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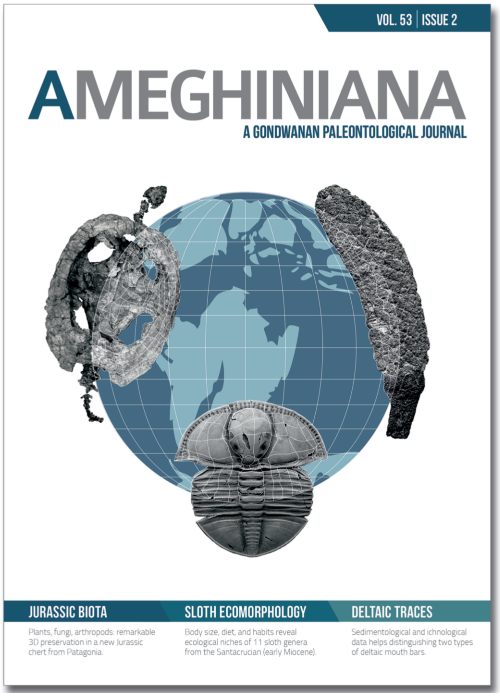

ICHNOLOGY OF DELTAIC MOUTH-BAR SYSTEMS OF THE LAJAS FORMATION (MIDDLE JURASSIC) IN THE SIERRA DE LA VACA MUERTA, NEUQUÉN BASIN, ARGENTINA

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ICHNOLOGY OF DELTAIC MOUTH-BAR SYSTEMS OF THE LAJAS FORMATION (MIDDLE JURASSIC) IN THE SIERRA DE LA VACA MUERTA, NEUQUÉN BASIN, ARGENTINA

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Abstract. Ichnologic and sedimentologic studies of the Lajas Formation (Middle Jurassic) in Sierra de la Vaca Muerta allowed the recognition of two different types of deltaic mouth bars, each of them showing trace fossil suites with different characteristics. Type I deltaic mouth bars consist of fine to coarse sandstones and fine conglomerates completely reworked by fair-weather and storm wave action, revealing a predominance of basinal hydraulic processes (*e.g.*, waves) during bar construction and progradation. Trace fossil assemblages are composed of *Ophiomorpha* and *Haentzschelinia* in the foreset beds, and *Polykladichnus*, *Skolithos*, and *Arenicolites* in the topset beds. Type II deltaic mouth bars comprise sandstones that are fine to coarse and massive or present high angle cross-stratification and current ripples migrating in the opposite direction to the inclination of the foresets. These bars are interpreted to have been deposited during intervals of extraordinary fluvial discharge when wave action was restricted to the topset part of the bars. Whereas equilibrium trace fossils occur in the bottomset beds, escape trace fossils and *Ophiomorpha* are recorded in the distal foreset beds. In the topset beds, *Skolithos* and *Polykladichnus* specimens are very abundant. In general, the two types of mouth bars show low diversity, low abundance of trace fossils and a simple tiering structure. Such traits reflect environmental stresses mainly produced by fluctuating hydraulic energy, salinity, sediment input and high mobility of the substrate.

Key words. Trace fossil. Fluvio-dominated delta. Wave action. *Skolithos* ichnofacies.

Resumen. ICNOLOGÍA DE BARRAS DE DESEMBOCADURA EN SISTEMAS DELTAICOS DE LA FORMACIÓN LAJAS (JURÁSICO MEDIO) EN LA SIERRA DE LA VACA MUERTA, CUENCA NEUQUINA, ARGENTINA. Estudios sedimentológicos e icnológicos de la Formación Lajas (Jurásico medio) en la Sierra de la Vaca Muerta, permitieron reconocer dos tipos de barras de desembocadura deltaicas (Tipo I y Tipo II), con suites de trazas fósiles características. Las barras de Tipo I están compuestas por areniscas finas a gruesas y conglomerados finos, completamente retrabajados por oleaje de buen tiempo y tormenta, sugiriendo que los procesos cuencales (*e.g.* oleaje) fueron dominantes durante la construcción y progradación de las mismas. Las trazas fósiles están principalmente compuestas por *Ophiomorpha* y *Haentzschelinia* en las capas de *foreset*, y *Polykladichnus*, *Skolithos* y *Arenicolites* en las capas de *topset*. Las barras de Tipo II comprenden depósitos de areniscas finas a gruesas masivas o con estratificación entrecruzada de alto ángulo, y óndulas de corriente migrando en dirección opuesta a la migración de las caras de avalancha. Estas barras fueron depositadas durante intervalos de descargas fluviales extraordinarias, estando el retrabajo de oleaje restringido a las capas del *topset*. Estructuras de equilibrio ocurren en las capas del *bottomset*, trazas de escape y *Ophiomorpha* en las capas del *foreset* distal y abundantes especímenes de *Skolithos* y *Polykladichnus* en las capas del *topset*. Como característica general, los dos tipos de barras muestran baja diversidad y abundancia de trazas fósiles y un patrón de escalonamiento simple. Esto refleja un importante estrés ambiental principalmente generado por las fluctuaciones hidráulicas en la energía, salinidad y el aporte de sedimentos, así como por la alta movilidad del sustrato en el sistema.

Palabras clave. Trazas fósiles. Delta fluvio-dominado. Acción de oleaje. Icnofacies de *Skolithos*.

River-dominated deltas formed in shallow-water basins typically exhibit a lobate shape with multi-scale coeval terminal distributary channels at different scales (Olariu and Bhattacharya, 2006). These authors also noted that terminal distributary channels are intimately associated with mouth-bar deposits and are infilled by aggradation and lateral or upstream migration of the mouth bars. In river-dominated deltas, channel bifurcation is common due to both the deposition of sediment at the river mouth that is not removed by basinal processes such as waves and tides, and to the high growth-rate of mouth bars (Olariu and Bhattacharya, 2006). Bioturbation in the distributary

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channels is believed to be characterized by the *Skolithos* or proximal *Cruziana* ichnofacies (*op. cit.*); however, a detailed ichnologic characterization and its paleoenvironmental and paleoecological implications has not yet been accomplished.

The Lajas Formation (Middle Jurassic) is well exposed along large areas in Sierra de la Vaca Muerta, Neuquén Province, Argentina, and is represented by about 700 meters of fine to coarse sandstones and conglomerates corresponding to prodelta and delta-front deposits (Fig. 1). Traditionally, the origin of this unit has been assigned to a deltaic environment with tidal and wave action (Gulisano *et al.*, 1984; Zavala, 1993, 2002; McIlroy *et al.*, 2005). In addition, Zavala and González (2001) recognized the presence of hyperpycnites associated with these deltaic deposits. Recently, Canale *et al.* (2015) interpreted deposits of the Lajas Formation as a river-dominated delta with subordinate hyperpycnal discharge. In the upper section of the unit, channel and mouth bar-lobe deposits are well developed. The distribution of trace fossils in this part of the section differs from what is seen in the lower part of the section (Canale *et al.*, 2015). In this sense, the study of trace fossils represents a useful tool when complementing sedimentologic and paleoecologic analyses, as there is a direct relationship between the physico-chemical parameters acting in a particular environment and the organisms' response to them. In the studied deposits, two different mouth bar arrangements have been recognized; one associated to extraordinarily high fluvial discharge and another one developed under normal conditions. Accordingly, these two types of bars exhibit different patterns of bioturbation. It is the main aim of this contribution to discuss these differences in bioturbation by analyzing the ethology of the tracemakers, as well as to decipher the main paleoecological stress factors affecting the different deltaic mouth bar environments.

STRATIGRAPHY OF THE STUDY AREA

Shallow-marine to continental sand and conglomerate deposits of the Lajas Formation (Weaver, 1931) cover the transition from the clastic Los Molles Formation underneath –composed of offshore and turbidite deposits– to the evaporitic Tábanos Formation on top (Fig. 1.2). These three formations constitute the Cuyo Group (Early–Middle Jurassic), which represents the first episode of prevailing marine deposition in the Neuquén Basin (Groeber, 1946). Different paleoenvironmental interpretations have been proposed for the Lajas Formation. For example, in Sierra de la Vaca Muerta and Covunco, Zavala and González (2001) and Zavala (2002) interpreted the Lajas Formation as deposited in a deltaic system affected by hyperpycnal discharge and partially reworked by tidal currents and wave action. Canale *et al.* (2015) reinterpreted those deposits as river-dominated deltas with hyperpycnal discharge. Nearby, sandstone deposits of the Lajas Formation have been assigned to different environments, including (1) distal delta front to upper shoreface in the Chacaico area (Spalletti, 1995), (2) a macrotidal tide-dominated deltaic system in the same sector (McIlroy, 2007), (3) sand-rich shallow marine deposits in Lohan Mahuida and Picún Leufú areas (Zavala, 1993; Martínez *et al.*, 2000, 2001), and (4) a river-dominated delta in Bajada de los Molles area (Gugliotta *et al.*, 2015).

The Sierra de la Vaca Muerta northwest of Zapala city has not yet been studied in detail from an ichnologic perspective. The only known study of these outcrops is the one carried out by Zavala and González (2001), who recognized five depositional sequences which present evidences of syndepositional tectonic activity. The first sequence displays paleocurrents from the southeast. The following four sequences illustrate a progressive switching of the current direction to the north of the depocenter and, concomitantly, an overall increase in grain size (Zavala and González, 2001). These sequences appear to have accumulated in elongate depocenters while tectonic activity controlled facies and isopach geometries during the Jurassic. Thus, changes in the sediment source area led to the idea of the growth of a morphological barrier in the area of the Dorsal de Huincul which may have progressively limited clastic input from the southeast (Zavala and González, 2001).

ICHNOLOGY

Diversity and abundance of the trace fossils that were recognized are, in general, relatively low. Additionally, their preservation is poor due to the presence of coarse host material in the studied deposits. Most of the ichnofossils occur as epireliefs or full-reliefs in coarse-medium sandstones. Among the identified ichnotaxa, the following are the most conspicuous (Fig. 2):

Arenicolites comprises a U-tube without spreiten and is most commonly interpreted as a dwelling burrow of a worm-like organism (*e.g.,* polychaetes, Goldring, 1962; Fürsich, 1974). This trace fossil is found both in shallow and deep-marine settings since the Cambrian (see Mángano and Buatois, 2014 and references therein). Furthermore, it can

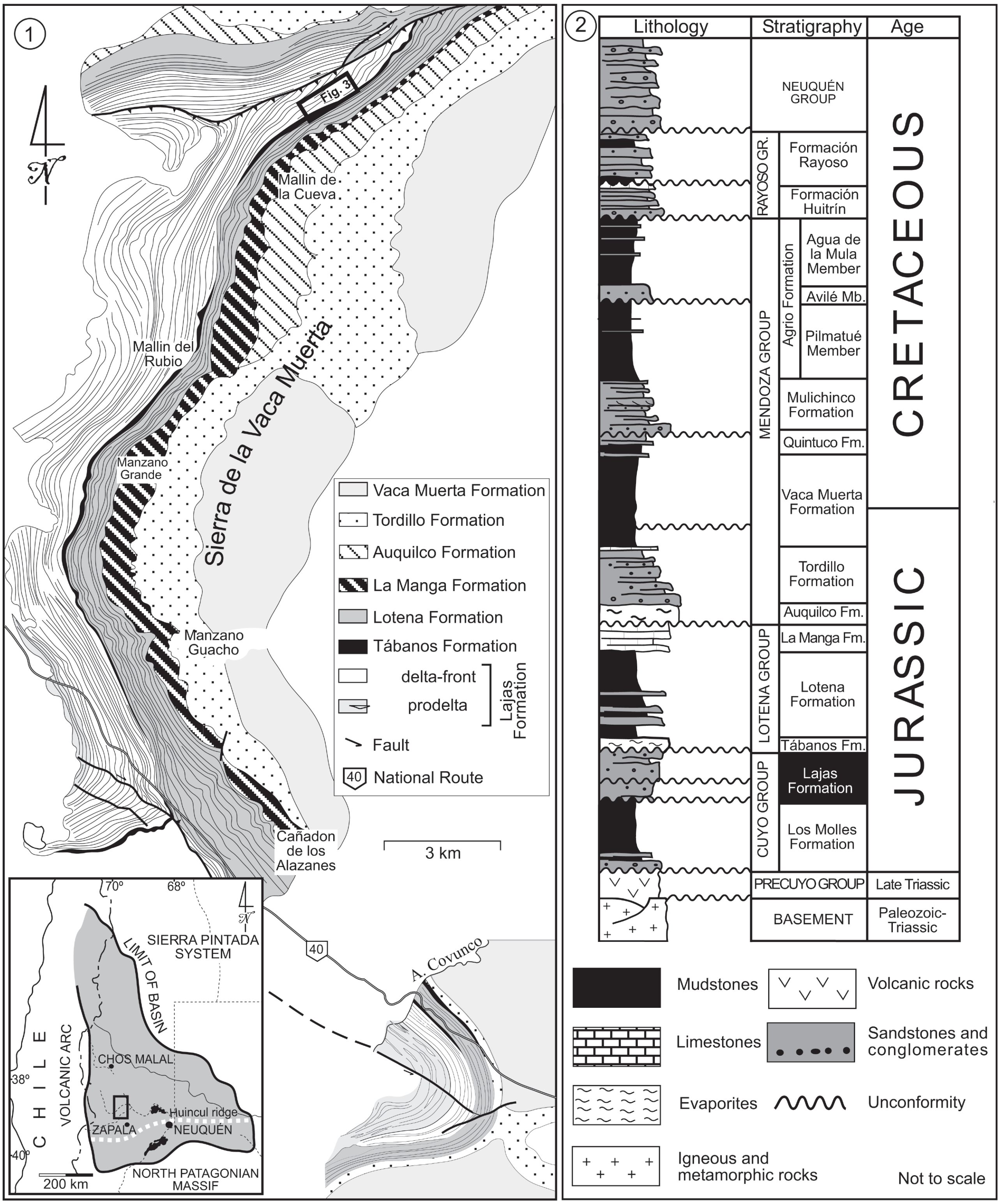


Figure 1.1, Geological map of the Sierra de la Vaca Muerta and Arroyo Covunco, showing the study area (black rectangle Fig. 3); **2,** Stratigraphic column of the Neuquén Basin. The Lajas Formation is indicated with a black rectangle (Figure 1 was modified from Zavala and González, 2001).

also be recognized in non marine environments associated to crevasse-splays, bars and oxbow-lake deposits (Netto, 2007).

Gyrochorte comprises curved to meandering, obliquely penetrating burrows, presenting a bilobate epichnial ridge and an underlying hypichnial groove (Fig. 2.1), both with transverse striate (Gibert and Ekdale, 2002). This ichnogenus has been assigned to detritus-feeding annelids (Gibert and Benner, 2002). Although there are some records corresponding to the Early Ordovician, most of the occurrences are Jurassic (Gibert and Benner, 2002 and references therein).

Haentzschelinia is a vertical, radial spreiten trace, having a central shaft (Fürsich and Bromley, 1985) (Fig. 2.2). This structure is interpreted as produced by a worm-like organism with a proboscis used for bioturbating the sediment from the central shaft (Fürsich and Bromley, 1985; Gibert *et al.*, 1995; Uchman and Pervesler, 2007; Wilmsen and Niebuhr, 2014). Recent lugworms such as *Arenicola marina* (Linnaeus, 1758) construct similar structures in modern shallow marine settings (Rijken, 1979). Additional interpretations suggest other potential tracemakers such as bivalves, amphipods and crustaceans (Seilacher, 2003). Although *Haentzschelinia* is known since the Triassic, most occurrences have been reported from the Cretaceous and Miocene deposits (Agirrezabala and Gibert, 2004).

Macaronichnus comprises horizontal to sub-horizontal trace fossils with a fill characteristically lighter than the host rock (Clifton and Thompson, 1978) (Fig. 2.3). *Macaronichnus* has been attributed to opheliid polychaetes (Pemberton *et al.*, 2001). This ichnogenus occurs since the Early Devonian (Quiroz *et al.*, 2010; Netto *et al.*, 2012), commonly in upper-shoreface and foreshore deposits, and generally in high densities (Pemberton *et al.*, 2001; Seike, 2009). In the studied deposits, even though the typical light-sandy infill was identified, the boundaries of the traces are not so well defined.

Polykladichnus is a vertical to oblique structure characterized by presenting upward directed Y- or U-shaped branches (Fig. 2.4), connecting to the bedding surface (Schlirf and Uchman, 2005; Mørk and Bromley, 2008). It ranges from the Devonian to the recent, both in marine and continental environments (Schlirf and Uchman, 2005). In recent settings, polychaetes, cerianthid anemones and chironomid larvae produce *Polykladichnus*-like structures (Schlirf and Uchman, 2005; Pearson and Gingras, 2006; Gingras *et al.*, 2007).

Ophiomorpha is a common structure that comprises simple or complex branching burrows exhibiting clearly distinctive thick pelleted walls (Fig. 2.5). This structure is interpreted as dwelling burrows of decapods (*e.g.,* callianassids) (Frey *et al.*, 1978; Pollard *et al.*, 1993; Curran, 2007). *Ophiomorpha* occurs in shallow-marine, high-energy environments (Frey *et al.*, 1978; Curran, 2007), but it has also been recorded in deep-marine settings (*e.g.,* Uchman, 2009 and references therein). Although they occur since the Carboniferous (Driese and Dott, 1984; Buatois *et al.*, 2002), they are more common in post-Paleozoic deposits.

Skolithos represents a simple and vertical burrow, lined or unlined (Fig. 2.6). This trace fossil is interpreted as a dwelling burrow of vermiform organisms such as polychaetes or phoronids (Schlirf and Uchman, 2005). *Skolithos* occurs in both shallow- and deep-marine environments, and it has also been recorded in continental settings. It ranges since the Cambrian (Howard and Frey, 1975; Mángano and Buatois, 2014).

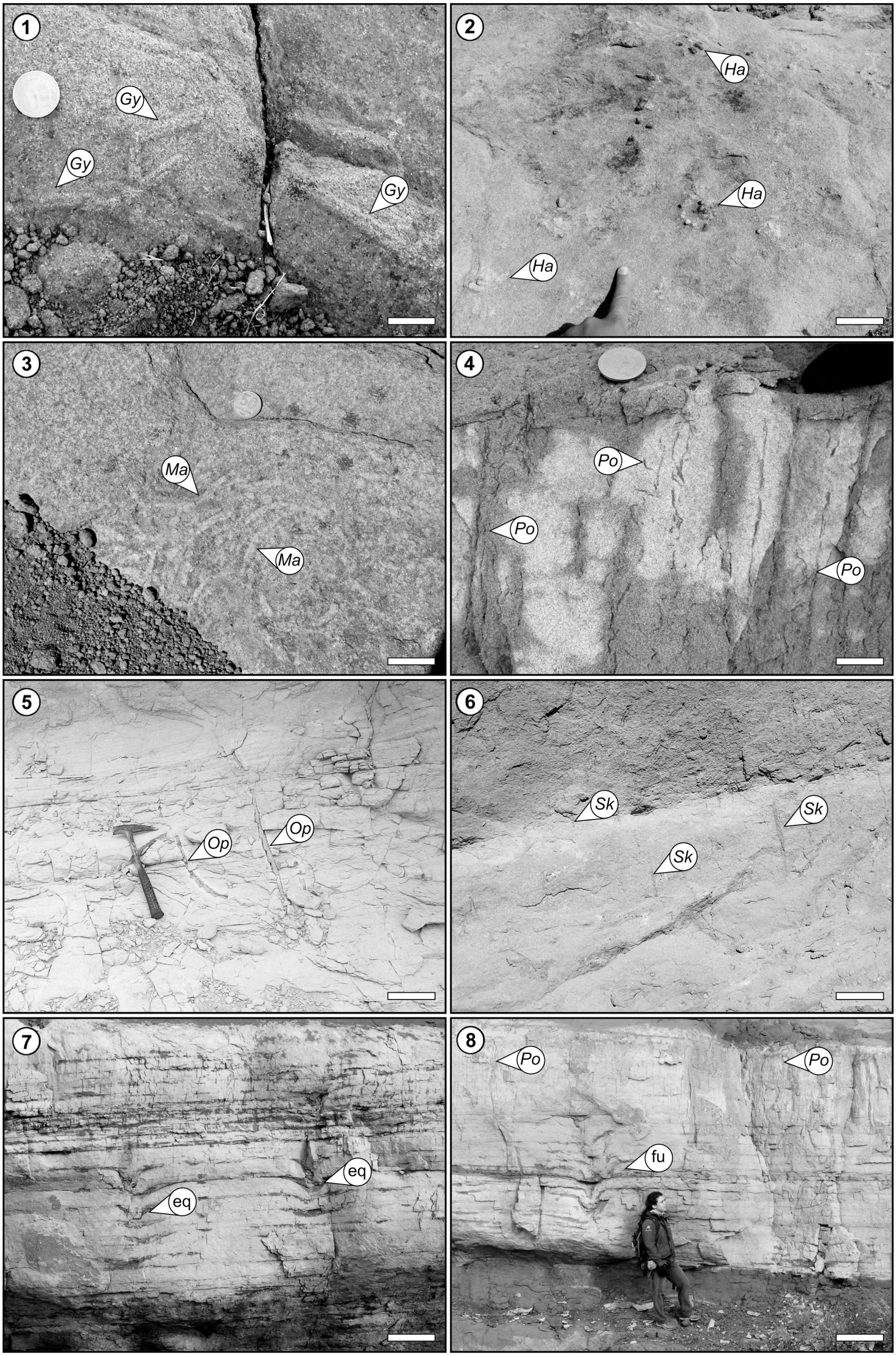
Equilibrium trace fossils have also been identified in the studied deposits and are characterized by a series of superimposed U- or V- shaped depressions reaching up to 1.6 m (Fig. 2.7). Similar traces, although smaller and less regular in morphology, have also been observed and most likely represent escape traces (Fig. 2.8).

SEDIMENTARY FACIES AND TRACE FOSSIL DISTRIBUTION

Four detailed stratigraphic sections totaling 150 m of the upper part of the Lajas Formation in the northern area of Sierra de la Vaca Muerta were measured and correlated (Fig. 3). These sections show a stacking pattern composed of deltaic lobes. Two main deltaic mouth bar arrangements, named Type I and Type II, display trace fossil suites with different characteristics.

Type I deltaic mouth bars

Sedimentology. Type I deltaic mouth bars consists of fine to coarse sandstones and fine conglomerates with large-scale cross-stratification or, less commonly, massive appearance resulting from partially or totally reworked by fair-weather and storm-wave action (Fig. 4.1–2). Paleocurrents of the


1
Gy
Gy
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Ha
Ha
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4
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eq
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large-scale cross-stratification range from 50° NE to 98° SE. Individual sets are continuous for tens of centimeters and cosets can be up to 10 meters in thickness. Grain size increases towards the top of each sandstone set reaching pebbly sandstone or fine pebble size. The symmetric ripples reflect important fair-weather and storm-wave action (Fig. 4.3–4). Small mud chips and allochthonous clasts of variable composition and size (until 10 cm) commonly occur in the lower part of the sets or in topsets of the mouth bars. Channelized geometries boast a lateral extent of a few meters and contain particulate organic matter and wooden fragments derived from continental sources, which are occasionally bored by *Teredolites*. Shell fragments and some bivalve casts, although not very common, can be usually recognized on the topsets.

Trace fossil content. The foreset beds of these bars are bioturbated mainly by *Ophiomorpha* and *Haentzschelinia* producers (Figs. 2.2, 3, 4.5–6). *Ophiomorpha* is locally very abundant and, in some cases, presents good preservation of pellets (Fig. 4.1, 4.5). *Haentzschelinia* has been observed in groups of up to ten specimens on top of the foresets (Fig. 4.1, 4.6).

In the topset beds of these bars, *Polykladichnus*, *Skolithos* (Fig. 2.6) and *Arenicolites* –and, subordinately, *Macaronichnus, Ophiomorpha* and *Gyrochorte* (in poor preservation)– have been found (Figs. 2.1, 2.3, 4.1). *Polykladichnus* and *Skolithos* are present in almost every topset bed while *Arenicolites* is less common. Length of these trace fossils is up to a few centimeters. Even though in some specimens silt sediment was recognized, the filling of the structures is the same as in the host rock. The topset beds where *Polykladichnus* is found are characteristically oxidized. *Macaronichnus* is also present in a few isolated intervals and it is recognized by its characteristic pale fill. When this trace fossil occurs, the sandstone shows a completely mottled appearance. Additionally, some levels within the topset intervals are penetrated by relatively short *Ophiomorpha* burrows some of which, characterized by presenting a U-shaped morphology, are inclined within the substrate. Few specimens of *Gyrochorte* have also been observed in the topset layers (Figs. 2.1, 4.1).

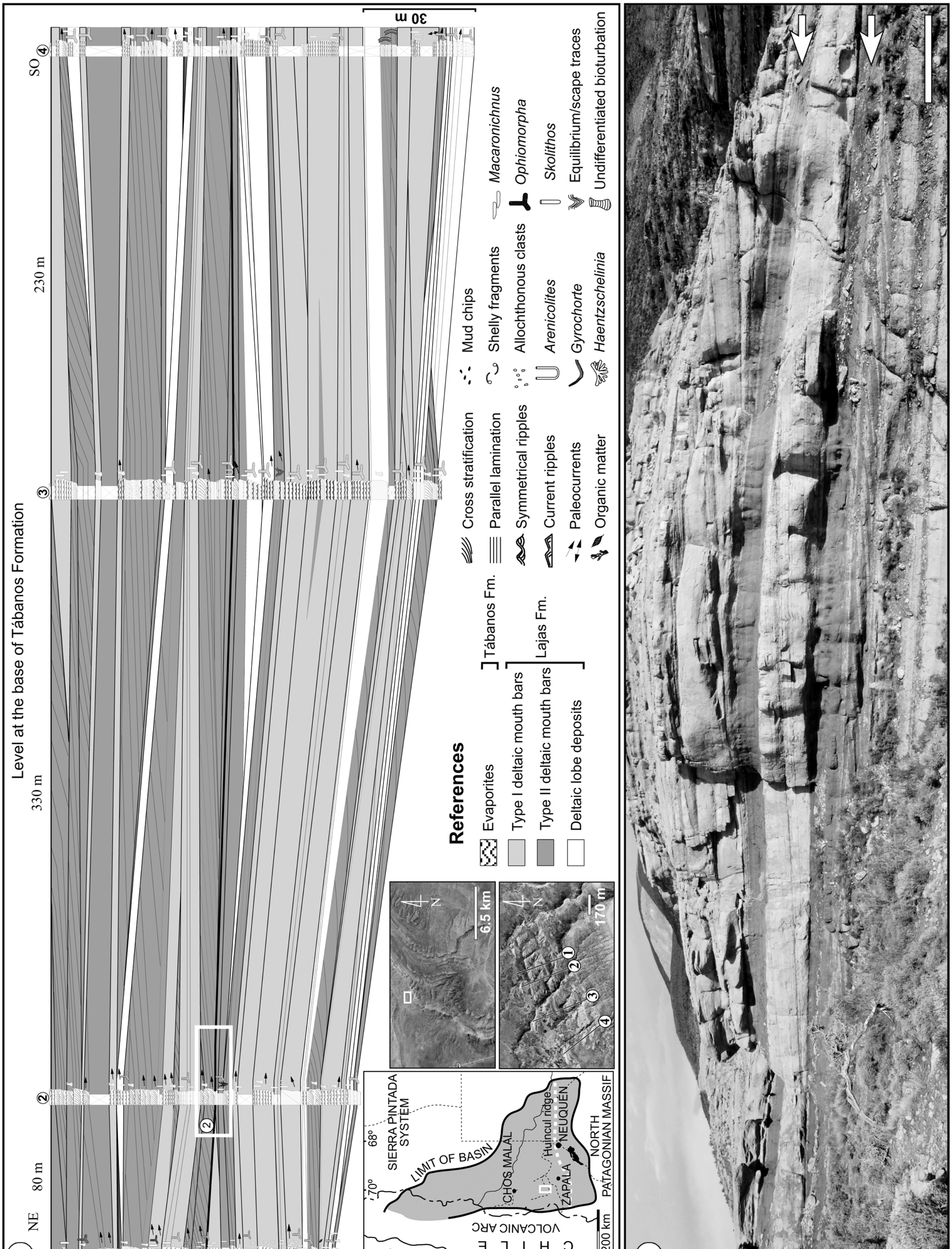
Type II deltaic mouth bars

Sedimentology. Type II deltaic mouth bars consists of coarse- to fine-grained deposits dominated by large-scale cross-stratified sandstones with current ripples migrating in the opposite direction to the inclination of the foresets. Such trait is produced by flow separation in the front of the bar, occasionally with reactivation surfaces and subordinately massive appearance (Figs. 3, 5.1–5.3).

Paleocurrents range from 45° NE to 173° SE. Towards the topset beds, these bars show fair-weather- and storm-wave action (Fig. 5.2) with mean paleocurrent direction of 130°. Individual sets reach up to 4 meters and cosets up to 11 meters in thickness. Grain size varies from medium and fine sand to gravel size in the foreset beds. Particulate organic matter and wood fragments of up to 20 cm in size are present. Small mud chips and allochthonous clasts occur in the mouth bar strata but prove more frequent at the top of the bars, where bivalve casts and shelly fragments are also commonly present.

Trace fossil content. The ichnologic content is represented by equilibrium/escape trace fossils, *Ophiomorpha*, *Skolithos, Polykladichnus*, and, subordinately, *Macaronichnus* (Figs. 2, 3, 5). Equilibrium traces occur in the bottomset beds, which reach a height of up to a meter (Figs. 2.7, 5.1, 5.3). Conversely, escape traces are recorded in the distal foreset beds (Figs. 2.8, 5.1, 5.3). Furthermore, *Ophiomorpha* specimens also occur in the foreset beds and can measure up to 60 cm, being mostly vertical or inclined to stratification

Figure 2.1, Specimens of *Gyrochorte* **(*Gy*)** in plain view. Preservation of these trace fossils is poor due to coarse sediment. Scale bar= 2.5cm; **2,** Plain view of *Haentzschelinia* **(*Ha*)**. Scale bar= 6 cm; **3,** Mottled pattern of *Macaronichnus* **(*Ma*)** in plain view. Characteristic fill lighter than the host rock is observed. Scale bar= 4 cm; **4,** Section view of a *Polykladichnus* **(*Po*),** characterized by having upward directed Y-shaped branches. Scale bar= 2.5 cm; **5,** Subvertical specimens of *Ophiomorpha* **(*Op*)** oriented in the opposite direction to the foreset stratification. Scale bar= 15 cm; **6,** Topset beds of the bars colonized by *Skolithos* **(*Sk*)**. Scale bar= 15 cm; **7,** Vertical section of an equilibrium trace fossil **(eq)** comprising several superimposed U-shaped depressions. Scale bar= 20 cm; **8,** Irregular U-shaped depressions assigned to escape traces fossils **(fu)**. Note *Polykladichnus* **(*Po*)** specimens in the topset of the bar. Scale bar= 45 cm.


1
Level at the base of Tábanos Formation
NE
SO
80 m
330 m
230 m
30 m
References
Evaporites
Type I deltaic mouth bars
Type II deltaic mouth bars
Deltaic lobe deposits
Tábanos Fm.
Lajas Fm.
Cross stratification
Parallel lamination
Symmetrical ripples
Current ripples
Paleocurrents
Organic matter
Mud chips
Shelly fragments
Allochthonous clasts
Arenicolites
Gyrochorte
Haentzschelinia
Macaronichnus
Ophiomorpha
Skolithos
Equilibrium/scape traces
Undifferentiated bioturbation
SIERRA PINTADA SYSTEM
LIMIT OF BASIN
CHOS MALAL
Huincul ridge
NEUQUÉN
ZAPALA
NORTH PATAGONIAN MASSIF
VOLCANIC ARC
CHILE
70°
68°
38°
40°
200 km
6.5 km
170 m
N
2

(Figs. 2.5, 5.1, 5.5). Aside from the straight specimens, somewhat coiled to spiral and complex burrow morphologies, which are better discerned in oblique cross-sections, have occasionally been observed. In the *Ophiomorpha* walls, fragments of organic matter are often present. Finally, in the topset beds, *Skolithos* and *Polykladichnus* specimens are very abundant (Figs. 2.4, 5.1, 5.3, 5.5). They range from a few centimeters up to a meter long. *Polykladichnus* is also associated with oxidized layers in the topset beds (white arrows in Figs. 3.2, 5.3). Subordinately, a few levels with *Macaronichnus* occur in the topset layers. Such phenomenon produces a completely mottled pattern.

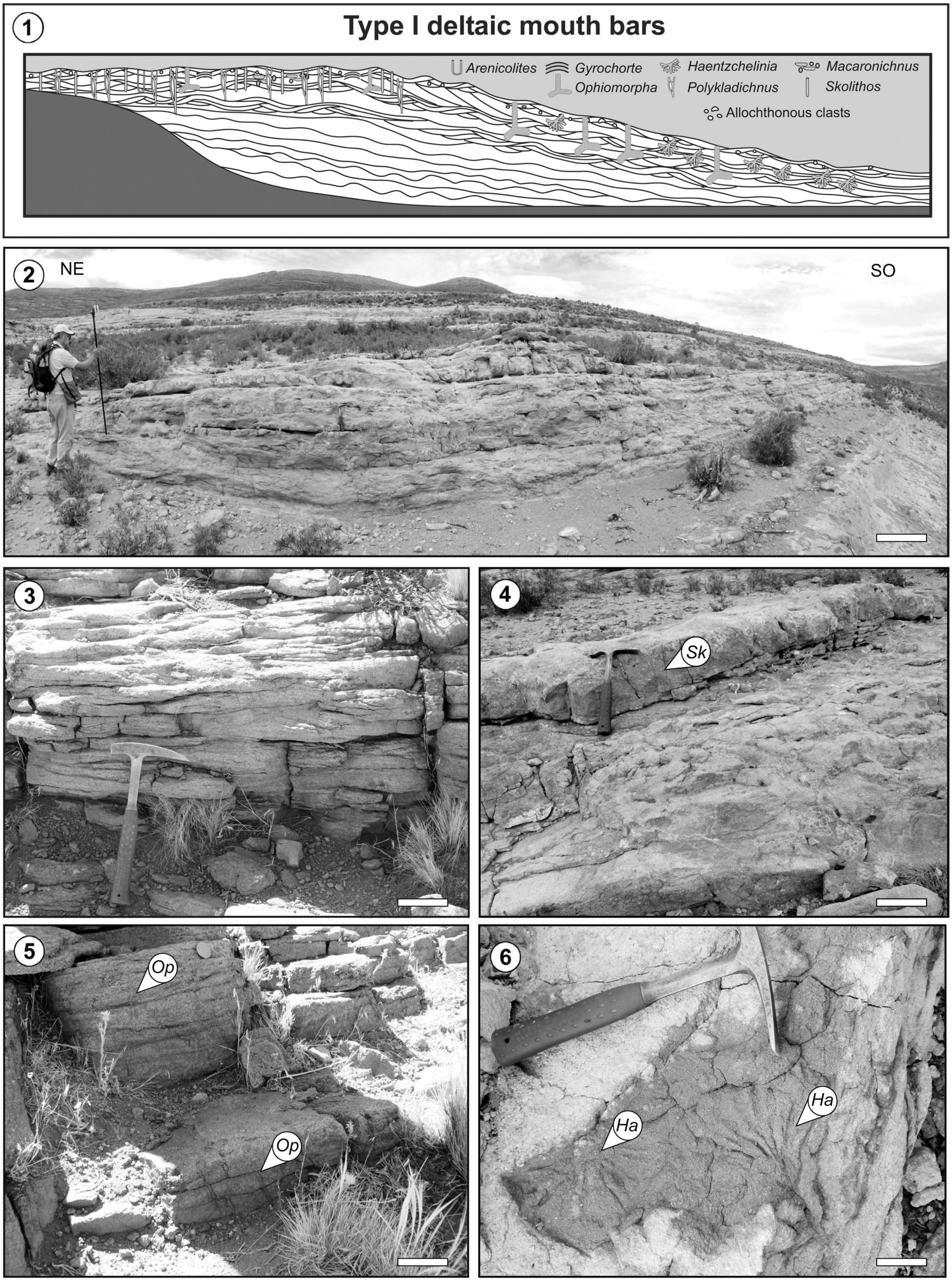
PALEOECOLOGICAL AND PALEOENVIRONMENTAL IMPLICATIONS

In general, the abundant though low-diversity trace fossils and the simple tiering structure observed in the delta-front deposits of the Lajas Formation most likely reflect the various environmental stresses resulting from fluctuating fluvial discharge and storm events that formed both these deposits. Among the ecological parameters, fluctuations in hydraulic energy and salinity can be considered the most severe in this setting. The alternating and contrasting hydraulic energy conditions produced by fluvial discharge and wave action (during fair-weather and storm conditions) severely affected the establishment and distribution of the endobenthic organisms as well as the preservation of the burrows. Moreover, some taphonomic constraints such as the general coarse grain size, did not favor the preservation of trace fossils in these mouth bar deposits.

In Type I deltaic mouth bars (Fig. 4), the continuous reworking of the topset and foreset beds by fair-weather and storm-wave action reveals a dominance of basinal processes during bar construction and progradation. Two main trace fossil assemblages are recognized: the suite developed in the topset beds is formed by *Skolithos, Polykladichnus, Arenicolites, Macaronichnus* and, subordinately, *Gyrochorte* and *Ophiomorpha*; and the suite occurring in the foreset beds consists of *Ophiomorpha* and *Haentzschelinia* (Fig. 4.1). The suite in the topset beds is mostly dominated by vertical structures (domichnia) of suspension-feeding organisms constituting a typical example of the *Skolithos* ichnofacies. This assemblage is commonly formed under relatively high hydraulic energy levels and typically found in well-sorted sandy marine environments (MacEachern *et al.*, 2005). The presence of *Macaronichnus*, interpreted as a result of deposit-feeding polychaetes, does not contradict the previous observation since this trace fossil is commonly found living below the high-energy sediment/water interface in high-energy environments such as foreshore settings (Pemberton *et al.*, 2001; MacEachern *et al.*, 2005). In addition, *Gyrochorte*, a trace fossil interpreted to be produced by a detritus-feeding vermiform organism, is considered a post-event burrow found in environments with moderate to relatively high hydraulic energy (Gibert and Benner, 2002). In the present case, *Gyrochorte* is not very abundant and, presumably, the producers colonized the topset surface after a high-energy event such as a storm.

In the foreset beds, the trace fossil suite becomes less diverse and abundant, with a clear dominance of *Ophiomorpha* burrows (some with complex morphologies), forming an almost monospecific assemblage (Fig. 4.1). Additionally, in some isolated levels of the foresets, *Haentzschelinia* has also been recognized, though never in co-occurrence with *Ophiomorpha*. These two ichnospecies have been associated to relatively high-energy settings with fluctuating sedimentation rates (Frey *et al.*, 1978; Wilmsen and Nieburh, 2014). *Ophiomorpha* burrows are understood to be indicative of relatively high hydraulic energy because of their reinforced walls (Howard and Frey, 1984; Anderson and Droser, 1998). In addition, *Haentzschelinia* has been commonly found in nearshore to deltaic food-rich settings with high sedimentation rates (see Wilmsen and Niebuhr, 2014). The potential tracemaker of *Haentzschelinia* is a worm-like organism of a presumably similar behavior to that observed in the recent lungworm *Arenicola marina* (Rijken, 1979). In-

Figure 3.1, Stratigraphic sections measured in detail and correlation panel of the upper part of the Lajas Formation in the north area of Sierra de la Vaca Muerta; **2,** Panoramic view showing the stacking pattern of the deltaic mouth bars. White arrows indicate the typical oxidation produced at the topset of the bars. This panoramic view corresponds to the white box indicated in Figure 3.1. Scale bar= 6 m.


1
Type I deltaic mouth bars
Arenicolites
Gyrochorte
Haentzchelinia
Macaronichnus
Ophiomorpha
Polykladichnus
Skolithos
Allochthonous clasts
2
NE
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Ha

terestingly, this organism changes its behavior when finding food-rich sediments and, instead of constructing U-shaped burrows for trapping surficial food particles, it generates radial tunnels from a central shaft, resembling the trace fossil *Haentzschelinia* in morphology (Rijken, 1979; Bromley, 1996; Wilmsen and Niebuhr, 2014). Therefore, it is probable that the organisms producing *Arenicolites* in the topset beds could have changed their behavior to build *Haentzschelinia* in the foreset beds of the bars (Fig. 4.6) when hydraulic energy and organic content of the sediment changed.

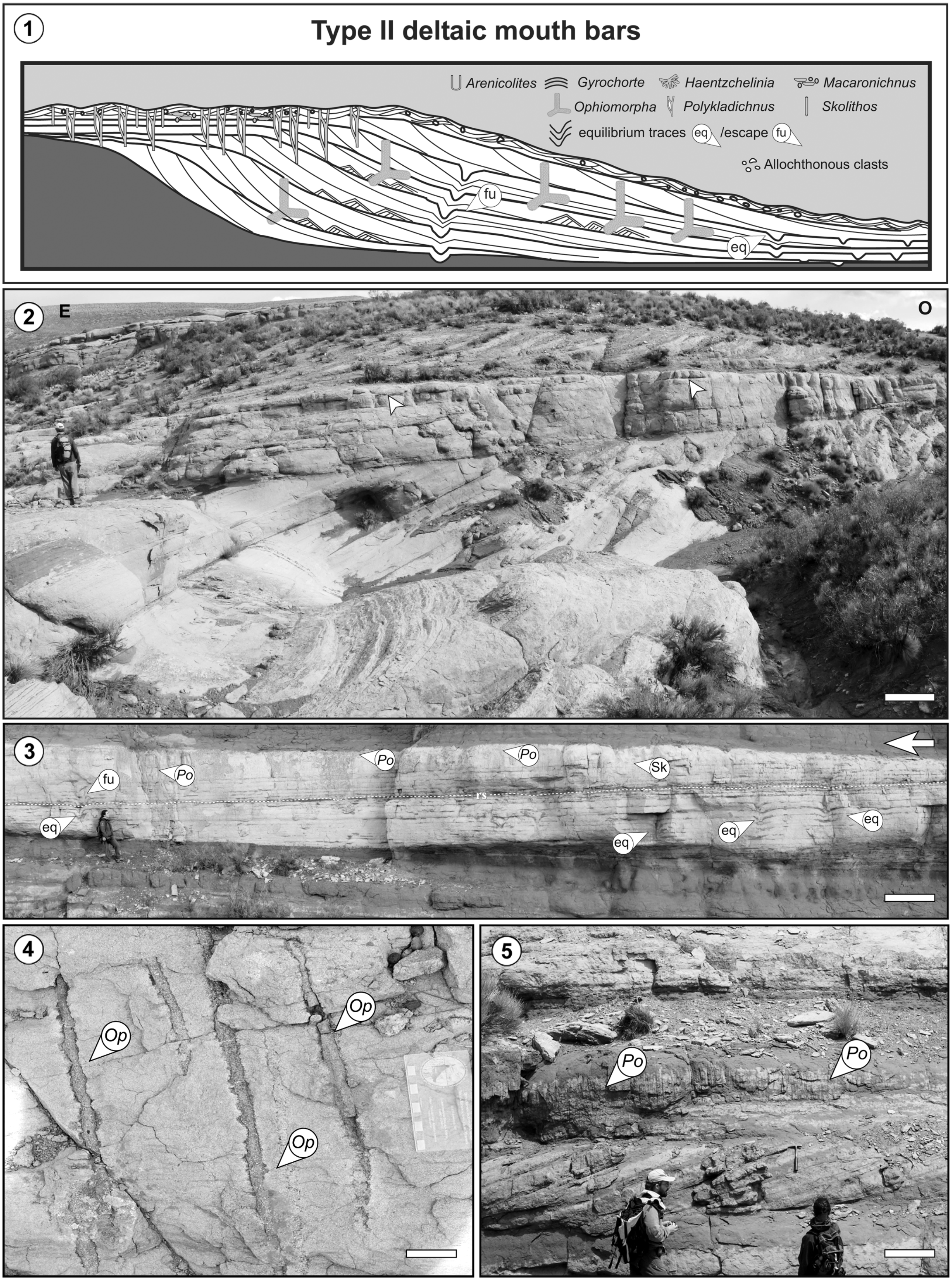
Type II deltaic mouth bars (Fig. 5) shows reworking by wave action only in the topset beds. Their great thickness of up to 9 m, the good preservation of sedimentary structures and the low diversity and abundance of trace fossils suggest that these mouth bars were strongly affected by fluvial discharge. In general, the absence of trace fossils in most of the Type II mouth bars is interpreted as a consequence of the rapid deposition of large amounts of sediment during periods of high fluvial discharge that resulted in high water turbidity and salinity fluctuations. All these factors inhibited the development of a normal marine fauna (MacEachern *et al*., 2005). This interpretation is supported by the presence of an interval with equilibrium traces occurring in the bottomset beds and escape traces in the distal foreset beds (Figs. 2.7–8, 5.1, 5.3). The equilibrium structures reflect the adjustment of the position of the tracemakers within the sediment in a gradually aggrading seafloor (Bromley, 1996). Conversely, escape traces indicate sudden burial of the organisms which attempt to survive by burrowing upward and moving in a fairly different and characteristic way through the sediment (Bromley, 1996). The latter behavior is documented when the mouth bars prograded rapidly due to high sediment accumulation in the distal foreset zone. In the upper foreset bed, *Ophiomorpha* burrows occur (Figs. 2.5, 5.1, 5.4).

In the topset beds, the trace fossil suite is similar, though less diverse, to the one observed in the Type I bars. *Skolithos* and *Polykladichnus* can be very abundant (Figs. 2.4, 5.1, 5.6) and range from a few centimeters to a meter in length. Subordinately, isolated levels with *Macaronichnus,* producing a completely mottled pattern, are also observed in the topset beds of the bars. In general, this suite is dominated by deep traces of suspension-feeders adapted to live in a high energetic setting with shifting sand bodies. As previously mentioned for the suite in Type I bars, *Macaronichnus* producers live deep in sediment as endobenthic deposit-feeders (MacEachern *et al*., 2005). Hence, they are not directly exposed to the high-energy conditions acting at the top of the bars.

Both types of mouth bars are subject to fluctuations of hydraulic energy and, subsequently, changes in sedimentation rates and high mobility of the substrate as well as salinity variations that affected the distribution and composition of the trace fossil producers. Fluctuating hydraulic energy has already been discussed for each particular subenvironment of the mouth bars.

Additionally, salinity fluctuations are an extremely important ecological parameter especially when dealing with deltaic systems as in the present case, in which proximal positions are addressed (see MacEachern *et al*., 2005). Close to the river mouth, the trace fossil suites commonly show a set of characteristics such as low diversity, reduction in size and dominance of infaunal over epifaunal strategies. These can be considered diagnostic of stressed settings. Even if ichnodiversity is low, abundance of trace fossils can be high, as many marginal marine settings can support a large biomass (MacEachern *et al*., 2005). The aggregate of these characteristics is known as "the brackish-water ichnological model" (Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; MacEachern *et al*., 2005 and references therein). In the studied mouth bars, several of these characteristics are found; particularly, the low diversity of the suites and the dominance of infaunal strategies. Although the abundance of trace fossils is high in some domains, the

Figure 4.1, Schematic model showing the main sedimentologic and ichnologic characteristics of Type I deltaic mouth bars; **2,** Panoramic view of a bar composed of massive coarse sandstones and conglomerates totally reworked by wave action. Scale bar= 70 cm; **3–4,** Detail of the sets showing wave action on top of the bars. Note in 4 the presence of vertical trace fossils attributed to *Skolithos* **(*Sk*)**. Scale bar in **3**= 10 cm and in **4**= 15 cm; **5,** Vertical section view of wave ripples with specimens of *Ophiomorpha* **(*Op*)**. Scale bar= 7 cm; **6,** Plain view of a level affected by wave action having specimens of *Haentzschelinia* **(*Ha*).** Scale bar= 5 cm.


1
Type II deltaic mouth bars
Arenicolites
Gyrochorte
Haentzchelinia
Macaronichnus
Ophiomorpha
Polykladichnus
Skolithos
equilibrium traces eq /escape fu
Allochthonous clasts
fu
eq
2
E
O
3
fu
Po
Po
Po
Sk
eq
rs
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4
Op
Op
Op
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Po
Po

suites are almost monospecific. Decrease in size has not been recognized in the suites of the Lajas Formation. However, as stated by MacEachern *et al*. (2005), these observations should be evaluated considering time-equivalent fully-marine counterparts. When comparing both mouth bars, diversity is slightly greater in Type I bars, which show greater influence of wave action. Conversely, Type II mouth bars, marked by more fluvial influence, prove to be less diverse. This could be reflecting that dilution of the seawater was intensified in the latter. Thus, such dilution becomes evident in the trace fossil suites recorded in those bars.

The occurrence of *Polykladichnus* in the topset beds of both Type I and II mouth bars deserves a special discussion. As stated above, most of the levels in which these structures appear are oxidized. *Polykladichnus* is an ichnogenus attributed to a great variety of producers (from polychaetes to chironomid larvae) recorded in both marine and continental environments (Schlirf and Uchman, 2005). Therefore, its occurrence in the oxidized levels could imply at least, some exposure of the topsets of these bars. Unfortunately, aside from the widespread oxidation of the levels, there is no other sedimentologic observation that can support this interpretation (*e.g.,* there are no dessication cracks as there is no mud in the setting to generate them). Nevertheless, modern examples of subaerially exposed mouth bars were observed in the modern Atchafalaya Delta, in areas with important lateral migration and upstream accretion of mouth bars (Olariu and Battacharya, 2006). Hence, the occurrence of these oxidized levels fully bioturbated by *Polykladichnus* could be indicating –albeit not conclusively– a subaerial phase in the growth of these mouth bars.

CONCLUSIONS

Two different mouth bar arrangements have been recognized in the studied deltaic deposits; that is, one with dominance of fair-weather and storm-wave action (Type I mouth bars), and the other one associated to extraordinary fluvial discharge (Type II mouth bars).

Diversity and abundance of trace fossils are, in general, relatively low. Ichnofossil preservation is poor due to coarse host material. Most of the structures are preserved as epireliefs and full-reliefs in coarse-medium sandstones.

Type I deltaic mouth bars consists of fine to coarse sandstones and fine conglomerates with large-scale cross-stratification or, less commonly, massive appearance partially or totally reworked by fair-weather and storm-wave action. While *Ophiomorpha* and *Haentzschelinia* occur in the foreset beds, *Polykladichnus*, *Skolithos* and *Arenicolites* are dominant in the topset beds. Subordinately, *Macaronichnus, Ophiomorpha* and *Gyrochorte* are also present in the topset beds.

Type II deltaic mouth bars consists of coarse- to fine-grained deposits dominated by large-scale cross-stratified sandstones with current ripples migrating in the opposite direction to the inclination of the foresets and subordinate massive appearing intervals. These mouth bars are interpreted as deposited during extraordinary fluvial discharge. The ichnologic content comprises equilibrium traces in the bottomset beds while escape traces are recorded in the distal foreset beds. *Ophiomorpha* specimens occur in more proximal parts of the foreset beds. In the topset beds, *Skolithos* and *Polykladichnus* specimens are very abundant and a few levels with *Macaronichnus* are also recognized.

Low diversity and abundance of trace fossils as well as simple tiering structures observed in the delta-front deposits of the Lajas Formation most likely reflect the various environmental stresses produced during strong fluvial discharge and by fair-weather- and storm-waves that formed both these deposits. Among the ecological parameters, the fluctuations in hydraulic energy, salinity and turbidity are considered the most dominant factors in this setting.

When comparing both mouth bars, diversity is slightly

Figure 5.1, Schematic model showing the main sedimentologic and ichnologic characteristics of Type II deltaic mouth bars; **2,** Coarse to fine sandstones with high angle cross stratification and wave reworking restricted to the topsets (see white arrows). Scale bar= 85 cm; **3,** Detail of the migration of Type II mouth bars with equilibrium **(eq)**/escape **(fu)** trace fossils on the foreset beds and vertical structures ascribed to *Polykladichnus* **(*Po*)** and *Skolithos* **(*Sk*).** The transition between equilibrium and escape traces relates to the reactivation surface **(rs)** which indicates a change in flow velocity during the fluvial discharge (dotted line). Scale bar= 1.5 m; **4,** Detail of vertical *Ophiomorpha* **(*Op*)** galleries; conical pellets as well as organic matter constitute part of the pellets. Scale bar= 5 cm; **5,** Vertical section of the topset beds of the bar being completely bioturbated by *Polykladichnus* **(*Po*).** Note how oxidation of the sediments affected the topset beds of the bars. Scale bar= 65 cm.

greater in Type I bars, which show more influence of wave action. Conversely, Type II mouth bars, marked by stronger fluvial influence, could entail greater dilution of the sea-water by freshwater obviously affecting the endobenthic community.

The occurrence of oxidized levels fully bioturbated by *Polykladichnus* in the topset beds of both Type I and II mouth bars could be indicative of temporary subaerial exposure during mouth bar formation. This hypothesis requires further substantiation.

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