), were controlled by 4th order relative sea-level changes.

The facies tract ascribed to the early lowstand systems tract (4th order cycles) is represented by GF1 deposits (Fig. 17). They comprise the coarsest-grained load made available by rivers and include the following architectural elements: (a) fluvial channel scours down to the shelf margin; (b) gravelly and sandy, usually fining-upward turbidite channel facies on the upper and lower slope, respectively; and (c) sandy turbidite lobes and heterolithic fan fringe deposits on the slope rise / basin plain setting. Turbidite channel and lobe facies are mostly related to high density, depletive turbidity flows. The high proportion of rip up clasts and flute casts in the turbidite beds point to turbulent flows. The fractioning of the load during transport would have led to the frictional freezing of the lower, denser portion of the flow through successively finer-grained sedimentation waves segregating the turbidite flow load: conglomerates in the upper slope, medium- to very coarse-grained sandstone in the lower slope and lobes and fine-grained sandstone and mudstone in the lobe fringes. It is here assumed that these turbidity surges with profuse plant debris have evolved from parental hyperpycnal flows at the shelf margin.

The GF 2 facies tract (Fig. 17) is finer-grained than the preceding type and supposed to represent more diluted flows produced during the late lowstand systems tract (4th order cycles). It includes the following architectural elements: (a) incised fluvial channels filled with stratified conglomerate and sandstone and covered by transgressive lags and shelf mudstone; (b) axial scours filled with matrix-supported conglomerate that grades towards both sides to undulating, sandy and eventually heterolithic overbank deposits (slope); and (c) undulating strata related to sandy turbidite lobe and heterolithic lobe fringe (slope rise / basin plain). Slope facies represent slightly confined, high density turbidity currents

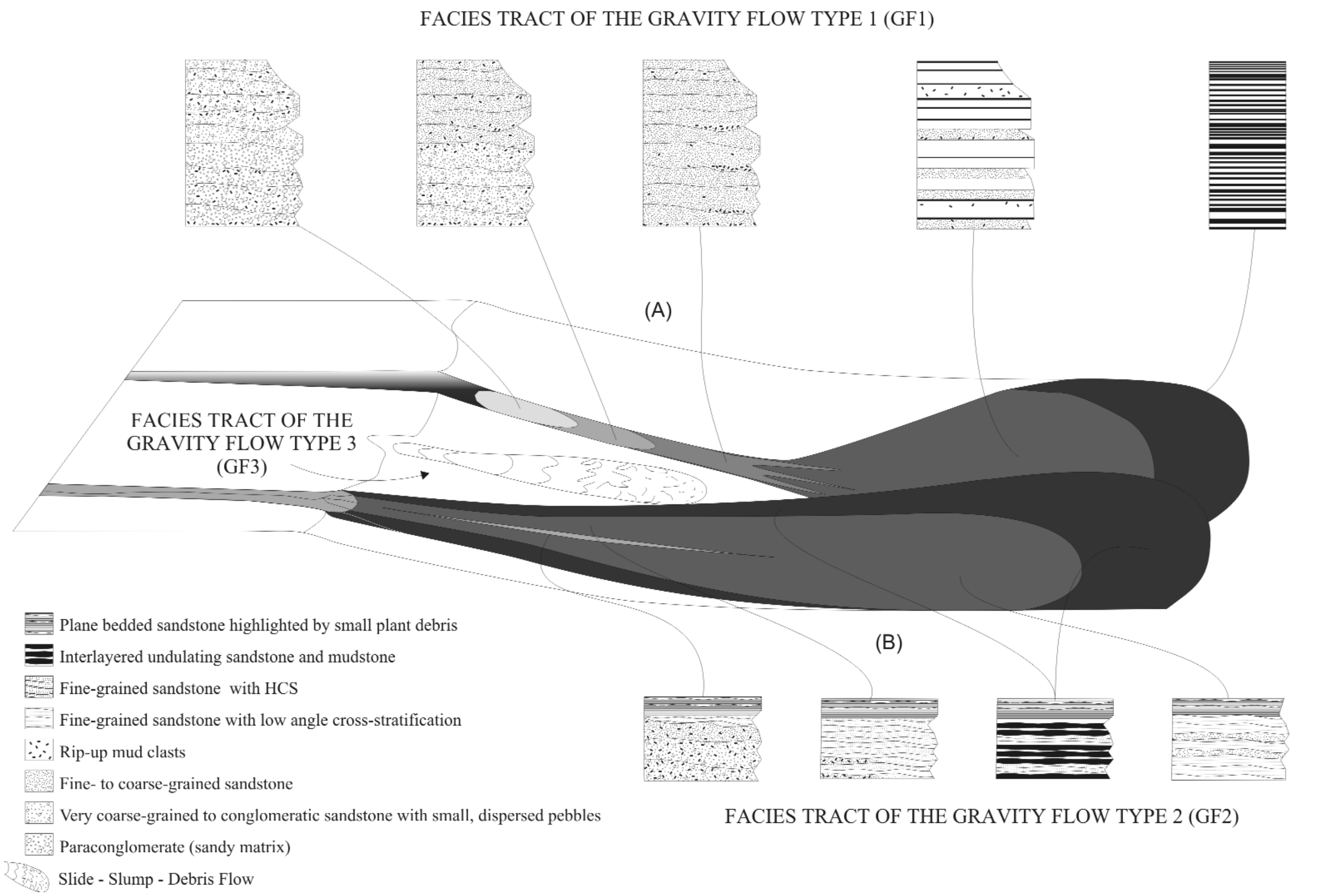

Figure 17: Facies tracts related to gravity flow type 1 (early lowstand systems tract), 2 and 3 (late lowstand systems tract).

(axial portion) that grade laterally and longitudinally to widespread low density flows. The undulating geometry of the beds and the abundance of HCS and low angle cross-stratification bring to light the question of whether these flows represent combined flows (unidirectional density currents modified by an oscillatory component) or simply unidirectional density currents. Based on the abundance of both fair-weather and storm wave deposits in the inner shelf and nearshore facies of the Lajas Formation it is possible to wonder whether these hyperpycnal flows (GF2) could have kept the storm-wave oscillatory component during their down slope course. During the late lowstand stage it is possible to envisage that waves, including storm waves, should strike a coastline located very close to the shelf margin and even be amplified due to the usually associated flood discharge (Mutti *et al.* 1996, 2000). Alternative hypothesis, such as internal waves at density interfaces within the hyperpycnal flows (Mutti *et al.* 1996, 2000) or even purely unidirectional flows related to very high sedimentation rates (Allen and Underhill 1989), can not be ruled out.

The GF3 facies tract, also ascribed to the 4th order lowstand wedge, encompasses the following components: (a) slide deposits, mostly composed of heterolithic and muddy slope deposits; (b) slump facies, including the same kind, but more intensely deformed strata than in the slides; and (c) debris flow deposits, a result of more extensive disruption of the slumped beds (Fig. 17). This facies tract stands for the classical short-lived, surge type gravity flows produced by failure of relatively steep slopes and usually related to high-sedimentation rates of fine-grained sediments. The large amount of fine-grained and poorly consolidated sediment is interpreted as a result of a nearby, mud rich fluvial discharge as most of the rivers bedload was trapped in the channels at this stage.

The muddy facies related to abandonment of both lobes and channels are associated with the transgressive and highstand systems tracts. Lastly, the shoreface facies of the middle to outer shelf that abruptly rest over offshore mudstone, and are scoured by the incised channels, stand for the falling-stage systems tract.

As a synthesis, it is here assumed that basin physiography, a legacy from a former rifting episode, and high frequency relative sea-level changes have strongly enhanced the conditions for gravity flows development. On the other hand, fluvial discharge at the shelf margin has propitiated the initial triggering mechanism (GF1), drove the flow (GF2) or produced proper conditions (GF3) for the occurrence of gravity flows.

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