The Cambrian-Ordovician siliciclastic sequence from the Tandilia System, Argentina

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The Tandilia System is situated in the Buenos Aires province, between latitudes 36° 30' - 38° 10' South and longitudes 57° 30'- 61° West (Fig. 1). Its maximum length is 350 km in the NW SE direction. The hills are composed of an igneous metamorphic basement and a Precambrian and Lower Palaeozoic sedimentary cover.

The sedimentary Precambrian succession exposes in the north-western part, around Olavarría and Barker-San Manuel region (Fig 1), while the Lower Palaeozoic crops out in a western belt of the range and mainly towards the south-east (Balcarce-Mar del Plata area, Fig. 1).

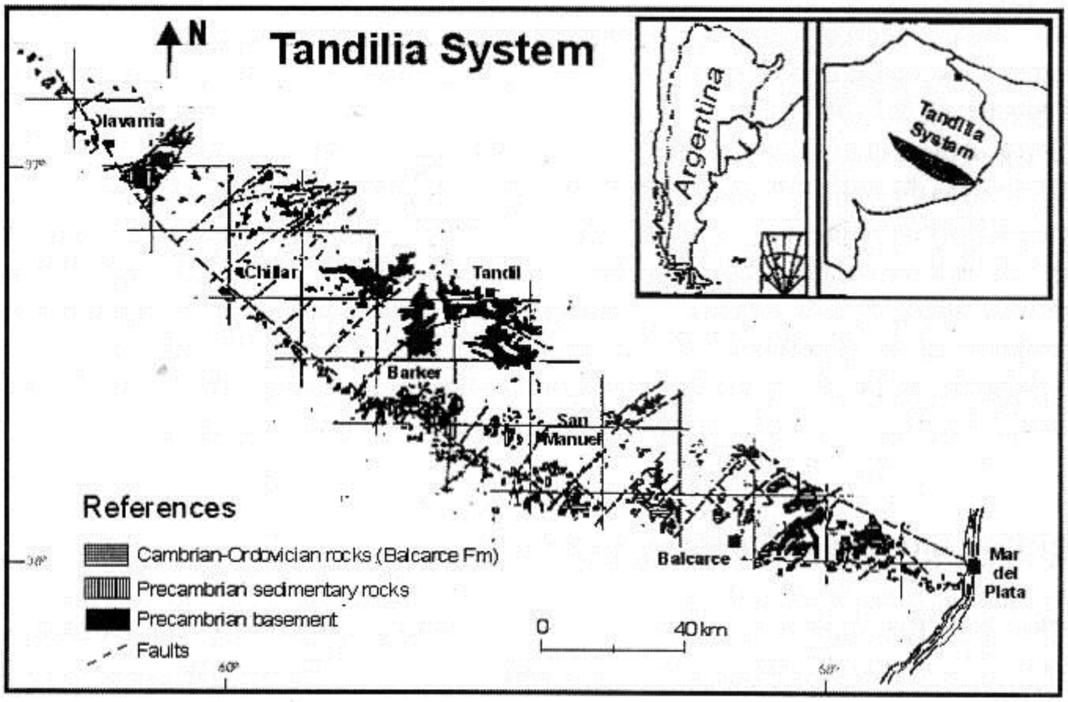


Figure 1.- Geological map of the Tandilia System.

These deposits líe on a crystalline basement named Buenos Aires Complex by Marchese and Di Paola (1974), which is older than 2,000 Ma and it is composed of granitoids, migmatites, ectinites, milonites, anfibolites and basic dykes.

Many authors have contributed to the knowledge of the Tandilia sedimentary succession (cf. Iñiguez et al., 1989). In this synthesis the framework proposed by Dalla Salda and Iñiguez (1979) and modified by Poiré (1987; 1993) for the Precambrian units is followed. In the same way, the sequencial setting composed of three Riphean sequences, a Vendían-Rephean sequence and a final Ordovician one (Iñiguez etal.,1989) is also accepted.

From the lithostratigraphic point of view (Table 1) the Precambrian sedimentary successions comprise a) the Villa Mónica Formation (Poiré, 1993) and its equivalent Las Aguilas Formation (Zalba, 1978), b) the Cerro Largo Formation (Poiré, 1993), and c) the Loma Negra Formation (Borrello,1966), all of these constituents of the Sierras Bayas Group (Dalla Salda and Iñiguez,1979; Poiré, 1993), and d) the Cerro Negro Formation (Iñigue2 and Zalba, 1974) and its equivalent Las Aguilas Formation (Zalba,1978). The Lower Palaeozoic succession is known as the Balcarce Formation (Dalla Salda and Iñiguez, 1979).

These lithostratigraphic units were grouped by Spalletti et *al.* (1996) finto five depositional sequences (Table 1): the Tofoletti (I), Malegni (II) and Villa Fortabat (II)) sequences are Riphean, the La Providencia sequence (IV) is Vendían-Riphean and the Batán sequence (V) is Cambrian-Ordovician. On the other hand, Andreis and Zalba (1998) for the Chillar-San Manuel named these sequences as A1, A2, B, C y D, respectively.

Between the crystalline basement and the sedimentary cover, arkosic and quartz-kaolinitic saprolites indícate palaeowethering surfaces (Zalba et al.,1992). A peculiar event is the presente of diamictites between the crystalline basement and the Balcarce Formation reported in the El Volcán Hill (Spalletti and del Valle,1984).

Being all these units unfossiliferous they carry biogenic sedimentary structures (trace fossils and stromatolites) as the only evidente of biocoenosis in the Precambrian and Lower Palaeozoic seas of this region. Precambrian stromatolites are located in the Villa Mónica Formation, where they are arranged in biostromes and bioherms dated between 800 and 900 Ma (Poiré, 1987; 1993). In the Precambrian units, trace fossils are scarce and show a poor ichnodiversity. *Palaeophycus* isp. and *Didymaulichnus isp.* have been described in the Cerro Largo Formation (Poiré et al., 1984), while *Helminthopsis isp.* and probable medusa resting traces have been found in the Loma Negra Formation. *Skolithos isp.* has recently been registered in the Lower part of the Cerro Negro Formation.

Upper Precambrian sedimentary rocks

The Upper Precambrian sedimentary cover of Tandilia in Sierras Bayas (close to Olavarría) is a 167 m thick succession (Sierras Bayas Group) composed of three depositional sequences separated by regional unconformities (Poiré,1987;1993).

The oldest depositional (Tofoletti) sequence (52 m thick) shows two sedimentary facies associations: a) quartz-arkosic arenites to the base and b) dolostones and shales to the top. The first one is composed of shallow marine siliciclastic rocks (conglomerates, quartz and arkosic sandstones, diamictites and shales), and the second is characterised by shallow marine stromatolitic dolostones and shales. This sequence has been dated in 800-900 Ma.

The second depositional (Malegni) sequence (75 m thick) consists of a basal succession composed of chert breccia, fine-stratified glauconitic shales and fine-grained sandstones, followed by cross-bedded quartz arenites which are in turn covered by fine-grained siliciclastic rocks (siltstones and claystones). This sequence represents a shallowing upward succession from sutidal nearshore to intertidal flat deposits. An age between 700-800 Ma has been defined from Rb/Sr dating (Bonhomme and Cingolani, 1980).

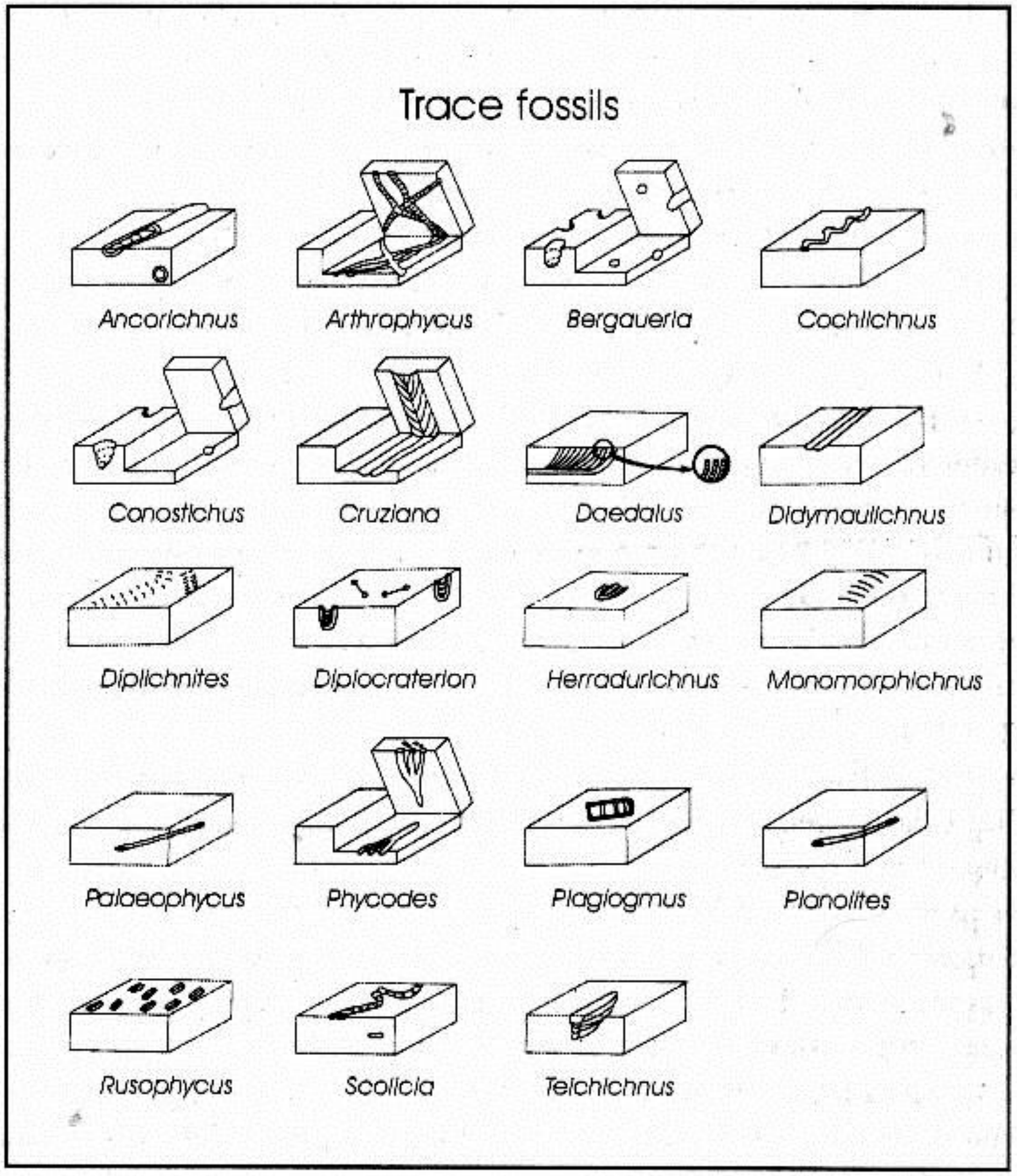


Figure 2. Trace fossils diagrams of the more characteristic ichnogenera from Balcarce Formation.

The younger depositional (Villa Fortabat) sequence is a 40 m thick unit composed almost exclusively of red and black micritic limestones, originated by suspension fall-out in open marine ramp and lagoonal environments.

On top of the Sierras Bayas Group a regional unconformity is recognised (Barrio el al, 1991). This surface has been related with a sea-level drop, meteoric dissolution-of the carboriatic sediments, and consequent development of a karstic surface on which residual clays and brecciated chert accumulated.

The Vendian Cerro Negro Formation (La Providencia Depositional Sequence) appears on top of the above described unconformity. It is a more than 100 m thick unit characterised by claystones and heterolithic fine-grained sandstone -claystone interbeds, mainly formed in upper to lower intertidal flats.

Lower Paleozoic sedimentary rocks

The Lower Palaeozoic siliciclastic succession is known as Balcarce Formation (Batán Depositional Sequence). This unit has been studied by del Valle (1987a). It is overlaying the crystalline basement or the former sedimentary units (Cerro Negro Formation, Las Agudas Formation, Sierra del Volcán Diamictites and Punta Mogotes Formation).

The Balcarce Formation (100 m. thick) is composed of white quartz sandstones and granule sandstones with subordinated levels of mudstones (kaolinitic-rich clays) and quartz conglomerates. The geometry of the sandstone beds is sheet-like; most sedimentary bodies are bounded by convex-upward surfaces, though some wide channel-like features are also present. Planar and tangential cross-stratifications are the dominant structures within sandstone bedsets, and large-scale sigmoidal bodies are frequent in most sections. Sheet-like and lenticular sandstone-mudstone interbeds are commonly intercalated among sandstone storeys. Trace fossils are abundant at the top surface of the sandstone member in sandstone-mudstone interbeds. The quarries all around Batán and Chapadmalal towns allow to depict the stratigraphic architecture of the Balcarce Formation. Based on their contrasting geometry; two main groups of layers can be defined in this siliciclastic succession: one group is characterised by a sub-horizontal stacking pattern (aggradational geometry) and the other shows very well developed depositional clinoforms (progradational geometry). The observatiónal facies of the Balcarce Formation as well as the inferred transport mechanisms and type of deposits are usted on Table 2.

Diagnostic criteria to recognise tidal processes in fair weather and storm events have been summarised on Table 3. Tidal processes are inferred from the features of cross-bedded sandstone facies (bars) and heterolithic (wavy and lenticular) facies (swales). Large to medium scale laterally persistent bodies of cross-bedded sandstones, exhibit rhythmic lateral variations in the thickness of foresets and in clay content due to spring and neap tide alternation. Clay drapes covering foresets and other sedimentation surfaces, herringbone cross-bedding, opposite palaeocurrent trends in successive sedimentary bodies and reactivation surfaces also suggest tidal deposition. The migration and accretion of bidimensional sand bars seem to be controlled by highly asymmetrical time-velocity tidal currents. Subordinated, high-energy storm episodes are suggested by hummocky cross-bedded sandstones, sheet conglomerates armouring previous tidal sand bodies, and heavy mineral concentrations in the wavy sandstone laminae of heterolithic facies.

An epicontinental shallow marine open shelf is inferred for the Cambrian-Early Ordovician in the Tandilia basin. Most sedimentary facies were developed in the nearshore and inner shelf environments of a fide-dominated and storm influenced platform.

Trace fossils

On the account referentes about the Precambrian trace fossils of Tandilia are scarce. *Palaeophycus* isp. and *Didymaulichnus isp.* have been descxibed in the Cerro Largo Formation by Poiré *etal.* (1984), while *Helminthopsis isp.* and probable medusa resting traces in the Loma Negra Foxmation. *Skolithos* isp. have recently been registered in the lower part of the Cerro Negro Formation.

On the other hand, the rich variety and the abundante of trace fossils in the Lower Palaeozoic Balcarce Formation have been mentioned by many authors: The first findings have been made by Hauthal (1896) and Nágera (1919, 1926), but it was Borrello (1966) who studied and described a wide trace fossil collection taken from different localities of Tandilia. Aceñolaza (1978) revised the subject a gave a modernised focus to the study of trace fossils from Tandilia, together with other Lower Palaeozoic ichnofossils of Argentina. Later records are due to Alfaro (1981) in the La Numancia-Licenciado Matienzo area, Regalia and Herrera (1981) in the San Manuel arca, Zalba *et al.* (1982) in the Las Aguilas Hill, Cingolani *et al.* (1985) in the Corral Hill, del Valle (1987a y b) in different localities from the Balcarce-Mar del Plata area, Poiré and del Valle (1994,1996) in the coastal outcrops of Mar del Plata, and Poiré (1998) in the Chillar area.

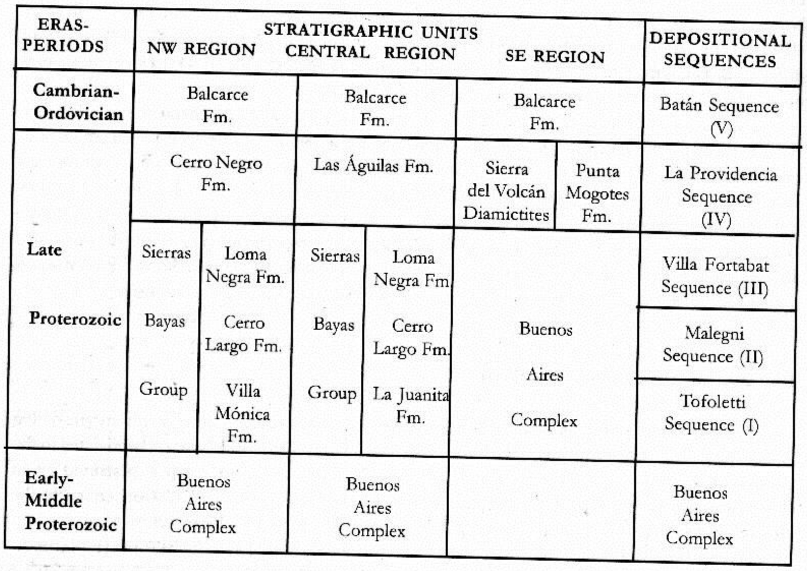
The Balcarce Formation shows a great quantity of trace fossfs and a much higher ichnodiversity. After revising the already published material thoroughly and taking into account the recent discoveries made by the authors, the following up-dated list of trace fossils is presented: *Ancorichnus ancorichnus, Arthrophycus alleghanensis, Arthrophycus isp., Bergaueria isp., Cochlichnus isp., Conostichuis isp., Cruziana furcifera, Cruziana isp., Daedalus labeckei, Didymaulichnus lyelli, Didymaulichnus isp., Diplichnites isp., Diplocraterion isp., Herradurichnur scagliai, ?Monocreterion isp., Monomorphichnus isp.,* ***Palaeophycus alternatus, Palaeophycus tubularis, Palaeophycus isp., Phycodes*** *aff. pedum, Phycodes isp., Plagiogmus isp., Planolites isp., Rusophycus isp., Scolicia isp.* and *Teichichnus isp.* (Fig. 2).

The age of Balcarce Formation

The precise age of the Balcarce Formation is difficult to determine. Through radiometric dating (600Ma) and the presence of acritarchs the underlying Cerro Negro Formation has been dated in the Vendian (Cingolani *et al.,* 1991). The upper limit of the Balcarce Formation is sustained by an intrusive diabase body dated around 450 and 498 Ma (Rapela *et al.,* 1974). Consequently the unfossiliferous Balcarce Formation would be assigned to the lapse Cambrian-Ordovician. During the seventies and eighties *Cruziana* has been considered a useful biostratigraphy indicator (cf Seilacher,1970; Crimes,1975). Based on this concepts, the presence of Cruziana *furcifera* has been one of the most substantial elements to accept an Arenigian age for the Balcarce Formation. Nevertheless, recent contribution by Marwood and Pemberton (1990) seriously questioned the validity of *Cruziana* in biostratigraphy. On the other hand the appearance of *Plagiogmus isp.* would strongly indicate a Cambrian age (Glaessner,1969; Crimes,1975).

According to the available stratigraphic and geochronologic information the Balcarce Formation can be either considered Cambrian and/or Ordovician. Future and more detailed ichnological studies and their comparison with other unfossiliferous quarzites rich in trace fossils from this Gondwana region, as the Lower Palaeozoic successions from South Africa and Malvinas Islands, could result to establish a more accurate age of such a peculiar unit of the Tandilia System

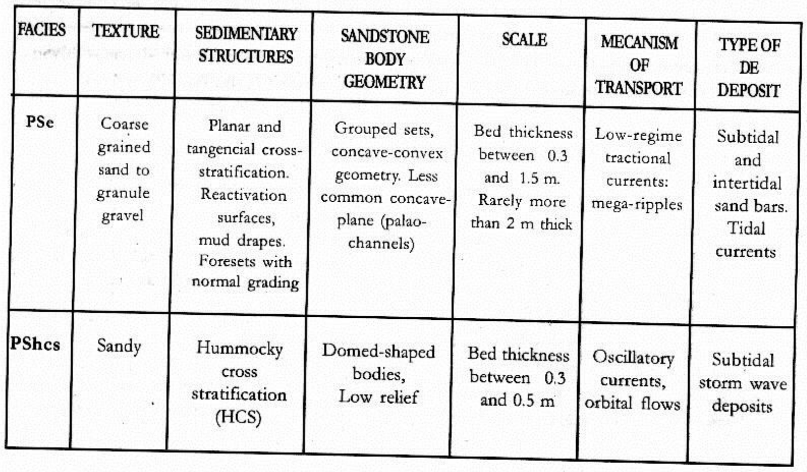
Table 1



ERAS-PERIODS	STRATIGRAPHIC UNITS						DEPOSITIONAL SEQUENCES
	NW REGION		CENTRAL REGION		SE REGION		
Cambrian-Ordovician	Balcarce Fm.		Balcarce Fm.		Balcarce Fm.		Batán Sequence (V)
Late Proterozoic	Cerro Negro Fm.		Las Águilas Fm.		Sierra del Volcán Diamictites	Punta Mogotes Fm.	La Providencia Sequence (IV)
	Sierras Bayas Group	Loma Negra Fm.	Sierras Bayas Group	Loma Negra Fm.	Buenos Aires Complex		Villa Fortabat Sequence (III)
		Cerro Largo Fm.		Cerro Largo Fm.			Malegni Sequence (II)
		Villa Mónica Fm.		La Juanita Fm.			Tofoletti Sequence (I)
Early-Middle Proterozoic	Buenos Aires Complex		Buenos Aires Complex				Buenos Aires Complex

Table 1. Stratigraphy of the Tandilia System

Table 2

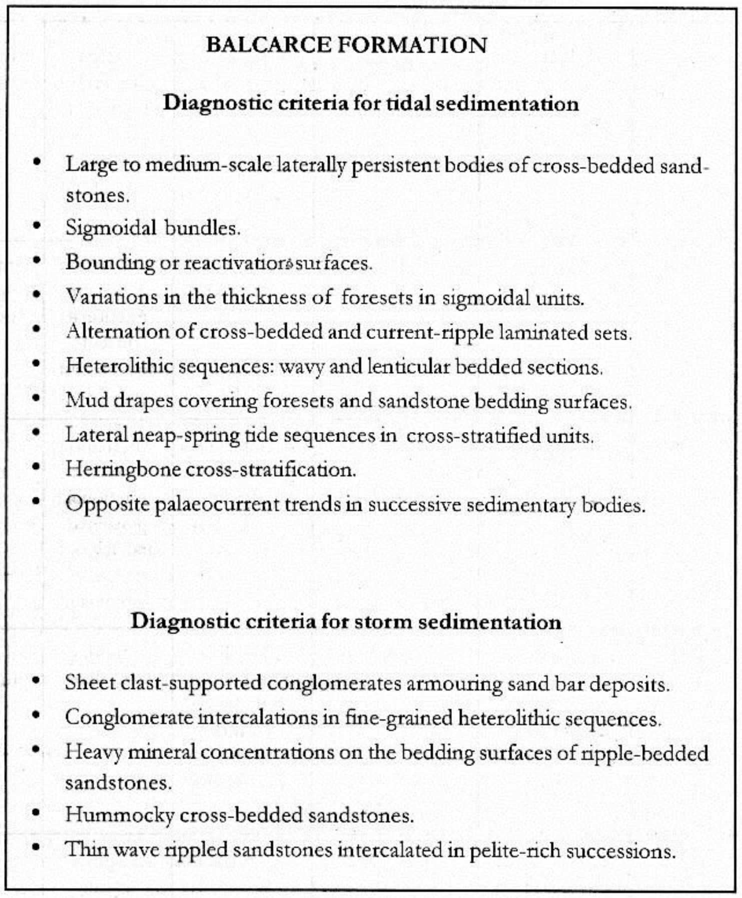


FACIES	TEXTURE	SEDIMENTARY STRUCTURES	SANDSTONE BODY GEOMETRY	SCALE	MECANISM OF TRANSPORT	TYPE OF DE DEPOSIT
PSe	Coarse grained sand to granule gravel	Planar and tangencial cross-stratification. Reactivation surfaces, mud drapes. Foresets with normal grading	Grouped sets, concave-convex geometry. Less common concave-plane (palaeochannels)	Bed thickness between 0.3 and 1.5 m. Rarely more than 2 m thick	Low-regime tractional currents: mega-ripples	Subtidal and intertidal sand bars. Tidal currents
PShcs	Sandy	Hummocky cross stratification (HCS)	Domed-shaped bodies, Low relief	Bed thickness between 0.3 and 0.5 m	Oscillatory currents, orbital flows	Subtidal storm wave deposits

Table 2

Hf	Heterolithic	Flaser	Tabular	Bed thickness less than 1.5 m	Alternation between tractional currents (dominant) and fall-out processes	Lower-middle intertidal flat
Hw	Heterolithic	Wavy	Tabular	Bed thickness less than 1.5 m	Alternation between tractional currents and fall-out processes	Intermediate Intertidal flat
Hl	Heterolithic	Lenticular	Tabular	Bed thickness less than 1.5 m	Alternation between tractional currents and fall-out processes (dominant)	Upper intertidal flat
He	Heterolithic	Alternation of mud and cross-laminated sand with cross-stratified sands	Tabular	Usually thin bedded, but thicker than the other heterolithic facies	Minor tidal bars	Lower intertidal flat
Cm	Fine to medium-grained gravel	Massive. Ripples on top, up to 15 cm long and high relief. sometimes ondulated	Sheet-like	Bed thickness less than 0.3 m	Shallow storm waves	Subtidal to intertidal
Cg	Fine to medium grained gravel	Normal grading	Tabular, scoured base. Gradational top to sands	Bed thickness less than 0.3 m	Post-storm deposits or begining of subtidal bars	Sandy subtidal flat

Table 2. Main sedimentary facies of Balcarce Fm. (modified from Spalletti and Poiré, 2000, base on del Valle, 1987b, 1990, Iñiguez *et al.*, 1989, Spalletti and del Valle, 1989, Spalletti *et al.*. 1996).



BALCARCE FORMATION

Diagnostic criteria for tidal sedimentation

- Large to medium-scale laterally persistent bodies of cross-bedded sandstones.
- Sigmoidal bundles.
- Bounding or reactivation surfaces.
- Variations in the thickness of foresets in sigmoidal units.
- Alternation of cross-bedded and current-ripple laminated sets.
- Heterolithic sequences: wavy and lenticular bedded sections.
- Mud drapes covering foresets and sandstone bedding surfaces.
- Lateral neap-spring tide sequences in cross-stratified units.
- Herringbone cross-stratification.
- Opposite palaeocurrent trends in successive sedimentary bodies.

Diagnostic criteria for storm sedimentation

- Sheet clast-supported conglomerates armouring sand bar deposits.
- Conglomerate intercalations in fine-grained heterolithic sequences.
- Heavy mineral concentrations on the bedding surfaces of ripple-bedded sandstones.
- Hummocky cross-bedded sandstones.
- Thin wave rippled sandstones intercalated in pelite-rich successions.

Table 3. Diagnostic criteria for tidal and storm sedimentation in the Balcarce Formation.

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