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Eocene graphoglyptids from shallow-marine, high-energy, organic-rich, and bioturbated turbidites, Fuegian Andes, Argentina

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ABSTRACT:

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Graphoglyptids are diagnostic ichnofossils of the *Paleodictyon* ichnosubfacies (*Nereites* ichnofacies), which is well represented in deep-marine Mesozoic–Cenozoic thin-bedded turbidites. However, unusual shallow-water records of Mesozoic–Cenozoic *Paleodictyon* and particular preservational restrictions of graphoglyptid burrows introduce the question of whether graphoglyptids are reliable bathymetric indicators. We document and discuss another unusual graphoglyptid association preserved in shallow-marine, high-energy, organic-rich, and bioturbated turbidites of leveed channels in the upper middle Eocene CCa member, Cerro Colorado Formation, Fuegian Andes. The member includes the facies associations: 1) mudstones, 2) interbedded mudstones and thin-bedded Tbc turbidites, and 3) thick-bedded sandstones and mudstones. Facies association 3), interpreted as channel deposits, records at least three horizons with *Desmograpton, Glockerichnus, Helicolithus, Helminthorhaphe, Megagrapton, Paleodictyon* and *Urohelminthoida*. Associated beds are lenticular, channeled sandstone turbidites with marked basal erosion surfaces and variable proportions of interbedded mudstone-sandstone with high content of plant debris. Trace fossils in the channeled sandstones are dominated by *Ophiomorpha rudis* and *O. annulata;* mudstones within the thick-bedded mudstone-sandstone beds bear *Nereites, Phycosiphon, Zoophycos* and *Paradictyodora,* with subordinate *Schaubcylindrichnus, Tasselia* and *Scolicia.* The unusual preservation of limited graphoglyptid-bearing beds within a highly energetic and bioturbated interval seems to support the concept that preservational restrictions on graphoglyptid burrows could be locally more important than bathymetric constraints.

Key words: Fuegian Andes; Eocene; Shallow marine; Graphoglyptids; Ichnology; Turbidites.

INTRODUCTION

Graphoglyptids are well known, particularly in the Mesozoic–Cenozoic, as diagnostic trace fossils of the deep-marine *Nereites* ichnofacies. Since its original definition, the concept of the *Nereites* ichnofacies (Seilacher 1967) has been expanded to include the *Nereites s.s.*, *Paleodictyon* and *Ophiomorpha rudis* ichnosubfacies (Seilacher 1974, 2007; Uchman 2001, 2009). Each of these ichnosubfacies is envisaged as characteristic of different substrates and depositional elements of submarine fans. Thus, it is thought that the *Nereites* ichnosubfacies characterises muddy substrates in fan-fringe, interfan, and basin plain areas;

the *Paleodictyon* ichnosubfacies, sandier substrates in lobe-fringe and distal levee areas; and the *Ophiomorpha rudis* ichnosubfacies thick, sand-rich beds in channel and proximal channel areas. This ichnosubfacies distribution has been found in most Cretaceous–Cenozoic flysch of the Mediterranean and Alpine foreland basins (Seilacher 1977; Crimes *et al*. 1981; Uchman 1995, 1998, 1999, 2001; Heard and Pickering 2008), and also in the Late Cretaceous flysch of Lago Argentino, in southern Patagonia (Olivero and López C., personal data).

However, there is a growing body of evidence that this ichnosubfacies distribution is controlled by a combination of palaeoecological and taphonomic conditions. Thus, whereas the biogenic structures of the *Nereites* and *Ophiomorpha rudis* ichnosubfacies are recorded in the original substrate colonised by the producers, the *Paleodictyon* ichnosubfacies is recorded in a foreign substrate, i.e. as casts at the sole of particular sandy turbidites. A clear understanding of this very important fact was first perceived by Seilacher (2007 and references therein) and now it is generally accepted that preservation of the delicate, open galleries built in muddy substrates by the graphoglyptid producers requires limited additional bioturbation, limited erosion, and rapid casting of the open gallery. In addition, the success of graphoglyptid makers in the oligotrophic conditions prevailing in the deep sea is explained by the special feeding behaviour of trapping or farming developed by the group (Seilacher 1977, 2007; Uchman 2003). The apparently anomalous Mesozoic occurrence of graphoglyptids in neritic settings, (Gierlowski-Kordesh and Ernst 1987; Uchman *et al*. 2004), sometimes associated with elements of the *Cruziana* ichnofacies (Fürsich *et al*. 2007), suggests that preservational restrictions on graphoglyptid burrows could be locally more important than palaeoecological and bathymetric constraints.

New data on another apparently anomalous graphoglyptid occurrence are presented in this study. We record an unusual, relatively diverse graphoglyptid association in high-energy, organic-rich, and bioturbated turbidites of leveed submarine channels in the upper middle Eocene CCa member, Cerro Colorado Formation, Fuegian Andes, Argentina. The CCa member was deposited in the wedge-top depocenter of the Austral foreland basin, situated near the orogenic front of the Fuegian thrust-fold belt (Torres Carbonell *et al.* 2008a, 2009). Benthic and planktonic foraminifera suggest that the wedge-top depocenter was relatively shallow, with restricted connections to the open sea. The main objectives of this study are to document this unusual record of Eocene graphoglyptids and to discuss its implications for the understanding of palaeoenvironmental and preservational controls on graphoglyptid distribution.

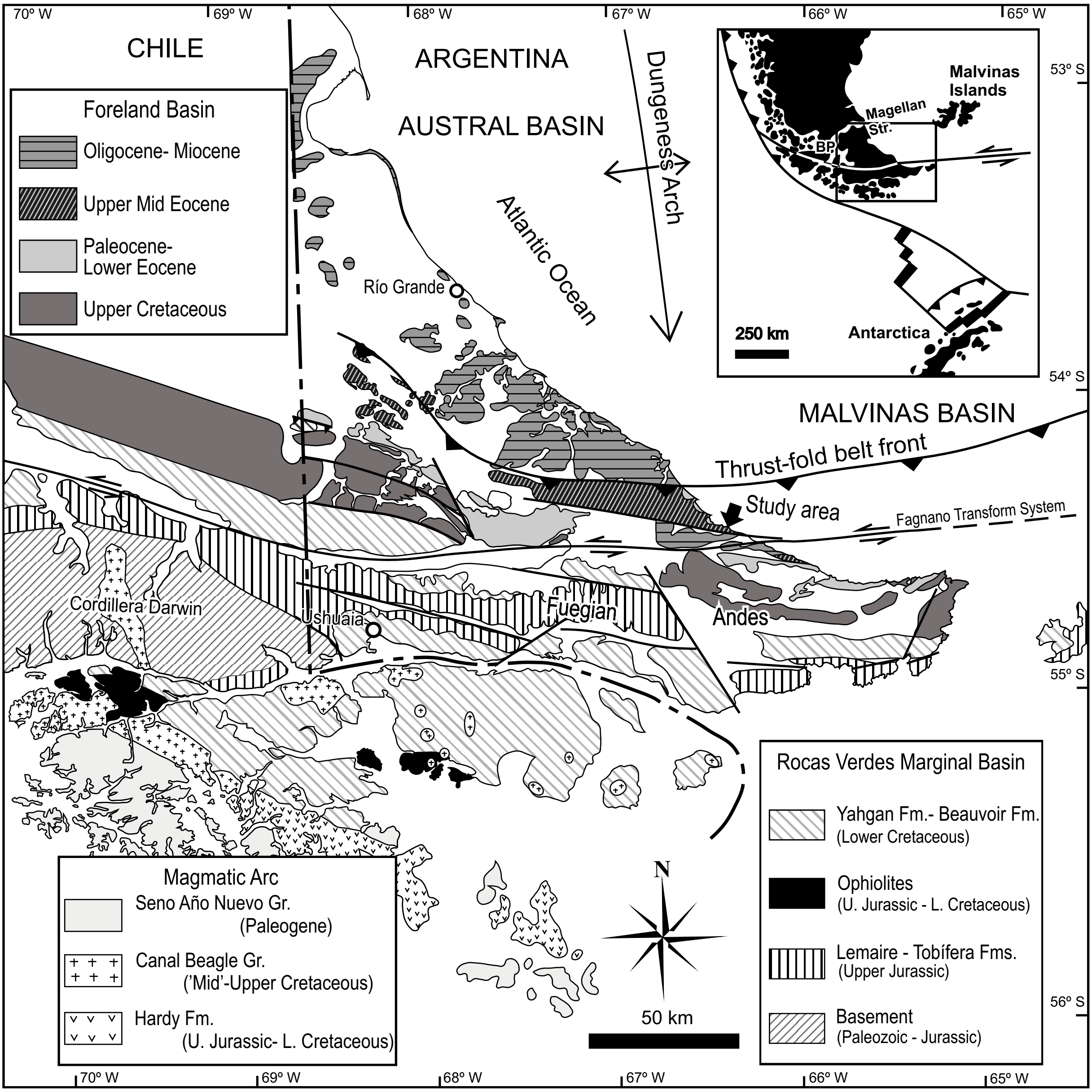
GEOLOGICAL AND ICHNOLOGICAL FRAMEWORK

At the southern tip of South America, the Mesozoic–Cenozoic geological history of the Fuegian Andes (Text-fig. 1) was characterised by Late Jurassic-Early Cretaceous extension, Late Cretaceous–Paleogene contraction, and Cenozoic strike-slip faulting (Dalziel *et al.* 1974; Klepeis and Austin 1997). The extensional regime was associated with rifting, widespread silicic volcanism and opening of the Rocas Verdes Marginal Basin. The Early Cretaceous, deep-marine deposits of the Rocas Verdes were affected by a contractional regime that produced the closure of the basin, ductile deformation, isoclinal folding, and metamorphism. This was followed by the development of a thrust-fold belt in front of the growing collisional orogen (Dalziel *et al.* 1974; Hanson and Wilson 1991; Klepeis and Austin 1997).

The foreland Austral-Malvinas basins (Biddle *et al.* 1986) originated as a result of tectonic loading and flexural subsidence at the northern margin of the Fuegian orogen. The propagation of the contractional deformation resulted in the migration to the north of the basin foredeep. Four main depocenters filled with thick clastic wedges of mainly deep-marine deposits are recognised (Text-fig. 1). Within the thrust-fold belt, the oldest clastic wedges include 1) the late Campanian to Danian Bahía Thetis-Policarpo formations 2) the late Paleocene–early Eocene Río Claro Group, and 3) the late middle to late Eocene La Despedida Group. They are highly deformed and reach an aggregate thickness in excess of 3500 m (Olivero and Malumián 1999, 2008; Olivero *et al.* 2002, 2003). Relationships between sedimentation and tectonics are more complex in the late middle to late Eocene La Despedida Group, which includes deposition in the foredeep as well as deposition in a shallower and partially disconnected wedge-top depocenter (Text-fig. 2), known as the María Luisa sub-basin (Torres Carbonell *et al.* 2008a, 2009).

The youngest, Oligocene-Miocene clastic wedge is the mainly subhorizontal Cabo Domingo Group, principally exposed outside the thrust-fold belt (Malumián and Olivero 2006; Olivero and Malumián 2008). During deposition of the Cabo Domingo Group the tectonic regime changed and a transform boundary between the Scotia Plate and the South American Plate was formed. The left-lateral strike-slip Fagnano-Magallanes fault system represents the portion of this plate boundary in Tierra del Fuego (Klepeis and Austin 1997; Torres Carbonell *et al.* 2008b).

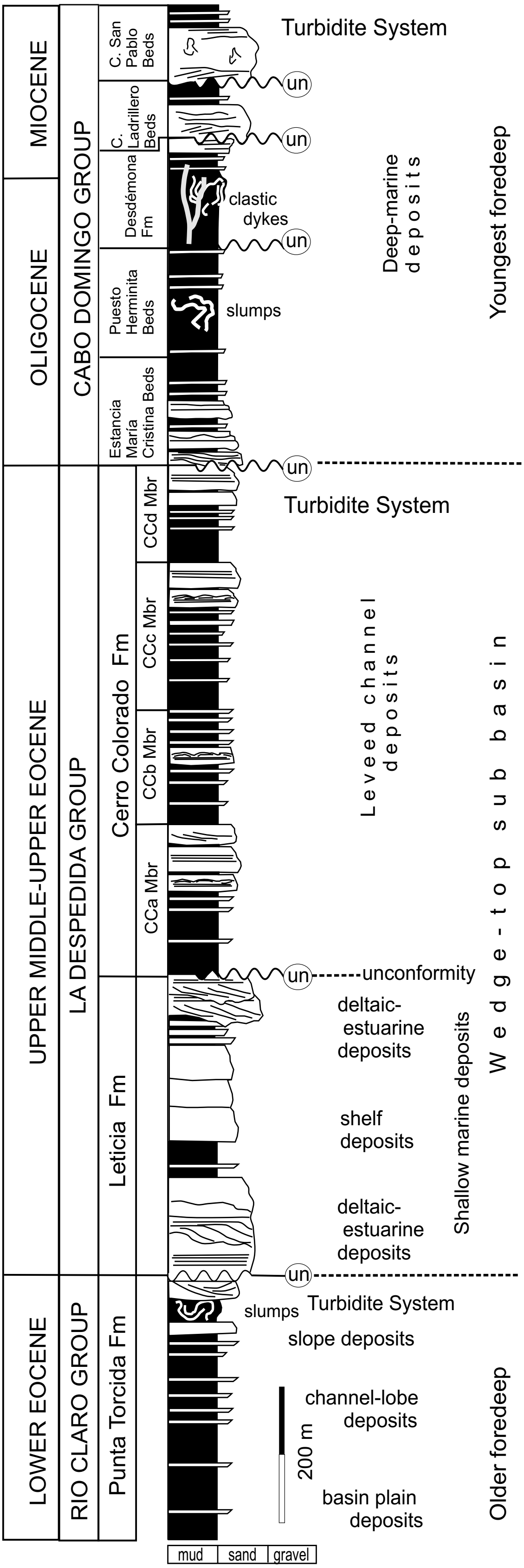
The relatively complete, marine Paleocene–Miocene stratigraphic column of the Fuegian Andes (Text-fig. 2) includes the *Cruziana* ichnofacies (Leticia Formation, late middle Eocene) as well as the *Zoophycos* and *Nereites* ichnofacies (early Eocene–early Miocene turbidite systems) (López C. *et al.* 2008). The early Eocene–early Miocene turbidite systems contain the only known deep marine Cenozoic trace fossils in Argentina and are characterised by the ichnogenera *Scolicia, Chondrites, Gyrophyllites, Nereites, Phycodes, Phycosiphon, Phymatoderma, Stelloglyphus, Zoophycos* and *Ophiomorpha* in addition to graphoglyptids. Graphoglyptids include *Cosmorhaphe, Desmograpton, Glockerichnus, Helicolithus, Helminthorhaphe, Megagrapton, Paleodictyon* and *Urohelminthoida*. Cenozoic graphoglyptids of the *Paleodictyon* ichnosubfacies are mainly recorded in thin-bedded turbidite and mudstone lobe deposits. *Ophiomorpha rudis* and *O. annulata* (*Ophiomorpha rudis* ichnosubfacies) are common in sandy, proximal channel-lobe deposits at the contact between thick-bedded turbidites and



Text-fig. 1. Situation map, geological sketch of the Fuegian Andes, distribution of the four depocenters in the foreland basin, and location of the study area mudstones, with abundant plant fragments. *Scolicia prisca* and *Nereites* isp. are common in rippled, fine-grained sandstones interbedded with thin mudstones. *Zoophycos* isp. is dominant in slope mudstones with synsedimentary slumps (López C. *et al.* 2008).

At the base of the La Despedida Group, the Leticia Formation includes three sandstone-dominated intervals, which have a complex architecture and display variable thicknesses over short distances, i.e. between 200 m and 500 m in less than 4 km. The lower and upper intervals consist of thick, cross-bedded and parallel-laminated, channelized sandstone bodies, with minor, highly bioturbated heterolithic beds, which represent deltaic and shallow marine settings. The scarcity of foraminifera, particularly of the planktonic forms, suggests marginal, shallow, and restricted marine conditions for the lower and upper intervals of the Leticia Formation. The middle interval consists of glauconitic, fossiliferous, and highly bioturbated fine-grained shelf sandstones (Olivero and Malumián 1999; López C. *et al.* 2008). The late middle Eocene Leticia Formation thus represents a transgressive-regressive cycle (Text-fig. 2) and bears the ichnogenera *Curvolithus, Diplocraterion, Gyrochorte, Rosselia, Patagonichnus, Asterosoma, Palaeophycus, Paradictyodora, Planolites, Rhizocorallium, Schaubcylindrichnus, Taenidium, Tasselia* and *Teichichnus*.

The overlying Cerro Colorado Formation (c. 855 m thick) consists of a vertical stacking of four coarsening- and thickening-upward successions, comprising the CCa, CCb, CCc and CCd members (Olivero and Malumián 1999). Each member is composed of dark grey mudstones at the base, regular intercalation of mudstones and turbidites at the mid part, and thick sandstones and pebbly sandstones at the top (Text-fig. 2). The uppermost CCd member bears abundant radiolarians and small planktonic foraminifera indicative of a late Eocene age and high production or fluctuating nutrients. Foraminifera of the three lower members of the Cerro Colorado Formation, including the focus of this study – the CCa member – represent neritic settings, whereas those in the uppermost CCd member record relative deepening. Overall, the Leticia and Cerro Colorado formations and the overlying Estancia María Cristina beds record a deepening succession that reflects increasing flexural subsidence



Text-fig. 2. Composite stratigraphic column of the lower Eocene to lower Miocene interval of the foreland basin and generalized depositional and tectonic settings. The leveed channel deposits of the CCa member unconformably overlie the shallow-marine Leticia Formation. (Adapted from Olivero and Malumián 1999; Malumián and Olivero 2006; Torres Carbonell *et al.* 2008a)

(Olivero and Malumián 1999; Malumián and Olivero 2006; Torres Carbonell *et al.* 2008a, 2009).

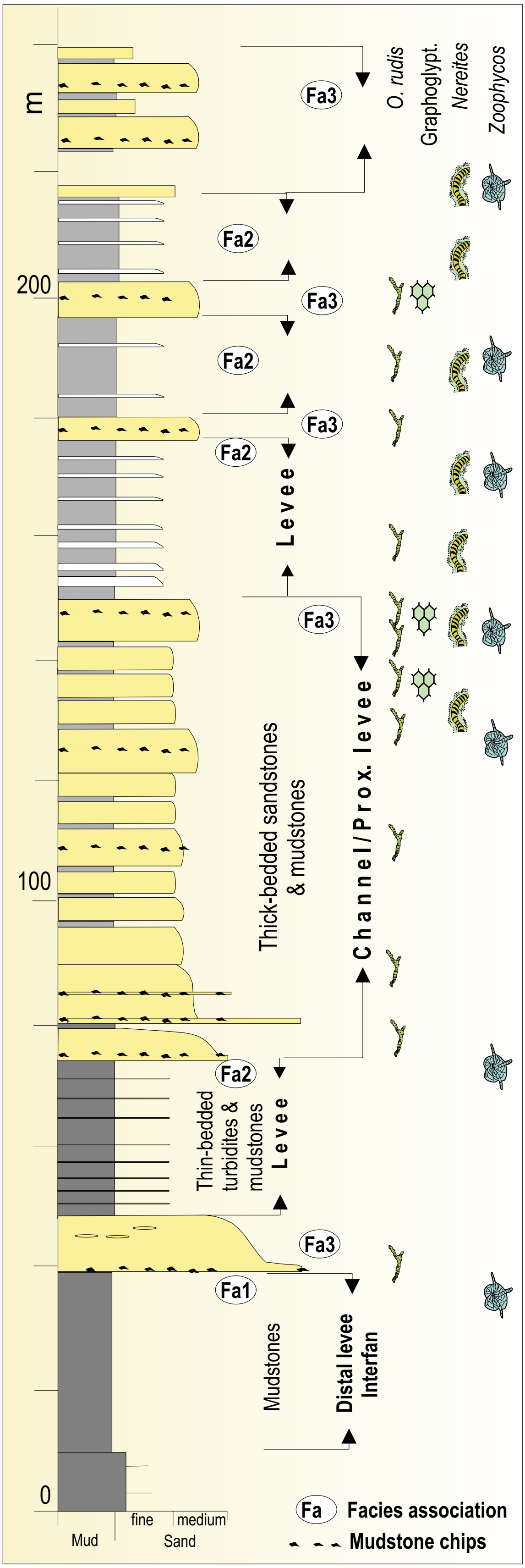
THE CCa MEMBER OF THE CERRO COLORADO FORMATION

Sedimentary facies and ichnology

The study area (Text-fig. 1) exposes the type section of the CCa member of the Cerro Colorado Formation (Olivero and Malumián 1999), which was deposited within the María Luisa wedge-top sub-basin (Torres Carbonell *et al.* 2008a, 2009). It comprises about 240 m of a coarsening and thickening upward facies association of: 1) mudstones and siltstones, 2) interbedded mudstones and thin-bedded Tbc turbidites, and 3) thick-bedded sandstones and associated thin- to thick- sandstones and mudstones interbedded in variable proportions (Text-fig. 3). Palaeocurrent vectors, measured from flute casts, current ripples, and climbing ripples indicate palaeoflow directions toward the ENE.

Facies association 1 is a thick, homogeneous package of poorly stratified, dark grey mudstones and sandy siltstones that overlies unconformably the shallow marine sandstones of the Leticia Formation. The unconformity is a sharp surface associated with a lag deposit enriched in angular concretion fragments, granules, and pebbles derived from the Leticia Formation. A few metres above the base, the dark-grey mudstones contain abundant gastropod and bivalve shells. At several levels, these fine-grained rocks bear abundant, dispersed, small carbonized plant fragments. Trace fossils appear to be scarce (*Phycosiphon* and *Zoophycos*), but this may result from poorly exposed strata at low tide.

Facies association 2 comprises regularly stratified packages ranging in thickness from few metres to tens of metres, composed of rhythmical alternations of thin, fine-grained Tbc turbidite and mudstones (Text-figs. 4A, B, I; 5A, C). Locally, slumped horizons of reduced thickness, affecting two or three beds, are recognised (Text-fig. 5A). Average bed thickness ranges from 5 cm to 15 cm. Sandstone beds are sharply based with common parallel lamination, climbing ripples and convolute lamination. Mudstone beds within the lower thick package of facies association 2, between c. 50



Text-fig. 3. Sedimentological section of the CCa member at the type area of the Cerro Colorado Formation and vertical distribution of facies associations 1 (distal levee/interfan), 2 (levees), and 3 (channel and proximal levees) and selected trace fossils


A
Fa 3
Fa 2
Fa 3
C
B
Fa 2
B
C
D
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G
H
I
J
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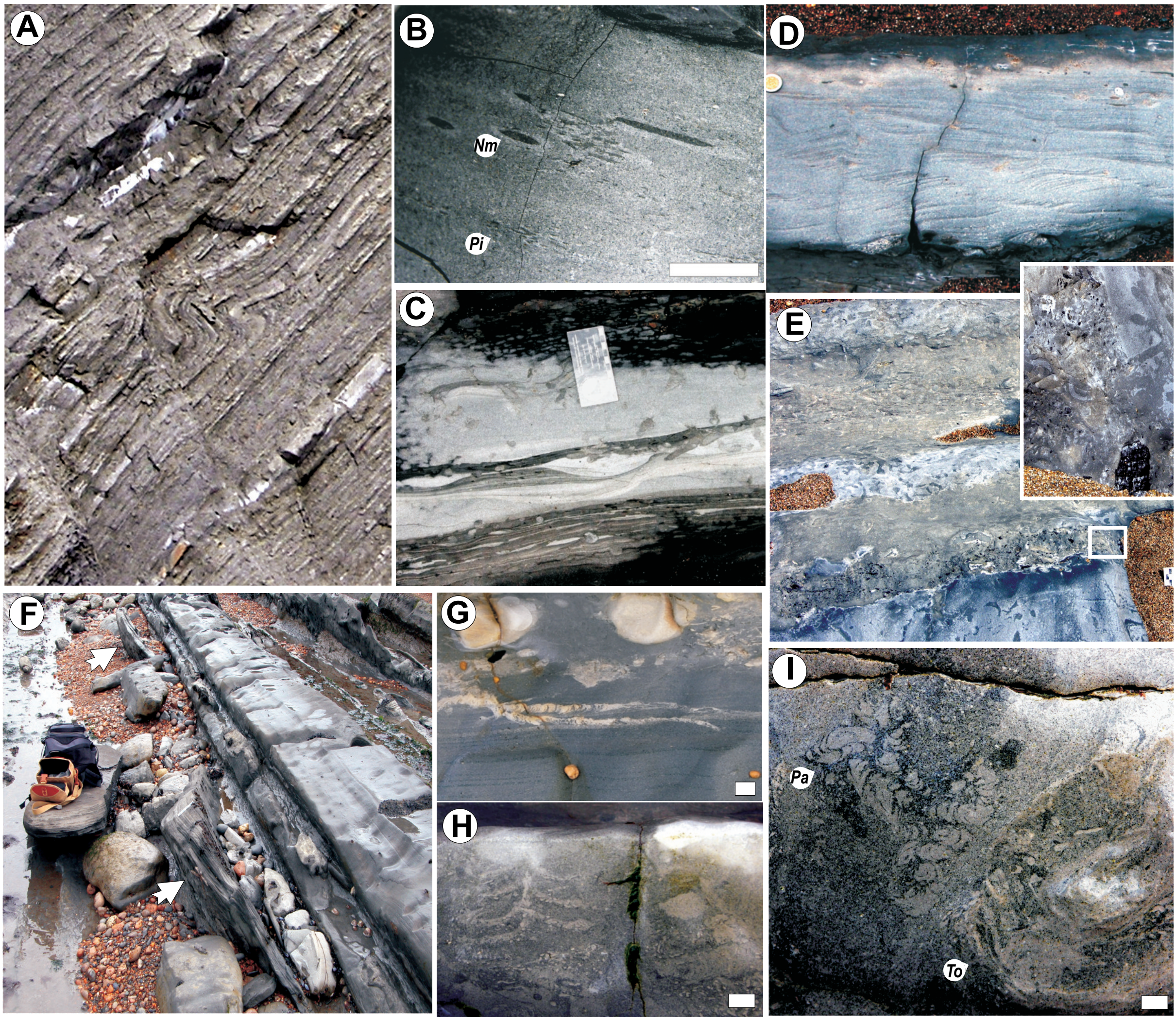
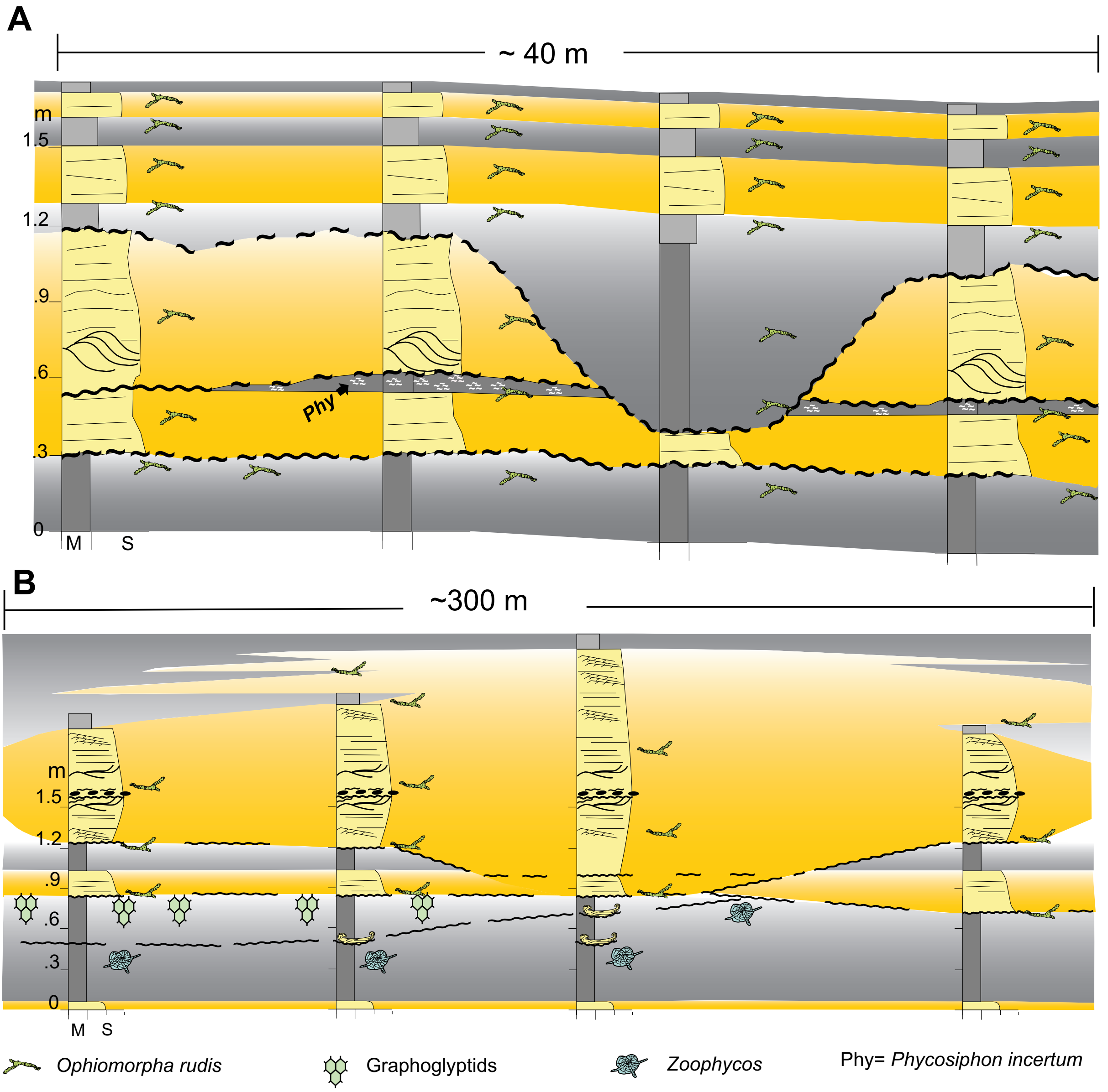
J



Text-fig. 5. Sedimentary structures and ichnology of Fa 2 and 3. A – localized slump in thin–bedded turbidites, Fa 2; B – *Nereites missouriensis* (Nm) and *Phycosiphon incertum* (Pi), Fa 2; C – climbing ripples, lenticular and flaser bedding in Tc turbidites cross–cut by *Ophiomorpha rudis*, Fa 2; D – climbing ripples in CCC turbidite, Fa 2; E – dense ichnofabrics of *O. rudis* in sandstones with abundant plant fragments (close–up); F – large, ball–and–pillow structures (arrows), c. 145 m level in Text-fig. 3; G-I – bioturbated lower mudstones in Text–fig. 6B, *Zoophycos* (G-H), vertical view, (I), *Paradictyodora antarctica* (Pa), *Tasselia ordamensis* (To), and mottling, upper bedding–plane view

and 75 m (Text-fig. 3), bear comminuted, carbonized plant fragments and bioturbation is rare, but again the lack of visible trace fossils could be an artefact of poor exposures in the intertidal area. In the upper packages of the section, where facies association 2 is recorded in close association with facies association 3, e.g. at the 150 to 220 m level of Text-fig. 3, the mudstones contain abundant plant fragments and the fine-grained silty sandstones have delicate climbing ripples, flaser and lenticular bedding structures (Text-figs 5A, C, D). Horizontal galleries of *Ophiomorpha rudis* and *O. annulata* can be extremely abundant at the contact between mudstone and sandstone beds; the mudstones commonly bear *Phycosiphon incertum* and *Nereites*

Text-fig. 4. Architecture and sedimentary facies. A – seacliff, c. 60–180 m stratigraphic interval in Text-fig. 3, showing alternation of facies associations (Fa) 2 and 3, note thickness change in the basal Fa 3 package, squares show the position of beds in Text-fig. 4B, C; B – Tc turbidite with climbing ripples, Fa 2; C-G – lenticular packages of structureless sandstones, Fa 3; E covers the c. 80–180 m interval and F the 180 m level in Text-fig. 3; H – cross bedding and cut and fill structures, Fa 3; I – the c. 130–230 m interval in Text-fig. 3 showing alternation of channel (Fa 3) and levee (Fa 2) deposits; labeled squares indicate positions of the 180 m bed (F) and 220 m bed (J); J – flat base, concave–upward lenticular package of Fa 3, white arrows mark stepped terminations of sandstone beds against erosive base of channels

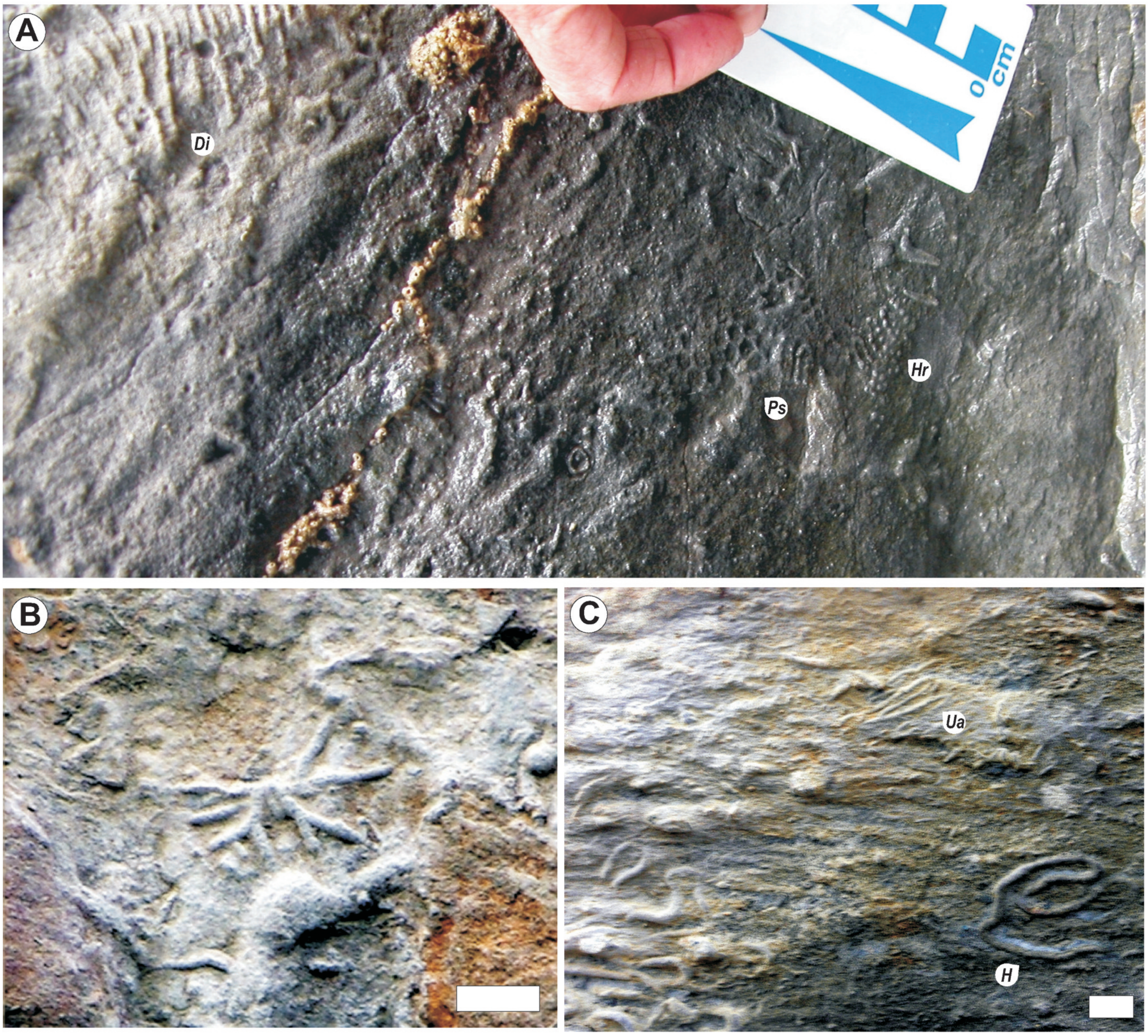


Text-fig. 6. Correlation panel of detailed sedimentary logs. A – thick amalgamated sandstone bed with mudstone partings illustrated in Text-fig. 4F; B – lenticular, complex sandstone–mudstone package, with multiple erosion surfaces separating different ichnoguilds, 145 m stratigraphic level in Text-fig. 3

missouriensis in high density (Text-figs 5B, E); and the soles of some sandy turbidites record the graphoglyptid *Paleodictyon* isp., *Helicolithus* isp. and *Urohelminthoida appendiculata*.

Facies association 3 is dominated by lenticular, thick-bedded sandstones with variable proportions of interbedded sandstones and mudstones (Text-fig. 3). The thick-bedded sandstones have a lenticular geometry; in the thickest part beds are up to 3 m thick and extend laterally for about 300 m; afterward they pinch out markedly and pass laterally into thin-bedded sandstones and mudstones. Other sandstone beds terminate abruptly near their thickest point and are draped by interbedded sandstones and mudstones. In vertical section, the thickest point of successive lenticular sandstone beds are laterally displaced, so that the superposition of these lenticular packages results in highly variable lithologies and geometries in parallel sections distant just a few tens of metres apart (Text-figs 4A, C–J).

The thickest beds consist of structureless, crudely parallel-stratified, and/or scoured, planar cross-stratified and wavy sandstones. They are generally amal-



Text-fig. 7. Graphoglyptids at the sole of a turbidite (0.9 m in Text–fig. 6B). A – *Desmograpton ichthyforme* (Di), *Paleodictyon strozzii* (Ps) and *Helicolithus ramosus* (Hr); B – *Glockerichnus alatus*; C – *Urohelminthoida appendiculata* (Ua) and *Helmithorhaphe* isp. (H). Scale bar in cm

gamated. Bed amalgamation is indicated by erosion of bioturbated mudstone partings or by layers of isolated mud clasts that pass laterally into mudstone partings (Text-figs 4F, 6A). Scour marks and/or cut-and-fill structures are common, with deposits that drape vertical or even overhanging surfaces, as well as dewatering structures and convolute stratification (Text-fig. 4H). Many sandstone beds are characterised by a basal portion with reverse grading and an upper portion with normal grading bounded by internal erosion surfaces. Both the basal and upper portions consist of very fine-grained sandstones with climbing ripples and parallel lamination. The intervening erosive surfaces are cut in medium-grained, structureless sandstones that may show pockets of fine gravel and shell fragments. Locally, they show also concentrations of large plant fragments, up to 5 cm in diameter.

The associated succession of interbedded sandstone and mudstone shows no systematic trends in bed thickness or granulometry. Sandstone beds include classic turbidites with common flute casts; turbidites with Tbc Bouma divisions, generally with convolute tops; and complex turbidites with repeated convolute lamination and hummocky-like cross stratification. Mudstone beds are laterally highly variable and show complex amalgamated beds bounded by high-relief erosive surfaces. The erosive surfaces are easily detected where marked by isolated, large ball-and-pillow structures with deformed laminated sandstones (Text-fig. 5F) or by single clast layers. Where these surfaces continue into massive mudstones, they are only noticed by the contrast in ichnotaxa and ichnofabric composition above and below the erosion surface (below and Text-fig. 6B).

The packages of thick, lenticular sandstone beds are commonly thoroughly bioturbated by *Ophiomorpha rudis* and *O. annulata* (e.g. packages between 75 m and 150 m in Text-fig. 3). Some mudstone partings also bear *Phycosiphon incertum, Nereites missouriensis* and *Paradictyodora antarctica*, with subordinate *Schaubcylindrichnus* isp., *Tasselia ordamensis* and *Scolicia* isp. Some thick sandstone beds record *Diplocraterion* isp. *Tasselia ordamensis* occurs at the contact between sandier and muddier divisions of thinner turbidite sandstone. The mudstone beds record two distinctive ichnoassemblages in different horizons separated by erosive surfaces (Text-fig. 6B). One ichnoassemblage is characterised by large *Zoophycos* isp., *Chondrites* isp. and *Paradictyodora antarctica* (Text-figs 5G–I). The other ichnoassemblage consists of graphoglyptids (for description of the trace fossils see López *et al.* 2008) recorded at the sole of classic turbidites (Text-figs 7A–C), including *Cosmorhaphe* isp., *Desmograpton ichthyforme, Glockerichnus alatus, Helminthorhaphe flexuosa, Helicolithus ramosus, Megagrapton submontanum, Paleodictyon strozzii, P. maximum, P. majus* and *Urohelminthoida appendiculata*.

Interpretation of facies associations: depositional elements

Text-figure 3 shows the vertical distribution of the described facies associations. The dominant facies associations 2 and 3 are interpreted as the vertical superposition of channels and associated levees as the main depositional elements. Our former, preliminary interpretation of the CCa member as storm-dominated deposits (Olivero and Malumián 1999) was influenced by the observation in some sandstone beds of hummocky cross-stratification, transported bivalve shells, and the apparently convex-upward shape of flat-based lenticular sandstone bodies, thought to represent some type of shelf sand bar. We now know that hummocky-like structures can occur in turbidites (Mulder *et al.* 2009). The reinterpretation of the sandstone bodies suggests that their convex-upward shape is not original, but resulted from differential compaction of the channel-shaped sandstone and overbank muddy deposits (Text-fig. 4J). Similar, regularly interbedded sandstones and mudstones in delta-influenced turbidite systems were also apparently misinterpreted as tempestites in the geological literature (see Mutti *et al.* 1999, 2003 for details).

The thick-bedded lenticular sandstones of facies association 3 are interpreted as channel deposits. As these sandstones consist of subvertical beds, exposed in a cliff oriented slightly oblique to the palaeocurrent vectors, the precise reconstruction of the channel geometry is not possible. Nevertheless, the lenticular geometry and metre-scale erosional relief of the bounding surfaces point to channel-like geometries hundreds of metres in width and several metres in depth. The abrupt termination of sandstone beds, their lapping on the basal erosive surface, the presence of high-energy sedimentary structures, and internal erosive surfaces commonly associated with pockets of fine-grained conglomerates are all features generally associated with channel deposits where the basal, coarsest sedimentary particles and highest flow energy are confined within the channel (e.g. Posamentier and Walker 2006; Mutti *et al.* 2003; Hubbard *et al.* 2008). The large ball-and-pillow structures, formed of convoluted parallel-laminated sandstones encased in mudstones, are associated with high-relief erosion surfaces indicating bypass and erosion of energetic, sand-dominated gravity flows. The sandstone turbidites with the characteristic coarsening- and then fining- upward trend separated by internal erosion surfaces, commonly associated with abundant plant fragments, are interpreted as the deposits of gravity flows originating in rivers in flood, i.e. hyperpycnal flows (Mulder and Alexander 2001; Mulder *et al.* 2003).

The thin, fine-grained, rhythmical bedded Tbc turbidites alternating with dark-grey mudstones of facies association 2 are interpreted as levee deposits. These beds show typical features of CCC turbidites, i.e. convolute bedding, climbing ripples, and mudstone clasts, which are commonly recorded in levee deposits (Posamentier and Walker 2006). Convolute lamination requires rapid deposition of sediment and trapping of pore fluid and the climbing ripples imply deposition of sediment from suspension while the ripples are still moving on the bed. Thus, the CCC turbidites suggest high rates of deposition from suspension and simultaneous traction of the bedload, a condition that is typical of levee areas (Walker 1985). These rhythmically bedded packages have localised slumps involving only few beds, a feature that is also considered typical of levee deposits (Posamentier and Walker 2006). In addition, these regularly stratified packages are closely associated with facies association 3, and commonly the thick-bedded sandstones of facies association 3 grades laterally to the regular stratified CCC turbidites of facies association 2, supporting the interpretation that they are part of juxtaposed channel and levee depositional elements. Within this context, the homogeneous package of dark grey mudstones and sandy siltstones of facies association 1 is best interpreted either as distal levees or as interfan deposits.

FORAMINIFERAN ASSEMBLAGES

In general, the benthic foraminifera of the CCa member are dominated by calcareous species characterised by large nodosariids; agglutinated and miliolid tests are scarce. *Globigerinatheka index* (Finlay) and *Subbotina angiporoides* (Finlay) represent the scarce planktonic foraminifera (Olivero and Malumián 1999).

To further evaluate the possibility of resedimentation of shallow-water fauna, additional samples were taken from mudstone beds just underneath the sole of turbidites bearing graphoglyptids. The recovered foraminiferan assemblages allow rejecting the possibility of significant resedimentation processes. They record a similar benthic assemblage in part with abundant buliminids, and others characterised by the large polymorphinids *Polymorphina lingulata* Stache, *Sigmomorphina pernaeformis* (Stache) and *Pseudonodosaria symmetrica* (Stache), nodosariid *Lenticulina pseudocalcarata* (Stache), and in some levels concentrations of *Vaginulopsis marshalli* (Finlay). The agglutinated forms are scarce and represented by *Reticulophragmium* sp. As in the rest of the member, planktonic foraminifera are very scarce.

The benthic assemblage suggests inner shelf settings. The abundance of buliminids suggests dysaerobic bottom conditions, which is consistent with the associated organic-rich mudstones and abundance of pyrite. The record of *Antarcticella antarctica* suggests cooling waters, and the scarce and small planktonic specimens restricted connections with the open sea. This latter condition is reflected in all the foraminiferal assemblages from the upper middle Eocene–upper Eocene of the Austral Basin (Panza *et al.* 1998).

DISCUSSION

Modern graphoglyptid-like biogenic structures are known from photographs in bathyal to abyssal settings only (e.g. Ekdale 1980, Wetzel 1983, Gaillard 1991), and Mesozoic–Cenozoic fossil graphoglyptids are usually considered diagnostic elements of deep marine settings. Nevertheless, unusual graphoglyptid occurrences do exist in shallow marine deposits; these involve different tectonic and palaeoenvironmental settings as exemplified by the following cases (see Fürsich *et al.* 2007 for a complete reference list of these shallow occurrences). In the upper Kusuri Formation, atop the Sinop-Boyabat flysch basin, central Pontides, Turkey, *Helicolithus, Helminthorhaphe, Megagrapton* and *Paleodictyon* were recorded in outer shelf deposits formed after a previous phase of deep-sea flysch sedimentation. The graphoglyptid occurrence was explained by a rapid regression following deep-water sedimentation (Uchman *et al.* 2004). In the Upper Cretaceous Nangurukuru Formation, southern Tanzania, *Cosmorhaphe, Paleodictyon, Spirorhaphe* and *Urohelminthoida* were mentioned in mid- to outer shelf tempestites interposed between shelfal Albian marls and Cenozoic shallow marine siliciclastic deposits (Gierlowski-Kordesch and Ernst 1987). Benthic foraminifera consist predominantly of agglutinated forms, including *Bathysiphon, Ammodiscus, Glomospira, Hormosina, Ammobaculites, Haplophragmoides* and *Trochammina*; calcareous benthic foraminifera are much less common. Planktonic foraminifera predominate or occur in equal numbers with benthics, suggesting outer shelf to upper continental slope settings at about 300–500 m water depth for the Nangurukuru Formation (Nicholas *et al.* 2006). In the Upper Jurassic of Iran a deepening-upward succession of fluvial sandstones, followed by shallow marine fan-delta sandstones, and then by shelf marly claystones of the Dalichai Formation, preserves the trace fossil *Paleodictyon,* which is first recorded at 50–70 m above the base of the formation in association with ichnotaxa of the *Cruziana* ichnofacies (Fürsich *et al.* 2007).

The graphoglyptids of the CCa member represent another unusual record of shallow marine, Cenozoic *Nereites* ichnofacies. They are recorded in sedimentary facies characteristic of deep-marine channel and levee complexes; however several lines of evidence suggest that the CCa member was deposited in relatively shallow marine settings. The CCa turbidites filled the structurally confined María Luisa sub-basin, which developed as a wedge-top depocenter on the orogenic margin of the Austral foreland basin system (Torres Carbonell *et al.* 2008a, 2009; see also Olivero and Malumián 2002); as such this sub-basin was shallower than the foredeep, the fill of which was partly deposited below the calcite compensation depth (Malumián and Olivero 2006). The foraminifera of the CCa member are characterised by abundant calcareous benthic specimens with very scarce planktonics, suggesting water mass conditions similar to those of the inner shelf and restricted connection to the open sea. Finally, the CCa member unconformably overlies the proximal marine deposits of the Leticia Formation, which bear shallow-water foraminifera (Olivero and Malumián 1999), trace fossils, and ichnofabrics typical of the *Cruziana* ichnofacies (López C. *et al.* 2008). In particular, the first graphoglyptid horizon is recorded about 140 m above the basal unconformity with the Leticia Formation, strengthening the inference of relatively shallow-water depositional settings for the CCa member.

Recent integrations of ichnological and sedimentological data in deep-marine channel-levee complexes have resulted in a detailed characterisation of trace fossil distribution in channel and levee architectural elements. Thus, sandstone-dominated channel fills and proximal levee facies are characterised by the dominance and local abundance of *Ophiomorpha rudis* and *O. annulata, i.e.* the *Ophiomorpha rudis* ichnosubfacies (Uchman 2001). *Ophiomorpha rudis* occurs also in distal levees or in fan-fringes facies, but in these cases it is associated with graphoglyptids, and the corresponding *Paleodictyon* ichnosubfacies is characterised by a higher ichnodiversity (Uchman 2009). Graphoglyptids (*Paleodictyon* ichnosubfacies) are dominantly distributed in levee deposits, generally displaying and increasing abundance and diversity of ichnotaxa away from channel margins. This distribution pattern has been found in several studies of deep-marine leveed channels, e.g. in the Upper Cretaceous Rosario Formation, Baja California (Kane *et al.* 2007); in the Cretaceous Cerro Toro Formation of Chile and Argentina (Hubbard *et al.* 2008; authors' personal observations); and in the Eocene Hecho Group of Spain (Uchman 2001; Heard and Pickering 2008 and references therein).

The ichnoassemblage in the levee facies (facies association 2) of the shallow marine CCa member is similar to that of deep-marine leveed-channel complexes. But the trace fossils of channel and proximal channel-levee deposits (facies association 3) differ from those typically recorded in similar deep-marine facies. The most notable difference is the presence of a relatively diverse graphoglyptid assemblage. Facies association 3 records at least three horizons with graphoglyptids, including *Desmograpton, Glockerichnus, Helicolithus, Helminthorhaphe, Megagrapton, Paleodictyon* and *Urohelminthoida,* which are preserved on the soles of thick-bedded sandy turbidites. Associated beds are lenticular, channeled sandstones with marked basal erosion surfaces and interbedded mudstone-sandstone beds with high content of plant debris. The channeled sandstones bear a dense bioturbation dominated by *Ophiomorpha rudis* and *O. annulata*; the mudstones are dominated by *Nereites, Phycosiphon, Zoophycos* and *Paradictyodora,* with subordinate *Schaubcylindrichnus, Tasselia* and *Scolicia*. Altogether, these beds seem to record in a very short stratigraphic interval a transition among the *Nereites*, *Paleodictyon* and *Ophiomorpha rudis* ichnosubfacies.

The occurrence of graphoglyptids in the shallow marine CCa member clearly indicates that they were not restricted to the deep sea in the Cenozoic. The unusual preservation of limited graphoglyptid-bearing beds within a highly energetic and bioturbated interval seems to support the concept of Fürsich *et al.* (2007) that taphonomic restrictions on graphoglyptid burrows could be locally more important than bathymetric constraints. The distribution pattern of graphoglyptids in levee facies also supports this argument. The finding that in channel-levee complexes there is a trend of increasing abundance and diversity of graphoglyptids away from the channel margins (Kane *et al.* 2007; Hubbard *et al.* 2008; Heard and Pickering 2008) is consistent with the accompanying progressive decrease in bottom energy of gravity flows in that direction. Thus, distal levees seem to offer the appropriate combination of gentle bottom erosion, exposure of the open graphoglyptid galleries, and rapid casting of the galleries at the sole of a turbidite bed, i.e. the required sequence of events needed for the preservation of graphoglyptids (cf. Seilacher 2007). A similar conclusion for preservation of graphoglyptids and other trace fossils in deep-marine channel and overbank deposits of the Kodiak Formation was established by McCann and Pickerill (1988). These authors stressed the point that high diversity and abundance of trace fossils in levees and interchannel environments reflect both favorable environmental conditions for the organisms and, more importantly, the lack of erosion of suitable substrates preserving the biogenic structures. In this regard it is interesting to note that the well-established bathymetric trend (Seilacher 1967, 1974; Uchman 2009) from shallower, inner fan, channel settings (*Ophiomorpha rudis* ichnosubfacies), to intermediate lobe fringe settings (*Paleodictyon* ichnosubfacies), to deeper, distal basin plains (*Nereites* ichnosubfacies) also follows a diminishing energy gradient. Thus, it should be not surprising that the same ichnofacies trend is recorded in both along channel and across channel directions. Although in the first case there is a clear bathymetric trend from proximal to distal fan settings in the second case there is not, supporting the idea that preservational restrictions could be more important than bathymetric constraints for the interpretation of graphoglyptid distribution.

Another problematic situation is the close association in the CCa member of graphoglyptids and organic-rich strata, partly originated in delta-influenced settings as interpreted from the high abundance of plant fragments and deposition from hyperpycnal flows. However, this apparently nutrient-rich setting contradicts the idea that the specialised farming behaviour of graphoglyptids is best understood as an adaptation to oligotrophic environments (Seilacher 1977, 2007; Uchman 2003). In this regards Fürsich *et al.* (2007) mentioned the possibility that preservation of graphoglyptids in nutrient-rich, delta-influenced sediments could indicate that the general preference of graphoglyptids for oligotrophic environments may not be a limiting factor for their distribution. A second, preferred, interpretation is that trophic resources probably fluctuated in time and the graphoglyptid producers colonised the sea bottom only during times of generalised oligotrophy. This scenario is consistent with the pattern of sequential colonisation of turbidite beds proposed by Wetzel and Uchman (2001): a process driven essentially by food fluctuations at the sea bottom. In this process, the available nutrients brought by turbidity current are sequentially consumed by different deposit feeding organisms, whereas graphoglyptids colonise the sea bottom only after the decline in nutrients.

CONCLUSIONS

A diverse graphoglyptid ichnoassemblage was found in relatively shallow-water deposits of the late middle Eocene CCa member of the Cerro Colorado Formation, Fuegian Andes, Argentina. The CCa member forms part of a turbidite system originated in a wedge-top depocenter, and represents leveed channel settings. In spite of the deep-marine characteristic of sedimentary facies, the basin's palaeogeography, foraminiferan assemblage and stratigraphic position of the CCa member suggest neritic water masses comparable to those of inner shelf environments and restricted connections with the open sea.

The relatively diverse graphoglyptid ichnoassemblage includes: *Cosmorhaphe* isp., *Desmograpton ichthyforme, Glockerichnus alatus, Helminthorhaphe flexuosa, Helicolithus ramosus, Megagrapton submontanum, Paleodictyon strozzii, P. maximum, P. majus* and *Urohelminthoida appendiculata*. The graphoglyptid-bearing turbidites occur in typical channel and proximal levee sedimentary facies associated with high-relief erosive surfaces, organic-rich, and highly bioturbated mudstones and sandstones. In addition to graphoglyptids, channel and proximal levee sandstones and mudstones record dense bioturbation of *Ophiomorpha rudis* and *O. annulata*, and *Nereites missouriensis, Phycosiphon incertum* and *Zoophycos* isp., respectively.

The trace fossils are characteristic of the deep-marine *Nereites* ichnofacies but the distribution of graphoglyptid trace fossils in high-energy, organic-rich, and bioturbated shallow marine settings is unusual. The shallow-marine setting and rarity of graphoglyptid-bearing turbidites support the idea that taphonomic restrictions on graphoglyptid burrows could be locally more important than bathymetric constraints. Furthermore, the bathymetric distribution of the characteristic deep-marine *Ophiomorpha rudis* (shallowest); *Paleodictyon* (intermediate), and *Nereites* (deepest) ichnosubfacies is similar to the distribution trend of the same ichnosubfacies in leveed-channel complexes, from proximal channels (*O. rudis*) to intermediate (*Paleodictyon*) and distal levees (*Nereites*). In leveed channels, this distribution is not controlled by bathymetry, but interestingly, in both settings the ichnosubfacies distribution follows a diminishing energy gradient. Fluctuation of nutrients with time may explain the apparently anomalous occurrence of graphoglyptids and associated organic-rich beds.

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