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Sharp-based marine sandstone bodies in the Mulichinco Formation (Lower Cretaceous), Neuquén Basin, Argentina: remnants of transgressive offshore sand ridges

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ABSTRACT

The interpretation of sharp-based shallow-marine sandstone bodies encased in offshore mudstones, particularly transgressive units, has been a subject of recent debate. This contribution provides a multiple-dataset approach and new identification criteria which could help in the recognition of transgressive offshore sandstone bodies worldwide. This study integrates sedimentology, ichnology, taphonomy and palaeoecology of Mulichinco Formation strata in the central Neuquén Basin (Argentina) in order to describe and interpret sharp-based sandstone bodies developed in ramp-type marine settings. These bodies are sandwiched between finer-grained siliciclastics beneath and thin carbonates above. The underlying sediments comprise progradational successions from offshore mudstones to offshore transition muddy sandstones, grading occasionally into lower shoreface sandstones. The surfaces capping the regressive siliciclastics are flat and regionally extensive, and are demarcated by skeletal concentrations and a *Glossifungites* suite; they are also marked by sandstone rip-up clasts, with encrustations and borings on all sides. These surfaces are interpreted as composite discontinuities, cut during a relative sea-level fall and remodelled during the initial transgression. The overlying transgressive sandstone bodies are 3 to 7 m thick, >4 km long and about three times longer than wide; they are composed of fine-grained sandstones with little lateral change in grain size. Cross-stratification and/or cross-lamination are common, typically with smaller-scale structures and finer grain size towards the top. Large-scale, low-angle (5° to 8°) inclined stratification is also common, dipping at *ca* 30° with respect to body elongation and dominant currents. These sandstone bodies are interpreted as offshore sand ridges, probably developed under the influence of tidal currents. Intense burrowing is typical at the top of each unit, suggesting an abandonment stage. Final deactivation favoured colonization by epibenthic-dominated communities and the formation of skeletal-rich limestones during the latest transgressive conditions. As partial reworking of pre-existing ridges occurred during this stage, the Mulichinco sandstone bodies are considered the remnants of transgressive offshore sand units.

Keywords: Lower Cretaceous ramp, Neuquén Basin, offshore sand ridges, siliciclastic/carbonate marine systems, transgressive sandstone units.

INTRODUCTION

Ancient sharp-based shallow-marine sandstone bodies can represent the product of: (i) gradual shallowing in high-energy systems (prograding barred deposits; Clifton, 1981, 2006); (ii) abrupt basinward shifts and shoreface migration (forced-regressive/lowstand deposits; Plint, 1988; Bergman

& Walker, 1999; MacEachern *et al.*, 1999a); (iii) incised shoreface during minor stillstands of long-term transgression (Bergman, 1999; MacEachern *et al.*, 1999b; Cattaneo & Steel, 2003); or (iv) transgressive shelf sandstones modelled as ridges or patches (Tillman & Martinsen, 1984; Posamentier, 2002). Several sharp-based sandstone bodies studied in the 1980s were interpreted initially as transgressive shelf ridges (Tillman & Martinsen, 1984, 1987; Krause & Nelson, 1991), but subsequent alternative interpretations were proposed, ranging from incised-valley deposits (Sullivan *et al.*, 1997) to falling-stage shoreface deposits (Bergman & Walker, 1999). As a result of this debate, unequivocal transgressive sandstone bodies as analogues of shelf ridges are almost absent in the literature (Snedden & Bergman, 1999; Suter & Clifton, 1999), with a few rare exceptions (Posamentier, 2002). Suter (2006), when reviewing the state of the art of sharp-based marine sandstone bodies, suggested that an unambiguous interpretation for ancient examples could be achieved solely by integrating multiple datasets.

On the other hand, Quaternary linear sand ridges are common and relatively easy to identify in many modern continental shelves; they form and evolve during transgressive conditions (Swift & Field, 1981; Snedden & Dalrymple, 1999; Berné, 2003; Suter, 2006), and the sand typically is provided by reworking of older sandy coastal deposits (palimpsest material; Swift *et al.*, 1971). Sand ridges may form both in storm and tide-dominated shelves (Snedden & Dalrymple, 1999), and they can be developed near the coeval coastline ('shoreface ridges') but also several kilometres away from it ('offshore ridges'; Swift & Field, 1981). Although linear sand ridges exceptionally can extend for many tens of kilometres and be up to 40 m thick (Berné *et al.*, 2002), smaller ridges, typically <10 m thick and a few kilometres long are fairly common in shallow shelves (Davis *et al.*, 1993; Snedden *et al.*, 1999; Harrison *et al.*, 2003; Bassetti *et al.*, 2006).

In the central Neuquén Basin (west-central Argentina), sharp-based elongated sandstone bodies up to 3 km wide and less than 7 m thick occur within a siliciclastic-dominated marine succession of the Valanginian Upper Member of the Mulichinco Formation. This unit is composed mostly of regressive fine-grained siliciclastics capped by thin transgressive skeletal carbonates, representing high-frequency sequences developed in a shallow and ramp-type marine setting (Schwarz & Howell, 2005; Schwarz *et al.*, 2006). Sharp-based sandstone bodies reported and discussed in this contribution invariably are sandwiched between the regressive fine-grained siliciclastics beneath and the carbonates on top, and they are interpreted as being developed several kilometres basinward of previous highstand shorelines.

This study integrates multiple datasets (three-dimensional sedimentology, ichnology, taphonomy and palaeoecology) from both the sandstone bodies and surrounding sediments of the Upper Member of the Mulichinco Formation in order to describe and interpret facies associations, as well as to document internal organization, geometry and key stratigraphic surfaces of sandstone units. This provides a better understanding of depositional systems and compelling evidence to define the basal bounding surfaces of sandstone bodies as composite erosional surfaces produced during relative sea-level fall and subsequent transgression. The transgressive genesis of the sandstone units, together with their internal attributes allowed for their interpretation as transgressive offshore accumulations. Subsequently, a discussion on their formation, evolution and preservation is presented. In this way, the lessons learned from the Mulichinco transgressive sandstone bodies could help in recognizing similar units worldwide (which are notably rare to date), as well as providing insights on characterization of reservoir analogues, for example in the Neuquén Basin, but also in the Western Interior (USA) and offshore Java.

The aims of this paper are two-fold: (i) to unravel depositional systems, key stratigraphic surfaces and sequence stratigraphic implications for fine-grained and sandstone-dominated units, as well as skeletal carbonates of the Upper Member of the Mulichinco Formation; and (ii) to illustrate the utility (and need) of multiple datasets to correctly understand the genesis of sharp-based marine sandstone bodies.

GEOLOGICAL CONTEXT AND STRATRIGRAPHIC FRAMEWORK

The Neuquén Basin is located on the eastern side of the Andes in west-central Argentina, between latitudes 32° and 40° south (Fig. 1). It covers an area of over 120 000 km^2 and comprises a nearly continuous record of up to 6000 m of stratigraphy from the Late Triassic to Early Cenozoic. This sedimentary record includes continental and marine siliciclastics, carbonates and evaporites that accumulated under a variety of basin styles, including syn-rift, post-rift/sag and foreland

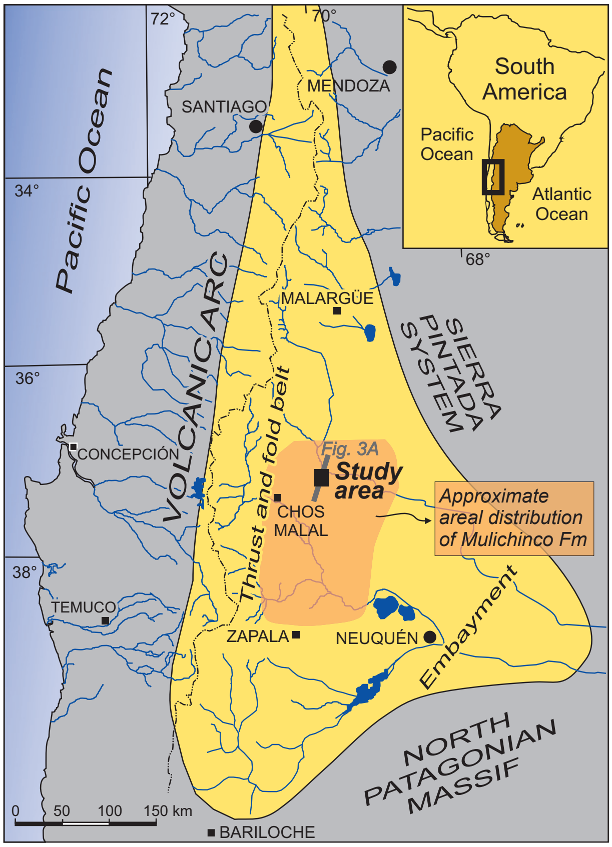


Fig. 1. Location map of the Neuquén Basin and the study area. The approximate areal extension of the Mulichinco Formation is also shown.

phases (Legarreta & Uliana, 1991; Howell *et al.*, 2005). The basin has a broadly triangular shape (Fig. 1) in which two main regions are recognised, the Andean thrust and fold belt to the west and the Neuquén Embayment to the east and south-east. Oil and gas production in the Neuquén Embayment provides about 50% of the total hydrocarbon extracted in Argentina.

The Mendoza Group (Late Jurassic to Early Cretaceous) was deposited in a broad, shallow water epeiric sea, characterized by a ramp-type profile along the east and south margins (Legarreta & Uliana, 1991; Spalletti *et al.*, 2000) but with a higher depositional profile towards the west (Spalletti *et al.*, 2008). This configuration, or back-arc setting, was controlled heavily by the development and growth of the Andean magmatic arc located to the west (Fig. 1). The sedimentary infill of the Mendoza Group records a series of large-scale, second-order sequences (Fig. 2), reflecting the interaction between eustacy and tectonics (Vergani *et al.*, 1995; Howell *et al.*, 2005; Schwarz *et al.*, 2006).

The Valanginian Mulichinco Formation represents a second-order lowstand wedge within the Mendoza Group (Fig. 2), and was deposited in response to a tectonically-induced major sea-level drop (Schwarz & Howell, 2005; Schwarz *et al.*, 2006). This unit consists of a 170 to 400 m thick succession, with terrestrial to marginal-marine deposits in the southern part of the basin (Fig. 2) grading to fully marine deposits towards the north and north-west (Schwarz & Howell, 2005). These authors described and interpreted a number of key, basin-wide stratigraphic surfaces as well as different stratal stacking patterns within the Mulichinco lowstand wedge that allow the identification of three third-order systems tracts: lowstand systems tracts (LST), transgressive systems tracts (TST) and highstand systems tracts (HST) (Fig. 2). Accordingly, this complex lowstand wedge was defined as the Mulichinco Lowstand Sequence (for further description and discussion on the internal stratigraphic architecture of this sequence refer to Schwarz & Howell, 2005 and Schwarz *et al.*, 2006).

In the downdip or marine sector of the basin (central Neuquén Basin) the Mulichinco Formation consists of up to 300 m of marine deposits and the exposed area represents the North-eastern Region described in Schwarz *et al.* (2006). The unit is divided into three informal members (Schwarz, 1999): Lower, Middle and Upper Members (Fig. 3A). The Lower Member (<70 m thick) is essentially siliciclastic, and comprises two progradational successions, with offshore mudstones grading upward into lower shoreface sandstones with hummocky cross-stratification (HCS). This siliciclastic system, developed under relatively low accommodation and high sediment supply, was prograding mainly to the west. The Middle Member (50 to 70 m) is primarily a carbonate unit, with abundant macrofossil and microfossil fauna (Fig. 3A). Bio-accumulations dominated by attached-living oysters and serpulids characterized this interval, interbedded with marls, wackestones and skeletal floatstones (Schwarz, 1999; Schwarz & Howell, 2005). This carbonate succession was interpreted to represent a low-energy, ramp-type open-marine carbonate system developed under low to null sediment flux during third-order transgressive conditions (Schwarz & Howell, 2005).

The Upper Member of the Mulichinco Formation (100 to 160 m thick), the unit containing the studied sharp-based sandstone bodies, is com-

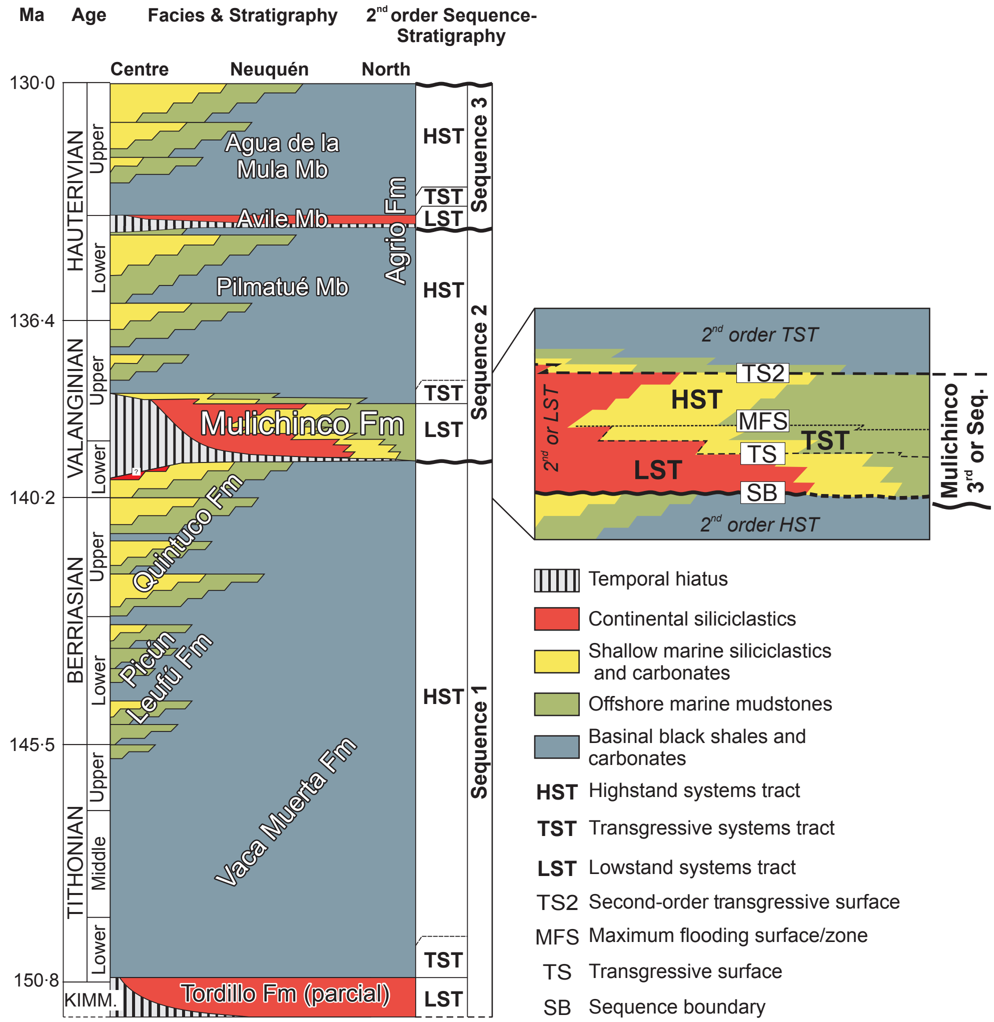


Fig. 2. Chronostratigraphic chart for the Tithonian–Huaterivian of the Neuquén Basin (modified from Schwarz *et al.*, 2006). Age of units from Leanza (1993), Aguirre-Urreta *et al.* (2005) and Schwarz & Howell (2005). Time scale after Ogg *et al.* (2004). The Mulichinco Formation, the study unit, represents a second-order lowstand wedge developed during a tectonically enhanced relative sea-level drop. Third-order systems tracts (LST, TST and HST) and key stratigraphic surfaces recognized within the Mulichinco strata (shown on the enlarged area of the figure) allow definition of a third-order sequence, the so-called Mulichinco Lowstand Sequence (Schwarz *et al.*, 2006).

posed principally of siliciclastic sediments (Fig. 3 A); they commonly comprise coarsening-upward successions (3 to 20 m thick) from offshore mudstones to shoreface sandstones interpreted to have been deposited in a marine ramp (Schwarz, 1999). These parasequences stack vertically forming parasequence sets (Schwarz & Howell, 2005), which commonly are capped by carbonate-dominated packages (Fig. 3A). Parasequence sets are most likely to record long-lived basinward migration of shorelines for a few kilometres to few tens of kilometres (Fig. 3B), although coastal plain deposits were never formed or preserved in this region (Schwarz & Howell, 2005). Carbonate packages are reflecting transgressive periods and landward shifting of facies belts. Within the Mulichinco third-order sequence, this upper unit represents an aggradational/progradational interval after the transgressive carbonate event (Fig. 3A) and therefore was interpreted as the HST (Schwarz & Howell, 2005).

The Upper Mulichinco Member is dominated by amalgamated fine-grained sandstones with HCS, planar-tangential cross-bedding or, more rarely, trough cross-bedding in the southern sector (Schwarz & Howell, 2005), but their proportion diminishes rapidly westward and northward (Fig. 3A), being replaced by muddy sandstones and mudstones, and thin skeletal carbonates. In terms of depositional systems, this

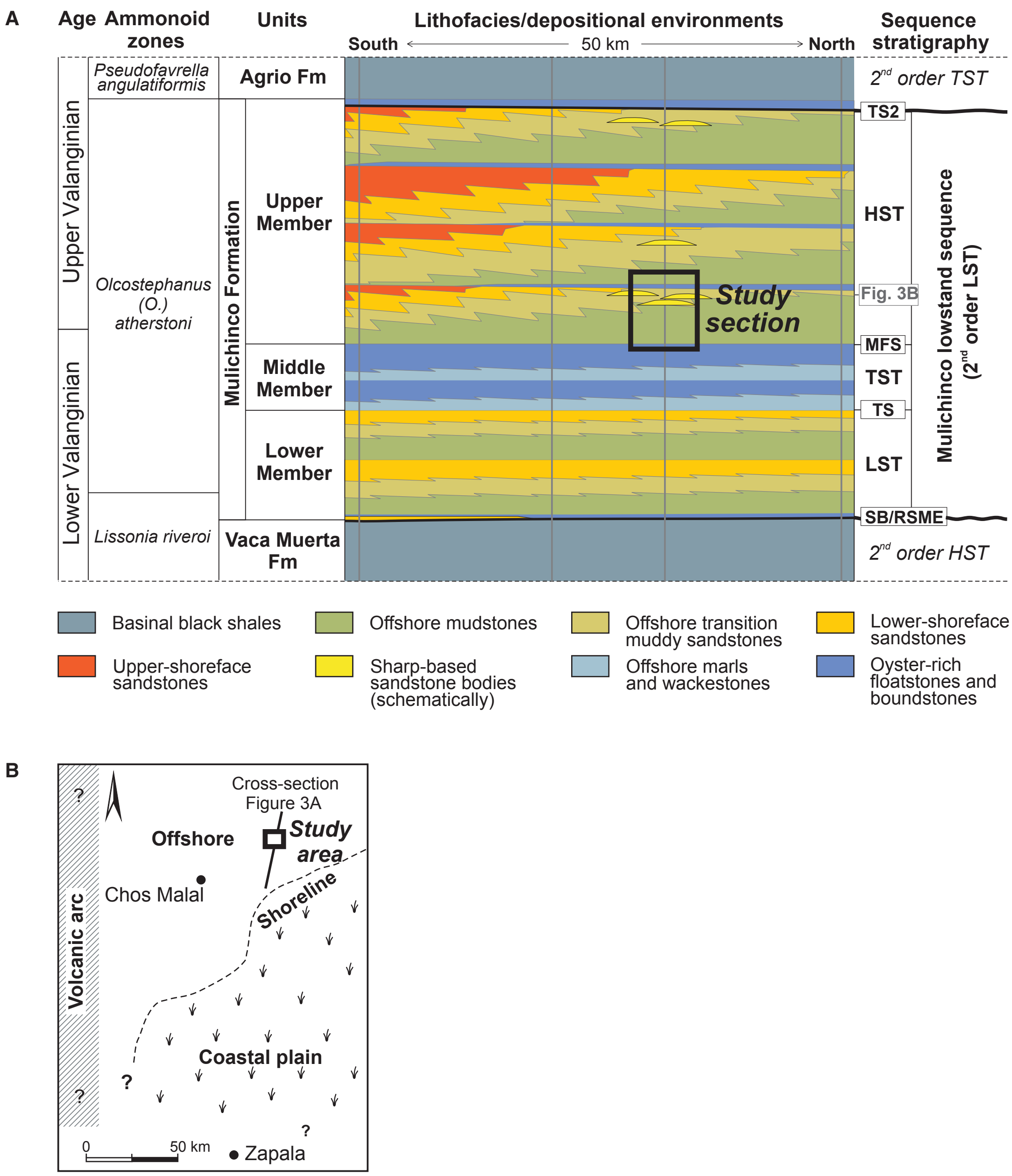


Fig. 3. (A) Cross-section showing age, facies, depositional systems and sequence stratigraphic framework of the Mulichinco Formation in the central region of the Neuquén Basin based on four sedimentological logs (grey vertical lines). See Fig. 1 for location of cross-section. Note the northward proximal to distal trend defined for the Upper Member of the Mulichinco Formation. The sharp-based sandstone bodies which are described and discussed in this contribution are shown schematically; they occur within a succession dominated by offshore and offshore-transition strata. SB, sequence boundary; RSME, regressive surface of marine erosion. See Fig. 2 for additional legend. (B) Highly schematic palaeogeographical reconstruction of the Upper Member of the Mulichinco Formation from a time slice indicated in (A). Reconstruction is based on previously reported data (Schwarz & Howell, 2005; Schwarz *et al.*, 2006) and this paper.

is suggestive of dominant upper and lower shoreface conditions in the south but more common offshore and offshore-transition settings to the west and north, defining a well-developed proximal–distal trend within the marine system. Thus, the depositional profile at this time was not only deepening in a westward direction (as during the LST), but also to the north (Fig. 3A and B). The area containing the investigated sharp-based sandstone bodies represents a middle to distal segment of this shoreface-offshore depositional system (Fig. 3A and B).

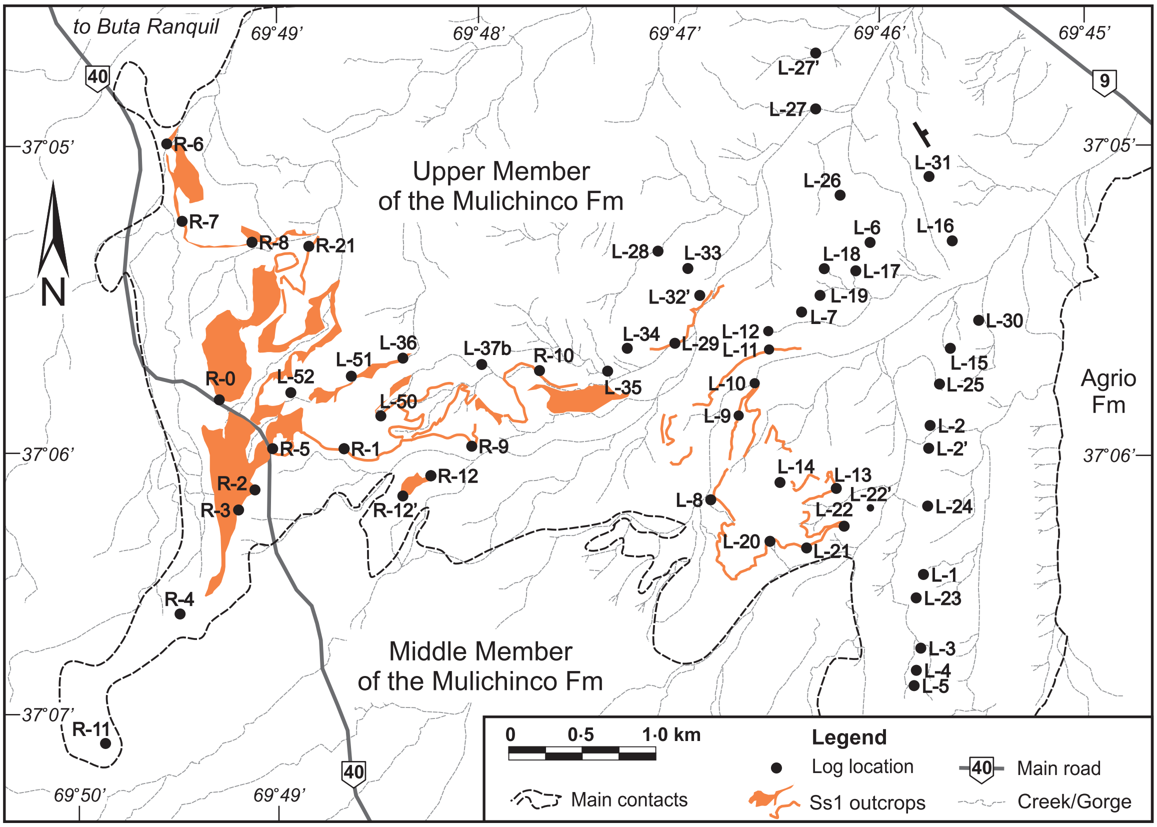


Fig. 4. Map of the study area showing the location of detailed sections measured in the Upper Member of the Mulichinco Formation (see Fig. 1 for location), and the contact with underlying (Middle Member of Mulichinco Formation) and overlying (Agrio Formation) units. Outcrops of selected sandstone bodies (Ss1) discussed in this paper are also shown.

STUDY AREA AND METHODS

The study area is located in the central part of the Neuquén Basin, near the town of Buta Ranquil, in the northern Neuquén Province (Figs 1 and 4). The investigated area is 8 km by 5 km (40 km^2) and it has an easy access from the 40 National Road (Fig. 4). The strata of the Upper Member of the Mulichinco Formation are almost horizontal or rarely gently dipping (<6°), and are well-exposed in poorly vegetated, accessible hillsides (Fig. 5). Besides, numerous gorges cut in different orientations providing a three-dimensional view of sandstone bodies and the surrounding sediments (Figs 4 and 5).

This investigation focused on the lower half (65 m thick section) of the Upper Member of the Mulichinco Formation (Figs 3 and 6). This succession is composed mostly of fine-grained siliciclastics cyclically interbedded with skeletal carbonates. Within this study window nine high-frequency cycles were recognized, each characterized by a relatively thin basal carbonate-dominated hemicycle and a thick, coarsening-upward, siliciclastic-dominated hemicycle (Fig. 6). The investigated sharp-based sandstone bodies are sandwiched between the coarsening-upward siliciclastics beneath and the carbonates on top, and they occur in the upper half of the study stratigraphic section (Fig. 6); they have also developed several kilometres down-dip from the shoreface deposits interpreted to be coeval of surrounding fine-grained siliciclastics (Fig. 3).

The studied succession was investigated by logging of more than 60 bed by bed sections (Fig. 4), typically less than 500 m apart. Conventional sedimentological description was carried out in each section, but also faunal, ichnofaunal and taphonomic data were collected (Fig. 6). Interpretation of macrofossil associations follows recent palaeoecological studies of Lower Cretaceous assemblages of the basin (Lazo *et al.*, 2005). Geobody architecture and key stratigraphic surfaces were walked-out and mapped laterally in the field (Fig. 4). In this

Fig. 5. Field view of the study interval in (A) the western sector and (B) the eastern sector of the study area with the location of selected logged sections. Sharp-based sandstone bodies are present in both regions but, although they occur in a similar stratigraphic position, they are independent bodies (see also Fig. 6).

way, physical correlation of key stratigraphic horizons between different sectors of the study area was achieved (Fig. 6). Petrography of 50 thin sections and X-ray diffraction studies of selected samples were conducted in the laboratory. Both east–west and north–south correlation panels were constructed to show facies association relationships and key stratigraphic surfaces (Fig. 7). The sandstone bodies are constrained stratigraphically between two carbonate intervals that are continuous across the study area, providing a lower and upper datum for the correlation of all the logs (Figs 5, 6 and 7).

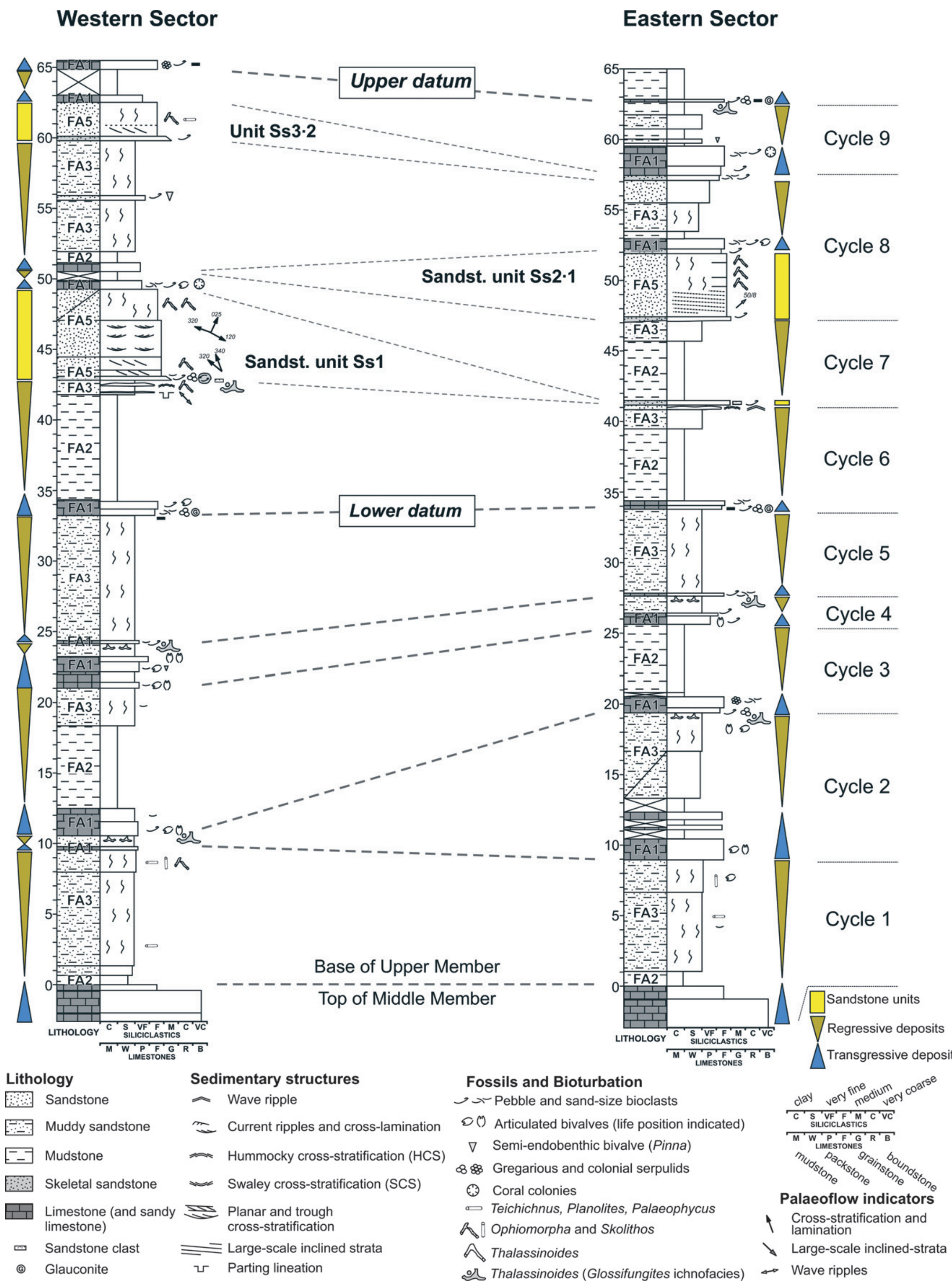
FACIES ASSOCIATIONS

Five facies associations were identified and interpreted within the 65 m thick study succession of the Upper Member of the Mulichinco Formation. One association is dominated by carbonate components (micrite and skeletal grains), whereas the rest essentially are composed of siliciclastic lithofacies with a low or null proportion of carbonate particles.

Facies Association 1: Skeletal limestones

Description

This facies association (FA1) comprises skeletal floatstones and packstones as well as silty wackestones (Fig. 8A). Floatstones typically comprise pebble-size shells floating in a micritic-dominated matrix, which also has poorly sorted finer bioclasts as well as terrigenous silt and very fine sand (Fig. 8B and C). Within shells, the articulation degree is moderate to high whereas fragmentation varies from low to moderate (Fig. 8B). Macrofossil associations in these shell-rich deposits are sometimes dominated at the base by attached-living suspension-feeder invertebrates, namely oysters (*Amphidonte sp.*) and gregarious serpulids (*Parsimonia sp.*). Locally, however, globose corals and colonial serpulids are dominant. Alternatively, endobenthic-dominated macrofaunal associations, composed mainly of shallow-burrowing and deep-burrowing bivalves, together with irregular echinoids and microgastropods, prevail within these skeletal floatstones (Fig. 8B and C). Skeletal packstones are uncommon and occur adjacent to the floatstone facies. Skeletal



Western Sector
Eastern Sector
Upper datum
Unit Ss3·2
Sandst. unit Ss2·1
Sandst. unit Ss1
Lower datum
Base of Upper Member
Top of Middle Member
Cycle 9
Cycle 8
Cycle 7
Cycle 6
Cycle 5
Cycle 4
Cycle 3
Cycle 2
Cycle 1
FA1
FA2
FA3
FA5
LITHOLOGY
C S VF F M C VC
SILICICLASTICS
M W P F G R B
LIMESTONES
Sandstone units
Regressive deposits
Transgressive deposit
Lithology
Sandstone
Muddy sandstone
Mudstone
Skeletal sandstone
Limestone (and sandy limestone)
Sandstone clast
Glauconite
Sedimentary structures
Wave ripple
Current ripples and cross-lamination
Hummocky cross-stratification (HCS)
Swaley cross-stratification (SCS)
Planar and trough cross-stratification
Large-scale inclined strata
Parting lineation
Fossils and Bioturbation
Pebble and sand-size bioclasts
Articulated bivalves (life position indicated)
Semi-endobenthic bivalve (Pinna)
Gregarious and colonial serpulids
Coral colonies
Teichichnus, Planolites, Palaeophycus
Ophiomorpha and Skolithos
Thalassinoides
Thalassinoides (Glossifungites ichnofacies)
clay
very fine
medium
very coarse
mudstone
packstone
grainstone
boundstone
Palaeoflow indicators
Cross-stratification and lamination
Large-scale inclined-strata
Wave ripples

Fig. 6. Representative sections through the study interval (lower half of the Upper Member of the Mulichinco Formation) illustrating facies successions, facies associations, datum and key stratigraphic surfaces in the eastern and western sectors of the study area. Nine high-frequency cycles bounded by composite stratigraphic discontinuities have been defined within the study interval. The lower six cycles start with transgressive carbonates, grading upwards into regressive fine-grained siliciclastics. Sharp-based sandstone bodies (Ss1, Ss2·1 and Ss3·2), well-constrained by a lower and upper datum, are interpreted in this paper to represent early transgressive conditions (see *Discussion* in the text for more explanations). Therefore, when present, they are placed at the base of the corresponding cycle. Legend is also for sections shown in Figs 7 and 9.

remains of previously described invertebrate fossils are highly fragmented and abraded in the packstone facies, and planar-tangential cross-stratification is common (Fig. 8D). In turn, wackestones are composed largely of shells <2 mm long, calcispheres and siliciclastic silt (Fig. 8E). Siliciclastics make up to 15% of the rock and quartz grains are dominant. The preserved macrofossil association is dominated by internal and external moulds of deep-burrowing bivalves (for example, *Panopea sp.*). These moulds can be abundant in a single bed and specimens in life position are common (Fig. 8E). The silty wackestones typically overlie both floatstones and packstones (Fig. 8A). This facies association is not volumetrically significant (typically less than 1 m thick), but is regionally extensive (Fig. 7).

Interpretation

A high proportion of micrite and low taphonomic indices suggest that skeletal floatstones represent low-energy marine environments (cf. Fürsich, 1995), subjected to low or moderate wave reworking. The interpreted parautochthonous to autochthonous macrofossil assemblages indicate normal-marine salinity conditions and probably temperate to warm waters (James, 1997). Epibenthic-dominated communities are interpreted to represent the lowest net accumulation rates (Brett, 1995), temporally and spatially replaced by endobenthic-rich communities. Cross-stratified skeletal packstones with higher taphonomic indices (high fragmentation, abrasion and orientation) originated by dune-scale bedforms, probably near the swept zone in a proximal middle to inner ramp setting (cf. James, 1997). Silty wackestones are considered to reflect minimum depositional energy but still under low sedimentation rates, as evidenced by the high concentration of articulated specimens in life position. All together, these carbonate-dominated packages within a siliciclastic-dominated succession are interpreted to represent transgressive conditions within high-frequency cycles (Schwarz, 2010). Transgressive carbonate-rich hemicycles have been reported in other mixed successions of the Neuquén Basin (Spalletti *et al.*, 2001) and elsewhere (Abbott, 1998; Morris *et al.*, 2006).

Facies Association 2: Massive mudstones

Description

This facies association (FA2) consists mainly of greenish and greyish massive mudstones and siltstones (Fig. 9A). Macrofauna is typically absent, but occasionally skeletal fragments are present at the base of the association having a fining-upward trend from FA1. Shells are distributed randomly, centimetres to millimetres in length and derived mainly from oysters. This association is up to 7 m thick and typically grades vertically and laterally to FA3 (Figs 7 and 9A).

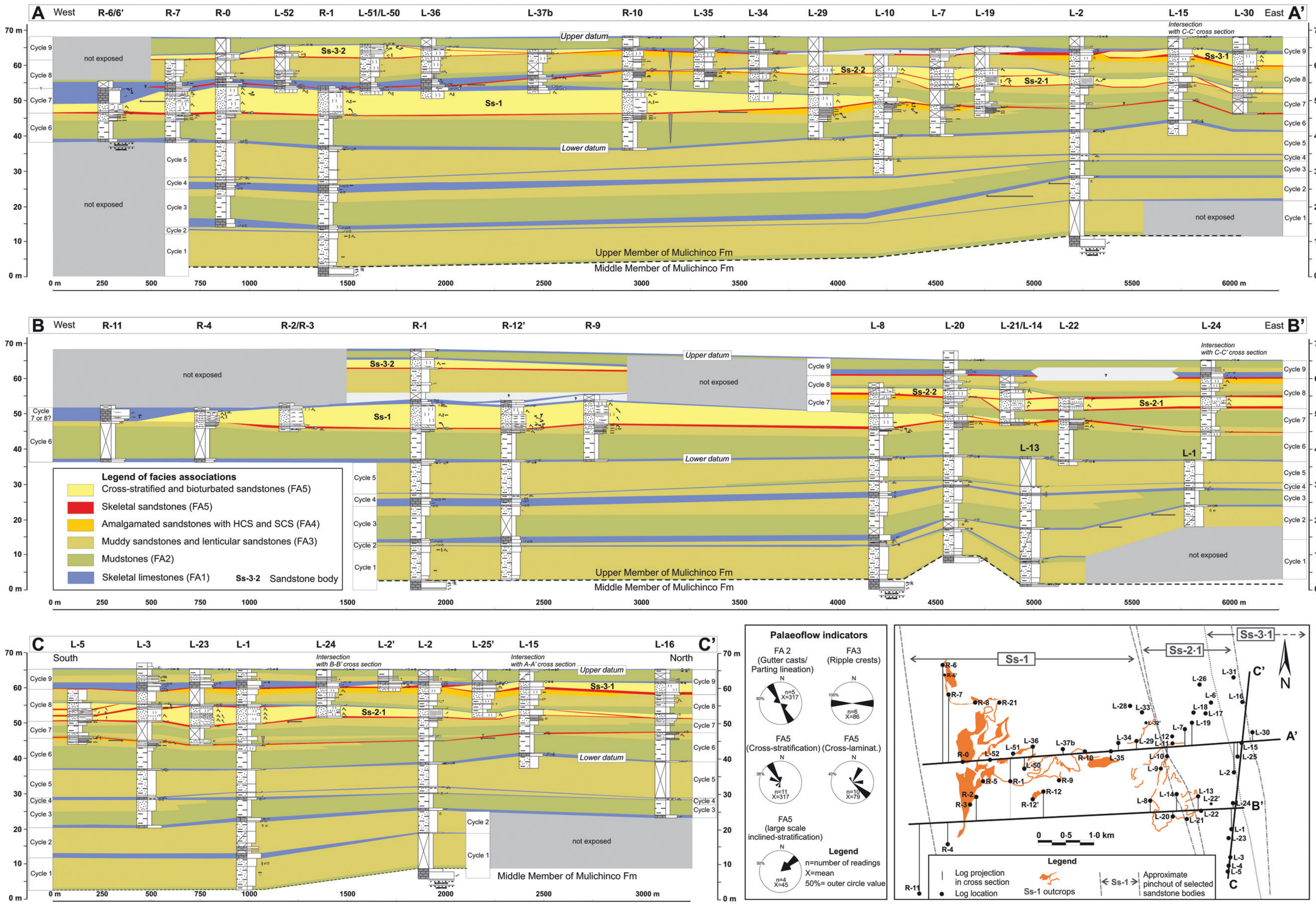
Interpretation

This association is interpreted to reflect settling from suspension onto a relatively well-oxygenated, low-energy sea floor. The close vertical relationship with FA1 and FA3 (see below) suggests that this low-energy setting represents a marine offshore depositional environment. Contrary to the previous facies association, however, siliciclastic mudstones and contemporaneous shell dilution indicate that FA2 marks a shift towards periods characterized by high terrigenous sediment flux from hinterland areas (Abbott, 1997).

Facies Association 3: Muddy sandstones and lenticular HCS-sandstones

Description

This facies association (FA3) is composed of muddy sandstones and subordinated hummocky cross-stratified sandstones (Fig. 9). Muddy sandstones have up to 30% mud, but terrigenous coarse silt and very fine sands dominate. Calcispheres and millimetre-long skeletal fragments (from bivalves and echinoids) are uncommon. This facies is heavily bioturbated and the trace fossil assemblage includes *Teichichnus*, *Planolites*, *Thalassinoides* and *Palaeophycus*. Macro-


A West R-6/6' R-7 R-0 L-52 R-1 L-51/L-50 L-36 L-37b R-10 L-35 L-34 L-29 L-10 L-7 L-19 L-2 L-15 L-30 East A'
Intersection with C-C' cross section
Upper datum
Lower datum
not exposed
Ss-3-2
Ss-2-2
Ss-2-1
Ss-3-1
Ss-1
Cycle 9
Cycle 8
Cycle 7
Cycle 6
Cycle 5
Cycle 4
Cycle 3
Cycle 2
Cycle 1
Upper Member of Mulichinco Fm
Middle Member of Mulichinco Fm
70 m
60
50
40
30
20
10
0 m
0 m 250 500 750 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000 m
B West R-11 R-4 R-2/R-3 R-1 R-12' R-9 L-8 L-20 L-21/L-14 L-22 L-24 East B'
Intersection with C-C' cross section
Cycle 7 or 8?
L-13
L-1
Legend of facies associations
Cross-stratified and bioturbated sandstones (FA5)
Skeletal sandstones (FA5)
Amalgamated sandstones with HCS and SCS (FA4)
Muddy sandstones and lenticular sandstones (FA3)
Mudstones (FA2)
Skeletal limestones (FA1)
Ss-3-2 Sandstone body
C South L-5 L-3 L-23 L-1 L-24 L-2' L-2 L-25' L-15 L-16 North C'
Intersection with B-B' cross section
Intersection with A-A' cross section
0 m 250 500 750 1000 1500 2000 2500 3000 m
Palaeoflow indicators
FA 2 (Gutter casts/ Parting lineation)
n=5 X=317
FA3 (Ripple crests)
n=6 X=86
FA5 (Cross-stratification)
n=11 X=317
FA5 (Cross-laminat.)
n=10 X=79
FA5 (large scale inclined-stratification)
n=4 X=45
Legend
n=number of readings
X=mean
50%= outer circle value
Ss-1
Ss-2-1
Ss-3-1
N
A'
B'
C'
C
0 0·5 1·0 km
Legend
Log projection in cross section
Log location
Ss-1 outcrops
Approximate pinchout of selected sandstone bodies

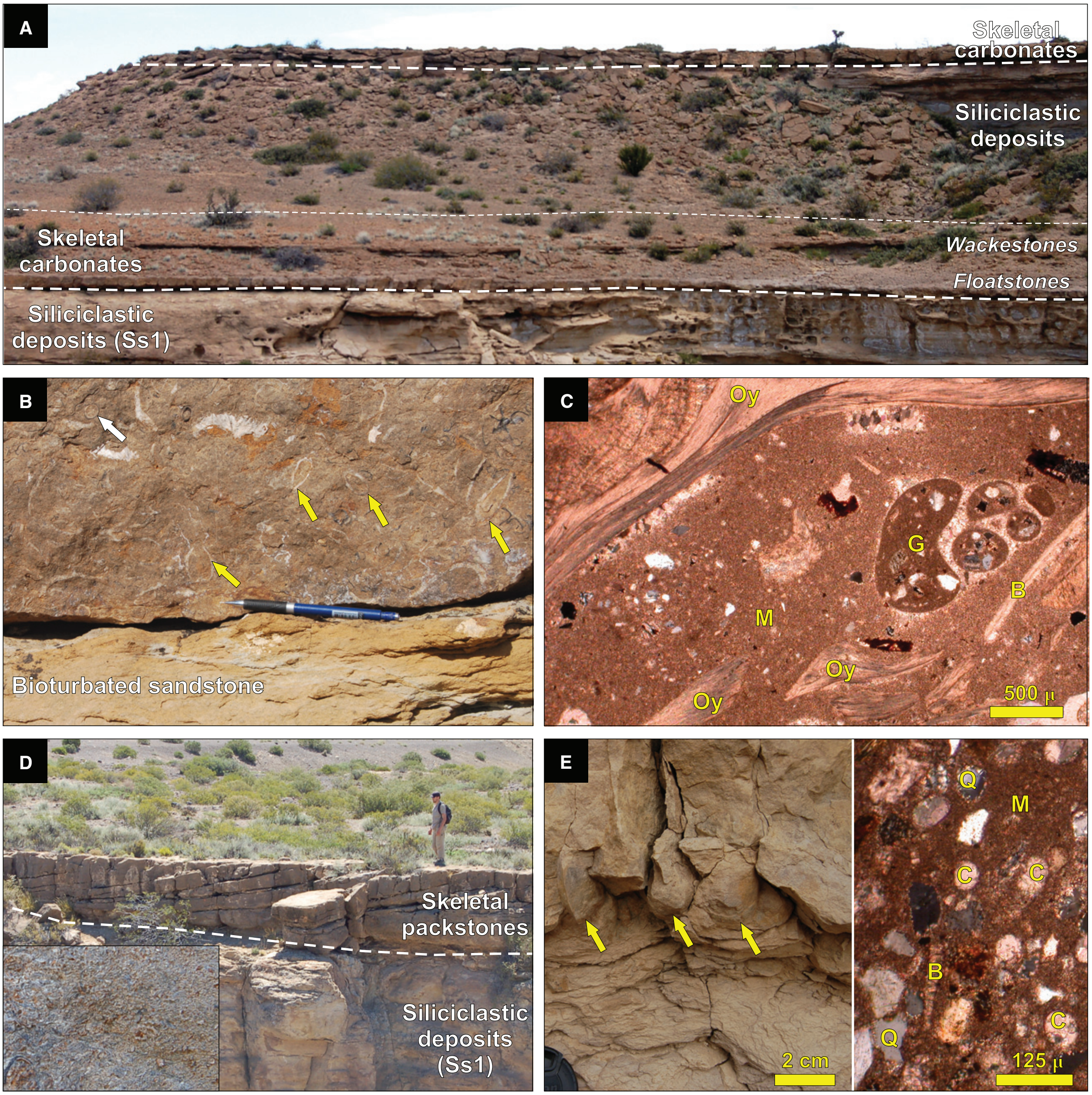


Fig. 8. Main attributes of Facies Association 1. (A) Field view of a carbonate-dominated interval sharply overlying siliciclastic deposits and grading from skeletal floatstones to wackestones. (B) Close-up view of the floatstone facies showing chaotically distributed bivalve remains with recrystallized shells (yellow arrows), but also oyster fragments and serpulids (white arrows). Note the pebble size of shells (up to 50 mm long) and the abundance of articulated bivalves, suggesting moderate to low fragmentation and probably low lateral transport (i.e. a parautochthonous fossil association). Pencil for scale (15 cm long). (C) Microphotograph (cross-polarized) of a skeletal floatstone showing a micrite-dominated matrix 'M' in which oyster 'Oy', gastropod 'G' and undefined bivalve 'B' fragments are dispersed. Bar for scale. (D) Cross-stratified packstones in the western sector. Person for scale, *ca* 1·8 m tall. Inset shows highly fragmented bioclasts. (E) Silty wackestones as seen in the field and under microscope. Internal moulds of deep-burrowing bivalves (for example, *Panopea* sp.) are common in this facies, typically oriented as in life position. Calcispheres 'C' and subordinated siliciclastic silt 'Q' are additional components of this micrite-dominated facies. Bars for scale.

Fig. 7. Correlation panels showing facies association distribution, sandstone body architecture and key stratigraphic relationships within the study interval of the Upper Member of the Mulichinco Formation. Two east–west correlation panels (A–A′ and B–B′) and one north–south panel are shown (C–C′). The position of the panels and projected sections are shown in the accompanying map. Main palaeoflow indicators mentioned in the text are also shown. Note that regressive siliciclastic units (Facies Associations 2 to 4) of successive cycles run across the study area whereas sandstone bodies (Facies Assocation 5) have terminations in different directions.

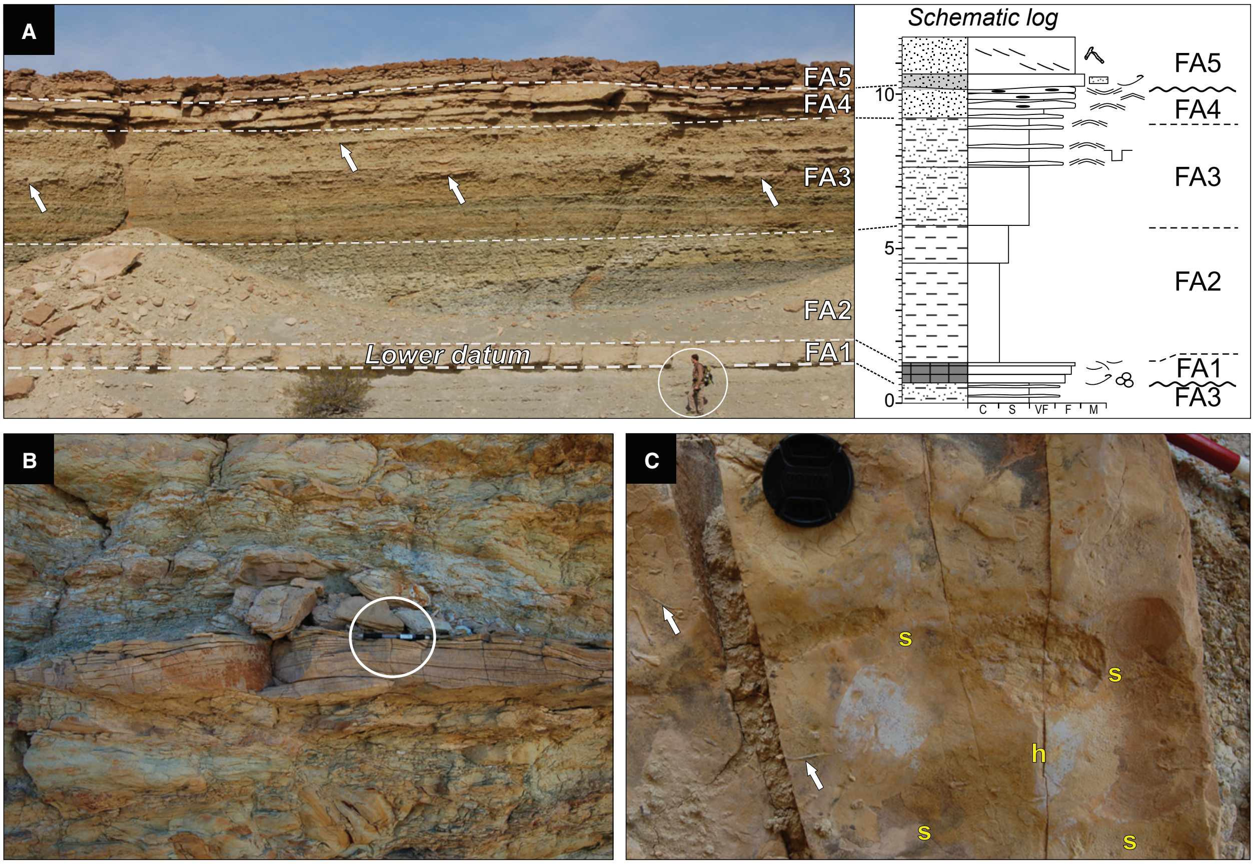


Fig. 9. Main attributes of Facies Associations 2 and 3 that together represent upward-coarsening and sandier siliciclastic successions. (A) Field view and corresponding logged section (L-10) of greenish mudstones of Facies Association 2 capping skeletal carbonates 'FA1' and, in turn, being gradually replaced upwards by muddy sandstones of Facies Association 3. Sandstone lenses with HCS (arrows) occur in the upper part of this association. Amalgamated sandstones 'FA4' and skeletal and cross-stratified sandstones 'FA5' occurring above FA3 are also seen. For log legend see Figure 6. (B) Close-up of upper part of Facies Association 3 showing pale-green massive muddy sandstones and a lenticular sandstone bed having nearly symmetrical hummocky cross-stratification. Pencil for scale (15 cm long). (C) Plan view of the top of a sandstone bed having ripples with swales 's' and hummocks 'h' representing 3D symmetrical small ripples (cf. Myrow & Southard, 1991). Small horizontal trace fossils are also observed in this top (arrows). Lens cap for scale (5 cm diameter).

fossils are rare but, when present, pockets and stringers of endobyssate bivalves (*Pinna* sp.) dominate; and moulds in life position are frequent. Interbedded sandstone beds are thin (<0·3 m thick), have lenticular geometry (Fig. 9A and B) and consist mostly of clean, very fine-grained sand. Hummocky cross-stratification is ubiquitous. In most cases the typical, gently dipping convex-up and convex-down fine lamination prevails (isotropic HCS; Fig. 9B). However, anisotropic internal stratification characterized by moderately inclined sigmoidal foresets and round crests also occurs in some sandstone beds. Parting lineation is common within lamination and small symmetrical 3D ripples (cf. Myrow & Southard, 1991) occur on top of beds in some places (Fig. 9C). Parting lineation and occasional gutter casts show a preferential north-west to south-east and NNW to SSE orientation (Fig. 7). These clean sandstones have a low degree of bioturbation dominated by dwelling structures (*Ophiomorpha*, and less common *Skolithos*, *Arenicolites* and *Gyrochortes*). Homogenous intervals of muddy sandstones up to 6 m thick are common (Figs 6 and 7), with the isolated HCS-sandstone beds occurring (when present) towards the upper part of this association (Fig. 9A).

Interpretation

The presence of a mud fraction in this facies association suggests that normal bottom energy conditions were frequently low enough to allow for mud deposition and preservation (cf. Mac-

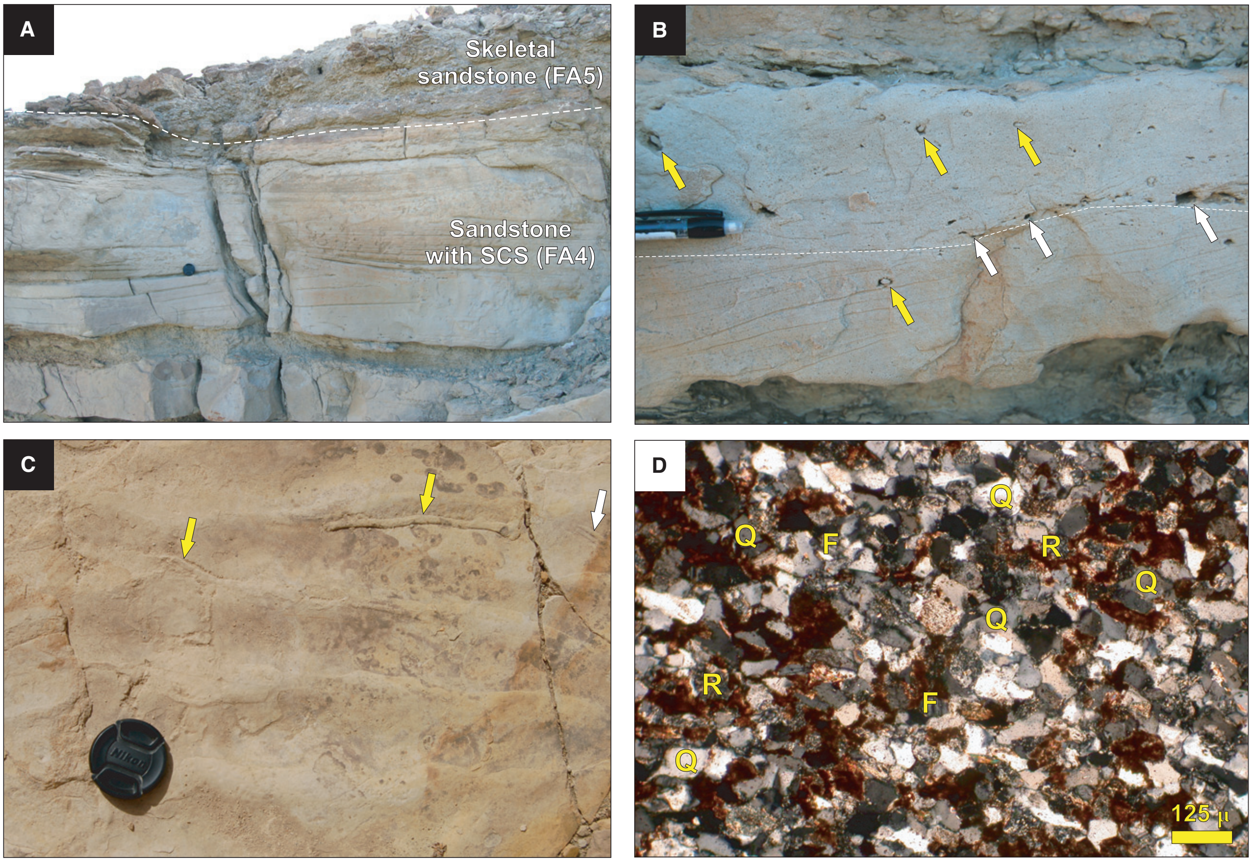


Fig. 10. Main attributes of Facies Association 4. (A) Whitish fine-grained sandstones with swaley cross-stratification (SCS). Lens cap for scale (5 cm diameter). (B) Sandstone bed having HCS. Note mudstone clasts (white arrows) demarcating the base of a set and the preferential occurrence of *Ophiomorpha* horizontal burrows (yellow arrows) in the upper half of the bed. Part of pencil for scale (4·5 cm long). (C) View of a sandstone top showing weakly asymmetrical ripples interpreted to be the result of combined flows. *Ophiomorpha* (yellow arrows) and *Gyrochortes* (white arrow) are also shown. Lens cap for scale (5 cm diameter). (D) Microphotograph (cross-polarized) of sandstone depicted in (B). The sandstones are composed of 100% terrigenous grains, and correspond to feldspathic arenites or lithic arenites dominated by quartz 'Q' (>60%), and subordinated feldspars 'F' and rock fragments 'R'.

Eachern *et al.*, 1999a,b; Morris *et al.*, 2006). Sea floor colonization by endobyssate bivalves also indicates moderate-energy levels, whereas echinoid fragments suggest an open-marine setting (cf. Fürsich, 1995). Storm events were common within this setting, but most of the silt and very fine sand probably was mixed with the mud through intense bioturbation. This observation is supported by the dominance of trace fossils attributable to deposit-feeding organisms within the muddy sandstones (belonging to a *Cruziana* Ichnofacies; MacEachern *et al.*, 2007a). Increasing storm frequency or proximity to the coastline allow for better preservation of storm deposits; these probably were emplaced under almost purely oscillatory flows and migration of near symmetrical bedforms (isotropic HCS), but also combined flows (anisotropic stratification) (Myrow & Southard, 1996; Dumas & Arnott, 2006). Once flows decayed, opportunistic filter-feeding organisms temporally colonized sandy substrates just before normal finer-grained sedimentation resumed. This facies association is interpreted to represent a storm-dominated offshore-shoreface transition, between the storm and fair-weather wave bases (Reading & Collinson, 1996). Post-storm offshore-directed flows were running preferentially at a high angle with respect to the inferred north-east to south-west palaeo-coastline.

Facies Association 4: Amalgamated sandstones with hummocky cross-stratification and swaley cross-stratification

Description

This facies association (FA4) grades vertically from the previous assemblage (FA3; Fig. 9A) but is uncommon within the study area (Fig. 7). It com-

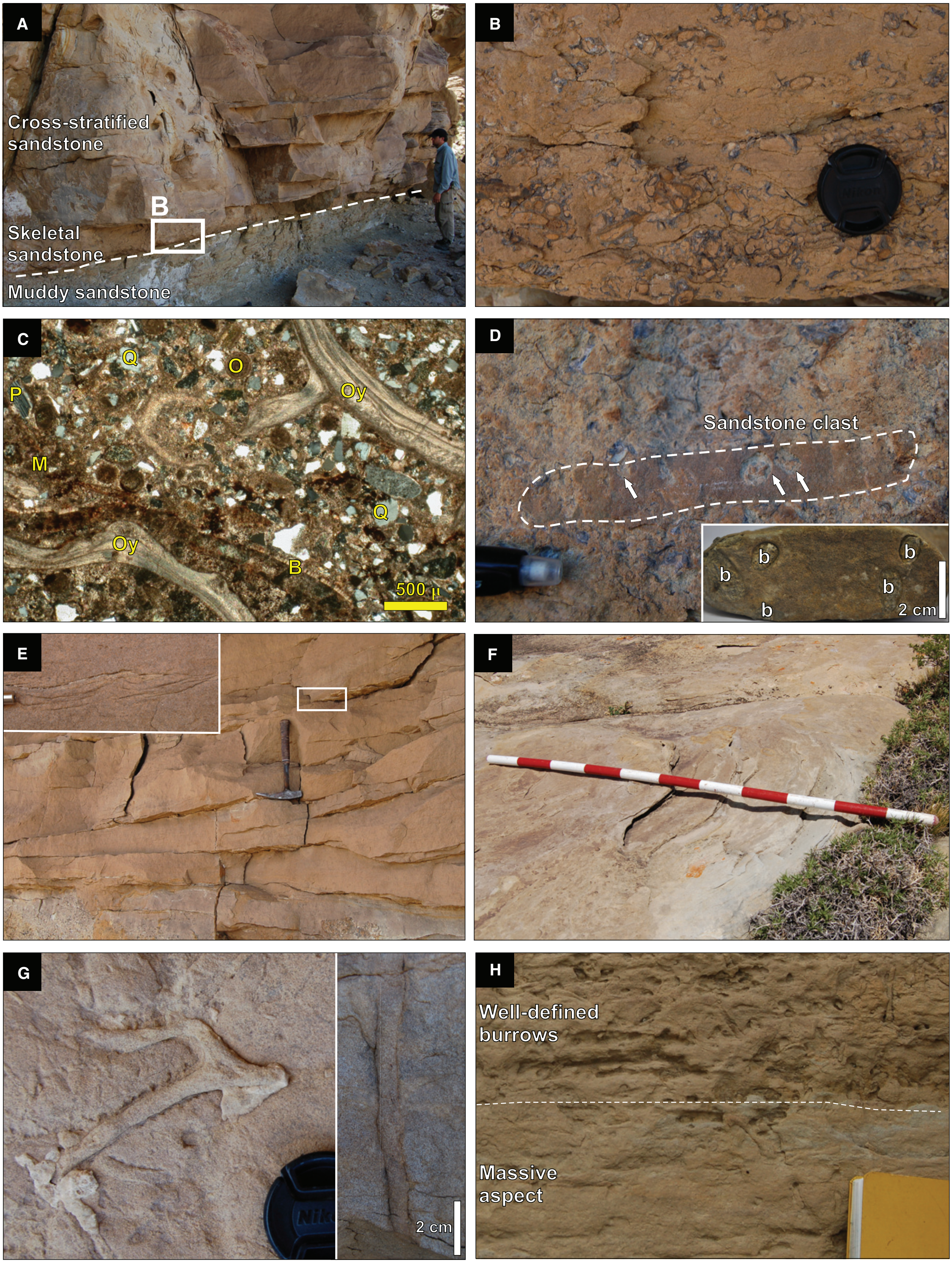

A
Cross-stratified sandstone
B
Skeletal sandstone
Muddy sandstone
B
C
Q
O
P
Oy
M
Q
Oy
B
500 μ
D
Sandstone clast
b
b
b
b
b
2 cm
E
F
G
2 cm
H
Well-defined burrows
Massive aspect

Fig. 11. Main attributes of Facies Association 5. (A) Skeletal sandstone, which invariably marks the base of sandstone bodies, sharply overlying muddy sandstones of FA3. Person for scale, *ca* 1·8 m tall. (B) Close-up view of skeletal sandstone (or basal shell bed). Skeletal fragments, typically pebble size, are principally dominated by epibenthic, attached-living oysters. Lens cap for scale (5 cm diameter). (C) Microphotograph (cross-polarized) of skeletal sandstone showing oyster 'Oy' and undifferentiated 'B' fragments together with terrigenous grains (quartz and feldspars) and subordinate ooids 'O'. (D) Cobble-size cemented sandstone clast within the skeletal sandstone facies. These clasts have evidence of encrustation by oysters and borings (arrows). Part of pencil (2 cm long) for scale. Inset shows that borings 'b', probably *Gastrochaenolites*, occur in all sides of the clasts. (E) Planar-tangential cross-bedding in fine-grained sandstones, typical of lower portions of the sandstone bodies. Hammer for scale (33 cm long). Cross-bedding sets are, in some cases, overlain by current-ripple cross-lamination (inset) whose foresets are dipping in the same direction as the larger sets. (F) Small-scale trough cross-stratification, commonly observed in the upper part of sandstone bodies. White and red segments of measuring stick are 10 cm long. (G) *Ophiomorpha* in plan view (lens cap for scale) and vertical burrow (*Skolithos*?) in cross-section, which are typically associated with the cross-stratified lithofacies. (H) Cross-section view of the bioturbated sandstone facies, which occur preferentially in upper intervals of sandstone bodies providing a massive aspect. However, some discrete horizons show well-defined *Ophiomorpha* burrows, suggesting relatively less intense bioturbation.

prises amalgamated beds of very fine and fine-grained sandstones having hummocky and swaley cross-stratification (Fig. 10A and B). Sets are typically less than 0·50 m thick and up to 4 m wide. Rip-up clasts are common at the base of sets and within internal stratification (Fig. 10B). Bioturbation varies from low to moderate and the trace fossil association is dominated by *Ophiomorpha* (Fig. 10C). Some beds are capped by weakly asymmetrical (combined flow) or symmetrical (wave) ripples; both types with crests mostly oriented east–west (Fig. 10C). This facies association reaches a maximum thickness of 2 m and is overlain sharply by skeletal sandstones of FA5 (Figs 7, 9A and 10A). As the sandstone beds of FA3, these clean sandstones are composed of more than 95% of siliciclastic grains (Fig. 10D), with rare or null skeletal grains.

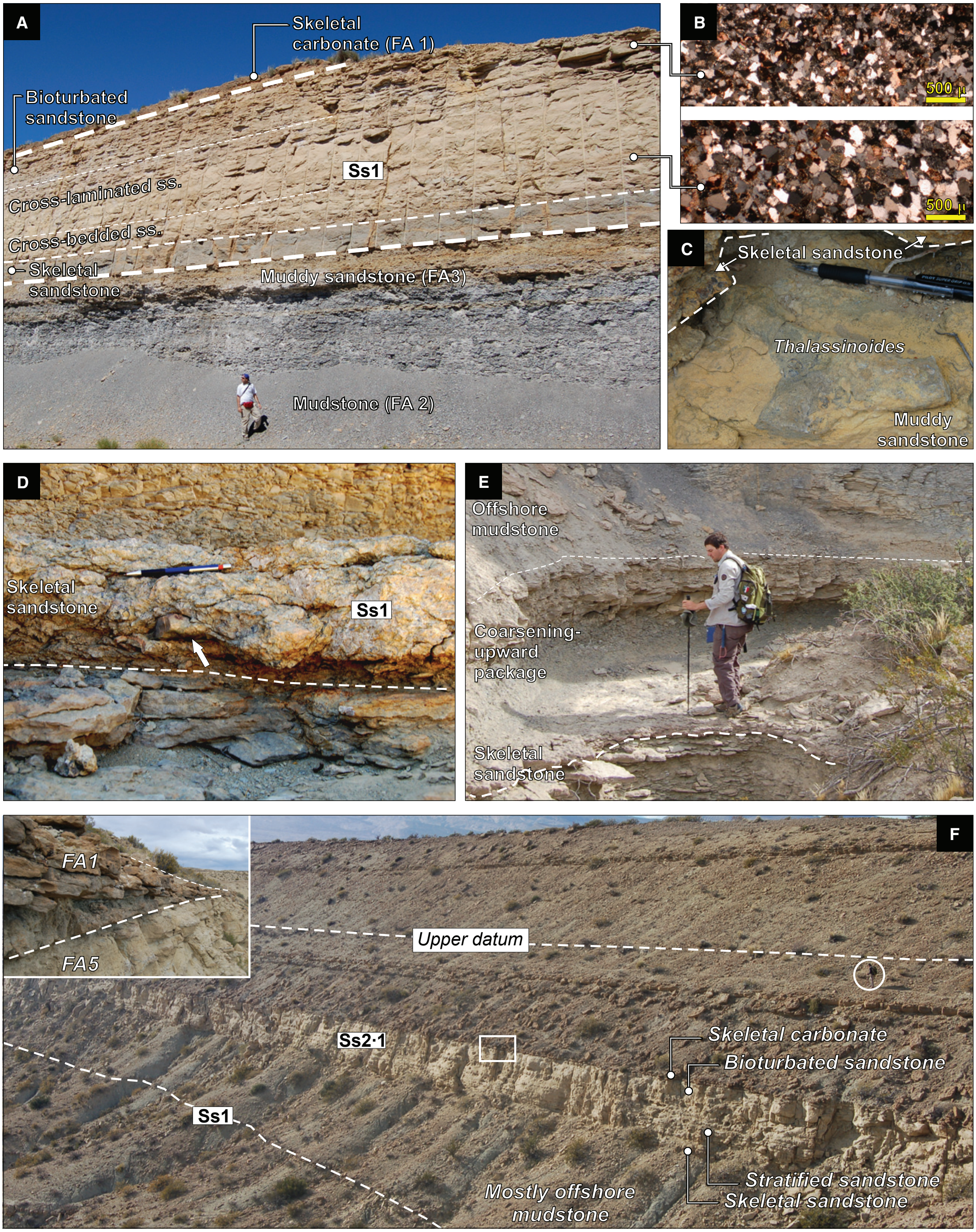
Interpretation

As in the case of FA3, preserved sedimentary structures suggest that sand was mostly transported and deposited by storm-generated, offshore-oriented currents. Amalgamation and abundant rip-up clasts suggest that flows initially were erosive in this setting. Subsequent deposition would have been controlled by migration and aggradation of hummocky bedforms, probably under combined flows (Dumas & Arnott, 2006). In some cases, low net aggradation rates would have favoured the formation of swaley cross-stratification (SCS) over HCS (Dumas & Arnott, 2006). The transition from hummocky bedforms to smaller-scale ripples suggests a waning-flow stage in which both purely oscillatory and combined (oscillatory and unidirectional) flows are recorded (Myrow & Southard, 1991, 1996). Hummocky cross-stratification and SCS-dominated sandstone packages similar to the ones reported here have been interpreted to reflect lower shoreface conditions both in the Mulichinco Formation (Schwarz & Howell, 2005) and in many other ancient examples (Walker & Plint, 1992; Hampson, 2000).

Facies Association 5: Skeletal, cross-stratified and bioturbated sandstones

Description

Lithofacies grouped in this facies association (FA5) represent the sandstone bodies discussed in detail in this contribution. The association comprises skeletal sandstones, together with mostly non-fossiliferous sandstones showing high-angle cross-stratification and ripple cross-lamination, or intense bioturbation. Skeletal sandstones comprise very fine to fine-grained siliciclastics together with pebble size randomly distributed bioclasts and less common sand-size ooids (Fig. 11A to C). These deposits are cemented with up to 30% of sparry calcite. The macrofaunal assemblage is dominated by attached-living oysters and serpulids, mixed with some skeletal remains of endobenthic and semi-endobenthic bivalves (for example, *Cucullaea* sp. and *Trigonia* sp.) and irregular echinoids. Subrounded cobble-size clasts of cemented siliciclastic sandstones reworked from the underlying succession occur within this facies (Fig. 11D). Original lamination is typically preserved and all edges of the clasts are bored extensively by lithophagid bivalves, as well as encrusted by oysters (Fig. 11D). Cross-stratified facies comprise either fine-grained sandstones with decimetre-scale sets of planar-tangential cross-stratification (Fig. 11A and E), or trough cross-stratification (sets 10 to 15 cm thick) and current-ripple cross-lamination developed mainly in very fine-grained



sandstones (Fig. 11F). Cross-lamination can be dominant throughout a sandstone body or can grade from planar cross-bedding. Palaeoflows inferred from the latter are fairly consistent to the north-west, whereas palaeocurrents in the smaller-scale cross-stratification are highly variable, ranging from north-west to south-east (Fig. 7). This facies having well-developed pri-

Fig. 12. External and internal characteristics of sandstone bodies. (A) Sandstone body Ss1 (7 m thick) in the eastern sector of the study area. It has a sharp and weakly erosional base truncating underlying offshore transitional muddy sandstones (FA3) and, in turn, is capped by skeletal carbonates (FA1). The basal skeletal sandstones facies rapidly grade into non-fossiliferous cross-stratified sandstones. Bioturbated sandstone facies dominate the uppermost interval. Person for scale, *ca* 1·8 m tall. (B) Microphotographs (cross-polarized) of the lower and upper intervals of Ss1 showing that it is composed of clean sand, but there is a subtle decrease in grain size from lower fine-grained to very fine-grained sand. Bars for scale. (C) A robust *Thalassinoides* encased within the topmost part of a muddy sandstone succession, but filled with shelly fine sand. As these burrows are passively filled and connected to the overlying skeletal sandstone which represents the base of a sandstone body (Ss2·2 in this case), they are interpreted as a *Glossifungites* ichnofacies suite. Pencil for scale (15 cm long). (D) At the western side of the study area Ss1 pinches out but its stratigraphic level is demarcated by the basal skeletal sandstone. It is important to note that the shoreface-derived sandstone clasts (arrow) are still present. Pencil for scale (15 cm long). (E) In some intermediate regions, the skeletal sandstone is overlain by a metre-thick coarsening-upward package which could be temporally equivalent to the sandstone body. Person for scale, *ca* 1·8 m tall. (F) General view of sandstone body 2·1 in the western sector, where it reaches 5 m in thickness. As for Ss1 body, it is bounded at the base by a skeletal sandstone, followed by a cross-stratified facies, in turn overlain by bioturbated sandstones (all from FA5). The unit is sharply capped by skeletal carbonates of FA1 (see also inset). Person (in white circle) for scale, *ca* 1·8 m tall.

mary sedimentary structures is commonly associated with low bioturbation, represented by relatively large horizontal burrows of *Ophiomorpha* (dominant) and *Palaeophycus*, with subordinate *Skolithos* (Fig. 11G). The bioturbated sandstone facies (the last included in the association) differs in that burrowing intensity varies from very high to high and physical structures are not preserved. For the most part individual traces are difficult to identify and a massive appearance predominates, but some discrete horizons have a high concentration of *Ophiomorpha* burrows and vertical shafts prevail (Fig. 11H). This facies association is up to 7 m thick and sharply overlies Facies Associations 2 to 4 all across the study area (Fig. 7).

Interpretation

The skeletal sandstones bounding this facies association suggest a period of fossil concentration and mixing of benthic invertebrates (living both above and below the water–sediment interface) to produce a shell-rich substrate. Sandstone-derived cobbles within some shell beds point to significant erosional exhumation of underlying sediments after cementation, whereas the borings and attached oysters indicate a time lag between clast generation and their final burial. Overlying cross-stratified clean sandstones suggest a rapid switch towards a siliciclastic-dominated sea floor and migration of mostly two-dimensional dunes under unidirectional currents running preferentially to the north-west. Smaller-scale bedforms replace both laterally and temporally the 2D dunes. Bioturbated sandstones are interpreted to reflect a similar flow regime, but under a relatively low net sedimentation rate, favouring intense burrowing by mostly filter feeders in well-oxygenated sandy substrates and probably clear waters (MacEachern *et al.*, 2007a). Together, FA5 represents an open, shallow-marine environment. High-angle cross-stratification is indicative of upper-shoreface conditions in classical siliciclastic offshore-shoreface upward-shallowing successions (Plint, 1988; Walker & Plint, 1992; Reading & Collinson, 1996) and is typically attributed to alongshore bars (i.e. migrating parallel to the shoreline). However, dunes interpreted in this facies association were probably migrating preferentially offshore (north-west) from the inferred north-east to south-west palaeoshoreline. Moreover, smaller-scale bedforms (small-scale dunes and ripples) overlying older dunes have not been reported widely in progradational, wave-dominated shoreface systems. In contrast, a planar bed produced by swash and backswash processes in a foreshore setting is commonly found capping progradational shoreface systems (Plint, 1988; Olsen *et al.*, 1999; Hampson & Storms, 2003; Tamura *et al.*, 2008). The vertical superposition (and inferred palaeoflows) of recorded structures, added to the fact that the basal bounding surfaces of FA5 are thought to represent stratigraphic discontinuities, warrant a closer inspection of this facies association in order to arrive at a more suitable interpretation of the resulting sandstone bodies.

SANDSTONE BODIES: KEY STRATIGRAPHIC SURFACES AND ARCHITECTURE

Within the investigated strata of the Upper Member of the Mulichinco Formation, sharp-based sandstone units occur at three different intervals and they are labelled, respectively, Ss1, Ss2 and Ss3 (Figs 6 and 7). Whereas Ss1 is a relatively simple sandstone body, for the most part, Ss2 and Ss3 are more complex (Fig. 7), consisting of two units stacked either vertically (Ss2·1 and Ss2·2) or laterally (Ss3·1 and Ss3·2). All the sandstone units have been studied in detail but, for the following section dealing with key stratigraphic surfaces and internal architecture, sandstone bodies Ss1 and Ss2·1 are invoked principally as examples.

Bounding surfaces, geometry and lateral correlations of sandstone bodies

Individual bases of sandstone bodies have been traced for up to 4 km in a west–east direction and 3 km in a north–south direction; they are typically flat, with less than 2 m of erosion recorded (Fig. 7). These basal contacts are sharply overlying finer-grained deposits of FA3 in most cases, and they are typically marked by the oyster-rich skeletal sandstones (Figs 11B and 12A). Locally, the underlying finer-grained deposits have *Thalassinoides* galleries passively filled with coarser shell debris of overlying shell beds (Fig. 12C). The gallery system penetrates up to 6 cm below the facies contact and burrows are <2 cm in diameter and up to 14 cm long. These *Thalassinoides* excavations are interpreted to represent a *Glossifungites* Ichnofacies suite (MacEachern *et al.*, 2007b).

Sandstone units are 3 to 7·5 m in thickness (maximum recorded in unit Ss1·1, Fig. 12A) and they extend 1 to 3·25 km in the west–east direction and more than 3 km in the north–south direction. Most of these bodies have only one lateral termination within the study area, but sandstone body Ss2·2 has well-defined lateral margins on both sides (Fig. 7, panel A–A′), defining a roughly NNW to SSE elongated body, more than 3 km long and 1·25 km wide. Abrupt terminations, for example bodies thinning from more than 3 m to zero in less than 250 m, are recorded in several units.

The sandstone bodies are composed of clean, cross-stratified and/or bioturbated sandstones of FA5 and they show little lateral facies changes for the most part (Fig. 7). As they thin rapidly towards the margins, they are represented solely by the basal skeletal sandstones (Fig. 7, for example, Ss1 body eastward of log ML-7 and 21 in panels A–A′ and B–B′, respectively). In the case of Ss1, the basal shell bed extends for more than 2 km beyond the sandstone body termination (Fig. 7), and even at the easternmost margin of the study area this 20 cm thick significant stratigraphic level is well-defined and contains cobble-size sandstone clasts (Fig. 12D).

Sandstone bodies are capped sharply by skeletal carbonates of FA1 (Figs 7, 8A, 12A and 12F). Although for the most part the carbonates mimic the sandstone geometry with relatively thin deposits (<0·5 m), locally their basal surfaces truncate underlying deposits (for example Fig. 7, cross-section A–A′), forming thicker and more complex carbonate packages (up to 4 m thick). Bounding basal surfaces of carbonate packages are demarcated locally by the presence of passively filled *Thalassinoides* into the underlying siliciclastic successions, which are attributed to a *Glossifungites* Ichnofacies suite (MacEachern *et al.*, 2007b).

Field observations show that these sandstone bodies do not pass laterally into siliciclastic finer-grained facies (either sharply or gradationally); they are based by skeletal sandstones and are capped by skeletal carbonates (Fig. 12A and F), and the two encasing facies merge together in all directions as the clastic bodies thin. On one occasion, however, the skeletal sandstone demarcating the stratigraphic base of an adjacent sandstone body (Ss1 in the eastern-region) is overlain by an up to 1 m thick upward-coarsening unit (Fig. 12E). This package comprises mudstones at the base and cross-laminated sandstones at the top, but it disappears rapidly to the north (Fig. 7, for example, panel C–C′ from ML-5 and ML-2, cycle 7). Lateral relationships observed between logs L-20 and L-24 (Fig. 7, for example, panel B–B′) suggest that this thin succession probably developed during the last stage of sandstone unit evolution rather than simultaneously with the skeletal carbonates.

Internal architecture and vertical trends of sandstone bodies

Sandstone bodies defined in this study show two different types of internal heterogeneities. Firstly, internal discontinuities cutting gently from top to bottom of units occur in Ss1, Ss2·1 and Ss3·2 (Fig. 7). These surfaces are marked by differentially cemented, skeletal sandstones (0·40 to 0·15 m thick). Surfaces are very gently inclined (0·15° to 0·40° or cutting 2 m in 300 m) and they dip preferentially towards the east and north-east (Fig. 7). Secondly, large-scale inclined stratification involving an entire sandstone body was clearly recognized in Ss2·1 (Fig. 13) and Ss2·2. These inclined bedsets are up to 3 m thick and

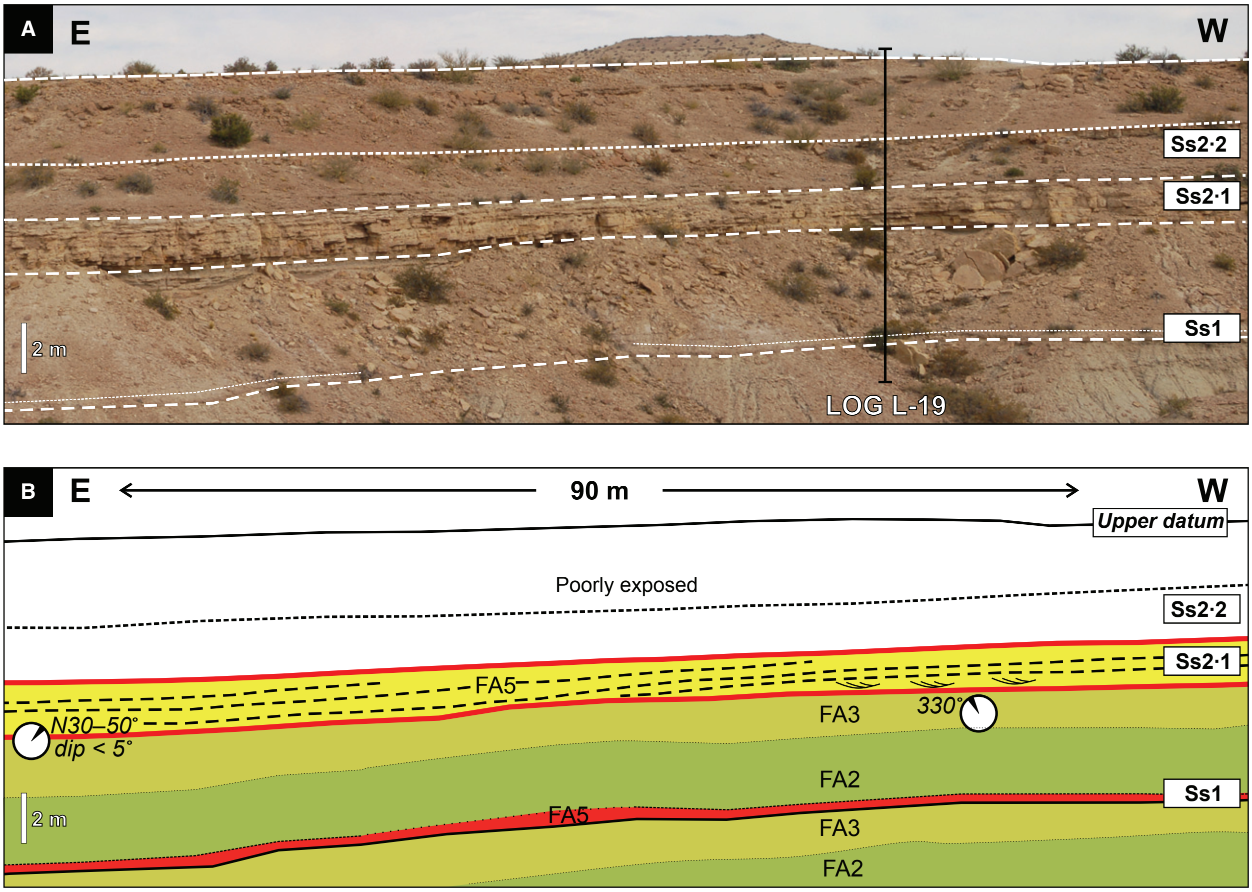


Fig. 13. (A) Uninterpreted field photograph and (B) interpreted diagram showing large-scale inclined stratification dipping gently (<5°) to the north-east in sandstone body Ss2·1. Trough cross-stratification within the inclined package suggests palaeoflows running preferentially to the north-west. Legend of coloured intervals and facies association codes as in Fig. 7.

they dip gently (<8°) to the north-east and ENE. This large-scale inclined stratification is dipping in an oblique direction with respect to sandstone body elongation, which in the case of the well-documented Ss2·1 is approximately NNW to SSE (Fig. 7). These inclined packages also dip at a high angle with respect to the avalanche surfaces of 2D and 3D dunes, which dip mostly to the north-west (Fig. 13).

Where bioturbation has not obliterated physical sedimentary structures, some Mulichinco sandstone units show well-defined vertical trends. Rapidly grading from the skeletal sandstone at its base, sandstone body Ss1 shows an upward trend from cross-stratified, to cross-laminated, to bioturbated facies, together with a gradual fining from fine to very fine-grained sandstone (Fig. 12A and B). Sandstone body Ss2·1 also grades upward from a lower interval dominated by cross-stratified sandstone into an upper intensively bioturbated interval (Fig. 12F). Fining-upward trends, increasing bioturbation and decreasing the scale of tractive structures from bottom to top of the sandstone bodies probably suggest that current energy and net sedimentation rates decreased gradually over time during sand accumulation.

DISCUSSION

Mulichinco sandstone bodies: A case for a transgressive offshore origin

The vertical (and lateral) gradual transition from FA2 to FA3, and occasionally from FA3 to FA4 (Figs 7 and 9), is interpreted as recording an overall shallowing from offshore to lower shoreface conditions in a storm-dominated open-marine setting. These progradational packages probably represent gradual basinward shifts of facies belts for a few kilometres. Similar upward-shallowing packages have already been recognized and interpreted in the Upper Member of the Mulichinco Formation southward of the study area (Schwarz & Howell,

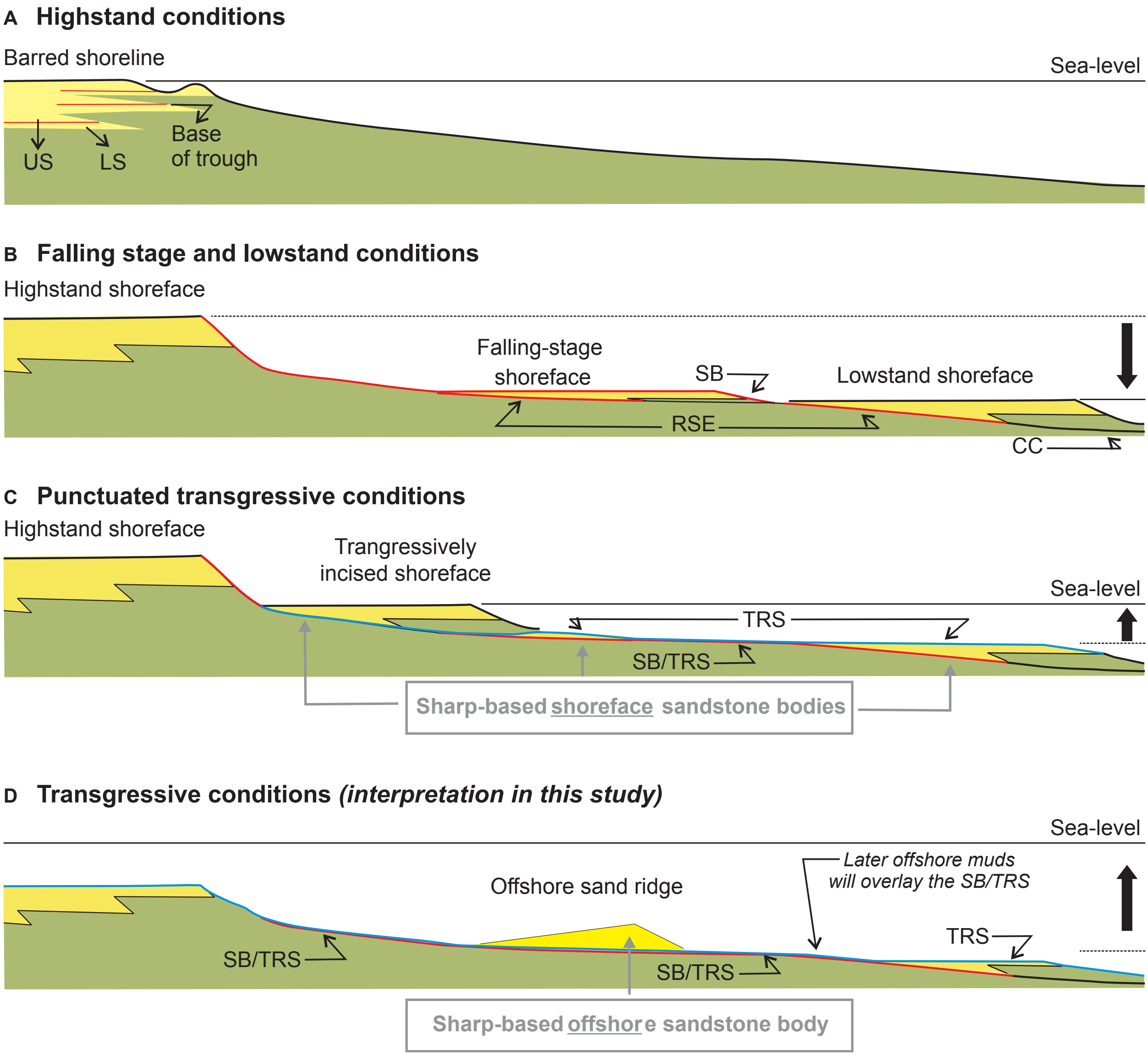


Fig. 14. Different sequence stratigraphic scenarios which can lead to the formation of sharp-based shallow-marine sandstone bodies encased in offshore mudstones. (A) Prograding barred shorelines in high-energy systems during 'normal regression' (Clifton, 1981, 2006). Erosive surfaces (red lines) from trough migration are developed invariably between lower-shoreface (LS) and upper-shoreface (US) sandstones and do not represent major breaks in sedimentation (simplified from Clifton, 2006, fig. 56B). (B) Abrupt basinward shifts and shoreface migrations during forced regression and/or lowstand conditions (Plint, 1988; Bergman & Walker, 1999; MacEachern *et al.*, 1999a). (C) Transgressively incised shorefaces during minor stillstands of longer-term transgressions (Bergman, 1999; MacEachern *et al.*, 1999b; Cattaneo & Steel, 2003). (D) Transgressive sandstones modelled as ridges in offshore/shelf settings (Tillman & Martinsen, 1984; Krause & Nelson, 1991; Posamentier, 2002; Bassetti *et al.*, 2006). The Mulichinco sandstone bodies are thought to have been formed under these transgressive offshore conditions. In this scenario, the late transgressive to early highstand offshore mudstones overlay a composite erosional surface (SB/TRS) which should not be present in highstand to lowstand scenarios. For illustration purposes the lowstand shoreface deposits in (C) and (D) are partially preserved, but they could be totally reworked during transgression. RSE, regressive surface of marine erosion; SB, sequence boundary; CC, correlative conformity; TRS, transgressive ravinement surface. No scale implied.

2005; Schwarz *et al.*, 2006), where they are gradually overlain by high-angle cross-stratified sandstones suggesting upper-shoreface conditions (Fig. 3A). On the contrary, in this case the upward-shallowing successions are truncated by erosive surfaces, overlain in turn by the reported thick sandstone bodies, whose interpretation is not straightforward.

As shown in Fig. 14, ancient sharp-based shallow-marine sandstone bodies can represent the product of: (i) prograding bar-trough systems in high-energy, upper-shoreface conditions during 'normal regression' (Clifton, 1981, 2006); (ii) abrupt basinward shifts and shoreface migration (forced regressive/lowstand deposits; Plint, 1988; Bergman & Walker, 1999; MacEachern *et al.*, 1999a); (iii) transgressively incised shorefaces during minor stillstands (Bergman, 1999; MacEachern *et al.*, 1999b; Cattaneo & Steel, 2003); or (iv) transgressive sandstones modelled as ridges, patches and/or sheets (Tillman & Martinsen, 1984; Krause & Nelson, 1991; Posamentier, 2002). Reworked sand-rich deposits developed within spit systems can also provide sandstone bodies encased in offshore mudstones, but they typically have a gradational contact with underlying fine-grained sediments (Nielsen & Johannessen, 2008) and therefore are not considered in the following discussion. In order to discriminate between sandstone units accumulated during a relative sea-level fall (from highstand to lowstand) or during a transgression, the nature and origin of the bounding surfaces have to be discussed in the first place. Subsequently, as different types of sandstone-rich transgressive deposits can be formed (Fig. 14C and D), evidence has to be added and discussed in order to understand whether the Mulichinco sandstone units were accumulated in a shoreface or offshore setting.

Basal bounding surfaces: Evidence for transgressively modified sequence boundaries

The Mulichinco sandstone bodies are overlying kilometre-scale, low-relief discontinuities created mostly onto mud-dominated offshore strata, but also onto sand-prone lower shoreface deposits. This fact suggests that underlying sediments and their inferred depositional conditions did not have any direct control on the formation of the sandstone units. Additionally, the uppermost centimetres of the underlying finer-grained sediments locally have *Thalassinoides* burrows filled with shell debris and coarser sand (Fig. 12C), representing a *Glossifungites* Ichnofacies suite (MacEachern *et al.*, 2007b). These pieces of evidence point towards an erosional hiatus between the underlying upward-shallowing successions and the sandstone bodies themselves, which is interpreted to be the result of a period of extensive erosion of underlying, unconsolidated fine-grained sediments. As the progradation of a bar-trough system would produce rather simple erosive surfaces between lower and upper-shoreface sands (Fig. 14A), this evidence allows such a scenario to be discarded.

The basal surfaces of the investigated bodies are at all times demarcated by skeletal sandstones (shell beds). Noteworthy, pebble-size skeletal fragments are uncommon in underlying sediments and they disappear rapidly above the thin shell beds (Figs 11A, 11B and 12A to C). Carbonate cementation increased significantly in these shell beds (Fig. 11C), suggesting that most of the present cement probably originated by dissolution of original carbonate particles and re-precipitation during diagenesis. Although, shell beds and preferential cementation have been widely associated with transgressive surfaces in several ancient and modern examples of transgressive deposits (Kidwell, 1991; Davis *et al.*, 1993; Dalrymple & Hoogendoorn, 1997; Spalletti *et al.*, 2001; Posamentier, 2002; Cattaneo & Steel, 2003; McBride *et al.*, 2004; Sixsmith *et al.*, 2008) and *Glossifungites* Ichnofacies suites were also reported preferentially related to transgressive surfaces of erosion and/or flooding surfaces (MacEachern *et al.*, 2007b and references therein), these attributes either individually or together cannot be invoked as enough evidence to unambiguously interpret a basal surface as of transgressive origin. For example, both shell concentration and firm ground development could well be the result of erosional exhumation and winnowing during falling or lowstand conditions, and resulting regressive surfaces of marine erosion (RSE) and/or sequence boundaries (SB) could be demarcated by *Glossifungites* Ichnofacies suites (Bergman, 1999; Olóriz & Rodríguez-Tovar, 2000).

Two additional pieces of evidence are used in the Mulichinco case to discriminate between a simple regressive versus a composite regressive/transgressive origin for the basal bounding surfaces of the sandstone bodies (compare Fig. 14B, C and D): (i) the regional extension of the shell beds having sandstone clasts; and (ii) the presence of boring and encrusting in those clasts, together with the macrofaunal assemblage of the shell beds.

The siliciclastic sandstone clasts within the basal shell bed of Ss1 are interpreted to represent a significant episode of erosion and possibly sediment bypass downdip. The reworking of partially lithified sediments probably was produced by wave action as relative sea-level was falling (forced regression and/or lowstand conditions), as suggested by Morris *et al.* (2006) for similar cemented shoreface sandstone clasts.

However, in storm-dominated systems (as represented by FA2 to FA4) erosion should not be significant basinward of fair-weather wave base during lowstand conditions (MacEachern *et al.*, 1999b). In other words, lowstand shoreface deposits would overlie a regressive surface of erosion (RSE), which is the time-equivalent of the subaerial sequence boundary (SB), but coeval offshore mudstones should overlie highstand mudstones through a correlative conformity of the RSE (Fig. 14B). In the Mulichinco case, the sandstone clasts within the basal shell bed of Ss1 are still demarcating the stratigraphic position of the unit far beyond the sandstone body pinch out and the shell bed is overlain by fine-grained deposits (Fig. 12D and F). This fact suggests that the surface remains erosional even in relatively distal locations. Its origin is therefore inconsistent with a simple RSE or SB as discussed by MacEachern *et al.* (1999b).

The second line of evidence is provided by the encrustation and boring of the sandstone clasts on all sides (Fig. 11D). This probably suggests a significant time lag between clast generation and final burial, as well as energy conditions strong enough to turn the clasts from time to time to expose their different edges in the sea floor. Additionally, the macrofaunal assemblage of shell beds is composed mainly of attached-living marine oysters and serpulids, which are typically favoured by low net sedimentation rates (Abbott, 1998; Schwarz *et al.*, 2006; Lazo, 2007). The skeletal remains eventually were fragmented and mixed with siliciclastic grains to form skeletal sands. The inferred complex history of sandstone clasts, relatively low sedimentation rates and development of epifauna cannot be reconciled with rapid accumulation driven by a forced regression. On the contrary, these conditions are interpreted here to indicate a long-lived and energetic transgression after relative sea-level fall. Bored and/or encrusted gravel-size clasts, recognized in many complex siliciclastic-carbonate successions, have similarly been associated with transgressively modified regressive surfaces of erosion (Abbott, 1998; Morris *et al.*, 2006; Nalin & Massari, 2009).

In summary, the pieces of evidence discussed above suggest that the bases of the sandstone bodies represent composite erosional surfaces, initially cut during relative sea-level fall, but subsequently heavily reworked and modelled during shoreline transgression. Thus, these polygenetic surfaces are interpreted to represent sequence boundaries (SB) and transgressive ravinement surfaces (TRS; following Cattaneo & Steel, 2003), cut by marine currents. There is no direct indication about subaerial exposure of the surfaces, but those indicators (if ever present) could have been removed during transgression. As the Mulichinco sandstone bodies overlie these composite SB/TRS surfaces, it follows that they are transgressive deposits as well.

Offshore versus shoreface transgressive deposits

Sandstone-dominated transgressive deposits in low-gradient open-marine environments (i.e. excluding incised valleys) can be generated either as shoreface or offshore/shelf accumulations (Fig. 14C and D; Cattaneo & Steel, 2003). Relatively thick (>1 m) transgressive shoreface deposits can be deposited and preserved when an overall transgression is punctuated with short-term periods of relative sea-level fall or stillstand (Swift *et al.*, 1991; Walker & Plint, 1992), but only if during those periods sediment supply rates temporally overcome the rates of overall increasing accommodation (Cattaneo & Steel, 2003). In that situation the shoreface deposits would overlie the composite SB/TRS, and they would have an upward-coarsening trend (Bergman, 1999; MacEachern *et al.*, 1999b) indicating the progradational episode (Fig. 14C). The Mulichinco sandstone bodies have upward-fining trends or they are not graded at all (Fig. 12A) and dune cross-stratification sometimes passes upwards to ripple cross-lamination. These vertical patterns do not seem to suggest an episode of shoreface progradation.

Alternatively, transgressive sandy accumulations can form in open shelves and large offshore embayments (Dalrymple, 1992; Berné, 2003; Cattaneo & Steel, 2003; Suter, 2006). Sand-rich deltaic and/or shoreface sediments deposited during regressive conditions (highstand to lowstand) can be reworked by marine currents during transgression, producing a significant volume of palimpsest sands. According to empirical and numerical models (Caston, 1972; Huthnance, 1982; Hulscher *et al.*, 1993; Snedden & Dalrymple, 1999), if these sands are available in areas with topographical irregularities and currents capable of moving them (at least periodically), linear sand ridges can be developed away from coeval coastlines (Fig. 14D). These prerequisites for the genesis and evolution of linear sand ridges can be achieved both in storm and tide-dominated settings (Snedden & Dalrymple, 1999), but preserved attributes would depend on the

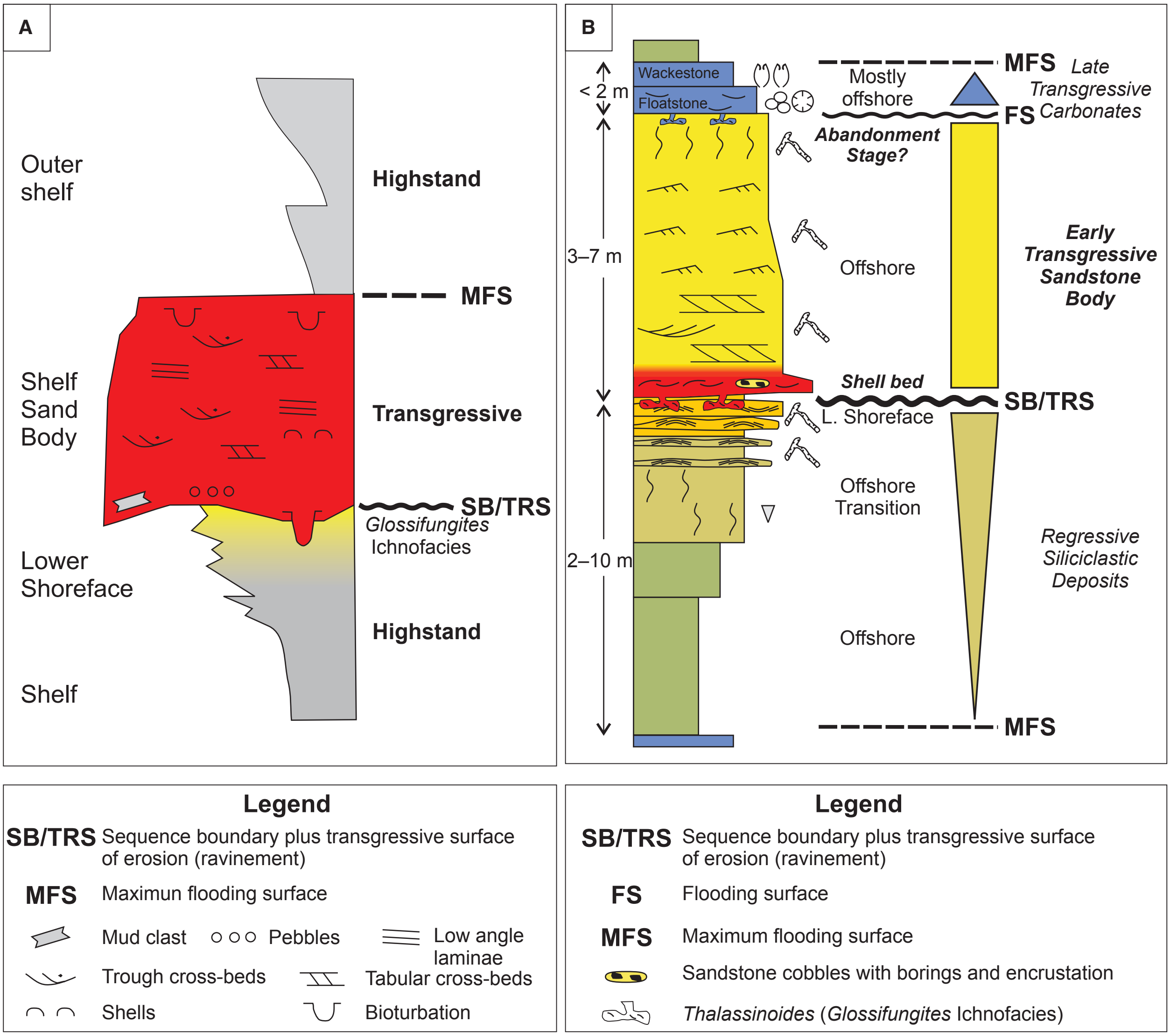


Fig. 15. (A) Hypothetical succession of a 'fully reworked' shelf sand ridge (redrawn from Suter, 2006), showing facies, depositional environments and sequence stratigraphic framework. It is assumed that HST mudstones draped the shelf body preserving it as a depositional element. (B) A vertical succession summarizing facies, thickness, depositional environments, key surfaces and sequence stratigraphic framework inferred for the Mulichinco high-frequency sequences. For log legend see Figure 6. The Mulichinco bodies are interpreted to represent the remnants of offshore sand bodies, partially reworked and capped by a carbonate-dominated system. The non-erosional upper contact into the overlying offshore mudstones is believed to reflect the onset of siliciclastic accumulation during renewed progradational conditions.

dominant depositional processes and final emplacement of sand ridges (Suter, 2006). These accumulations are common in several modern shelf environments (Snedden & Dalrymple, 1999; Berné, 2003; Suter, 2006), where they have been investigated principally by geophysical means, but also by vibracoring. On the other hand, apart from a case reported in Miocene strata off the coast of Java (Posamentier, 2002), unequivocal reports concerning the analogues of transgressive sandstone bodies of linear shelf ridges are almost non-existent (Snedden & Bergman, 1999; Suter, 2006).

Suter (2006) attempted to synthesize the identification criteria for ancient shelf sandstone bodies in core or outcrop (Fig. 15A). These bodies should have an erosional base, probably marked by a *Glossifungites* Ichnofacies suite and they would be encased within offshore or lower shoreface finer deposits. Units would be composed mostly of clean fine to coarse-grained sandstones with a variable amount of shell material. Authigenic minerals may be present. Physical sedimentary structures would include cross-stratification, cross-lamination, low-angle lamination, HCS and/or graded storm beds (Fig. 15A), depending on the grain size of the ridge and the dominant oceanic processes (waves, tides and shelf currents). Any type of vertical grain-size pattern can be expected within these bodies, but a fining-upward trend could probably be preserved if a gradual decrease in current action takes place as the ridge deactivates (Suter, 2006). Sandstone bodies could also have laterally accreting packages or clinoforms (2° to 10°), which in Quaternary shelf ridges dip in the direction of ridge migration and lie highly oblique with respect to ridge elongation. Bioturbation in these isolated marine sandstone bodies may vary from rare to pervasive depending on energy conditions, and burrows belonging to the *Skolithos* Ichnofacies should be dominant (Suter, 2006). Many of these criteria were invoked by Posamentier (2002) to postulate a transgressive shelf origin for linear sandstone-dominated reservoirs in Miocene strata off the coast of Java.

The Mulichinco transgressive sandstone bodies meet most of the criteria suggested by Suter (2006); they rest on erosional but relatively flat surfaces (SB/TRS) that commonly are marked by passively filled *Thalassinoides* attributable to a *Glossifungites* Ichnofacies suite (Fig. 15B). Units typically are composed of clean, fine-grained sandstones with basal shell beds. Where bioturbation is not pervasive, cross-stratified sandstones are common at the base, whereas current-ripple cross-lamination predominates in the upper sections of sandstone units (Fig. 15B). Some Mulichinco sandstone units also have low-angle (5° to 8°) large-scale inclined stratification dipping to the north-east (Fig. 13), oblique to the inferred elongation of bodies (NNW to SSE). Bioturbation varies from rare to pervasive in different sandstone bodies and even within a single unit (Fig. 15B). The ichnofossil association is dominated by *Ophiomorpha*, representing a low-diverse *Skolithos* Ichnofacies. Based on the integration of all these criteria and the comparison with transgressive shoreface deposits it is proposed that the Mulichinco sandstone bodies reported here represent transgressive offshore deposits and they superficially resemble some linear sand ridges developed during the last post-glacial transgression.

Mulichinco offshore bodies: From onset to abandonment

Each of the Mulichinco sharp-based sandstone bodies discussed in this contribution are transgressive features formed below fair-weather wave base within a low-gradient marine setting. Prior to transgressive sand accumulation, an erosional discontinuity was cut during sea-level fall into siliciclastic upward-shoaling successions (Facies Associations 2 to 4), which deposited in storm-dominated offshore to lower shoreface settings (Fig. 16A). This erosional stage produced exhumation of underlying sediments, as well as cemented sandstone clasts that mark the sequence boundary (Fig. 16B). Subsequent transgression and shoreline retreat favoured bioerosion and encrustation of sandstone clasts and development of attached-living fauna covering extensive regions of the sea floor (Fig. 16C). The ongoing transgression also provided palimpsest material that mixed with the skeletal remains to form skeletal sandstones (which eventually mantled the basal discontinuity). Bioclasts were even incorporated, and increasingly fragmented, in the earliest bedforms of the transgressive sands (Fig. 16D). Early bedforms were mostly 2D dunes migrating preferentially seaward (towards the north-west), recording sand transport and accumulation by unidirectional offshore currents (probably exceeding 0·5 m s^{-1} for the given grain size). The early stages pictured for the Mulichinco offshore sand-rich deposits match well with observations of recent sand ridges developed in the Florida Platform (Davis *et al.*, 1993; Harrison *et al.*, 2003) and in the Mediterranean (Bassetti *et al.*, 2006). In those cases shelf sand ridges are bounded at the base by a mixing of terrigenous sediments and skeletal fragments marking the position of the transgressive ravinement surface, and in one case it has been postulated that sand accumulation initiated as 2D dunes that merged gradually to form sand ridges (Harrison *et al.*, 2003). In the Mulichinco case, the topographical irregularities needed for the nucleation and growth of sand ridges (cf. Huthnance, 1982; Snedden & Bergman, 1999) could have been provided by low-relief depressions (<2 m) associated with the ravinement surfaces.

Once the Mulichinco sand ridges formed they probably migrated with time (Fig. 17A), as suggested by the large-scale gently inclined betsets reported within several of them (Fig. 13). These gently inclined packages geometrically resemble the ‘internal clinoforms’ described for several recent sand ridges (McCave & Langhorne, 1982; Davis *et al.*, 1993; Berné *et al.*, 2002; Bassetti *et al.*, 2006). These clinoforms typically dip in the same direction as the lee face of the ridge and represent the migration of the sand bodies (Berné

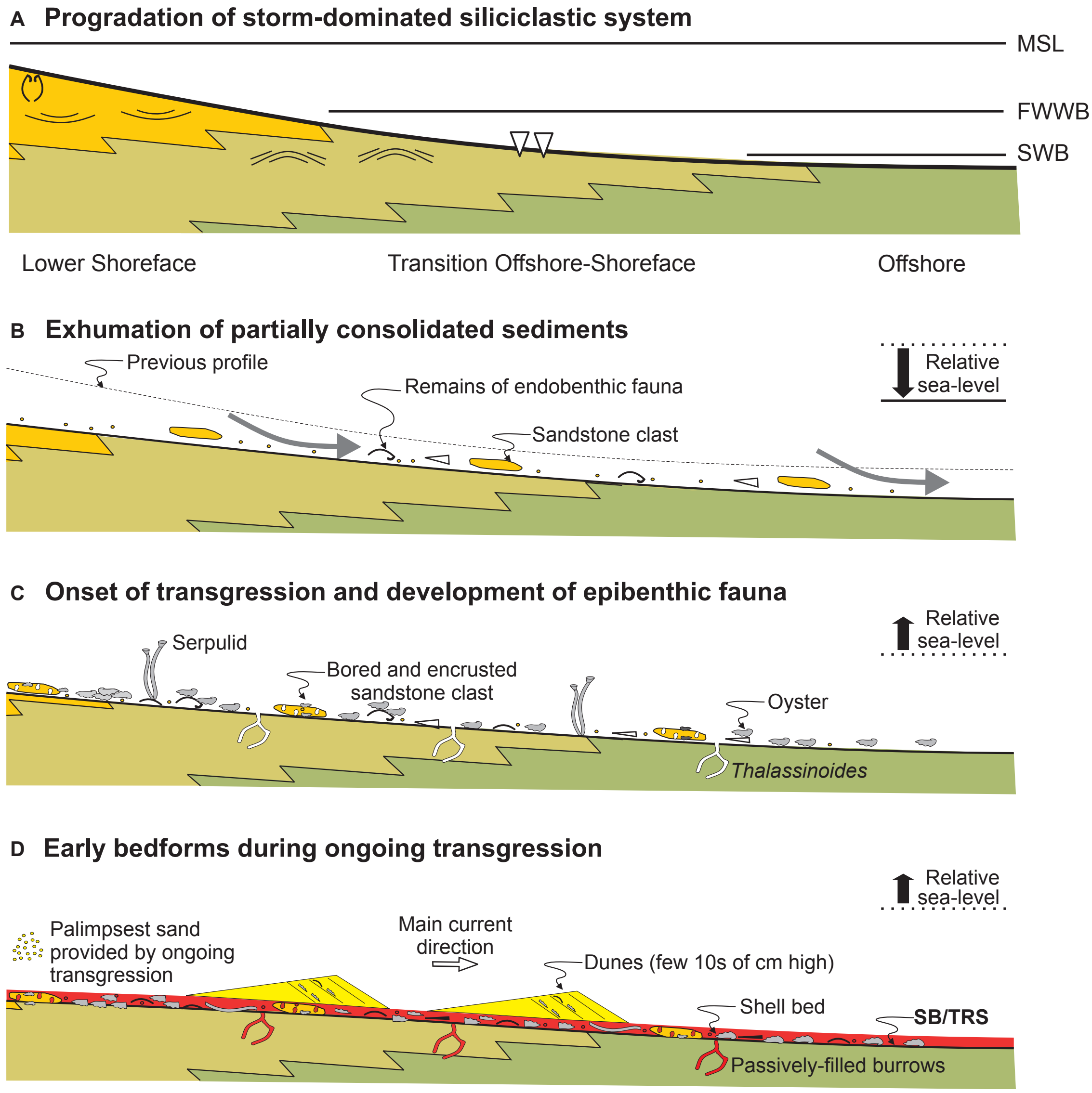


Fig. 16. Conceptual model to illustrate the composite nature of the basal surfaces of the Mulichinco sandstone bodies (no scale implied). Siliciclastic progradational conditions (A) are interrupted by a relative sea-level fall (B) producing exhumation of dewatered fine-grained sediments as well as cemented sandstone clasts. Subsequent transgression (C) and shoreline retreat favour bioerosion and encrustation in sandstone clasts and development of attached-living fauna covering extensive regions of the sea floor. Thus, the basal bounding surfaces represent sequence boundaries and transgressive surfaces of erosion (SB/TRS). Later on, the skeletal remains available in the shelly sea floor mix with palimpsest sand forming skeletal sandstones or basal shell beds. (D). Small dunes representing the earliest stages of ridge formation develop after the deposition of skeletal sandstones. SB, sequence boundary; TRS, transgressive ravinement surface

et al., 1994, 2002; Dalrymple & Hoogendoorn, 1997). Lateral migration and growth of these sand accumulations results from the interaction between the dominant flow and the initial perturbation, also known as the Huthnance Model (Huthnance, 1982; Hulscher *et al.*, 1993). Typically, when flows turn into the irregularity, they accelerate in the up-current flank due to flow constriction and then wane over the crest and down-current side, favouring erosion in the up-current side and deposition in the crest and down-current side (Swift & Field, 1981; Huthnance, 1982). As a result, upward growth and/or lateral migration of the ridge occur and preferential elongation is developed oblique (20° to 30°) to the dominant flow. Considering the existing knowledge on sand ridge migration and the attributes of the studied sandstone bodies (Figs 13 and

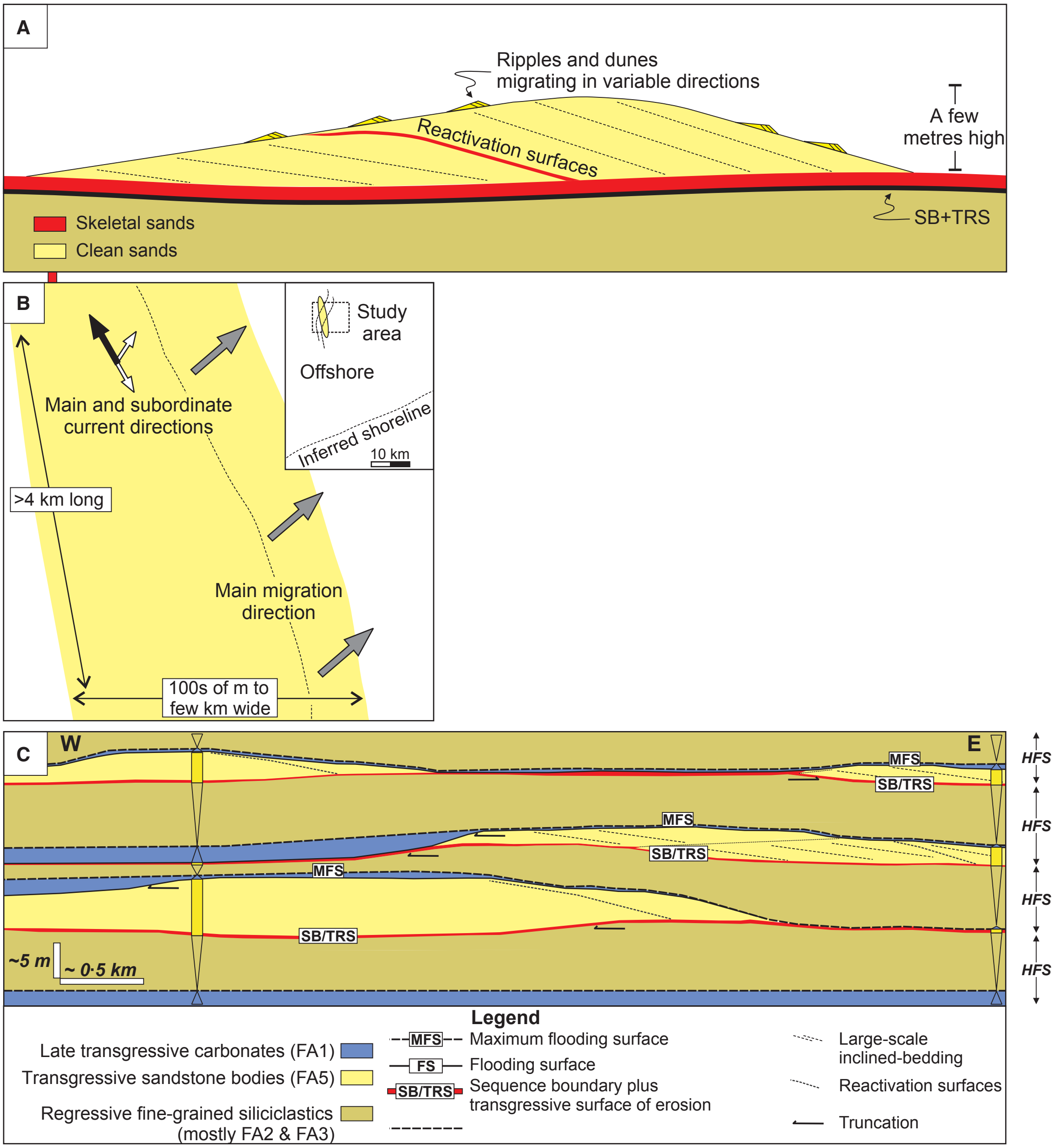


Fig. 17. (A) Schematic cross-section of Mulichinco offshore sand ridges, taking into account their preserved features combined with observations from modern and recent sand ridges (Davis *et al.*, 1993; Snedden *et al.*, 1999; Bassetti *et al.*, 2006) and conceptual models (Snedden & Dalrymple, 1999). Internal clinoforms, reactivation surfaces and superimposed bedforms are shown. (B) Plan view of an inferred Mulichinco sand ridge showing approximate size and orientation, as well as recorded main and subordinate current directions. Ridges developed sub-parallel to prevailing currents and migrated oblique to them. Inset shows palaeogeographic reconstruction indicating the location of sand bodies in the study area and the inferred shoreline orientation and location. All the evidence points to tidal currents being responsible for generation and migration of the Mulichinco ridges. (C) Simplified sequence stratigraphic scheme for the investigated sandstone bodies and surrounding strata in a cross-section oriented roughly perpendicular (west–east) to elongation of sandstone units. In this section high-frequency sequences (HFS) are composed of early transgressive sandstone bodies, late transgressive carbonates and regressive siliciclastics separated by regional key stratigraphic surfaces. As truncation is associated not only with the SB/TRS, but also with the base of capping carbonates (FS), the Mulichinco sandstone bodies are not regarded as preserved depositional elements but remnants of offshore sand ridges. Also note that where sandstone bodies pinch out, SB/TRS and FS merge together.

15), it is inferred that both the crests and axes of the Mulichinco sand ridges were elongated roughly north–south and the bodies migrated preferentially to the north-east (Fig. 17B).

Small-scale dunes and ripples migrating in variable directions commonly covered the Mulichinco sand ridges (Fig. 17A and B), as has been observed in modern counterparts (McCave & Langhorne, 1982; Davis *et al.*, 1993; Harrison *et al.*, 2003). Larger scale flow-transverse bedforms (i.e. sand waves), which are sometimes associated with sand banks or ridges (McCave & Langhorne, 1982; Berné *et al.*, 1994), have not been recognized in this study. In any case, substrates apparently were unstable and mobile in the early stages of Mulichinco ridges, precluding extensive colonization (and burrowing) of endobenthic fauna (Fig. 15B). Nonetheless, the lee faces of ridges occasionally were colonized by attached-living fauna, probably favoured by short-term deactivation or changes in current regime (Berné, 2003). Renewed stages of ridge growth and migration are presently marked within sandstone bodies by thin skeletal-rich layers (reactivation surfaces; Fig. 17A).

The vertical reduction in grain size and the scale of bedforms recorded in individual Mulichinco sand-rich units (Fig. 15B) suggest that current energy dropped gradually through time, probably as transgression proceeded. At the same time, net sedimentation rate probably decreased with time, favouring a final stage of evolution with relatively stable substrates and burrowers destroying physical structures (Fig. 15B). This abandonment phase recorded in the Mulichinco sandstone bodies is difficult to compare with observation in active modern sand ridges. However, buried transgressive sand sheets with upward-fining trends (McBride *et al.*, 2004), and moribund tidal sand ridges with intense bioturbation restricted to the top (Davis & Balson, 1992), could reflect comparable conditions. Similar trends were proposed by Suter (2006) for sand ridges that gradually become moribund and eventually are covered by offshore mudstones (Fig. 15A). In some Mulichinco cases, however, long-lived transgression within a single transgressive phase could have allowed more than one cycle of nucleation, growth and abandonment of sand ridges, resulting in vertically and/or laterally stacked sandstone bodies (Fig. 17C).

Once the Mulichinco sand ridges became fully deactivated they commonly were colonized by an attached-living invertebrate fauna composed of oysters, serpulids and corals, suggesting a stage of relatively low siliciclastic supply and sedimentation rates, but high carbonate productivity. In this carbonate-dominated system the skeletal remains and lime mud were re-distributed by unidirectional currents, forming micrite-rich and micrite-poor limestones. Existing marine currents could also have been responsible for re-shaping ridges, as demonstrated by erosional truncation (up to 4 m deep) recorded at the top of some sandstone bodies (Fig. 17C). In this sense, the Mulichinco sandstone bodies should not be regarded as preserved depositional elements but as remnants of offshore sand ridges. Within the high-frequency Mulichinco sequences, these carbonate packages are more likely to represent late transgressive conditions (Figs 15B and 17C), and the high concentration of bivalves at their tops probably represents conditions of 'maximum condensation' (Abbott, 1997; Schwarz, 2010). This situation probably coincided with the maximum landward shift of facies belts just before the turnaround to regressive conditions.

Processes building Mulichinco offshore bodies

Processes governing sand accumulation and ridge formation within offshore/shelf settings include mostly storms and tides, but perhaps also internal shelf currents (Berné, 2003; Suter, 2006). Graded beds containing hummocky cross-stratification, such as the ones reported for storm-dominated ridges (Dalrymple & Hoogendoorn, 1997), are common in the underlying Mulichinco regressive succession, but totally absent in the overlying sharp-based sandstone bodies; thus, they seem to have little storm influence in their recorded construction and migration. Wind-induced currents apparently are capable of eroding and transporting fine sand in outer-shelf settings (Bassetti *et al.*, 2006) and, therefore, could help in modelling offshore sand ridges. However, as palaeoceanographic reconstructions are not available for the Lower Cretaceous Neuquén Sea, it is not possible to test this possibility further. On the other hand, several pieces of evidence are suggestive of a tidal origin for the construction of the Mulichinco offshore ridges.

The recognition of bidirectional flows with the main (north-west) and subordinate (south-east) unidirectional currents, as well as the sub-parallel orientation of the Mulichinco sand ridges to those bidirectional flows (Fig. 17B), seems to correlate well with observations in tide-built and tide-influenced modern sand ridges (McCave & Langhorne, 1982; Davis *et al.*, 1993; Edwards *et al.*, 2003; Snedden & Dalrymple, 1999). This observation could be further supported by the fact that in tide-dominated ridges the imbalance of transport in opposing directions can result in ridge lateral migration (Snedden & Dalrymple, 1999), as interpreted for the Mulichinco ridges. Additionally, fining-upward trends observed in Mulichinco bodies are apparently more likely to develop in tide-built, rather than storm-built, offshore ridges (Snedden & Dalrymple, 1999). Finally, the Mulichinco sandstone bodies have their major axis at a high angle with respect to the inferred palaeoshoreline (Fig. 17B); a fact that seems to be common in, but not exclusive to, tide-built sand ridges (Suter & Clifton, 1999).

Although several attributes suggest that tidal currents might have been responsible for the construction of the inferred Mulichinco ridges, the best criteria for recognizing tidal action such as mudstone drapes, double mud drapes and rhythmic deposition (Nio & Yang, 1991) are totally absent in these sand bodies. However, as the Mulichinco sand units probably developed in an open offshore setting where rotary tides probably do not experience slack water periods (Suter, 2006), the absence of these criteria may not preclude tidally modelled ridges. Interestingly, many tide-built modern sand ridges are thought to lack mudstone layers or muddy facies (McCave & Langhorne, 1982; Davis *et al.*, 1993; Edwards *et al.*, 2003) and in those recent examples in which mud couplets do exist (for example, offshore sand ridges of East China Sea), they are interpreted as older estuarine deposits forming the 'core' of the sand ridge (Berné *et al.*, 2002). In any case, one striking feature recorded in the transition from the Mulichinco regressive siliciclastics to the transgressive siliciclastics is the dramatic change from a shoreface-offshore system in which storm-derived, sporadic flows were mostly responsible for sand entrainment and deposition (event beds) to a transgressive system in which fairly constant unidirectional flows (mostly likely to be tidal currents) dominated transport and accumulation. The reason behind this drastic change could be related to the significant impact that small changes in relative sea-level might have on the wave regime and/or tidal resonance of a basin.

Offshore sandstone bodies: Preservation and identification in the rock record

Mulichinco sandstone bodies (<7 m thick, <3 km wide and >3 km long) are thinner and smaller than the Quaternary tidal sand ridges of the North Sea and the East China Sea, where individual bodies can exceptionally be up to 40 m thick, 10 km wide and tens of kilometres long (Berné *et al.*, 1998, 2002). Nonetheless, they are comparable in size with smaller-scale sand ridges, typically <15 m high and few kilometres long, which are common in modern shallow shelves (Davis *et al.*, 1993; Snedden *et al.*, 1999; Harrison *et al.*, 2003; Bassetti *et al.*, 2006). The Mulichinco bodies are also size-comparable with the Miocene seismic features reported by Posamentier (2002, table 1), which were interpreted as current-built sand ridges. In that example, however, preserved sandstone bodies were inferred to retain most of their depositional ridge morphology (Posamentier, 2002). In contrast, the preserved thickness and cross-section of individual Mulichinco sandstone bodies do not reflect true depositional geometry or the size of the bedforms while migrating, because they underwent a phase of abandonment and significant reworking during the late transgressive stage (Fig. 17C). Post-depositional compaction would further complicate the resulting geometries. Therefore, caution should be taken when comparing the size and/or external geometry of ancient units with modern analogues.

On the other hand, some internal attributes present in the Mulichinco sandstone bodies and modern sand ridges could be used to better identify ancient transgressive offshore bodies worldwide, which are notably rare or ambiguous features (Snedden & Bergman, 1999; Suter, 2006). In addition to the criteria suggested by Suter (2006) and discussed in this contribution (Fig. 15), a key observation in the Mulichinco units is that they are composed of almost 100% clean sandstone and they do not pass laterally into mud-prone facies (Fig. 17C). The absence or very low proportion of mud-rich facies in transgressive, tide-dominated sand ridges developed in relatively open-marine settings does not seem unreasonable considering two factors: (i) tidal currents in offshore settings will not experience slack periods (Suter, 2006); and (ii) during transgression the overall reworking ratio is high and therefore fines have time to bypass to distal low-energy sectors of a basin (Swift & Parsons, 1999). In this way, muds would not commonly be deposited in any part of the offshore ridge, and erosion of pre-existing muddy sediments would lead to winnowing of fines. The resulting sand-dominated accumulations could eventually enter into the rock record. In contrast, transgressive sandstone-rich units passing laterally into similarly thick muddy facies could represent transgressively incised shorefaces (MacEachern *et al.*, 1999b) or even shore-attached linear ridges ('juvenile' ridges according to Snedden & Dalrymple, 1999), but are very unlikely to be offshore-developed sand ridges. If these criteria are used as a template, then the Shannon Sandstone (Western Interior, USA) would contain additional evidence against such an interpretation, because several studies have described abundant mud drapes and/or mixed (sandstone/mudstone) lithologies laterally away from the axis of the sandstone bodies (see Suter & Clifton, 1999 for a compilation of data).

Finally, the absence of mudstone-rich facies in transgressive offshore sandstone bodies could provide insights for characterization of reservoir analogues. Snedden & Bergman (1999, fig. 4A) proposed a reservoir-model conceptualization in which significant volume would be represented by mixed facies acting as internal barriers to flow. However, this proposed scenario was heavily influenced by the knowledge of the author on Atlantic shore-attached storm-dominated sand ridges. On the contrary, the lessons learned from the Mulichinco and similar reviewed examples would suggest that fully detached, tide-built sandstone bodies would probably have >85% of net sand, with the remaining volume being non-reservoir cemented skeletal sandstones. This alternative scenario could help to improve the understanding and modelling of offshore-developed, sand-ridge reservoirs.

CONCLUSIONS

1 Based on the integration of multiple datasets (three-dimensional sedimentology, ichnology, taphonomy and palaeoecology) facies associations and architecture of sharp-based sandstone bodies and surrounding sediments were identified and interpreted in the lower half of the Valanginian Upper Member of the Mulichinco Formation.

2 Massive mudstones (Facies Association 2) grading upward to muddy sandstones with lenticular hummocky cross-stratification beds to the top (Facies Association 3), in turn passing vertically to amalgamated sandstones with hummocky cross-stratification and swaley cross-stratification (Facies Association 4) are considered to be siliciclastic upward-shoaling successions deposited in storm-dominated offshore to lower-shoreface settings. Skeletal sandstones, together with cross-stratified and burrowed sandstones (Facies Association 5) comprise discrete packages interpreted to represent early transgressive offshore bodies. Skeletal carbonates (Facies Association 1), occurring between Facies Association 5 and Facies Association 2 are believed to reflect minimum net sedimentation rates in later transgressive conditions, before the turn around to regressive siliciclastic systems.

3 Each of the Mulichinco sandstone bodies discussed in this contribution is a transgressive feature formed below fair-weather wave base within a low-gradient open-marine setting. Prior to their formation, an erosional discontinuity was cut during sea-level fall, which produced exhumation of dewatered fine-grained sediments as well as cemented sandstone clasts. Subsequent transgression favoured bioerosion and encrustation in sandstone clasts and development of attached-living fauna onto the sea floor, as well as loose sand by reworking of sand-prone older deposits. Therefore, the bases of the sandstone bodies are interpreted as composite erosional surfaces representing sequence boundaries and transgressive ravinement surfaces (SB/TRS).

4 Within sand ridges, deposition probably started as two-dimensional and three-dimensional dunes migrating preferentially seaward which subsequently coalesced to form larger bedforms. These large-scale bedforms or linear ridges could have been a few metres high and hundreds of metres to a few kilometres wide, and had their crests oriented sub-parallel to prevailing flows (most likely to be tidal currents). They migrated at a highly oblique angle with respect to their main elongation and probably also at a high angle with respect to the inferred palaeo-shoreline orientation.

5 The vertical reduction in grain size and scale of bedforms recorded in the Mulichinco sand-rich units suggest that current energy dropped gradually through time, probably as transgression proceeded. Intense burrowing that was able to totally destroy physical structures seems to mark an abandonment stage in which ridges became moribund. Once fully deactivated, they commonly were colonized by epibenthic communities (oysters, serpulids and corals) and a carbonate-dominated system developed.

6 Partial reworking of sand ridges might have occurred during this late transgressive stage and therefore the preserved thickness and cross-section of these units do not reflect true depositional geometry and size of the bedforms while migrating, and caution should be taken when using size and/or external geometry to compare with modern analogues.

7 The Mulichinco transgressive sandstone units are interpreted to represent shore-detached elongated bodies developed (or finally preserved) in offshore conditions. About 90% of the sediments are clean sands and they do not grade laterally or vertically to mud-prone facies. Mud deposition (or preservation) was uncommon during ridge evolution.

8 A multiple-dataset approach was successful for ambiguously understanding the transgressive genesis and evolution of sharp-based marine sandstone bodies. This approach and new identification criteria discussed in this contribution, such as the nature of the basal skeletal sandstones and the lack of mud-prone facies, could be used to identify offshore transgressive sandstone bodies worldwide.

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