PALAIOS
Emphasizing the impact of life on Earth's history

PALAIOS, 2022, v. 37, 201–218
Research Article
DOI: http://dx.doi.org/10.2110/palo.2020.028

1926 SEPM Society for Sedimentary Geology

ICHNOLOGY OF MUDDY SHALLOW-WATER CONTOURITES FROM THE UPPER JURASSIC–LOWER CRETACEOUS VACA MUERTA FORMATION, ARGENTINA: IMPLICATIONS FOR TRACE-FOSSIL MODELS

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ABSTRACT: **Contourites are increasingly being recognized in ancient fine-grained depositional environments. However, detailed ichnologic analyses focusing on shallow-water examples of these deposits are scarce. The Upper Jurassic–Lower Cretaceous Vaca Muerta Formation from Argentina constitutes an important unconventional reservoir that displays dm- to m-thick, laminated, rippled and bioturbated, crinoidal mudstone and fine to coarse mudstone deposited by wind- and thermohaline-driven contour currents. Four ichnofabrics were recognized in three facies associations. The *Palaeophycus heberti* ichnofabric is dominant in facies association 1, forming highly bioturbated intervals. The *Palaeophycus heberti*, *Nereites* isp., and *Phycosiphon incertum* ichnofabrics are present in facies association 2, displaying highly, moderately and sparsely bioturbated intervals, respectively. This association is locally characterized by m-thick successions comprising an upward decrease and then increase in bioturbation index, which may have a similar origin to bigradational sequences. The Equilibrichnia-Fugichnia ichnofabric mostly occurs in facies association 3 and less commonly in 2, forming distinctive bioturbated intervals within sparsely bioturbated successions. Benthic activity was controlled by food distribution, oxygenation, hydrodynamic energy, and water turbidity. Food was delivered to the surface or in suspension by currents, promoting deposit- or suspension-feeding strategies in the infauna, respectively. Oxygen levels increased during contour current activity yet remained relatively low (upper dysoxic). Hydrodynamic energy controlled bioturbation intensity, resulting in lower degrees of bioturbation during higher energy events. Suspension-feeding strategies suggest that water turbidity was relatively low during current transport. The herein example increases our understanding of environmental controls of shallow-water contour currents, supporting the fact that high bioturbation levels are typical of contourite deposits and providing an example of muddy contourites showing high preservation of sedimentary structures due to oxygen deficiency in bottom waters.**

INTRODUCTION

Shallow-water contour currents occur within 50–300 m of water depth and are induced by thermohaline-, wind-, or tide-driven circulation (Stow et al. 1998; Verdicchio and Trincardi 2008). The action of currents generates abundant traction structures at the seafloor, owing to the constant transport of sediment by water mass movement. During the last two decades, special attention has been paid to the presence of structures such as silt laminae and current ripples in fine-grained depositional systems (Schieber 1994, 2016; Macquaker and Bohacs 2007; Schieber et al. 2007), which in many cases have been interpreted as the product of sediment reworking by thermohaline-driven contour currents (e.g., Frébourg et al. 2013; Knapp et al. 2017; Ayranci et al. 2018). These deposits share many characteristics with the herein example, because they comprise fine-grained, organic-rich sediments accumulated under oxygen-deficient conditions.

Trace-fossil analysis represents a useful tool to unravel environmental controls on bioturbated contourites (see reviews by Wetzel et al. 2008; Rodríguez-Tovar and Hernández-Molina 2018). However, ichnologic studies of shallow-water ancient and modern contourites are scarce and insufficient to illustrate the entire range of ecologic constraints on these systems (e.g., Virtasalo et al. 2011; Ayranci et al. 2018). One of the most important problems to delineate contour current transport in shallow-water realms is related to the existence of tidal, storm and wave action, which may modify the sedimentary deposits, masking the evidence for ambient contour currents. For this reason, a wide variety of ancient and modern mid- and deep-water contourites examples are documented in the literature, and most ichnologic studies have focused on these (Fu and Werner 1994; Baldwin and McCave 1999; Savrda et al. 2001; Löwemark et al. 2004; Wetzel et al. 2008; Rasmussen and Surlyk 2012; Rodríguez-Tovar and Hernández-Molina 2018; Míguez-Salas and Rodríguez-Tovar 2019; Reolid and Betzler 2019; Rodríguez-Tovar et al. 2019; Dorador et al. 2019; Hovikoski et al. 2020). Other ichnologic analyses have been made on shallow-marine straits and corridors, where current activity is intensified due to flow constraint (Miguez-Salas and Rodríguez-Tovar 2021). Studies documenting contourite deposits in deep-marine environments serve as the

Published Online: May 2022

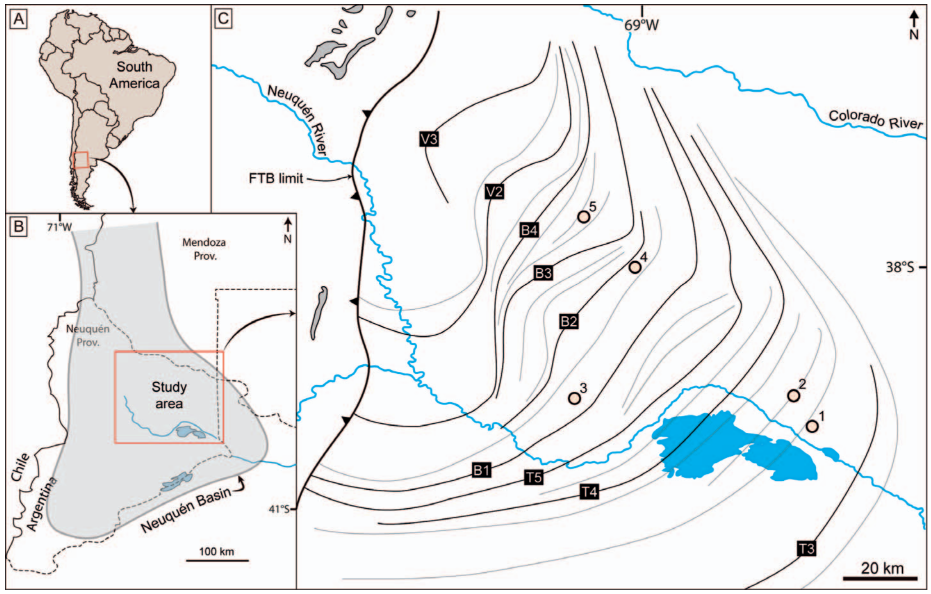

FIG. 1.—Location maps. **A**, **B**) Location of the study area and the Neuquén Basin within a regional context. **C**) Location of the five wells analyzed in the present study and of clinoform breaks from the different stratigraphic surfaces of the Vaca Muerta Formation (T3, T4, B1–B4, V2, V3; modified from Domínguez et al. 2020). Gray areas located west of the fold and thrust belt (FTB) are outcrops of the Vaca Muerta Formation.

basis for comparison with the present shallow-water example in terms of both physical and biologic processes.

This paper documents trace fossils in a muddy, bioclastic-rich, laminated, rippled and bioturbated succession interpreted to be deposited by shallow-marine contour currents (Paz et al. in press). The contourites occur within the Upper Jurassic-Lower Cretaceous Vaca Muerta Formation of the Neuquén Basin, Argentina (Fig. 1). This formation represents an important unconventional resource, which has triggered growing interest from the oil and gas industry (González et al. 2018; Minisini et al. 2020). Several authors have suggested the activity of bottom currents in this formation previously (Spalletti et al. 1999; Scasso et al. 2002; Kietzmann et al. 2008, 2014; Zeller et al. 2015; Notta et al. 2017; Reijenstein et al. 2020; Rodríguez Blanco et al. 2020), although detailed sedimentologic and ichnologic analyses of these deposits are currently lacking. The objectives of this study are to document in detail the ichnology of shallow-water contourites and infer potential environmental controls on the benthos. The present analysis supports the notion that high bioturbation levels are associated with contouritic deposition and provides an example of muddy contourites with a high degree of preservation of sedimentary structures.

MATERIALS AND METHODS

Sedimentologic descriptions and interpretations of intervals attributable to contour current deposition were based on core observations from five wells (660.5 m) located in the Central Neuquén Basin (Paz et al. in press; Figs. 1–3, Table 1). Macroscopic observations, thin sections (59 sections from cores, 18 from outcrop samples) and mineralogic composition from X-ray diffraction (XRD) analysis on cores were combined in order to define lithology. Lithology is described following Lazar et al. (2015) for mudstone (where fine mud is <8 μm, medium mud is 8–32 μm, and coarse mud is 32–62.5 μm). The present study is focused on ichnologic analysis of these intervals, which included characterization of ichnotaxa, bioturbation index, ichnodiversity, tiering, ichnofabrics, and inferred ethologies, trophic types, and producers. Burrow size was recorded where burrow cross-section views were available. Description of core samples was facilitated by spraying samples with ethanol and applying image-enhancement techniques to photographs. Short-wave (254 nm) and long-wave (365 nm) UV light was utilized to delineate trace fossils in monotonous black mudstone. Because the Vaca Muerta Formation is

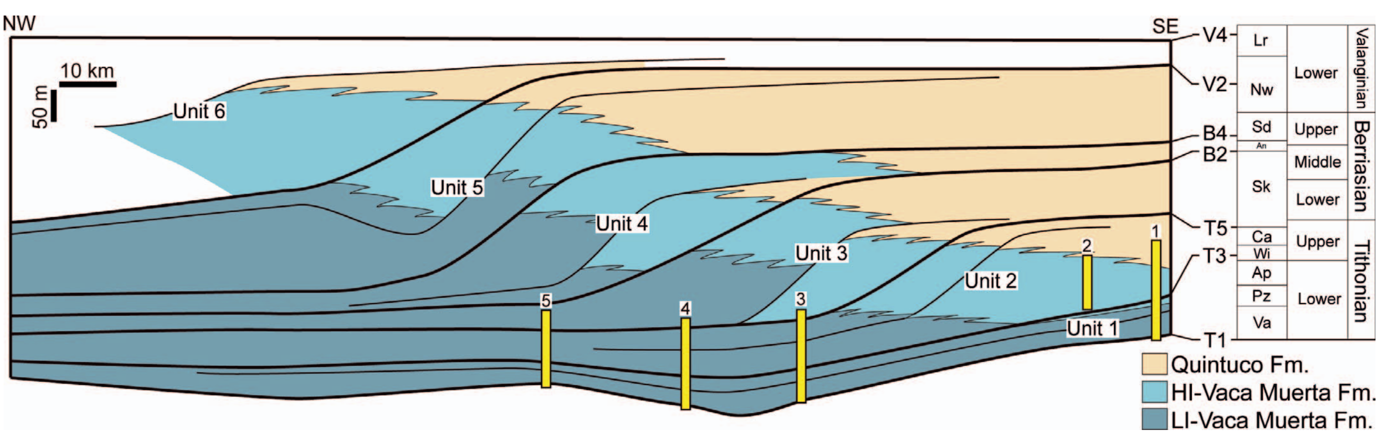

FIG. 2.—Regional stratigraphic cross-section showing location of the studied cores within the Vaca Muerta-Quintuco system. The Vaca Muerta Formation is subdivided into a high (HI) and low (LI) impedance units (adapted from Sattler et al. 2016 and Reijenstein et al. 2017). Sequence-stratigraphic surfaces (T1, T3, T5, B2, B4, V2, V4) and Units (1 to 6) are from Desjardins et al. (2018) and Domínguez et al. (2020), and Andean ammonite zones (right) from Kietzmann et al. (2018). Abbreviations: Va = *Virgatosphinctes andesensis*; Pz = *Pseudolissoceras zitteli*; Ap = *Aulacosphinctes proximus*; Wi = *Windhauseniceras internispinosum*; Ca = *Corongoceras alternans*; Sk = *Substeueroceras koeneni*; An = *Argentiniceras noduliferum*; Sd = *Spiticeras damesi*; Nw = *Neocomites wichmanni*; Lr = *Lissonia riveroi.*

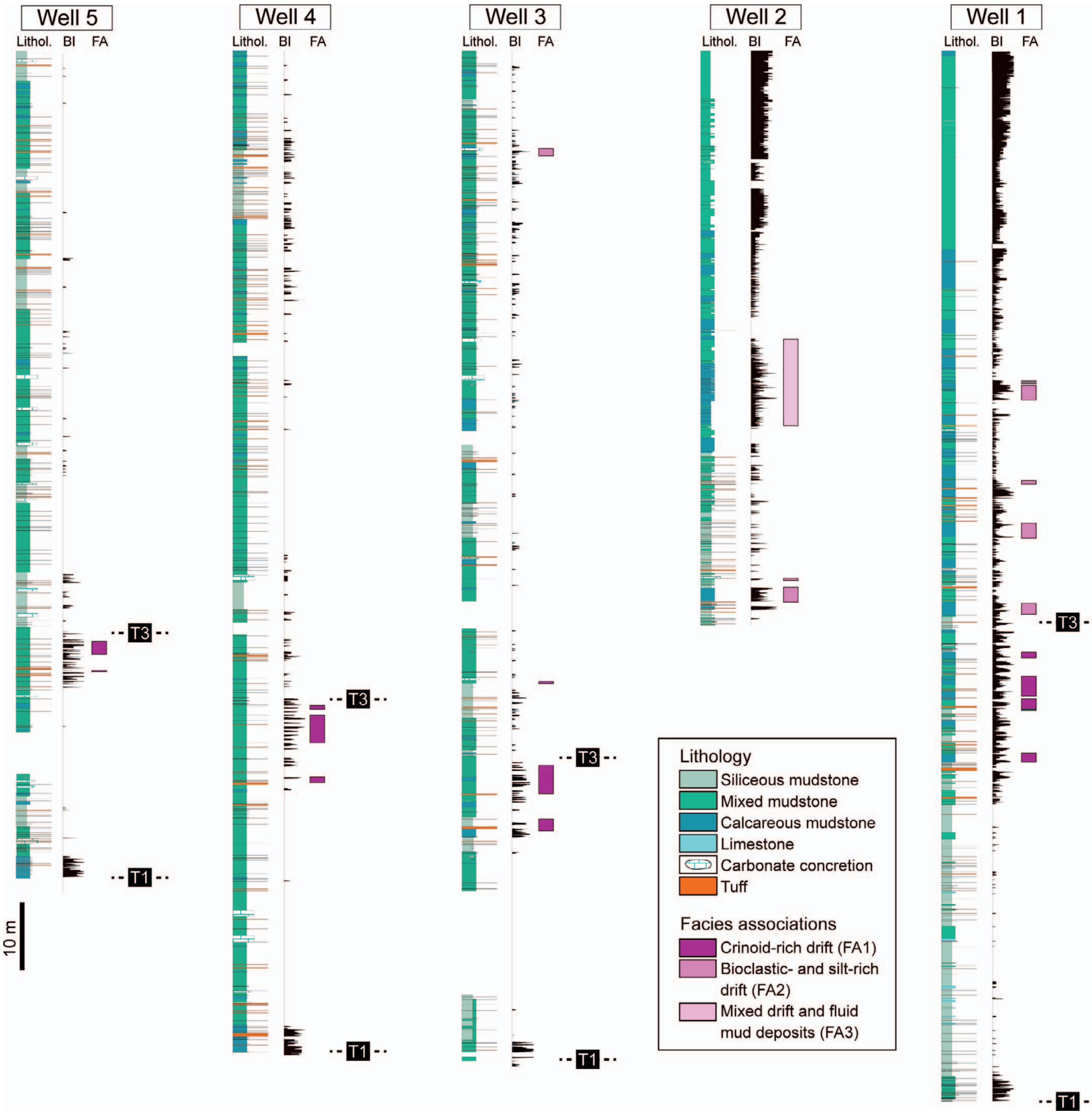

FIG. 3.—Lithologies from XRD analysis, bioturbation index (BI), and facies associations (FA) described in the five wells, with the location of contourite facies association (FA1, FA2, FA3). T1 and T3 are stratigraphic surfaces from Desjardins et al. (2018).

predominantly dominated by mudstone successions lacking sediment contrast and showing biodeformational structures, measuring bioturbation index (BI) was challenging. However, BI analysis was accomplished following the approach of Taylor and Goldring (1993, after Reineck 1963), which focused on recording bed preservation. In addition to calculating BI, estimates of bioturbated area corresponding to specific ichnotaxa were made for intervals containing discrete ichnotaxa. Trace fossils were classified following conventional practice in ichnotaxonomy, such as the use of ichnotaxobases (see below for details) and are briefly described and discussed in Table 2. Ichnofabrics were defined and characterized in order to interpret environmental factors affecting the benthos.

GEOLOGIC SETTING

The Neuquén Basin and the Vaca Muerta Formation

The Neuquén Basin of western central Argentina constitutes a triangular basin hosting a more than 6000 m-thick sedimentary succession (Fig. 1;

TABLE 1.—*Description and interpretation of the contourite facies.*

Facies	Description	Composition	Interpretation	Facies distribution
$M_{cr}h$, $M_{cr}l$, $M_{cr}w$	2-15 cm-thick intervals showing discontinuous to continuous, planar, parallel-, low-angle to rare wavy-laminated crinoidal mudstone (Fig. 4A)	Dominant *Saccocoma* crinoids and minor ammonites and bivalves. Bioclasts with random orientations. Radiolarians, plagioclase, quartz, and volcanic rock fragments.	Bedload traction transport in crinoid-rich sediments. Low energy unidirectional currents associated with winnowing of muds.	Dominant in FA1
$M_{cr}r$	2-15 cm-thick intervals of crinoidal mudstone with lenticular-shaped (0.5-3 mm-thick), crinoid-rich structures (Fig. 4A)		Starved bioclastic ripples as suggested by their common gradation from crinoid-rich laminae. Moderate energy conditions.	Dominant in FA1
$M_{cr}p$	5-15 cm-thick, cross-bedded crinoidal mudstone with sharp to erosive bases		Bioclastic dune migration affected by high energy unidirectional currents	Subordinate in FA1
$M_{cr}b$	5-50 cm-thick, completely bioturbated crinoidal mudstone, with rare bedding observed. Biodeformational structures are abundant, with minor discrete trace fossils.		High abundance of organisms supported by high food and oxygen availability. Hydrodynamic energy remains low and the burrowing infauna keeps pace with seafloor accretion.	Dominant in FA1
Mh, Ml	0.2-5 cm-thick intervals of parallel- to low-angle cross-laminated coarse mudstone encased in fine mudstone (Fig. 4C)	Silt-sized plagioclase, carbonate intraclasts, recrystallized radiolarians, forams, bivalves, undifferentiated skeletal fragments and mudstone intraclasts. Minor quartz, pellets, and echinoderm fragments. Illitic and coccolith-rich matrix. Silt- to very fine-grained sand-sized fragments of *Rhaxella*, forams and unidentified, calcite-replaced radiolarians and spherical grains and mudstone intraclasts in laminae.	Silt and mud floccule segregation from bedload traction transport. Unidirectional currents associated with low energy and sedimentation rate.	Dominant in FA2 and FA3
M_sh, M_sl	0.2-5 cm-thick, lenticular to tabular, parallel- to low-angle cross-laminated fine to coarse mudstone (Fig. 4B, D)		Bedload traction transport under moderate energy and low sedimentation rate, above the threshold of mud floccule deposition	
M_sr, M_sw	0.2-5 cm-thick, lenticular to tabular, current- and wave-ripple cross-laminated fine to coarse mudstone with black-colored laminae (Fig. 4B)		Bed erosion and bedload traction transport under higher energy and sedimentation rate. Rare oscillatory current influence.	
$M_{cm}b$	1-30 cm-thick, completely bioturbated fine to coarse mudstone. Some remaining bedding can be recognized. Dominant biodeformational structures and rare discrete traces are distinguished.		Similar as $M_{cr}b$ but of silty and bioclastic composition	Dominant in FA2
M_pl	20-70 cm-thick, low-angle cross-bedded peloidal mudstone with ripple cross-lamination and cross-bedding on bedding surfaces	Silt-sized lens-shaped peloids, quartz, plagioclase, micas and calcite-replaced radiolarians, and pebble-sized carbonate intraclasts. Well-preserved to minor partially fragmented gastropods, crinoids, ammonites and bivalves (1-5%), displaying random or concordant orientations to bedding. Gastropod and bivalve shell cavities typically filled with sparite.	Migration of compound dunes due to high-energy unidirectional currents. Possible tidal influence.	Subordinate in FA2
M_sg, M_sm	0.2-20 cm-thick, sharp-based, normal-graded to massive, fine to coarse mudstone	Silt- to granule-sized, pellets, organic matter aggregates, plagioclase, quartz, volcanic glass and carbonate intraclasts. Fossils such as bivalve, microcrinoid, and carbonate-replaced radiolarian.	Normal grading suggests low-density turbidity flows, whereas massive beds indicate more concentrated flows	Subordinate in FA1, FA2 and FA3
M_cm, Mcomp	0.1-5 cm-thick, massive, calcareous medium to coarse mudstone and composite beds of calcareous mudstone showing current-ripple cross-lamination, parallel-lamination and normal and inverse grading	Pebble-sized, elongated, deformed, mudstone and bindstone intraclasts and coarse sand-sized, rounded, carbonate intraclasts. Silt-sized, terrigenous (quartz and plagioclase) grains, dolomite microspar, clay and organic aggregates, bivalve bioclasts and peloids.	Mudstone intraclasts suggest matrix strength, indicating fluid mud flows. Rare current ripples point toward turbulent conditions typical of transitional flows.	Dominant in FA3
Tg, Tm	1-20 cm-thick, normal-graded to massive, tuff to lapilli ash-tuff	Very fine-grained sand- to silt-sized euhedral plagioclase, quartz and arcuate to tabular glass shards, minor mudstone intraclasts, radiolaria, forams, benthic pellets and pumice fragments.	Submarine volcanic fallout deposition and resedimented volcaniclastic deposits	Subordinate in FA1
B_m	5-20 cm-thick, microbial bindstone	Laminae composed by microsparite dolomite and minor organic matter and cubic pyrite.	Substrate stabilization by microbial mats	Subordinate in FA3

TABLE 2.—*Description of the ichnotaxa from the contourite deposits.*

Ichnotaxa	Characteristics	Remarks	Ethology	Trophic type
Crininicaminus isp.	Horizontal, passively infilled burrows with bioclastic lining made up of crinoids. Burrows are 5-6 mm wide.	Specimens were only observed in cross-section views as strongly compacted full reliefs.	Domichnia	Predation/ suspension feeding
Lockeia siliquaria	Passively infilled, oval-shaped structures with rounded bases. Locally, one end with a straight tapering and another rounded end. Burrows are 2-5 mm wide and 5-7 mm long.	Occurrence of typically more than one positive hyporelief and negative epirelief. Specimens are observed on bedding planes within intervals containing other structures seen in cross-section and inferred to have been produced by the same trace maker (e.g. ?*Lockeia* isp., escape and equilibrium structures).	Domichnia-Cubichnia	Suspension feeding
?*Lockeia* isp.	Passively infilled, bowl-shaped structures with rounded bases. Burrows are 1.3-9.5 mm wide.	Specimens only observed in cross-section. Present in intervals that show *Lockeia siliquaria* on bedding-plane views.	Domichnia-Cubichnia	Suspension feeding
Nereites isp.	Horizontal burrows with an actively filled, muddy dark core and a white to gray mantle. Burrows are 2.5-10 mm wide.	Classified at ichnogenus rank as details of overall morphology and mantle are not possible to observe in cross-section.	Fodinichnia	Deposit/ detritus feeding
Palaeophycus isp.	Horizontal, curved to straight, passively infilled, typically lighter core and thin dark-lined burrows. Burrows are 1-2.5 mm diameter.	Classified at ichnogenus rank as details of overall morphology and wall are not possible to observe in cross-section.	Domichnia	Predation/ suspension feeding
Palaeophycus heberti	Horizontal to oblique, passively infilled burrows with a 1 mm-thick white muddy wall. Burrows are 4-8 mm wide.	Presence of thick lined walls supports ichnospecific assignment.	Domichnia	Predation/ suspension feeding
Phycosiphon incertum	Oblique to horizontal, actively infilled burrows with a dark muddy core and white mantle. Burrows are 0.5 mm wide.	Ichnotaxonomic assignment based on diagnostic features of the mantle as spreiten are not possible to detect in core.	Fodinichnia	Deposit feeding
Planolites isp.	Simple, dominantly horizontal, unlined, straight to curved burrows with a dark or white infill. Burrows are 1-4 mm wide.	Classified at ichnogenus rank as details of overall morphology and fill are not possible to observe in cross-section.	Fodinichnia	Deposit feeding
?*Skolithos* isp.	Vertical, tube-shaped, passively infilled structures. Burrows are 3-7 mm long and 0.5-3 mm wide.	Ichnogeneric assignment cannot be fully confirmed due to a low number of specimens.	Domichnia	Suspension feeding
Escape trace fossils	Oblique to vertical U- and V-shaped, nested structures.	Differentiated from equilibrium structures by their occurrence in cm-thick deposits indicating rapid sedimentation. However, this distinction is not always possible.	Fugichnia	Suspension feeding
Equilibrium trace fossils	Oblique to vertical, U- and V-shaped, nested, vertically aligned, sharp-lined structures. Locally ?*Lockeia* isp. is present at interfacial basal surfaces.	Differentiated from escape traces by their sharp-lined burrow boundaries indicating re-establishment of the organism into a new colonization surface. Present in layers interpreted as formed under low sedimentation rates rather that event deposition. However, distinction from escape trace fossils is not always possible.	Equilibrichnia	Suspension feeding

Howell et al. 2005; Casadío and Montagna 2015). A syn-rift extensional phase associated with the Late Triassic break-up of Pangea marked the beginning of the basin. Associated volcanic and epiclastic deposits are grouped into the Precuyano Cycle (Gulisano et al. 1984). The re-establishment of a subduction regime along the western margin of Gondwana generated a volcanic arc and a shift towards a back-arc basin stage during the Early Jurassic (Casadío and Montagna 2015). The back-arc phase involved multiple marine transgressions and regressions recorded in the Cuyo, Lotena, Mendoza, and Bajada del Agrio groups (Arregui et al. 2011). During the Late Cretaceous, the connection with the Pacific Ocean was cut off, and continental deposits filled the foreland basin (Casadío and Montagna 2015).

The Vaca Muerta Formation represents a marine event developed during the back-arc stage from the early Tithonian to the early Valanginian (Leanza 1973; Leanza et al. 2011). This formation is bounded at the base and top by the Tordillo and Quintuco formations, respectively, constituting the Lower Mendoza Mesosequence of Legarreta and Gulisano (1989). The Tordillo Formation consists of a Kimmeridgian continental phase indicated by eolian, lacustrine, and fluvial deposits (Spalletti et al. 2011). The Vaca Muerta Formation comprises marine deposits forming part of a mixed carbonate-siliciclastic clinoform system of up to 1800 m thick, showing a clear progradational pattern towards the NW at the southern margin, and W and SW at the northern margin (Gulisano et al. 1984; Legarreta and Gulisano 1989; Spalletti et al. 2000). The bottomset and lower foreset of the clinoform system correspond to the Vaca Muerta Formation, whereas the nearshore upper foreset and topset correspond to the Quintuco Formation (Mitchum and Uliana 1985).

The study area is in the Neuquén Embayment area, 70 km northwest of Neuquén city (Fig. 1), and the analyzed interval comprises Units 1 and 2 of the Vaca Muerta Formation (Fig. 2; Desjardins et al. 2018). Biostratigraphic correlation based on ammonite zones suggests a late early Tithonian to late Tithonian stratigraphic range for the wells studied (Riccardi 2015; Desjardins and Aguirre 2018; Desjardins et al. 2018). Seismic data, core descriptions, and XRD mineralogy in the study area indicate the existence of a low angle (0.2–0.3°) mixed carbonate-siliciclastic clinoform system during Unit 1, that changed to higher angles during the following units (1–3°; Minisini et al. 2020), consisting of mixed (siliceous-calcareous-argillaceous) mudstone, calcareous mudstone, and argillaceous ash beds (tuffs). These lithologies occur with different arrangements recording marginal marine, basin, drift and slope environments (Paz 2021). Organic-rich mudstone in the basin environments (3–8% TOC with upper values of 10–12%, Uliana et al. 1999) reflects high water-column productivity and represents important unconventional reservoirs. Sedimentologic aspects of the Vaca Muerta Formation have been extensively documented based on both outcrop studies (e.g., Spalletti et al. 2000; Kietzmann et al. 2014; Ponce et al. 2015; Zeller et al. 2015; Paz et al. 2019; Otharán et al. 2020) and core investigations (e.g., González Tomassini et al. 2014; Repol et al. 2014; Notta et al. 2017, 2020; Desjardins and Aguirre 2018; Desjardins et al. 2018; Gómez Rivarola and Borgnia 2018; Estrada et al. 2020; Minisini et al. 2020). In contrast, ichnologic studies of this formation are very rare and have been restricted to outcrops in southern Mendoza Province (Doyle et al. 2005), or to local trace-fossil identifications in cores and outcrops (Kietzmann et al. 2014; Ponce et al. 2015; Desjardins and Aguirre 2018; Paz et al. 2019, 2021; see also Leanza et al. 2020).

The Contourite Deposits

Sedimentologic analysis of the contourite deposits in the Vaca Muerta Formation have been described elsewhere (Paz et al. in press). Twenty-one facies have been characterized for contourites and associated deposits (Table 1, Fig. 3). In turn, these are grouped into three facies associations corresponding to contourite drift environments (Fig. 3), which occur in bottomset and lower foreset locations of the clinoform system.

Following the nomenclature of Paz et al. (in press), facies association 1 (FA1) is composed of an alternation of bioturbated (M_{cr}b), laminated and rippled (M_{cr}h, M_{cr}l, M_{cr}r), crinoidal mudstone facies, whereas other crinoidal mudstone (M_{cr}p, M_{cr}w), fine to coarse mudstone (M_sm, M_sg) and tuff (Tm, Tg) facies are minor components (Fig. 4A). Mean BI is 1.78 (n = 462). FA1 represents sedimentation in crinoid-rich drift environments.

Facies association 2 (FA2) consists of an alternation of bioturbated (M_{cm}b), laminated and rippled (Mh, Ml, M_sh, M_sl, M_sr), fine to coarse mudstone facies generating heterolithic bedding, whereas other fine to coarse mudstone (M_sw, M_sm, M_sg) and peloidal mudstone (M_pl) facies are rare (Fig. 4B, 4C). Mean BI is 2.17 (n = 193). This facies association records sedimentation in a more proximal position than FA1, in a bioclastic- and silt-rich drift (Paz et al. in press).

Facies association 3 (FA3) comprises laminated and rippled, fine to coarse mudstone facies (Mh, Ml, M_sh, M_sl, M_sr), intercalated with massive calcareous mudstone facies (M_cm). Subordinate facies include normal-graded fine to coarse mudstone (M_sg), composite beds of mudstone (Mcomp), and bindstone (B_m) (Fig. 4D). Mean BI is 1.75 (n = 239). Meter-thick slumped intervals also occur. FA3 is the most landward of the three facies associations, and it has been mapped in seismic data as an along-shelf body, interpreted to be deposited by contour currents (Reijenstein et al. 2020). Both bottom current (Mh, Ml, M_sh, M_sl, M_sr) and sediment-gravity flow (M_cm, Mcomp) activity occurred in FA3, suggesting sedimentation in a mixed drift and fluid mud deposit (Paz et al. in press).

The circulation system generating the contourite deposits is likely to have been wind- and thermohaline-driven, enhanced during times of arid and cool climates and low sea-levels (Paz 2021). Production of dense, high-salinity, and low temperature waters cascading from the shelf intensified the currents and provided oxygen to deeper watermasses (e.g., Rodríguez Blanco et al. 2020). NE-directed winds might have occurred in the Neuquén Basin during the Tithonian, suggesting that wind forcing probably affected the shallow shelf areas, generating a counter-clockwise circulation (Zeller et al. 2015). Currents of intermediate waters reworked bottomset and lower foreset areas with clockwise circulation (Paz et al. in press). Other processes, such as tidal currents or internal waves or tides affecting the contour currents, are disregarded. Tidal currents represent a mechanism in shelf areas that may rework fine-grained depositional systems (Schieber 2016). However, a volcanic arc to the west might have caused microtidal conditions in the Neuquén Basin (Wells et al. 2005; Canale et al. 2020). Internal waves or tides may be involved because of a position close to a density stratification surface (oxycline), but the high across-shore extension of the contourite deposits (∼ 160 km in bottomset and foreset locations) indicates a process that is not restricted to areas where the pycnocline intersects the seafloor (Paz et al. in press).

RESULTS

Remarks on the Classification of Trace Fossils

Biogenic structures in fine-grained deposits are notoriously difficult to identify and classify (see Schieber et al. 2021). Also, identifying trace fossils in core presents its own challenges (see Pemberton et al. 2001). In spite of these difficulties, we follow the recommendation of Bromley (1990) and attempt to classify ichnotaxa at ichnospecific rank wherever possible (Table 2). In addition, special effort has been made to analyze available horizontal views in order to support ichnotaxonomic determinations that are otherwise only based on 2D vertical cross-sections. For example, this has helped to identify the diagnostic morphology of the ichnospecies *Lockeia siliquaria* when horizontal preservation is available in beds hosting the Equilibrichnia-Fugichnia ichnofabric.

Irregular-shaped structures showing evidence of vertical adjustment after sedimentation events are abundant. They occur on bed bases and rarely on top of beds, showing passive fill from the overlying bed, or recording sediment that has been eroded. In cross-sectional views, apparent small bowl-shaped forms resemble the ichnogenera *Bergaueria* and *Conichnus* typically assigned to burrowing anemones (Pemberton et al. 1988). However, where bedding planes are available for analysis, oval-shaped, positive hyporeliefs or negative epireliefs identical to *Lockeia siliquaria* occur. This observation suggests that the structures seen in cross-sectional views are most likely bivalve trace fossils, although the connection to *Lockeia siliquaria* cannot be confirmed. We adopt, however, a parsimonius decision and refer to all these structures as ?*Lockeia* isp. Following this line of reasoning, the associated biodeformational structures indicating vertical adjustment are regarded as equilibrium (Equilibrichnia) or escape trace fossils (Fugichnia) produced by bivalves.

Differentiation between equilibrium and escape trace fossils is not always possible. Both behaviors indicate the vertical adjustment of an organism either under high and rapid, or low and background sedimentation rates, respectively. In principle, however, we can distinguish two end members recording normal versus rapid adjustments. Normal

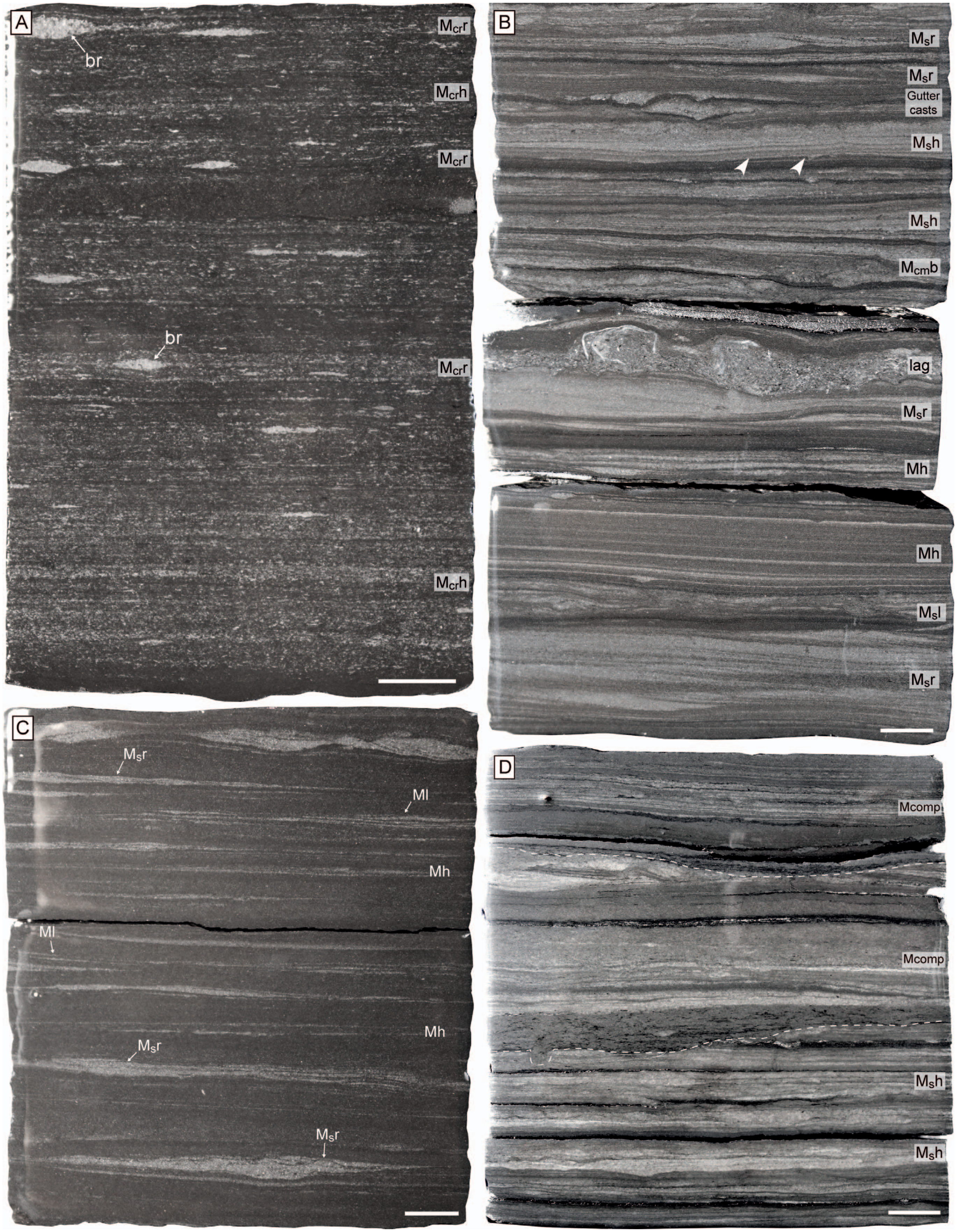

FIG. 4.—Core photographs of the contour current facies, scale bars = 1 cm. **A**) Current-rippled ($M_{cr}r$) and parallel-laminated ($M_{cr}h$) crinoidal mudstone facies. Bioclastic ripples (br) are delineated. **B**, **C**) Parallel- to low-angle cross-laminated coarse mudstone encased in fine mudstone (Mh, Ml), parallel-, low-angle, and current ripple-cross laminated fine to coarse mudstone ($M_{s}h$, $M_{s}l$, $M_{s}r$) and bioturbated, calcareous to mixed mudstone ($M_{cm}b$) facies. **D**) Parallel-laminated coarse mudstone ($M_{s}h$), and composite mudstone beds (Mcomp). Bed bases are delineated with dashed lines.

adjustment is interpreted to record equilibrium structures in those cases in which (1) vertical, chevron-shaped structures indicate migration after deposition of a thin sediment layer, and (2) vertically associated, sharp-lined basal boundaries suggest re-establishment of the organism in the newly deposited substrate. In contrast, escape behavior is interpreted when inclined to vertical structures display deformed laminae crossing thicker (cm-thick) deposits, representing rapid adjustment synchronous with event bed deposition (Bromley 1990; Buatois and Mángano 2011). Differentiation between rapid and background sedimentation, which is relatively straightforward in settings affected by sediment gravity flows or storms, is difficult in environments influenced by contour currents. Accordingly, in the cases in which a distinction is not possible, we refer to these structures as Equilibrichnia-Fugichnia.

Ichnofabric Analysis

Our ichnofabric analysis focused on the three contourite drift facies association (Fig. 3), where four ichnofabrics have been recognized: *Palaeophycus heberti*, *Phycosiphon incertum*, *Nereites* isp., and Equilibrichnia-Fugichnia ichnofabrics. In addition to the trace fossils present in these ichnofabrics, other biogenic structures (e.g., *Teichichnus rectus*, *Alcyonidiopsis longobardiae, Planolites* isp., *Phycosiphon incertum*, *Coprulus oblongus*, rare *Thalassinoides* isp.) occur locally in associated intervals dominated by hemipelagic deposits (Paz 2021). These intervals, typical of basin environments of the Vaca Muerta Formation, are not considered further in this study.

Description and Interpretation of Ichnofabrics

The *Palaeophycus heberti* ichnofabric consists of discrete, shallow-tier *Palaeophycus heberti*, *Planolites* isp., *Crininicaminus* isp., and rare *Palaeophycus* isp. (Fig. 5) overprinted onto a mottled background recording irregular biodeformational structures. BI is typically 4–6, with mean burrow diameter of 4.8 mm. This ichnofabric occurs in 10–50 cm-thick, highly bioturbated, crinoidal mudstone or fine to coarse mudstone intervals (facies $M_{cr}b$, $M_{cm}b$). Discrete trace fossils occur in highly variable densities. Although the sedimentary fabric is typically obliterated by bioturbation in most instances (Fig. 5A, 5B), a relict primary lamination may be preserved in some cases (Fig. 5C). Dominant superimposed discrete structures may represent the domiciles of passive predators, and/or suspension feeders (Ettensohn 1981; Pemberton and Frey 1982). Deposit feeding is represented by *Planolites.* High density of bioturbation suggests high food availability in oxygenated environments, and low hydrodynamic energy that allowed complete sediment homogenization. Moreover, completely bioturbated background textures most likely record foraging in a soft to soupy sediment. The thick lining of *P. heberti* and agglutinated lining of *Crininicaminus* isp. represent a strategy for maintaining open burrows in soft substrates. The epibenthic tubes likely served to raise the organism head above the sediment surface, providing access to low-energy flows and high suspended food concentration (Ettensohn 1981).

The *Phycosiphon incertum* ichnofabric is represented by shallow-tier *Phycosiphon incertum*, *Nereites* isp., *Planolites* isp., *Palaeophycus* isp., and rare ?*Lockeia* isp. (Fig. 6A–6C). BI is mostly 1, with a few intervals showing 2, and mean burrow diameter of 3.0 mm, except for *Phycosiphon incertum,* which is 0.2–0.5 mm. The *Phycosiphon incertum* ichnofabric occurs in 1 to 10 cm-thick, sparsely bioturbated, current-ripple cross- and parallel-laminated, fine to coarse mudstone intervals (facies Mh, Ml, M_sh, M_sl, M_sr). This ichnofabric represents opportunistic colonization and selective deposit-feeding on the organic matter-rich lamination (Wetzel 2010).

The *Nereites* isp. ichnofabric is dominated by shallow-tier structures, such as *Nereites* isp., *Phycosiphon incertum*, *Planolites* isp., and *Palaeophycus* isp. (Fig. 6D, 6E). *Palaeophycus heberti*, ?*Skolithos* isp.,

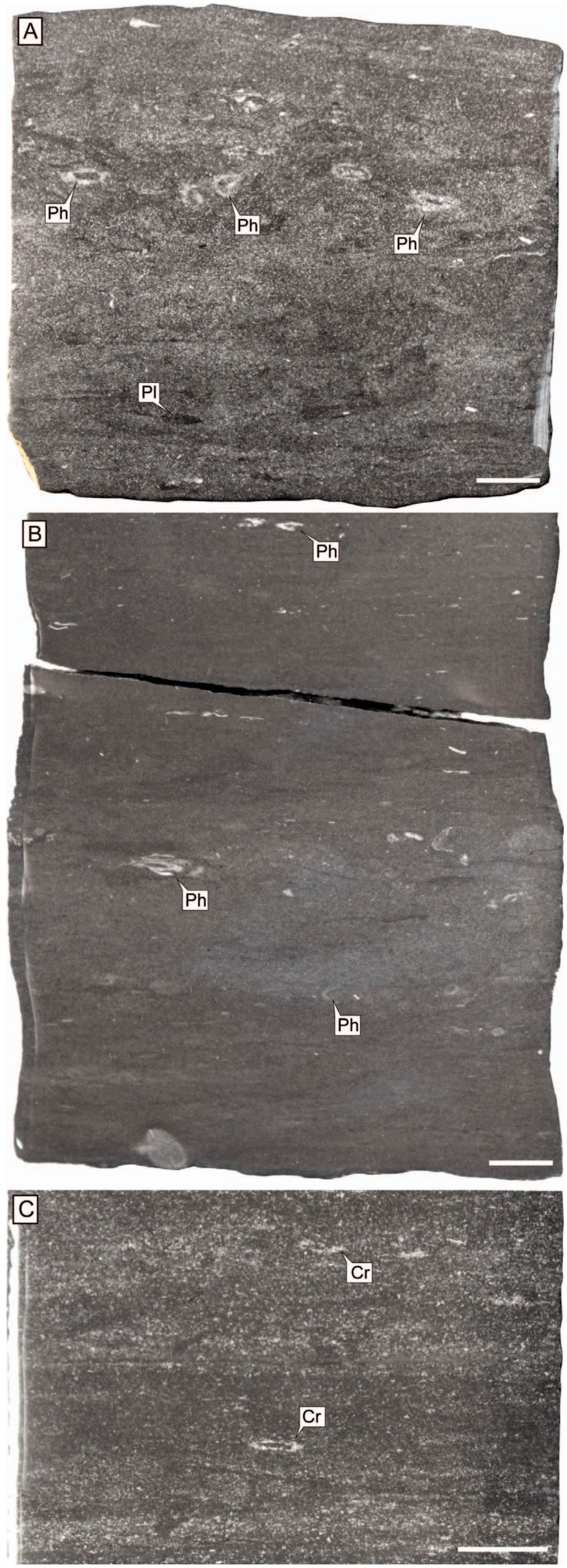

FIG. 5.—Core photographs of the *Palaeophycus heberti* ichnofabric, scale bars = 1 cm. **A, B**) *Palaeophycus heberti* (Ph) and *Planolites* (Pl) in highly bioturbated intervals with massive appearance ($M_{cm}b$). **C**) *Crininicaminus* isp. (Cr) from bioturbated crinoidal mudstone ($M_{cr}b$) showing relatively good preservation of the primary fabric.

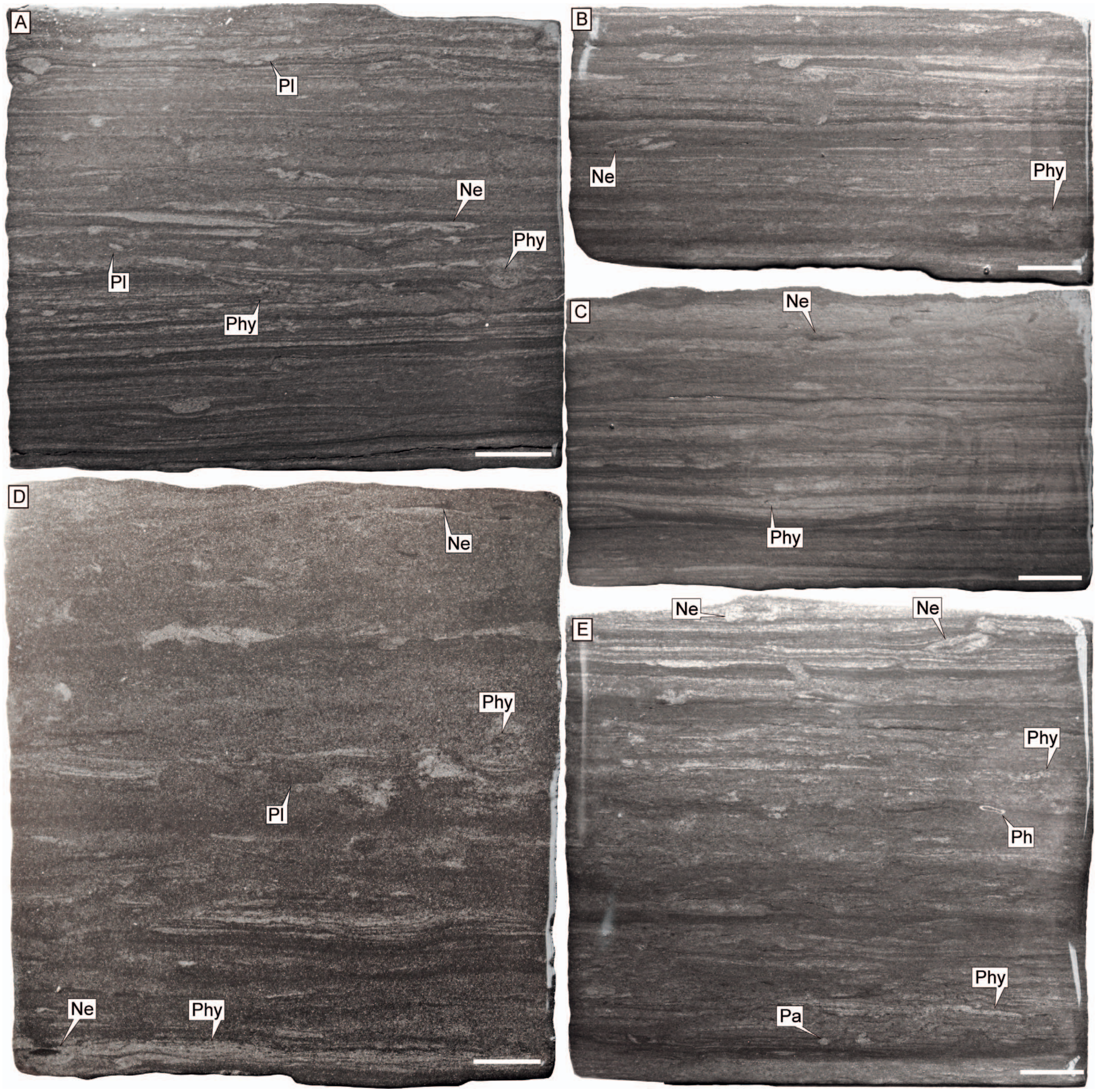

FIG. 6.—Sparsely to moderately bioturbated intervals of the *Phycosiphon incertum* and *Nereites* isp. ichnofabrics, scale bars = 1 cm. **A–C**) Sparsely bioturbated intervals with parallel- to low-angle cross-laminated fine to coarse mudstone (Mh, Ml, M_sh, M_sl), showing the *Phycosiphon incertum* ichnofabric with *Nereites* isp. (Ne), *Phycosiphon incertum* (Phy), and *Planolites* isp. (Pl). **D**, **E**) Moderately bioturbated, fine to coarse mudstone (M_{cm}b) and parallel-laminated coarse mudstone (M_sh), depicting the *Nereites* isp. ichnofabric, constituted by *Nereites* isp. (Ne), *Palaeophycus* isp. (Pa), *Palaeophycus heberti* (Ph), *Phycosiphon incertum* (Phy), and *Planolites* isp. (Pl).

and ?*Lockeia* are rare. Small burrow-mottled patches represent biodeformational structures. BI is 3–5, and mean burrow diameter is 3.6 mm. The *Nereites* isp. ichnofabric occurs in 1–10 cm-thick, dominantly moderately bioturbated, fine to coarse mudstone intervals (facies M_{cm}b, Mh, Ml, M_sh, M_sl, M_sr). Primary fabric is partially preserved in most instances. This ichnofabric consists of structures of deposit- and detritus-feeders in soft substrates, most likely indicating times of current pauses or decreased current velocity, facilitating food accumulation at the sediment surface. Suspension feeding or predation are only represented by rare *Palaeophycus heberti* and *Palaeophycus* isp. On the other hand, *Nereites* and *Phycosiphon* are typical trace fossils associated with abundant food input, which is also characteristic of areas affected by contour currents (Thistle et al. 1985; Wetzel 2010; Hovikoski et al. 2020). Some elements of the *Nereites* isp. ichnofabric have been commonly recorded in the literature as post-depositional trace fossils on top of turbidites (Uchman and Wetzel 2011); in the example herein, however, they are part of drift facies

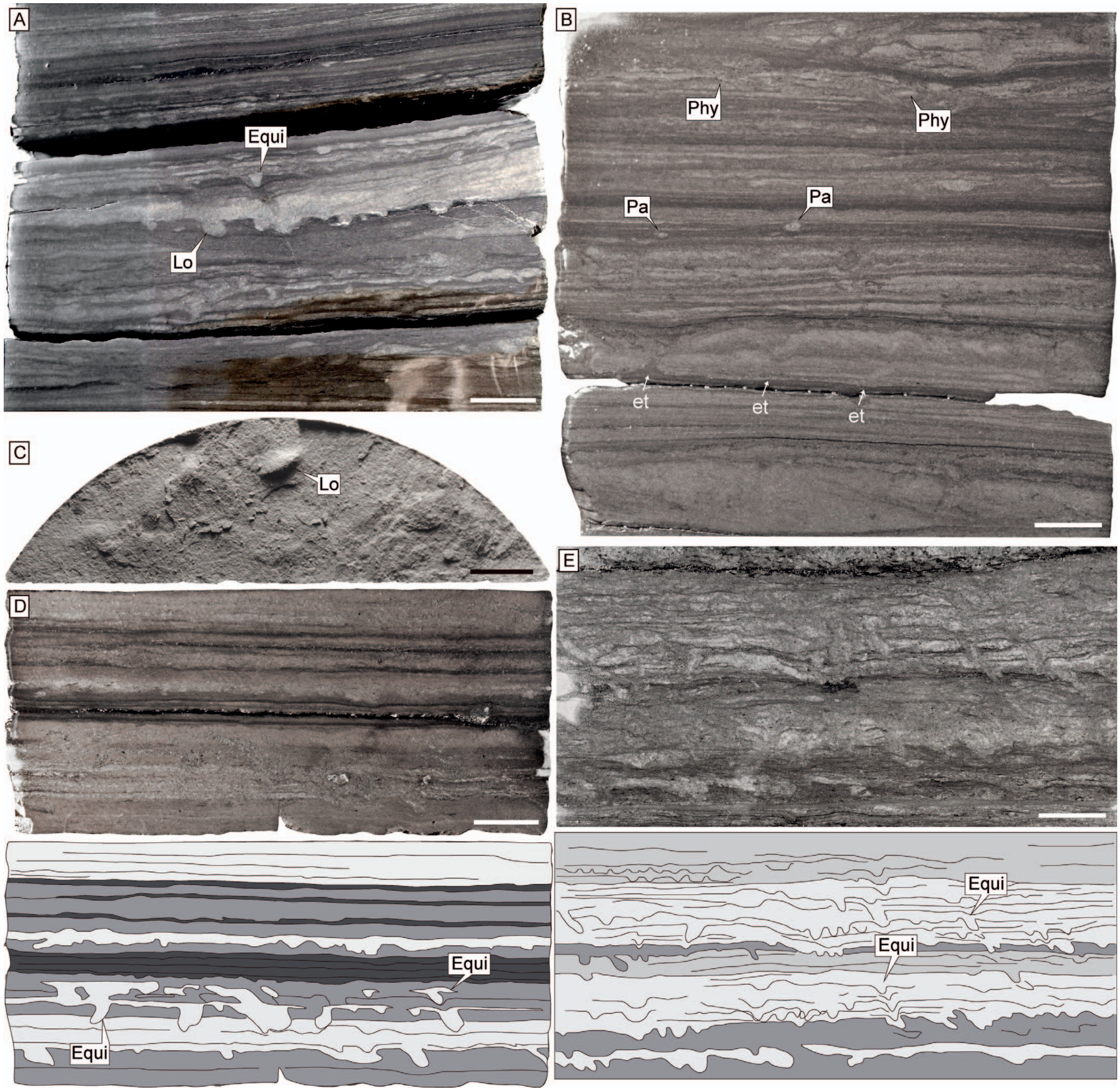

FIG. 7.—Equilibrichnia-Fugichnia ichnofabric, scale bars = 1 cm. **A**) Sparsely bioturbated intervals with ?*Lockeia* isp. (Lo) in current-ripple cross-laminated coarse mudstone (M_sr) with equilibrium structures (Equi). **B**) Escape trace fossils (et) of the Equilibrichnia-Fugichnia ichnofabric in parallel-laminated and current-ripple cross-laminated coarse mudstone (M_sh, M_sr). On top, moderately bioturbated intervals displaying parallel-laminated fine to coarse mudstone (Mh, M_sh) with *Palaeophycus* isp. (Pa) and *Phycosiphon incertum* (Phy), are part of the *Nereites* isp. ichnofabric. **C**) Positive hyporelief preservation of *Lockeia siliquaria* (Lo). **D**, **E**) Moderately to highly bioturbated intervals of parallel-laminated to normal-graded fine to coarse mudstone (Mh, M_sh, M_sg), showing equilibrium structures (Equi, see drawing below for delineation of structures). Contrast in (D) has been enhanced to increase visibility of structures.

association and do not occur in sediment gravity flow deposits of the Vaca Muerta Formation.

The Equilibrichnia-Fugichnia ichnofabric is characterized by very shallow-tier, bowl-shaped structures referred to as ?*Lockeia* isp., U- and V-shaped, nested vertical to highly inclined structures, interpreted as equilibrium and escape structures, and rare ?*Skolithos* isp. (Fig. 7). In several instances, *Lockeia siliquaria* has been identified on bedding planes, as both negative epirelief and positive hyporelief (Fig. 7C). BI is typically 1–2, with dense populations of equilibrium and/or escape structures forming more pervasively bioturbated intervals (BI 3–4; Fig. 7E). Burrow mean maximum diameter is 3.2 mm. Locally, vertical axes of burrows displays a preferred orientation, showing a lateral displacement towards the paleocurrent direction, inferred from the presence of unidirectional current ripples (Fig. 7A). This ichnofabric forms 1–30

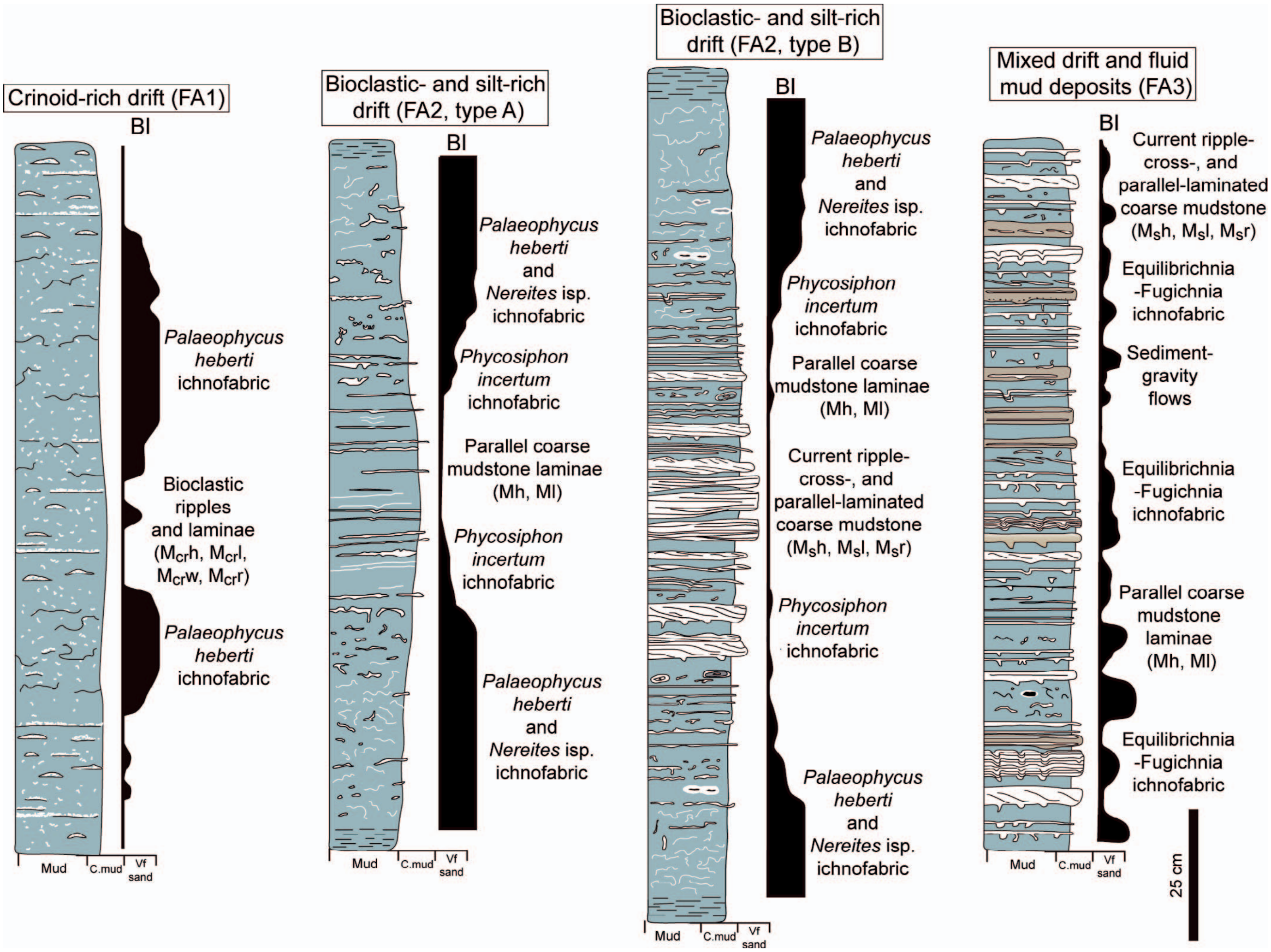

FIG. 8.—Idealized succession for each shallow-water contourite drift facies associations documented from the Vaca Muerta Formation, displaying lithology, sedimentary structures, ichnofabrics, and bioturbation index.

cm-thick, sparsely to moderately bioturbated, parallel-laminated fine to coarse mudstone intervals (facies Mh, Ml, M_sh, M_sl, M_sr). Primary fabric is well preserved in most intervals. Consistent equilibrium behavior is inferred from the successive vertical association of these structures, with vertical movements episodically through 0.1–2.0 cm of sediment. Based on the identification of *Lockeia siliquaria* on numerous bedding planes, this ichnofabric is interpreted as most likely produced by suspension-feeding bivalves. The equilibrichnia strategy reflects an animal able to respond and adjust its position to keep pace with sedimentation and maintain the connection to the seafloor in order to access suspended food particles (Mángano et al. 1998). A similar burrow size for individual colonization surfaces suggests the activities of a single population of opportunistic species. Burrow orientation can be caused by the alignment of suspension feeders with respect to a constant current (Over 1988). Times of low sedimentation rate coupled with sufficient suspended food are inferred from the densely populated chevron equilibrium structures that indicate retrusive burrowing (Hanken et al. 2001). Higher and rapid sedimentation rates are recorded from the escape structures. Irregular burrow boundaries suggest soft, mud-rich substrates, whereas locally, well-defined burrow boundaries (associated with these very shallow-tier structures) indicate development of relatively stiff substrates.

Patterns of Ichnofabric and Trace-Fossil Distribution

The ichnofabrics display a pattern of distribution in relation to the contourite deposits (represented by both facies and facies associations) that reflects spatial trends in bioturbation in drift environments (Figs. 8, 9). FA1 is host to the *Palaeophycus heberti* ichnofabric, showing a predominance of *Crininicaminus* isp. over other discrete trace fossils, and high intensities of bioturbation (Fig. 5C).

FA2, located in a shallower-water setting, shows sparsely bioturbated intervals hosting the *Phycosiphon incertum* ichnofabric, moderately bioturbated intervals comprising the *Nereites* isp. ichnofabric, and highly bioturbated intervals with the *Palaeophycus heberti* ichnofabric. The Equilibrichnia-Fugichnia ichnofabric is a minor component, except for well 2, where it forms sparsely to moderately bioturbated successions. Locally, FA2 shows m-thick intervals displaying a decreasing and then increasing BI, which can be differentiated into type A and B successions (Figs. 8, 10). Type A has a high percentage of intensely bioturbated intervals (facies $M_{cm}b$, ~ 50–60%) and dominance of parallel-laminated fine to coarse mudstone (facies Mh and Ml). Type B exhibits a lower percentage of highly bioturbated intervals (facies $M_{cm}b$, ~ 15–30%), and includes a greater abundance of parallel-laminated and ripple cross-laminated fine to coarse mudstone (facies M_sh, M_sl and M_sr).

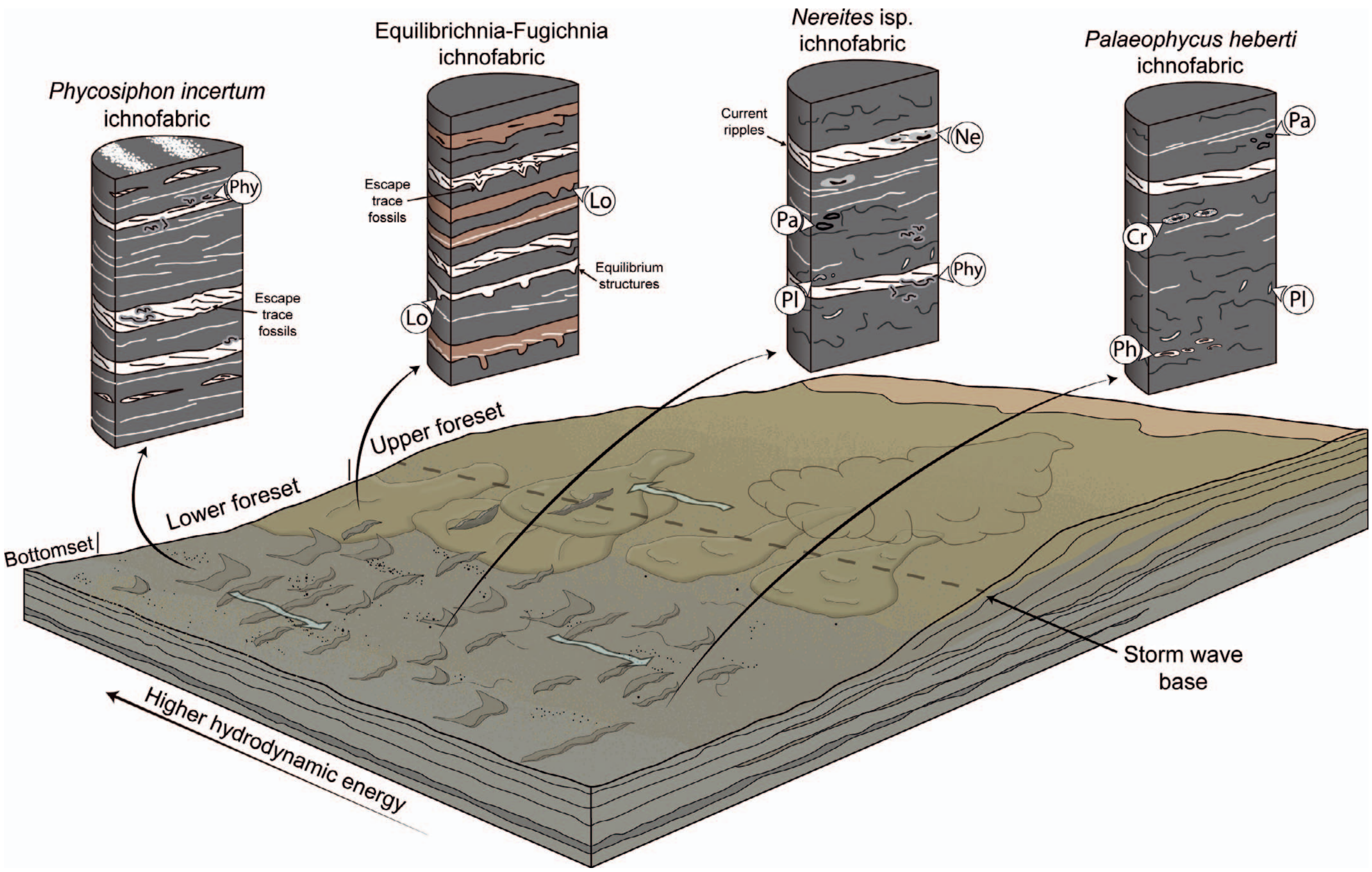

FIG. 9.—Block diagram showing the environmental distribution of the ichnofabrics depending on the clinoform location and hydrodynamic energy of the contour currents. Abbreviations: Cr = *Crininicaminus* isp.; Lo = *Lockeia siliquaria*; Ne = *Nereites* isp.; Pa = *Palaeophycus* isp.; Pl = *Planolites* isp.; Ph = *Palaeophycus heberti*; Phy = *Phycosiphon incertum*. See text for explanation.

FA3 is the most landward facies association of the three. This facies association shows a dominance of the Equilibrichnia-Fugichnia ichnofabric, displaying low to moderate intensities of bioturbation.

Paleoenvironmental Implications

Environmental controls on bioturbation can be summarized via the integration of the available sedimentologic and ichnologic datasets (Fig. 11). Food, oxygenation, hydrodynamic energy, and water turbidity are suggested to have been the main controlling factors on trace-fossil distribution in the studied deposits. Extensive documentation on the effects of deep-water contour currents on benthic ecology serve for comparison with benthic communities affected by shallow contour currents (cf. Thistle et al. 1985, 1991; Aller 1989, 1997; Flach et al. 1998; Lavaleye et al. 2002; Wetzel et al. 2008).

Food.—In contour current-affected areas, benthic standing stock and biologic mixing is sustained by a higher food input compared with areas of continental slope or abyssal plain (DeMaster et al. 1985; Thistle et al. 1985). Different intensities in current speed generate distinctive scenarios of benthic responses to food distribution. High velocity currents of > 25 cm/s promote removal of metabolites, organic matter, microorganisms, larvae and juveniles (Aller 1989), and an increase in suspension-feeding and, to a lesser extent, surface-feeding organisms (Flach et al. 1998; Flach 2003; Wetzel et al. 2008). In particular, suspension feeders benefit from food becoming enriched at the boundary layer (Rosenberg 1995; Flach and Thomsen 1998; Lavaleye et al. 2002). In contrast, slower currents (< 10 cm/s) make organic matter available at the sediment surface, and deposit feeders tend to be dominant (Flach and Thomsen 1998; Lavaleye et al. 2002; Wetzel et al. 2008). A switch between these two feeding strategies may also be adopted by the same organism (namely deposit-suspension feeders) when flow conditions change (e.g., bivalves, Olafsson 1989; polychaetes, Taghon and Greene 1992).

High productivity suggested by the high TOC content of the Vaca Muerta Formation indicates that food was not a limiting factor. However, the contourite deposits in this unit imply a complex mosaic of feeding strategies in response to variable types of food available for the benthos, namely suspended food for the Equilibrichnia-Fugichnia ichnofabric, food on the surface and within the sediment in association with the *Nereites* isp. and *Phycosiphon incertum* ichnofabrics, and mixed suspended and surface-deposited food for the *Palaeophycus heberti* ichnofabric. The predominance of *Nereites* isp. and *Palaeophycus heberti* ichnofabrics associated with intensely to moderately bioturbated intervals suggests lower energy or intermittent currents with food delivered at the sediment surface and subsequently shallowly buried. The presence of suspension-feeding structures in the latter also suggests the suspension of food particles in the water column. The *Phycosiphon incertum* ichnofabric reflects opportunistic colonization of areas with benthic food affected by moderate energy currents during short colonization periods.

The Equilibrichnia-Fugichnia ichnofabric, with its dominance of vertical structures produced by suspension-feeding bivalves and the absence of deposit-feeding traces, indicates abundant organic particles were present in the water column. This ichnofabric occurs in deposits formed in the most landward environments affected by contour currents (FA3), where predominant coarse mudstone deposits indicate velocities above the

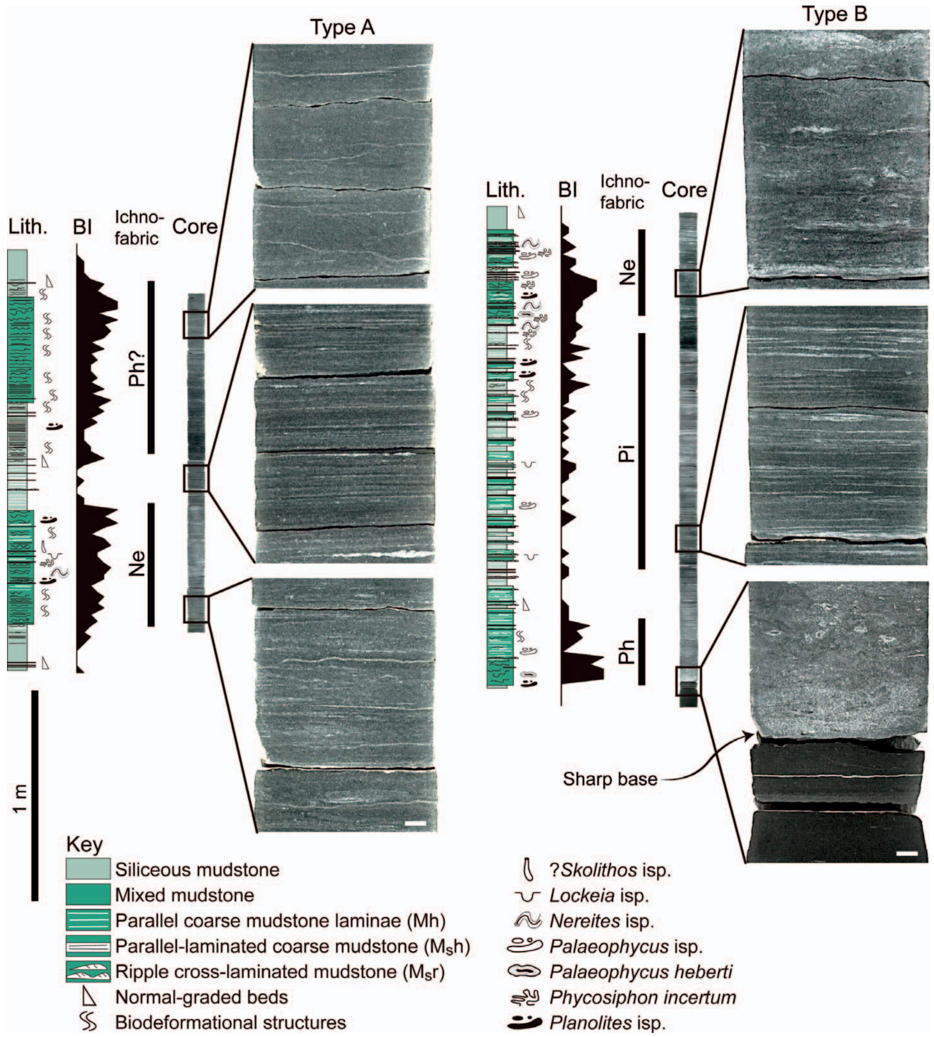

FIG. 10.—Examples of the contourite successions showing decreasing and then increasing BI (FA2 type A and B), with distribution of the *Palaeophycus heberti* (Ph), *Nereites* isp. (Ne), and *Phycosiphon incertum* (Pi) ichnofabrics. All scale bars at the bottom right of the cores = 1 cm.

threshold of mud accumulation (> 25 cm/s, Yawar and Schieber 2017). Thus, this area is envisioned as having high content of suspended organic matter transported by moderate-energy currents. The organisms probably presented an exposed body area for suspension feeding and adjusted to the surface following sedimentation events. The contour current direction may have influenced the orientation of burrows (with a preferred orientation towards the paleocurrent direction, Fig. 7A). Similar small (0.2–0.5 cm wide, 1–2 cm long), cone-shaped *Lingulichnus* in the Silurian Delorme Group of Canada show orientations that were caused by bottom current transport in a shelf-slope transition (Over 1988). Suspension feeders orient their burrows in a direction opposite of the dominant flow to prevent filling of their burrows with fine-grained material that could block their feeding apparatus, to optimize feeding surfaces and respiration, and to passively remove waste materials (Over 1988; Zonneveld and Pemberton 2003). However, the occurrence of slump structures in FA3 indicates that burrow orientation could also be an artifact of downslope sediment creep or current-induced sediment shearing (Gingras and Bann 2006).

Oxygenation.—Contour currents provided oxygen to the generally oxygen-deficient Vaca Muerta Formation seafloor and pore waters, generating an environment suitable for the establishment of a low to moderately diverse benthic fauna. The oxygen supply in bottom waters is evidenced by the high bioturbation observed in the drifts (mean BI of 1.78 in FA1, 2.17 in FA2 and 1.75 in FA3), that contrast with the otherwise parallel-laminated basin deposits of this formation (mean BI of 0.09, n = 9110; Paz 2021). Deep water renewal by cascading of dense, surface watermasses likely contributed to increase oxygen levels at the seafloor (Meier et al. 2006; Coppola et al. 2017).

However, shallow-tier bioturbation structures and small burrow sizes (mean burrow diameter of 3.47 mm, n = 174) are characteristic of all the studied facies association. This clearly contrasts with examples of modern environments oxygenated by contour currents (e.g., Fu and Werner 1994; Reolid and Betzler 2019), where high oxygen and food levels allow establishment of a diverse, deep-burrowing infauna with normal sizes and complete sediment homogenization. Oxygenation is regarded as one of the main controlling factors on bioturbator body size and burrowing depth, with decreasing oxygen producing a gradational decrease of burrow size and depth (Savrda et al. 1984). Current speed could not have controlled burrow size, because highly bioturbated intervals also display small sizes.

Therefore, relatively low-oxygen levels, probably in the range of upper dysoxia, might be the cause of size reduction, constituting an environmental stress that aided in preservation of sedimentary structures (e.g., Robinson et al. 2007). Similarly, the existence of trace fossils restricted to shallow-tiers indicates oxygen-deficient conditions. For example, bottom-water ventilation in oxygen-deficient basins results in

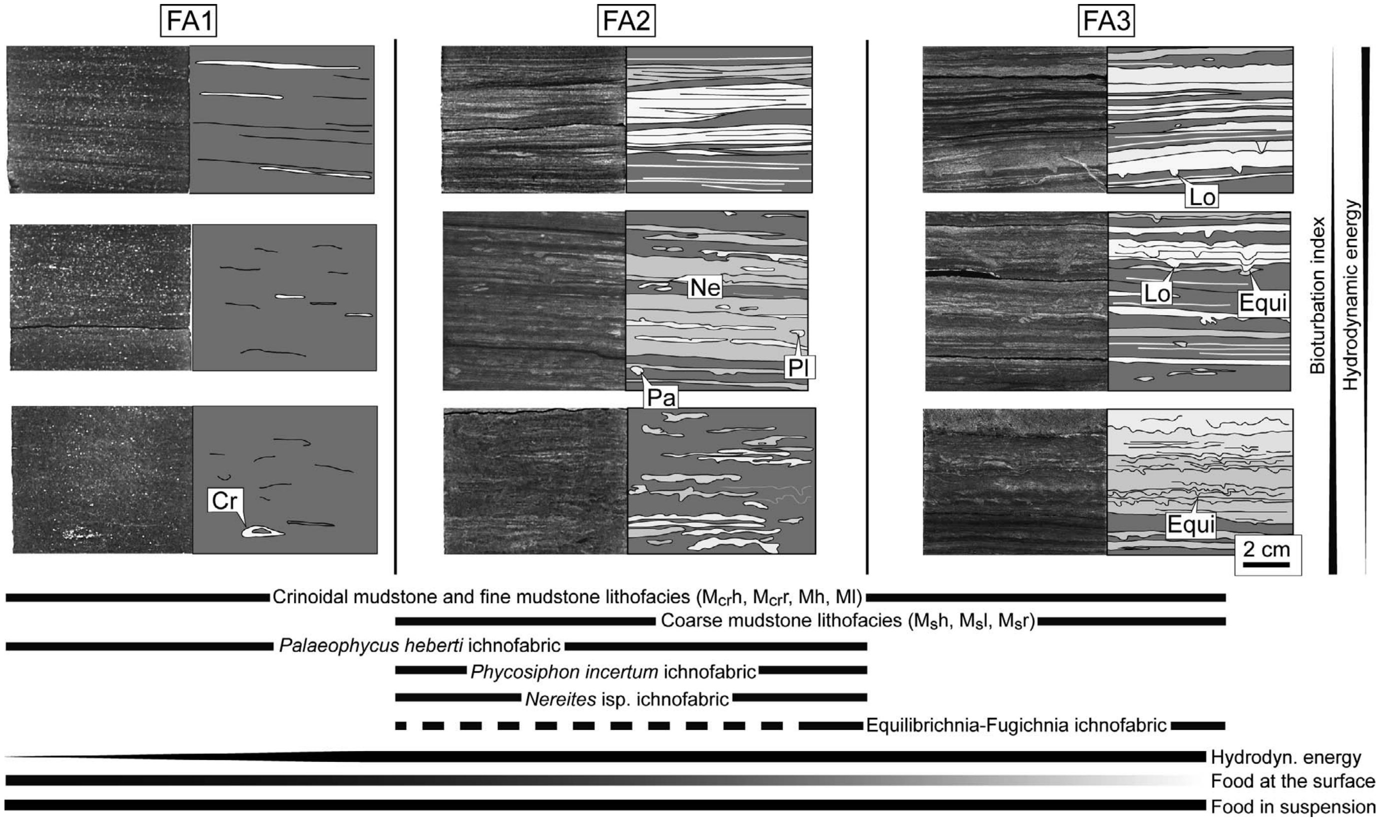

FIG. 11.—Summary of environmental factors controlling ichnofabric distribution in the different contourite facies association. Abbreviations: Cr = *Crininicaminus* isp.; Equi = equilibrium structures; Lo = *Lockeia siliquaria*; Ne = *Nereites* isp.; Pa = *Palaeophycus* isp.; Pl = *Planolites* isp.

thin (up to 1 cm) bioturbated intervals dominated by shallow-tier trace fossils (Virtasalo et al. 2011). Oxygen-deficient contour currents can occur in glaciated margins (e.g., Antarctic Peninsula margin; Lucchi and Rebesco 2007) or in basins affected by anoxic-dysoxic conditions (e.g., Baltic Sea, Sivkov et al. 2002; Virtasalo et al. 2011; California Continental Borderland, Robinson et al. 2007).

Hydrodynamic Energy.—Hydrodynamic energy controlled bioturbation and the preservation of traction structures. The pattern of decreasing and then increasing BI in FA2 type A and B successions indicates a change from high to low to high hydrodynamic stress over the benthos. Hence, at the base of the successions, low energy and probably intermittent currents promoted extensive biogenic reworking and beds were completely homogenized (*Nereites* isp. and *Palaeophycus heberti* ichnofabrics). Middle parts of the successions record high-energy and more continuous currents that preserved physical sedimentary structures and host the *Phycosiphon incertum* ichnofabric, characterized by sparse bioturbation. However, a few colonization surfaces suggest currents were intermittent (e.g., Rodríguez-Tovar et al. 2019; Dorador et al. 2021). The upper part of the succession reflects a decrease in energy towards low-energy conditions, which allowed organisms to completely rework the sediment (*Nereites* isp. and *Palaeophycus heberti* ichnofabrics). Oxygenation controlled bioturbation in these successions by restricting bioturbation depth.

The increasing-then-decreasing energy gradation resembles the bi-gradational sequence characteristic of the contourite facies association model (Gonthier et al. 1984; Stow and Faugères 2008). The bi-gradational pattern demonstrates the shift of bottom currents from lower-velocity marginal areas to the higher-velocity core and viceversa. These bi-gradational successions show a similar thickness than the type A and B intervals documented in this study (~ 0.2–3 m thick; Figs. 3, 10; Stow and Faugères 2008). Moreover, the rise in hydrodynamic energy from FA2 type A to type B is reflected by an increase in the abundance and thickness of current-ripple cross- and parallel-laminated beds, and by a decrease in the abundance and thickness of bioturbated beds. A similar gradation in sedimentary structures has been documented in ancient examples of contourites (Martín-Chivelet et al. 2008 and references therein). Changes in ichnotaxa composition and tiering associated with the distance from the bottom current core have been also recorded in modern and ancient contourites due to differences in sedimentation rate and nutrient availability (Dorador et al. 2019, 2021; Míguez-Salas et al. 2020). Similarly, the present case shows changes in ichnofabrics associated with food distribution, which in turn is controlled by hydrodynamic energy.

Water Turbidity.—The suspension-feeding strategy inferred for the burrows in the Equilibrichnia-Fugichnia ichnofabric and the abundance of current ripples indicate low levels of water turbidity during deposition of FA3 and some intervals of FA2. Substrates with high water content and influenced by high turbidity typically exclude suspension-feeding organisms, because turbidity results in the clogging of filtering structures and the inability to attach to the bottom (Rhoads and Young 1970). Notably, however, this ichnofabric is abundant in the facies association that shows deposition of sediment gravity flows. This indicates that there was a rapid alternation between high-turbidity flow events, and low-turbidity, current-dominated times that allowed the establishment of the Equilibrichnia-Fugichnia ichnofabric.

IMPLICATIONS FOR THE ANALYSIS OF SHALLOW-WATER CONTOURITES

The analysis herein explores a special case of shallow-water contourites within an oxygen-deficient, epicontinental basin, where different paleoenvironmental factors played a role in trace-fossil distribution. The highly bioturbated intervals associated with traction structures suggest contour currents can supply oxygen to environments with background anoxic conditions, in contrast with deposits from other processes, such as sediment-gravity flows, which rarely show complete bioturbation (Wetzel et al. 2008; Reolid and Betzler 2019). Sediment-gravity flows (e.g., wave- and current-enhanced sediment gravity flows, turbidity currents, hyperpycnal flows) cannot sustain long-term oxygenation, and most likely result in "doomed pioneer" ichnofabrics when they occur in oxygen-deficient environments (i.e., discrete occurrences of *Thalassinoides* and *Gyrolithes* encased in unbioturbated laminated dark mudstone; Föllmi and Grimm 1990). For example, in the Santa Barbara Basin, USA, turbidity currents were able to introduce oxygen in the deeper, oxygen-deficient areas, but the basin chemistry was restored after one month (Sholkovitz and Soutar 1975). This pattern is detected in the Vaca Muerta Formation, where bioturbation index in the contourite deposits ranges from 0 to 5 (mean BI of 1.85, $n = 894$), controlled by hydrodynamic energy, dropping to between 0 and 2 in intervals rich in sediment-gravity flow deposits (mean BI of 0.95, $N = 336$; Paz 2021). However, variable oxygen levels are implied by bioturbation being absent to intense in other muddy contourite deposits; indicating the existence of contour currents that do not supply oxygen to the seafloor (Frébourg et al. 2013; Reisdorf et al. 2014; Knapp et al. 2017; Ayranci et al. 2018). In the Vaca Muerta Formation, unbioturbated bottom current deposits are also observed in basin environments, which support the idea of anoxic currents (Paz 2021).

Moreover, this study suggests that bioturbation can be suppressed in contourites when different environmental stresses are combined, increasing the chance of preserving sedimentary structures. In the present case, it is suggested that the sparsely bioturbated intervals of FA2 resulted from the combined effects of deposition under upper dysoxic conditions and high hydrodynamic energy. Analyses of similar muddy contourite deposits highlighted the role of sedimentation rate in the preservation of sedimentary structures (Frébourg et al. 2013; Knapp et al. 2017). However, the long-term character of contour currents in modern environments and their low sediment concentration suggest variable degrees of sediment erosion and bypass indicative of relatively low sedimentation rate. In fact, the higher accumulation areas within modern silty and muddy contourite drifts are highly bioturbated (Faugères et al. 1984; Wetzel et al. 2008), indicating that elevated sedimentation rate cannot suppress bioturbation. In the Vaca Muerta Formation, colonization surfaces within the sparsely bioturbated intervals suggest that traction structures did not form during a single, high sedimentation rate event, but by successive discrete episodes. This pattern highlights the role of hydrodynamic energy (instead of sedimentation rate *per se*) in suppressing bioturbation.

The extent of bioturbation in contourites is still a topic of disagreement. Some studies have incorporated biogenic structures into contourite facies models, suggesting that a highly bioturbated, coarsening and then fining upward, bigradational succession is typical of these deposits (Faugères et al. 1984; Gonthier et al. 1984; Stow and Piper 1984; Stow and Faugères 2008; Rodríguez-Tovar and Hernández-Molina 2018; Reolid and Betzler 2019). However, the paucity of bioturbation structures and the abundance of traction structures in deposits attributed to contour current activity have been emphasized in other studies (e.g., Hollister and Heezen 1972; Shanmugam et al. 1993; Martín-Chivelet et al. 2003, 2008; Shanmugam 2017, 2018). Previous authors indicated that this discrepancy may reflect contrasting energy conditions between muddy and sandy contourites, precluding bioturbation in the latter case (Stow and Faugères 2008; Rebesco et al. 2014; Rodríguez-Tovar and Hernández-Molina 2018). The muddy contourite deposits of the Vaca Muerta Formation reveal both intensely bioturbated intervals interbedded with successions displaying extensive preservation of traction structures. Hence, the present analysis agrees with both facies models and demonstrates that sedimentary structures could be preserved in fine-grained depositional environments when stress factors (dysoxia and high hydrodynamic energy in the present case) limit bioturbation. In addition, the observed pattern of an upward decrease and then an increase in bioturbation index supports the existence of bigradational successions in contourites associated with long-term fluctuations in hydrodynamic energy (Fig. 8; Stow and Faugères 2008), whereas a few colonization surfaces in the middle of the successions agree with the idea of short-term fluctuations in contour current intensity (Rodríguez-Tovar et al. 2019; Dorador et al. 2021).

CONCLUSIONS

The ichnology of muddy contourite deposits of the Upper Jurassic–Lower Cretaceous Vaca Muerta Formation was analyzed to assess environmental controls on the benthos. These deposits occur in drift environments of a mixed carbonate-siliciclastic clinoform system, and comprise laminated, rippled and bioturbated, crinoidal mudstone and fine to coarse mudstone. The ichnofauna consists of *Crininicaminus* isp., *Lockeia siliquaria*, ?*Lockeia* isp., *Nereites* isp., *Palaeophycus* isp., *Palaeophycus heberti*, *Phycosiphon incertum*, *Planolites* isp., ?*Skolithos* isp., and escape and equilibrium trace fossils. Four ichnofabrics, namely *Palaeophycus heberti*, *Phycosiphon incertum*, *Nereites* isp., and Equilibrichnia-Fugichnia ichnofabrics, have been characterized. Ichnofabric distribution is linked to facies and facies associations. Facies association 1 comprises crinoidal mudstone facies and hosts the *Palaeophycus heberti* ichnofabric forming highly bioturbated intervals. Facies association 2 consists of fine to coarse mudstone facies, with the *Phycosiphon incertum, Nereites* isp. and *Palaeophycus heberti* ichnofabrics in sparsely, moderately and highly bioturbated intervals, respectively; and rare Equilibrichnia-Fugichnia ichnofabric forming sparsely to moderately bioturbated intervals. Locally, facies association 2 shows m-thick successions with a decreasing and then increasing bioturbation index pattern. Facies association 3 consists of fine to coarse mudstone facies, recording not only deposition from contour currents but also from sediment gravity flows. This facies association displays a predominance of the Equilibrichnia-Fugichnia ichnofabric. The most likely environmental controls on benthos included food supply, oxygenation, hydrodynamic energy, and water turbidity. Food was variably delivered in suspension or at the sediment surface depending on the current energy, resulting in the alternation between the Equilibrichnia-Fugichnia (suspension-feeding dominant), the *Nereites* isp. and *Phycosiphon incertum* (deposit-feeding dominant), and *Palaeophycus heberti* (a mixed of suspension- and deposit-feeding structures) ichnofabrics. Suspension feeding strategies (Equilibrichnia-Fugichnia ichnofabric) are abundant in the most landward facies association (FA3), indicating higher energy currents were able to maintain organic matter in suspension. Bottom water oxygen levels were increased by the contour currents, supporting a moderately diverse benthos that contrasts with the typical unbioturbated intervals of the Vaca Muerta Formation. However, small burrow diameters and shallow bioturbation depths indicate oxygen levels were relatively low (upper dysoxic conditions). Hydrodynamic energy controlled biogenic reworking and preservation of sedimentary structures, particularly in the successions with decreasing-to-increasing bioturbation index. Water turbidity remained low during contour current development, supporting a community of suspension feeders, but alternated with high turbidity during sediment-gravity flow deposition. The present analysis supports the fact that high bioturbation levels are common in contourites, highlights their role in ventilating bottom waters, and provides an example of muddy contourites with high preservation of sedimentary structures.

ACKNOWLEDGMENTS

We thank Shell and Tiser S.R.L., and Germán Canto, Adrián Dolso, Sebastián Estrada, Sebastián Galeazzi, and Fabián Lamarque from Total Austral S.A. for sharing core information with us. Patrick Orr, Javier Dorador, and an anonymous reviewer remarkably improved the content and coherence of the manuscript. We also appreciate the valuable comments of Andreas Wetzel and Juan José Ponce on an early draft of the manuscript. This work was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC Discovery Grants 311727–20 to MGM), PI-UNRN 2017 40-A-616 and PIP-CONICET 11220170100129CO to NBC, 2016 Student Research Grant from Society for Sedimentary Geology (SEPM), 2016 and 2018 Research Grant from the Geological Society of America (GSA), 2016 Grants-in-Aid Program of the American Association of Petroleum Geologists (AAPG), and 2018 Postgraduate Grant from the International Association of Sedimentologists (IAS). MGM also acknowledges support by the George McLeod Enhancement Chair in Geology.

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Received 13 April 2020; accepted 14 March 2022.