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RECOGNITION OF ANCIENT TIDAL DEPOSITS AND FACIES SUCCESSIONS CHANGES ACCORDING TO STRATIGRAPHIC CONTEXT. EXAMPLES FROM UPPER CRETACEOUS GALLUP CLASTIC WEDGE, NEW MEXICO

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RESUMEN

Un estudio de estratigrafía genética de alta resolución fue realizado en el área de cuatro esquinas, Nuevo Méjico, EE.UU. Observaciones faciales y geométricas detalladas hechas en la parte inferior y superior de la cuña clástica del Gallup permitieron aprender acerca de 1. cómo los depósitos influenciados y dominados por mareas son incorporados en el registro estratigráfico, 2. cómo esos depósitos se expresan en afloramiento, 3. cómo estos depósitos cambian con respecto a la posición estratigráfica.

Siete facies fueron usadas para caracterizar sucesiones de facies influenciadas por procesos de mareas. Estas reflejan un cambio paleogeo-morfológico a escala intermedia de ambientes dominados por olas a ambientes influenciados por mareas. En el Gallup, los depósitos de Shoreface difieren de los depósitos influenciados por marea en que los depósitos de marea ocurren dentro de un contexto de condiciones de incremento de Acomodación / Suministro de Sedimento (A/S) a escala intermedia. Adicionalmente, tres facies fueron usadas para caracterizar sucesiones de facies dominadas por procesos de mareas. Estas reflejan un cambio paleo-geomorfológico a gran escala de ambientes dominados por olas a ambientes dominados por mareas. En la cuña clástica del Gallup, los depósitos dominados por mareas se diferencian de los influenciados por mareas en que los que son dominados se presentan en un contexto de incremento de condiciones de A/S a gran escala.

Las sucesiones verticales de facies son un producto de la transición de elementos geomorfológicos pendiente abajo y la migración de subambientes lateralmente ligados. Las tendencias preservacionales de los depósitos influenciados por mareas asociados con la caída del nivel base difieren de aquellos depositados en la subida del nivel base. Los depósitos influenciados por mareas, relacionados con tendencias a gran escala de caída de nivel base, son mas amalgamados, menos extensos y mas homogéneos que los depósitos dominados por mareas, los cuales son asociados a condiciones de subida de nivel base. Se muestran ejemplos de cómo identificar ambientes influenciados por mareas y como distinguirlos de aquellos dominados por mareas.

La cuantificación de atributos dimensionales y geométricos de los depósitos influenciados o dominados por mareas proveen información adicional que debe ser considerada cuidadosamente en la caracterización y simulación de reservorios.

Palabras clave: Estratigrafía genética, sedimentología, sucesión de facies, modelamiento, simulación, Nuevo Méjico, Gallup, mareas, yacimientos.

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ABSTRACT

A high-resolution genetic stratigraphic study was conducted on the four corners area, New Mexico, USA. Sedimentologic and stratigraphic observations made on the Gallup Clastic Wedge help us to learn about 1. how tidal influenced or dominated deposits are incorporated into the stratigraphic record, 2. how they are expressed in outcrops 3. the way they change according to stratigraphic position.

Seven facies were used to characterize facies successions influenced by tidal processes. They reflect an intermediate-scale paleogeomorphic change from wave dominated to tidal influenced environments. In the Gallup, shoreface differ from tidal influenced deposits in that tidal deposits occur within a context of intermediate scale increasing Accomodation/Sediment Supply (A/S) conditions. Additionally, Three facies were used to characterize facies succession dominated by tidal processes. They reflect a large scale paleogeomorphic change from wave dominated to tidal dominated environments. In the Gallup Clastic Wedge, tidal dominated deposits differ from tidal influenced deposits in that the tidal dominated occur within a context of large scale increasing A/S conditions.

Vertical facies successions are a product of translation of geomorphic elements downslope and migration of laterally linked subenvironments. Preservational trends from tidal deposits associated with base level fall differ from those deposited in base level rise conditions. Tidal influenced deposits, related with large scale base level fall trends are more amalgamated, less wide, and more homogeneous that tidal dominated deposits, associated to large scale base level rise conditions. Examples of how identify tidal influenced environments are shown.

Quantification of geometric and dimensional attributes of tidal influenced deposits provides additional information to be carefully considered in reservoir characterization, and simulation.

Key words: Genetic stratigraphy, sedimentology, facies successions, modeling, simulation, New Mexico, Gallup, tidal, reservoirs.

INTRODUCTION

Tidal processes and environments have been generally treated statically and out of a stratigraphic context; see James (1984). Stratigraphic context give us a worthy scenario to observe changes in facies diversity and differentiation and to learn how tidal processes and products are dynamically recorded in rocks under a frame of large to intermediate scale increasing or decreasing Accommodation / Sediment Supply (A/S) conditions.

The main goal of this paper is to show how tidal influenced or dominated facies tracts can be interpreted, distinguished and characterized from sedimentary structures, facies, facies successions and associations under a stratigraphic context. This paper also uses a stratigraphic context to observe changes in facies diversity and differentiation and to learn the way tidal processes and products are dynamically recorded in rocks.

Common structures observed and associated with tidal processes are: large- and small-scale planar tabular and trough cross-stratified sandstones with foresets oblique or nearly tangential to bedding surfaces. Foresets show counter-flow current ripples, bidirectionality (herringbone), couplets, double mud drapes, and sigmoidal bundles and phosphate nodules. Large (2 – 3 m thick), fully preserved, landward-directed sandwaves are also observed. Biogenic criteria consist of body fossils (i.e., Inoceramids), trace fossils (i.e., *Ophiomorpha* and *Thalassinoides)*, and shark teeth. Moreover, bidirectional paleocurrent data suggest current reversals characteristic of tidal processes.

The Gallup clastic wedge allow us to study and learn about changes in tidal facies successions and environments according to stratigraphic context. FIGURE 1 shows the study area and the locations of the measured stratigraphic sections. FIGURE 2 shows the occurrence of Gallup, Torrivio and Tocito, litho-stratigraphic units relevant to this study, within a genetic stratigraphic context.

THE TIDAL INFLUENCED OPEN BAY FACIES TRACT

This facies tract consists of seven facies (FIGURE 11): burrowed, low-angle cross-bedded sandstone (BLAXBT); large to small-scale tangential or concave cross-bedding (LTXT) herringbone cross-bedded sandstone (HRBXT); sigmoidal bundled sandstone (SIGT); isolated burrowed low-angle and bundled sandstone (IBLAT); wave rippled, low-angle laminated sandstone (WRLT); and, large-scale fully preserved trough-cross and planar-tabular sandstone (LXPT).

Burrowed, Low-Angle Cross-Bedded Sandstone Facies (BLAXBT)

BLAXBT consists of beige, upper medium to upper coarse sandstone. Major sedimentary structures are bidirectional low-angle cross stratification, couplets, rippled bounding surfaces and burrowing.

Low-angle cross stratification consists of low-angle laminae and set contacts, which are inclined seaward (NE). The set contacts are erosional and non-erosional, and laminae lie fairly parallel to set contacts. Couplets consist of foreset laminae, millimeter to centimeter thick, alternating in a thick and thin pattern and commonly associated with mud-draped laminae between foresets. Rippled bounding surfaces consists of centimeter scale (<3 cm thick) current ripples located at the boundary between decimeter-scale beds or laminasets.

Centimeter-scale lamination is faint due to burrowing (FIGURE 3). Beds of this facies are 0.2 to 1 m thick; bedsets are 0.5 to 3 m thick. Bedsets change progressively upward from bioturbated, planar, coarse-grained, muddy beds, to cross-bedded, finer grained, more amalgamated, and less burrowed beds. In addition, beds decrease in thickness, and foresets become less steep. These beds may be laterally continuous for 10s to 100s of meters.

Thalassinoides and *Ophiomorpha* are the main burrow types. Unidentified horizontal burrows are filled with fine material rich in dark constituents such as carbonaceous detritus and mica. Burrowing is associated with interbedding of white to beige and gray sandstones, rich in white mica and organic material.

Contacts between beds are usually sharp and irregular. Contacts with overlying large-scale tangential cross-bedded sandstone facies (LTXT) are sharp and irregular. Contacts with underlying planar low-angle bedded sandstone facies (LAXSS) of the shoreface facies tract and the heavily burrowed or bioturbated fine sandstone facies (BFSS) are sharp and irregular, and are characterized by a recessive interval.

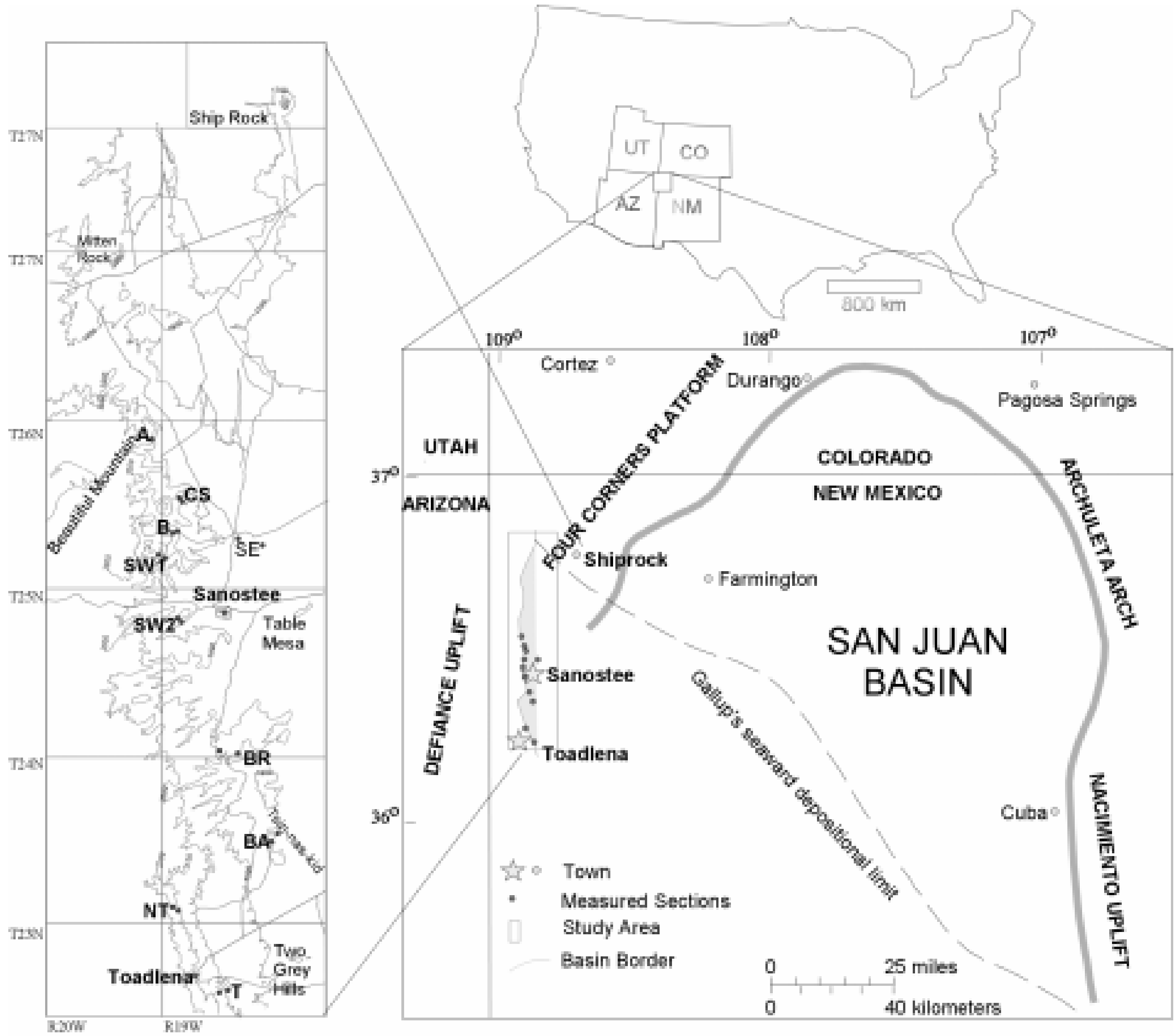

FIGURE 1. Location of the San Juan basin and the study area.

Isolated beds consist of slightly burrowed laminae, 0.5 cm thick on average, and couplets. This facies changes upwards to beds of planar-laminated sandstones with laminae 2-3 cm thick. Beds of this facies are 10 to 40 cm. Beds are discontinuous and mudstones are usually interbedded with them.

BLAXBT facies is expressed as white rounded cliffs capping shoreface facies successions. This facies is interpreted as tidal bars. Recessive intervals are interpreted as intertidal flat deposits. In the high tidal flats mud is deposited by suspension during with high-water slack tide. Isolated, oppositely directed cross beds suggest bed load deposition by reversing tidal currents of nearly equal velocity. Plane beds are inferred to be deposited in shallow water. Klein (1970) reports lower flow regime plane beds as being formed by tidal currents below 2.0 cm/sec, in water depths shallower than 2.3 m The transition from shoreface SXS and LAXSS facies to overlying tidal BLAXBT facies is a distinct change in environmental conditions.

The presence of low-angle cross stratification associated with abundant mud, burrowing, couplets and rippled bounding surfaces suggests the interpretation of BLAXBT facies as part of tidal bars. This facies is associated with processes such as tidal current scouring on the shoreface (Klein, 1977).

Large- to Small-Scale Tangential Cross-Bedded Facies (LTXT)

LTXT consists of green to pink, lower medium, subrounded, well-sorted sandstone. This facies usually contains mud as matrix. Major sedimentary structures are large- and small-scale trough cross stratification with tangential foresets, cut-and-fill structures, reactivation surfaces, bidirectional cross bedding and burrowing.

Trough-shaped sets consist of an elongate scour filled with curved laminae that commonly have a tangential relationship to the lower bounding surface (Boggs, 1987). Trough cross stratification originates by small to large downstream-accreting sinuous crested dunes.

Scour-and-fill or cut-and-fill structures consist of small, asymmetrical decimeter- scale troughs 20-30 cm thick with axes that point downcurrent and which commonly have a steep upcurrent slope and more gentle downcurrent slope. Foresets within the scour are nearly indistinct and tangential or concordant to the scour. These structures are formed as a result of scour currents and subsequent backfilling as current velocity decreases (Reineck and Singh, 1980).

Reactivation surfaces are surfaces resulting from partial erosion of megaripples followed by reversing currents during an asymmetrical tidal cycle. These surfaces are followed by redeposition during the next tidal cycle (Boggs, 1987). Reactivation surfaces represent current reversals, or current or depth changes under unidirectional flow (Weimer et al. 1982).

Facies LTXT has centimeter thick foresets that dip 20^{o} to 30^{o} seaward (NE). They usually show a slight concave upward curvature and terminate tangentially with the lower bounding surface (FIGURE 4). Beds are 20 to 70 cm thick and become thinner and more amalgamated upwards. Bed sets are up to 2 m thick and are laterally continuous for 10s of meters. Burrowing at distinct bedding surfaces indicates episodic sedimentation followed by recolonization of the sea floor. Casts of *Pelecypods* are observed.

This facies commonly becomes more amalgamated upwards. It changes upwards into low-angle beds, and is closely related to internal scour-and-fill structures. Contacts with scour-and-fill structures are sharp and irregular, and individual beds likewise have sharp contacts. Contacts with overlying sigmoidal bundled sandstone facies (SIGT) are

transitional. Contacts with underlying low-angle facies (LAXSS), herringbone facies (HRBXT), and bioturbated facies (BFSS) are sharp and irregular.

This facies is expressed as a white cap on the steep cliffs typical of shoreface successions. When observed from a distance of more than 10 meters, this facies is not easily distinguished from the underlying shoreface facies succession.

Paleoflow directions measured on these beds reveal a SE (shore parallel) trend at Beautiful Mountain, a SW (landward) trend at SW2 and Big Reentrant, and a NE (seaward) trend at the Breached Anticline section (FIGURE 7).

This facies suggests deposition in an intertidal sand flat environment under time velocity asymmetry, where dune and sand wave migration occur in water depths exceeding 2.3 m and tidal current velocities exceed 10 cm/sec (Klein, 1977). Amalgamation and scouring toward the top of this facies is interpreted as due to increase in tidal energy. Transitions to lower-flow regime low angle cross stratified beds forming sand flats suggests a temporal decrease in water depth due either to a period of water retreat (i.e., ebb tidal currents) or to a terminal phase of the flooding of a flood tidal current. Recognition of these intervals and their association with underlying burrowed surfaces and with overlying sigmoidal bundled and mud-draped facies suggests oscillating water depths associated with flood and ebb tides.

Herringbone Cross-Bedded Sandstone Facies (HRBXT)

HRBXT consists of white to orange lower medium to upper coarse sandstone. Major sedimentary structures are bidirectional trough and planar cross stratification and minor burrowing.

Herringbone cross-bedding consists of foreset toes which terminate tangentially or obliquely to the lower bounding surfaces. Bounding surfaces are usually planar but may have a slight concave upward curvature. The dip of laminae above and below the same bounding surface changes roughly 180^{o} (FIGURE 5). Grain size variations between laminaesets overlying and underlying specific bounding surface are not abrupt.

Laminaeset thickness is 10-40 cm and increases upwards. Laterally, the HRBXT facies can be followed for 10s of meters.

This facies overlies planar to low-angle bedded sandstone facies (LAXSS) of the shoreface facies tract with sharp and irregular to planar contacts. It underlies large- to small-scale tangential cross-bedded facies (LTXT) with sharp to transitional irregular contacts. Laterally, this facies may be replaced by LTXT facies. Lower and upper contacts are usually obscured by weathering.

This facies is expressed as either sharp cliffs or as white beds capping shoreface facies successions. It may be mistaken easily for BLAXBT, LTXT or LAXSS facies.

Paleocurrent data acquired at the Breached Anticline section on beds containing this facies indicate a bipolar and tetramodal NE and SW, NW and SE distribution of paleocurrents (FIGURE 7).

Herringbone cross stratification is produced by alternating flow directions during flood and ebb tides of nearly equal velocity. Each cross set represents megaripple or sandwave migration during a single part of a tidal cycle (Klein, 1977).

Paleocurrent data support current reversals typical of tidal processes. Seaward (NE), ebb tidal current is a bit weaker than landward (SW) flood tidal current. This is supported by the average landward direction of the foresets. SE and minor NW directions are associated with longshore currents parallel to the shoreline direction, which has a trend N65^{o}W. Amalgamation of sets should be the result of reduced accommodation conditions, shallow water or of deficient sediment supply and energetic tidal currents reworking sediment. The lack of heavily burrowed beds suggests that rates of deposition were high relative to rates of burrowing.

Sigmoidal Bundled Sandstone Facies (SIGT)

SIGT consists of light green to beige lower to upper medium, subangular, well-sorted sandstone. Major sedimentary structures are sigmoidal bundles, couplets, reactivation surfaces and burrowing.

Sigmoidal bundles consist of groups of centimeter-scale foreset laminae (<5 cm thick) frequently separated by double mud drapes. Laminae topsets and bottomsets are nearly tangential to upper and lower bounding surfaces (FIGURE 6). Foresets have a sigmoidal shape and dip 10^{o} to 30^{o} either seaward (NE) or landward (SW). Each laminaeset is bounded by mud drapes or by a reactivation surface representing a single dominant current stage. A series of bundles is referred to as a tidal bundle sequence (Nio and Yang, 1991). Beds of tidal bundles are 20 to 50 cm thick and can be followed laterally for less than 10 meters. The sigmoidal bundles commonly show bidirectional paleocurrents. Bounding surfaces may be planar or irregular, dipping a few degrees (<15^{o}).

This facies overlies the large- to small-scale tangential cross-bedded facies (LTXT) and the large-scale fully preserved trough-cross and planar-tabular sandstone facies (LXPT), which are composed of seaward-migrating megaripples and sandwaves, respectively. It lies below (LTXT) facies and rippled (flaser) sandstone facies (RFB) of the bay-margin/intertidal flat facies tract.

Contacts with overlying (LTXT) and (LXPT) facies are sharp and slightly irregular. Contacts with underlying (LTXT) and (RFB) facies are also sharp and slightly irregular.

Paleocurrent data acquired at the Cone Shape section on beds containing this facies indicate a bipolar and trimodal NE and SW, and SE distribution of currents (FIGURE 7). Current directions are slightly oblique to paleoshoreline, which has a trend of N65^{o}W (Jones, 1991).

Sigmoidal bundled facies is interpreted as characteristic of subtidal depositional settings. The depositional process associated with this facies is the time-velocity asymmetry. Reactivation surfaces generally intersect sigmoidal bundles. They are developed during a destructive or subordinate phase of a tidal cycle and are preserved by resumption of sandwave migration during the constructional or dominant phase. Paleocurrent data support the idea of current reversals as characteristic of tidal processes. Landward (SW, flood tidal) currents are a bit weaker than seaward (NE, ebb tidal) currents. This evidence suggests time-velocity asymmetry associated with subtidal settings. SE direction is associated with longshore currents parallel to shoreline direction (N65^{o}W).

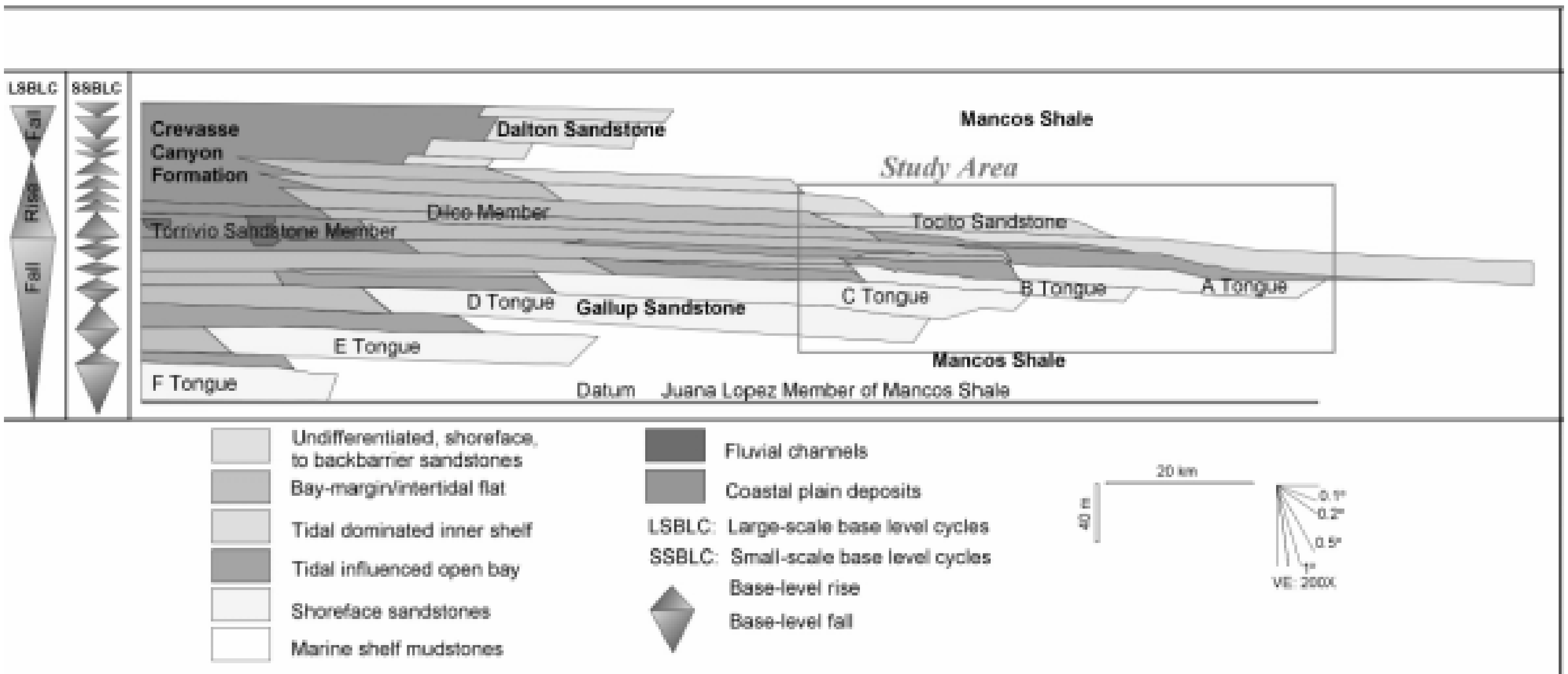

FIGURE 2. Schematic lithostratigraphic cross section of the Gallup Sandstone and genetically associated units showing interfingering relationships. In this study Dilco and Torrivio are considered members of the Crevasse Canyon Formation

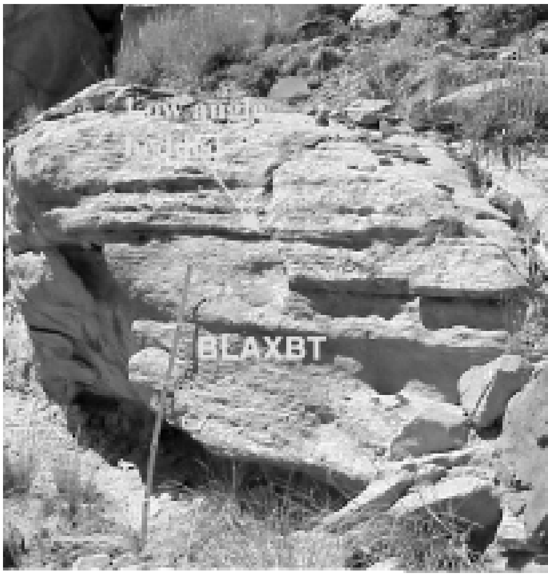

FIGURE 3. Burrowed, low-angle cross-bedded sandstone facies (BLAXBT). Observe low-angle laminae (1cm thick). Folding ruler is 1m. Location: Amphitheater section.

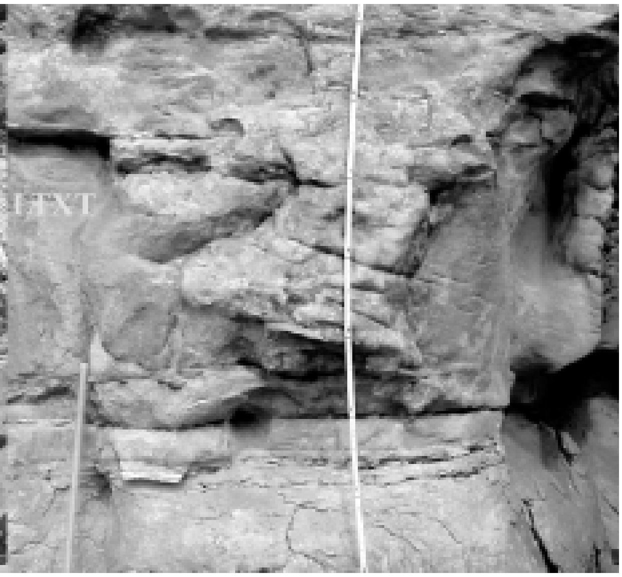

FIGURE 4. Large- to small-scale tangential cross-bedded facies (LTXT). Observe curvature of foresets and bed dimensions. Each segment of folding ruler is 21.7 Cm. Location: Cone Shape section.

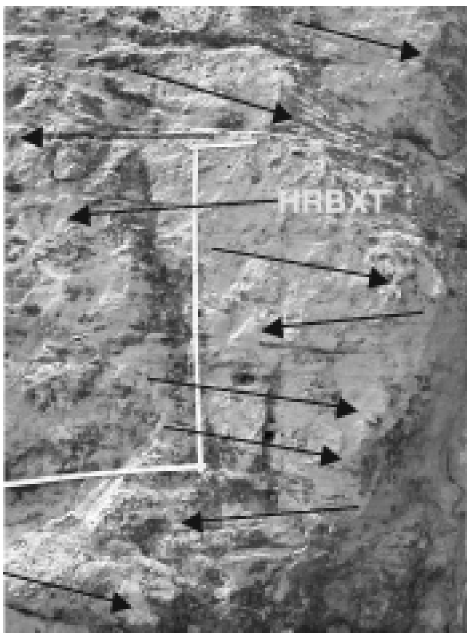

FIGURE 5. Herringbone cross-bedded sandstone facies (HRBXT). It consists of foresets toes which terminate tangentially or obliquely to lower bounding surfaces. Bounding surfaces are usually planar but may have a concave upward curvature. Arrows indicate paleoflow direction. Segment of folding ruler is 21.7 cm. Location: Sanostee West 1 section.

FIGURE 6. Sigmoidal bundled sandstone facies (SIGT). Bundles dip landward. Staff is nearly 1m. Location: Cone Shape section.

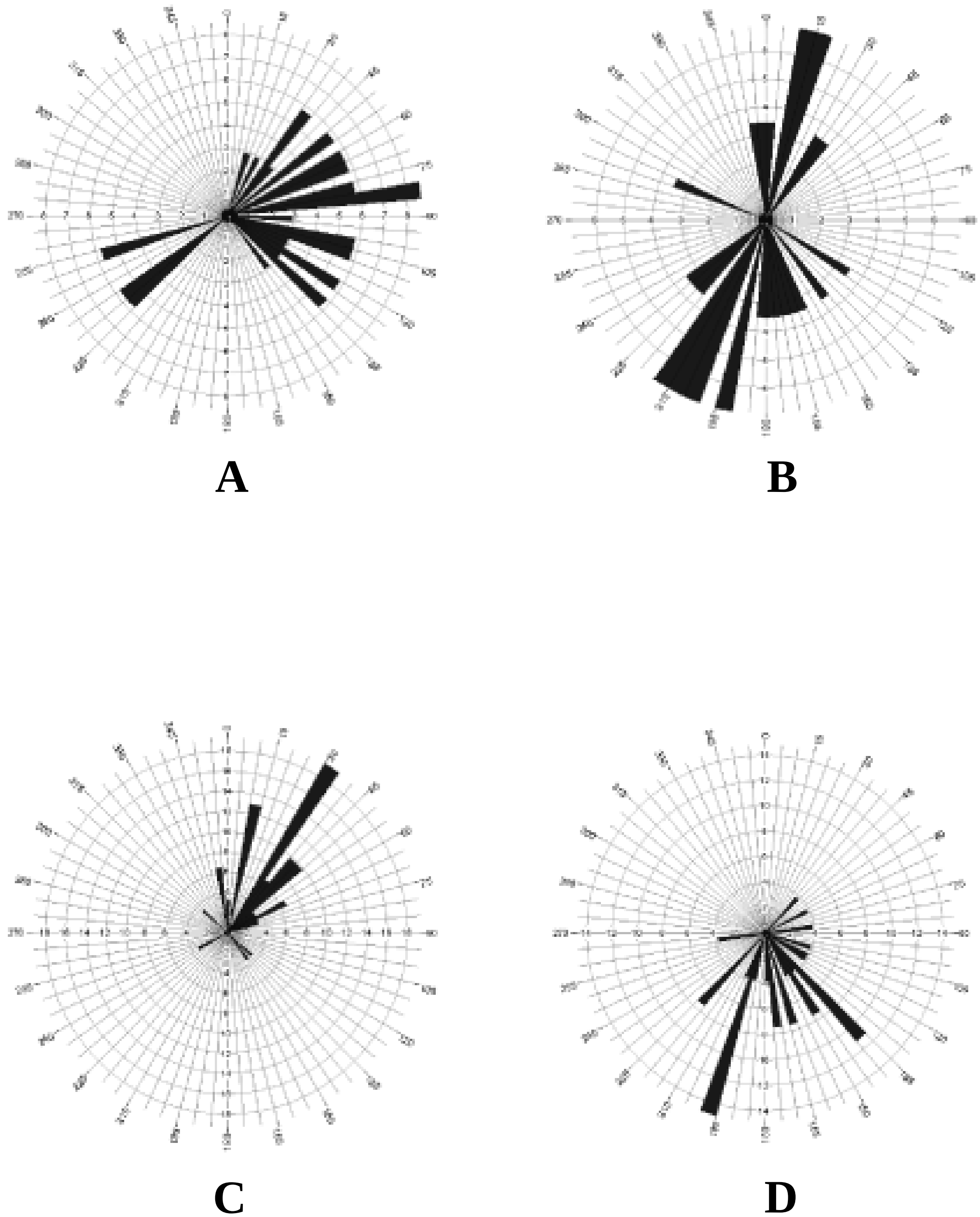

FIGURE 7. Paleocurrent data for: A. Sigmoidal bundles facies (SIGT) that cap shoreface facies succession at Cone Shape Section. B. Herringbone cross-bedded sandstone facies (HRBXT) that cap the shoreface at Breached Anticline Section. C. Large scale fully preserved trough cross and planar tabular sandstone facies (LXPT) capping heterolithic facies succession at Sanostee East Section. D. Large scale fully preserved trough cross and planar tabular sandstone facies (LXPT) located at upper positions of sandwaves at Sanostee West 1 Section.

FIGURE 8. Isolated burrowed low-angle and bundled sandstone facies (IBLAB). Foresets dip seaward. Hammer is 37.5 cm. Location: Sanostee West 2 section.

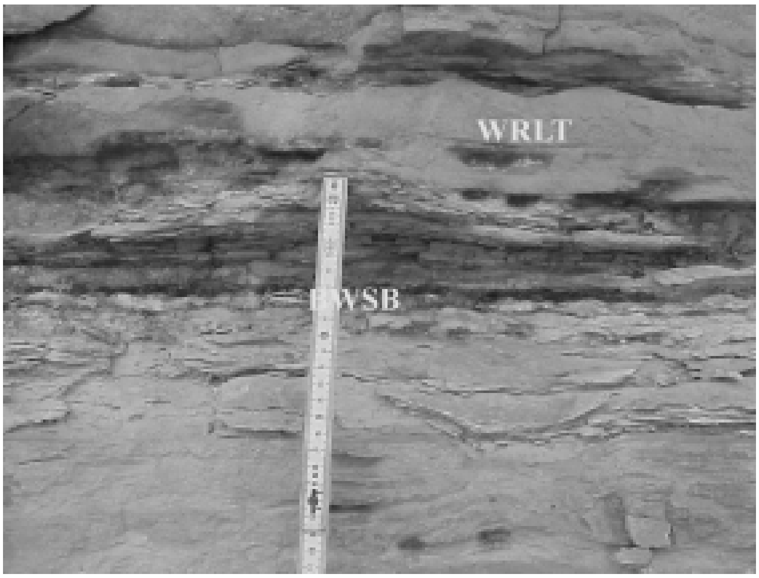

FIGURE 9. Wave-rippled and low-angle sandstone facies (WRLT). Segment of folding ruler is 21.7 cm. Location: Amphitheater section.

FIGURE 10. Large-scale fully preserved trough cross and planar tabular sandstone facies (LXPT). Foresets dip SW, suggesting current reversals. Foresets in the central sandwave dip seaward (NE). Ripples cap this sandwave. Segment of folding ruler is 21.7 cm. Location: Sanostee East section.

Isolated Burrowed Low-Angle and Bundled Sandstone Facies (IBLAT)

IBLAT consists of light green to beige, lower medium sandstone. Major sedimentary structures are low-angle cross bedding, small bundles, couplets and burrowing. Laminae have a tangential contact with lower bounding surfaces. Laminae are centimeter scale, with beds usually thinner than 20 to 40 cm, and bedsets about 0.8 to 1.2 m thick (FIGURE 8). Burrowing is dominated by *Ophiomorpha* and *Thalassinoides*. This facies is laterally continuous for 10s of meters.

This facies is interbedded with carbonaceous siltstone (CSPBC) facies. Contacts with (CSPBC) facies are sharp and fairly planar. Beds of these facies are discontinuous and dip either NE (landward) or SW (seaward).

This facies is interpreted as isolated sand bodies of mixed intertidal flats. Burrowing suggests marine conditions and normal salinity. Slightly bundled beds interbedded with carbonaceous siltstones suggest alternating periods of water mass flooding and retreat in a tidally influenced bay.

Wave-Rippled and Low-Angle Sandstone Facies (WRLT)

WRLT consists of white to beige, lower to upper medium sandstone. Major sedimentary structures are wave ripples, mud drapes, low-angle cross beds and burrowing. Sets of ripples are 1 to 3 cm thick and 10 to 20 cm long. Individual beds of this facies are not thicker than 15 cm. Bed sets are 0.5 to 1 m. This facies can be followed laterally for several meters and changes gradually into the basal part of the large-scale fully preserved trough and planar tabular cross-stratified facies (LXPT).

Wave ripples occur on bedding surfaces. Their troughs and sometimes their crests are mud draped (FIGURE 9).

This facies has sharp to transitional contacts with underlying carbonaceous siltstone facies (CSPBC). Contact with overlying (LXPT) facies is sharp and irregular or gradational within less than a meter.

This facies is considered the toesets of large sandwaves. It forms a transition zone between mud-rich wavy laminated facies of the bay-margin/intertidal flat facies tract and the planar tabular facies of the tidal influenced open bay facies tract, and is a good indicator of tidal processes (FIGURE 9). This facies is interpreted as being the result of late-stage emergence runoff. It originates by the progressive emergence of intertidal sand bodies during the ebb stage of a tidal cycle (Klein, 1977). That process involves simultaneous lowering of water level, changes in flow direction and changing of current velocities.

Large-Scale Fully Preserved Trough Cross-Stratified and Planar Tabular Sandstone Facies (LXPT)

LXPT consists of white to beige, lower medium to upper very coarse sandstone. Quartz and chert grains 5mm in diameter (average) and up to 2 cm occur. *Pelecypods*, shark teeth, and small silicified wood fragments are found at the top of these beds. Major sedimentary structures are planar trough and tabular cross stratification, couplets, sigmoidal bundles, reactivation surfaces, bidirectional cross beds and burrowing (FIGURE 10).

Tabular cross beds have long (2- 10s m) crest lines, set thickness of 0.5 - 3 m and planar surfaces >10 m. The laminae of tabular cross-beds are commonly planar and oblique to the lower bounding surface, but curved laminae tangential to the bounding surface occur. Planar tabular cross stratification is formed by migration of straight-crested sandwaves (Harms, et al. 1982). This facies is interpreted as intertidal to subtidal sandbodies (i.e., tidal megaripples to sandwaves) that are deposited under meso- to macrotidal conditions.

This facies has foresets forming couplets 5 to 6 cm thick, with foresets dipping 15^{o} to 30^{o}. Beds are 0.2 to 0.5 m thick where amalgamated and bedsets are 1 to 6 m. They are continuous for 10s to 100s of meters (FIGURE 10). Carbonaceous drapes occur rarely between laminae and current ripples occur on some bedding surfaces. Beds became thinner and more amalgamated through bedsets of this facies. Some bidirectional cross beds overlie or are interbedded with tabular cross beds. Although not conspicuous and not in all beds, *Ophiomorpha* dominates burrowing.

This facies typically overlies tidal related facies like the rippled and low-angle sandstone facies (WRLT), bay related facies like the burrowed and wavy sandstone facies (BWSB), and coastal plain related facies like the carbonaceous siltstone facies (CSPBC). Laterally, LXPT facies may interfinger with CoalC1 and CSPBC facies. This facies may underlie CSPBC facies. Contacts with underlying or overlying CoalC1 and CSPBC facies are generally sharp and somewhat irregular. At the contact with BWSB facies, heavily burrowed basal contacts, predominantly *Planolites* and *Gyrochorte*, associated with carbonaceous and woody remains are observed.

Paleocurrent data acquired at Sanostee West 1 section on beds containing this facies have a predominant unidirectional SW (landward) direction (FIGURE 7). However subtle bipolar to tripolar NE, SE, SE distributions also occur (FIGURE 7). Paleocurrent data acquired at the Cone Shape, Sanostee East, Sanostee West 2, and Big Reentrant sections on beds containing this facies indicate NE (predominant) and SW (subordinate) distribution of currents (FIGURE 7). Bipolar to tetrapolar NE, SW, and NW, SE distributions occur (FIGURE 7).

Main processes that might have operated are time-velocity asymmetry characterized by a preferential unimodal orientation of cross stratification, reactivation surfaces, and no conspicuous tidal reversal current indicators. In general, sandwaves seem to migrate in a seaward (e.g., NE) direction. However, landward migrating (e.g., SW) bedforms occur. This supports the time-velocity asymmetry of currents in intertidal to subtidal environments in meso-to macrotidal settings. SE and SW directions are associated with longshore currents due to the elliptical trajectory of propagation of the tidal wave that tends to border the shoreline (Dalrymple, et al. 1992).

DISCUSSION

Seven facies compose the facies associations and succession that record sediment deposition in a tidal influenced open bay (FIGURE 11). It is difficult to compare these facies with facies assemblages identified by previous studies (Flores et al., 1991; Nummedal et al.,1992; Miall, 1992; Nummedal and Molenaar, 1995). The main point of disagreement is the interpretation of tidal instead of fluvial processes for the coarse facies overlying Gallup shorefaces.

From the review of previous studies, see (Álvarez Bastos, 2002) for detailed discussion, we identify some controversial points as well as some points of agreement. For us Gallup Sandstone consists of a genetic couplet of wave-dominated shorefaces overlain by tidally influenced coarse sand strata of open bay environments. We agree with Miall (1992) in that the Torrivio has sedimentary structures that suggest tidal influence. We agree with Nummedal and Molenaar (1995) that tidal influenced units overlie Gallup shorefaces, although we consider this genetic couplet and not a product of stratigraphic dislocation. We disagree with their interpretation of estuaries and distributaries in that we do not see either drowned river valleys nor river deposits. We compare their estuary-mouth sand plug with the tidal component of our shoreface/tidal couplets which formed part of the tidal influenced open bay facies tract. Their central estuary mud deposits are comparable to our strata forming the bay-margin/intertidal flat facies tract. Finally, their bay-head deltas is comparable with strata forming part of our coastal plain and bay-margin/ intertidal flat facies tracts.

This study agrees with Nummedal and Molenaar (1995) in that transgressions are not only recorded by surfaces in the stratigraphic record. We disagree in that there is not a sequence boundary separating Gallup shorefaces from overlying strata because we identify several transgressive surfaces between the shoreface and overlying tidal units and associate them with changes in A/S with base level cycles.

Tidal influenced Open Bay Association and Successions

The tidal influenced open bay facies tract is usually above the shoreface facies tract, below either the bay-margin/intertidal flat facies tract or the tidal dominated inner shelf facies tract, and seaward of its coeval bay-margin/intertidal flat facies tract (FIGURE 2).

This facies tract occurs as a couplet with shorefaces in seaward-stepping genetic units and as sandwich between tidal dominated inner shelf and shoreface or bay-margin/intertidal flats facies tracts, in landward-stepping genetic units.

The distribution of facies within the tidal influenced open bay facies tract is illustrated in FIGURE 12. In

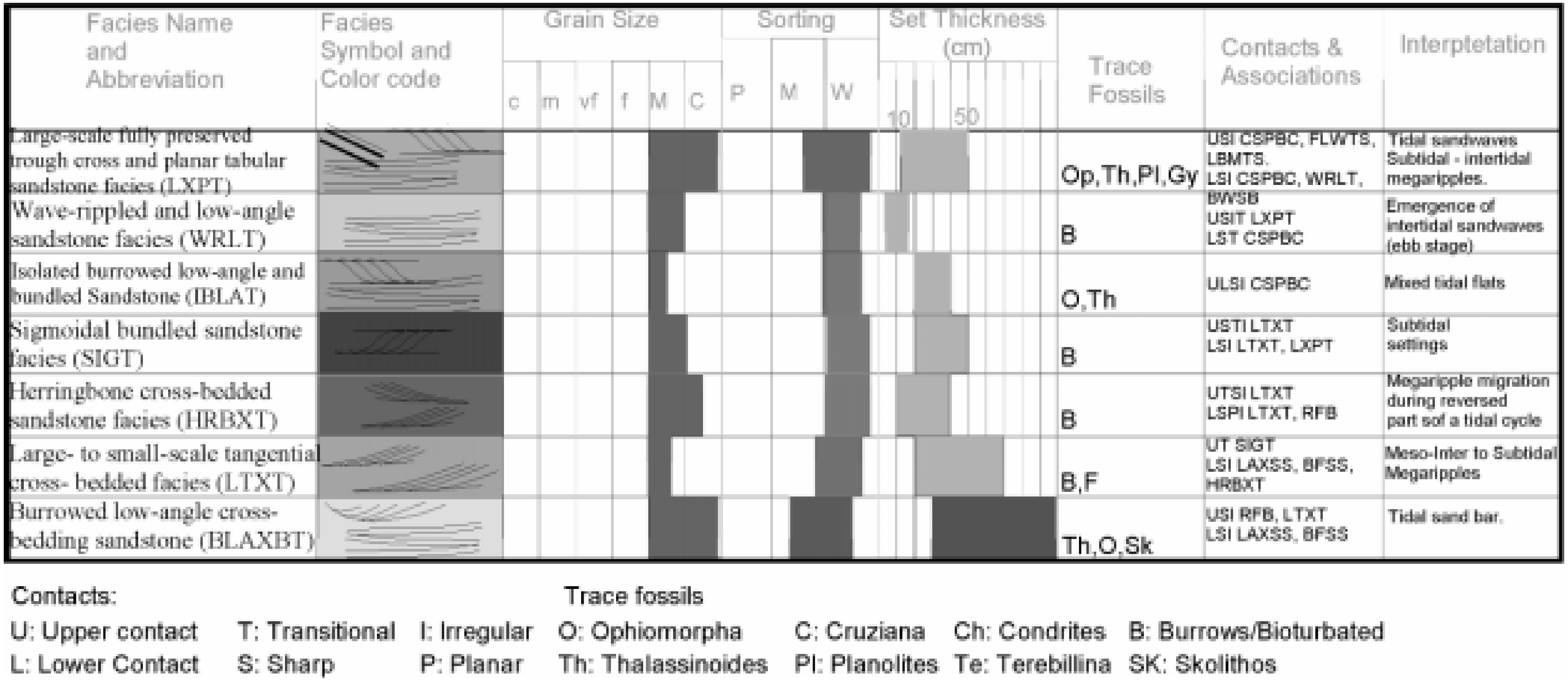

FIGURE 11. Summary of facies described as part of the tidal influenced open bay facies tract

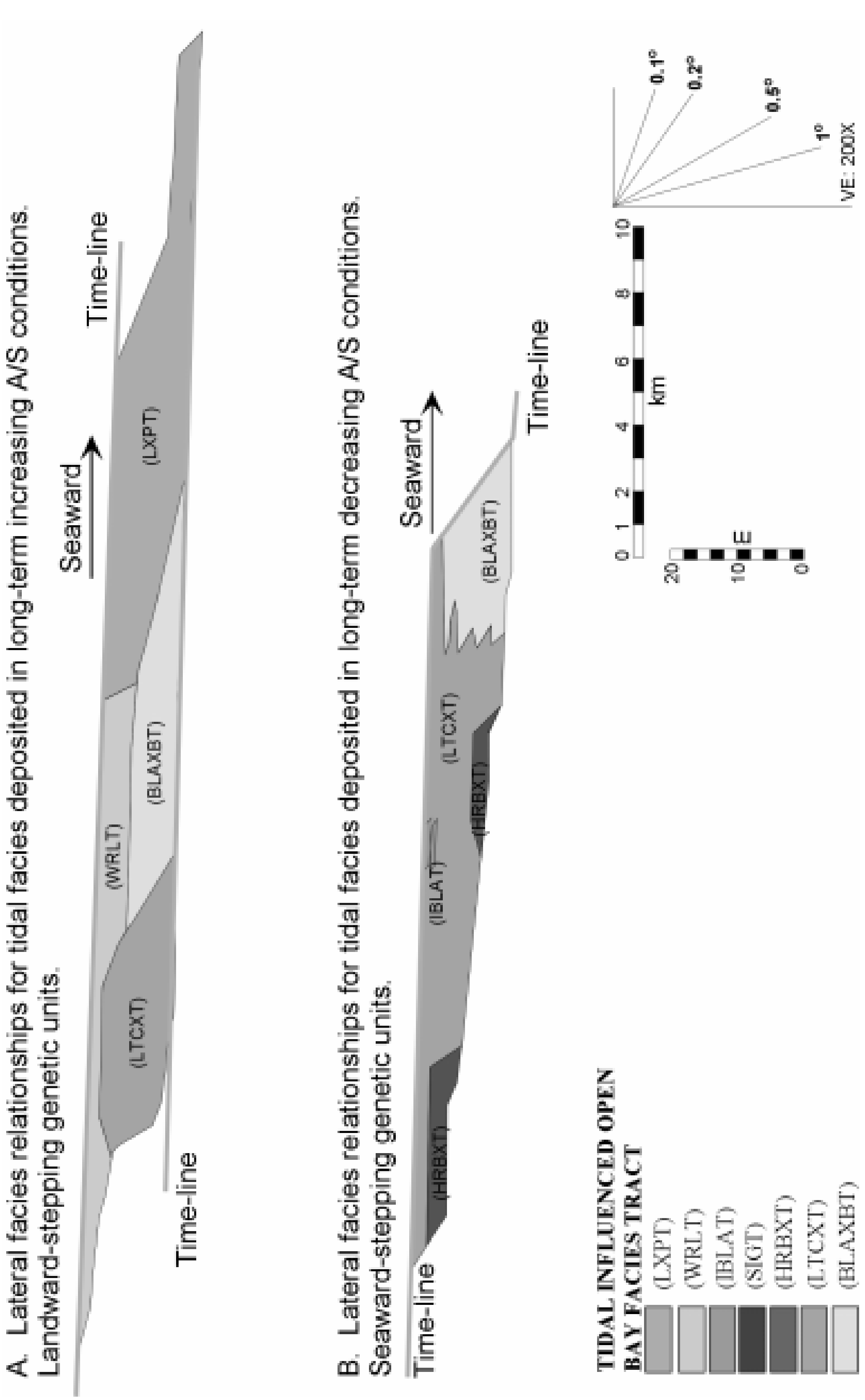

FIGURE 12. Stratigraphic dip cross-section showing lateral facies associations within the tidal influenced open bay facies tract. Facies change laterally (from landward to seaward positions) from tidal influenced to tidal dominated facies. Observe that facies representing tidal dominated conditions migrate landward (e.g., LXPT over BLAXBT).

the study area, 2-10 m thick tidal influenced open bay bedsets extend laterally over several 100s of meters. Interrupted outcrops make it difficult to walk continuously on beds over 100s of meters. However, lateral continuity helps us extrapolate and define a generalized lateral relationship among tidal influenced open bay facies (FIGURE 12).

The tidal influenced open bay facies tracts are 25-40 km long and 9 m thick on average. This facies tract usually thins both landward and seaward. It changes into the bay-margin/intertidal flat facies tract in a landward direction. Seaward, it is bounded by younger shoreface units or passes transitionally into the tidal dominated inner shelf facies tract.

Tidal influenced open bay facies tracts extend up to 4-7 km landward of the landward depositional limit of the underlying shoreface. They rarely go beyond its seaward depositional limit. Its seaward depositional limit is 8-22 km landward of the seaward depositional limit of the underlying shoreface. In landward-stepping genetic sequences, the landward depositional limit of facies tract is located up to 20 km landward of the landward depositional limit of the nearest underlying shoreface. These facies tracts are 35-40 km broad. Tidal influenced open bay facies tracts that are couplets with underlying shorefaces are 25-30 km long.

Under long term increasing A/S conditions tidal influenced open bay facies tracts are laterally more extensive, although thinner, than those deposited under long-term decreasing A/S conditions.

Tidal influenced open bay units forming part of shoreface/tidal couplets are more laterally continuous, thicker, and more amalgamated. Facies within this facies tract in landward-stepping genetic sequences are laterally discontinuous and very well preserved.

Along a depositional profile, facies distributions occur in two geometries, depending on the position of the genetic sequence within the long-term cycle.

(1) For tidal units deposited under long-term decreasing A/S conditions (FIGURE12), there is a progressive landward change from burrowed and low-angle cross-bedded sandstone facies (BLAXBT) to large- to small-scale tangential and concave cross-bedded facies (LTCXT), to herringbone cross-bedded sandstone facies (HRBXT). As a consequence of aggradation during intermediate-term base-level rise, vertical successions through this facies tract show a shoaling up profile of the same seaward to landward facies successions. This succession coarsens upward

(2) For tidal units deposited under long-term increasing A/S conditions, there is a landward transition from large-scale fully preserved trough and planar tabular cross-stratified sandstone facies (LXPT) to wave-rippled and low-angle cross-stratified sandstone facies (WRLT) and from BLAXBT facies to LTCXT facies (FIGURE 12). The vertical succession shows the basic pattern described in (1) but capped by better preserved tidal macroforms.

Facies successions in seaward-stepping genetic sequences (FIGURE 13) begin with amalgamated (HRBXT) or burrowed beds (BLAXBT) and change upwards into more less amalgamated bedforms (LTCXT) or (IBLAT) facies. The GR signature has a blocky shape. Facies successions in landward-stepping genetic sequenced (FIGURE 14) usually begins with heterolithic or burrowed strata (BLAXBT) and changes upwards into fully preserved bedforms (LXPT) facies. The GR signature has a funnel shape (FIGURE 14).

The facies succession motifs described above suggests a stratigraphic control associated with changes in A/S. In the seaward-stepping motif, cross-bedded bedsets are amalgamated and laterally continuous (FIGURES 12 and 13). This succession is bounded seaward by younger shoreface units. These characteristics are associated with long-term decreasing A/S conditions, where amalgamation is an expression of reduced accommodation. In the landward-stepping motif, better-preserved and less continuous tidal influenced open bay units overlie heterolithic and carbonaceous facies of the bay-margin/intertidal flat facies tract (FIGURES 12 and 14). We observe that the first motif one is capped by tidal dominated facies (LXPT) that progressively migrate landward as long-term A/S increases. Tidal facies units change seaward into the tidal dominated inner shelf facies tract. These characteristics are associated with long-term increasing A/S conditions, where high preservation is an expression that high accommodation conditions existed during deposition.

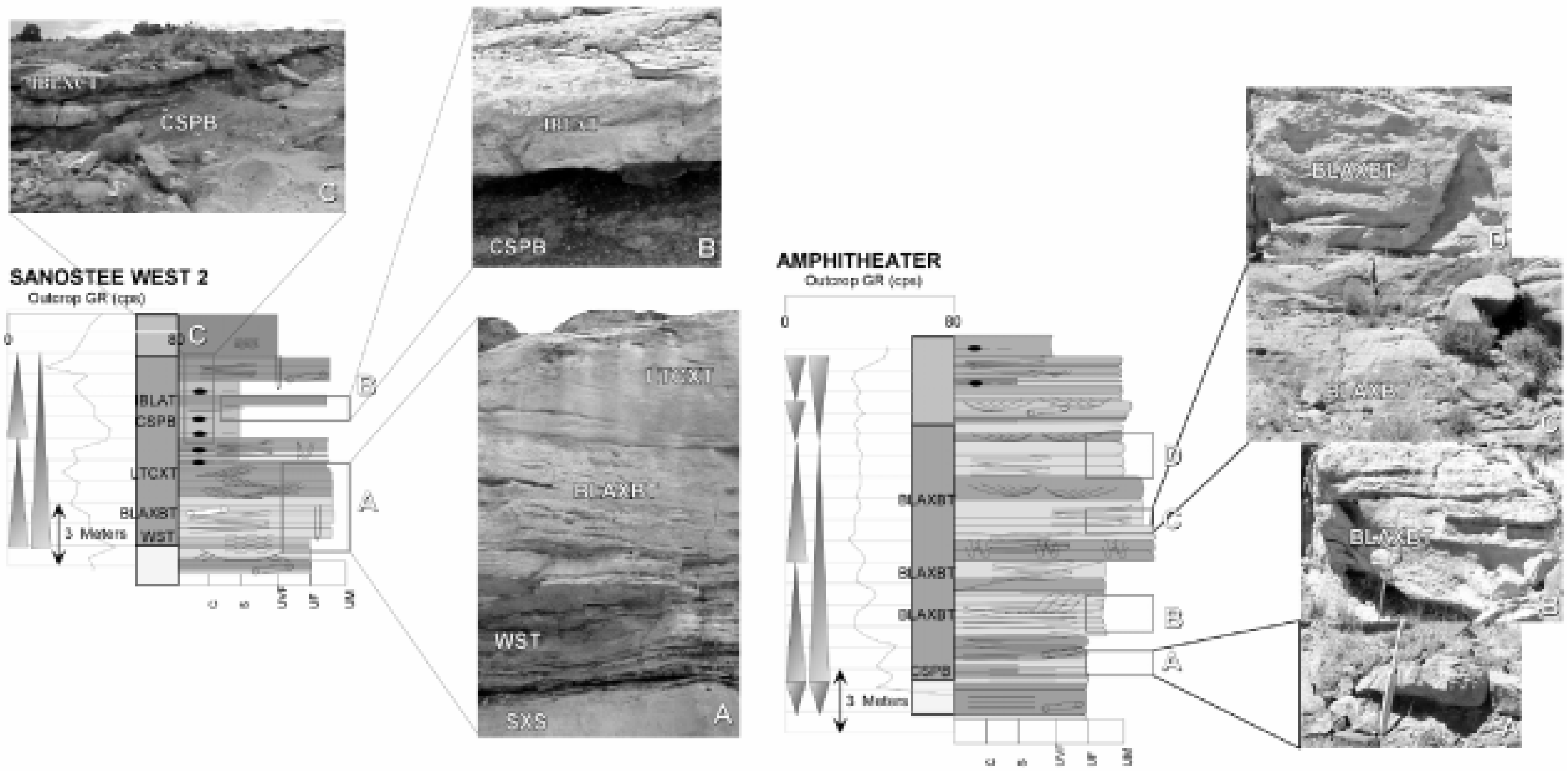

FIGURE 13. Amalgamated tidal facies motif. This motif consists of a recessive basal interval which can be composed of isolated or wavy beds (e.g., facies IBLAT and WRLT). These facies are overlain by more amalgamated and coarser facies (e.g., facies BLAXBT, LTCXT). These facies describe a coarsening and deepening up succession. Tidal units stacked in a seaward-stepping pattern overlie shoreface strata. The basal portion of the succession is thin (<2M) and the upper portion is amalgamated. The gamma ray (GR) signature has a blocky shape.

FIGURE 14. Highly preserved bay-margin to tidally influenced open bay facies succession motif. This motif consists of a recessive basal horizon which can be composed of isolated or wavy beds (e.g., (IBLAT) and (WRLT) facies). Upwards, these facies are overlain by fully preserved and coarser facies (e.g., LXPT facies). Tidal units are stacked in a landward stepping stacking pattern. They overlie transitional bay-margin strata; basal portion of the succession may be >2m and upper portion of the succession is fully preserved. The succession has a funnel shape GR signature.

Subtle changes of specific facies attributes (e.g., degree of preservation of cross-bedded strata, mud content, mud draping, couplets and bundling, degree of burrowing, bed thickness, and relative proportion of facies help characterize changes in the tidal influenced open bay facies tract in different stratigraphic positions (Alvarez-Bastos, 2002). Facies change transitionally in a seaward direction from HRBXT to LTCXT to BLAXBT at the base of a base-level rise hemicycle, and from WRLT to LXPT towards the top of the hemicycle (FIGURE 15).

TIDAL DOMINATED INNER SHELF FACIES TRACT

The tidal dominated inner shelf facies tract is composed of the following facies: fine low-angle to wavy sandstone facies (FLWTS), lenticular, bundled, bioturbated and muddy sandstone facies (LBMTS), and coarse burrowed and bundled sandstone facies (CBBTS). These facies describe a fining and thinning upward facies succession where LBMTS facies change laterally into toes of CBBTS facies.

Tidal dominated inner shelf facies tract overlies in a landward direction shoreface, tidal influenced open bay, and bay-margin/intertidal flat facies tracts (FIGURE 2). The environmental interpretation for the tidal dominated inner shelf facies tract has been controversial. The Tocito is interpreted as transgressive tidal-sand bodies above a ravinement surface on a restricted shelf (Jones et al. 1991); as a result of migration of subtidal bars within broad estuaries (Jones et al. 1991); as deposited in a tide-dominated delta within a bay or strait sheltered from ocean waves and later as a series of tidal ridges on a tide-dominated shoreface during a regional transgression driven by reverse fault movement (Nummedal and Riley, 1999).

In this study the facies associations within the Tocito are interpreted as tidal sand ridges deposited in a tidal dominated inner shelf.

Fine Low-Angle to Wavy Sandstone Facies (FLWTS)

FLWTS consists of light green to beige upper very fine sandstone. This facies has centimeter-scale planar to wavy parallel laminae (FIGURE 16). Bounding surfaces are planar and burrowed. These beds are well cemented and contain little mud. Laminae are 1-3 cm thick. Beds are typically thin (10-30 cm) and can be followed laterally for 10s of meters.

FLWTS facies is interbedded with the base of lenticular, bundled, bioturbated, muddy sandstone facies (LBMTS), FIGURE 16. Contacts with LBMTS facies are sharp and fairly planar. It is expressed as thin and discontinuous flat beds at the base of (LBMTS) facies. Debris coming from overlying LBMTS facies and coarse burrowed and bundled sandstone facies (CBBTS) typically cover these beds.

The internal wavy aspect of the laminae, the concordant relationship between laminae that resemble hummocks and the interbedded relationship with LBMTS facies suggests that this facies was deposited during isolated storm events, in an environment where tidal currents were dominant between storms.

Lenticular Bundled Bioturbated and Muddy Sandstone Facies (LBMTS)

LBMTS consists of brown to gray, upper very fine, structureless sandstone rich in clay and organic matter. It is interbedded with lenticular beds of beige coarse to very coarse sandstone that commonly show bundling (FIGURE 17).

Lenticular beds become more amalgamated, thicker and laterally more continuous through a succession of this facies (FIGURE 17). Beds are a few centimeters thick and can be followed laterally for 100s of meters.

This facies overlies large-scale fully preserved cross- and planar-tabular sandstone facies (LXPT) and wave-rippled and low-angle sandstone facies (WRLT). It underlies or is interbedded with coarse burrowed and bundled sandstone facies (CBBTS).

Contacts with overlying CBBTS facies are transitional and irregular within 1-6 m. Contacts with underlying FLWTS and LXPT facies are sharp and slightly irregular.

LBMTS facies forms beige cliffs 1-6 m thick, characterized by a coarsening and bed thickening upward profile.

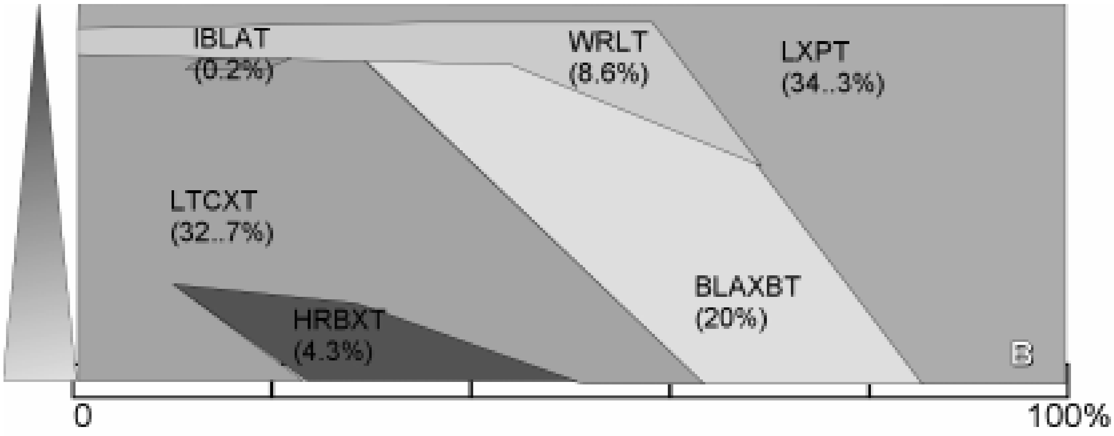

FIGURE 15. Facies succession and substitution diagram within the tidal influenced open bay facies tract.

Similar facies are identified by Nummedal and Riley (1999) as their bioturbated muddy sandstone of their lower Tocito sandstone and their interbedded sandstone and heterolithic strata of their upper Tocito sandstone. The bioturbated muddy sandstone is associated with 2-7% of green micas (i.e., glauconite), partial cementation of carbonate nodules, locally high concentrations of phosphate nodules, high mud content and *Cruziana* ichnofacies.

Nummedal and Riley (1999) interpreted their facies as shallow marine, and slow rates of sedimentation associated with lagoons or estuaries. Their interbedded sandstone and heterolithic strata was associated with lower degree of burrowing by the *Cruziana* ichnofacies and was traced laterally into the toesets of their cross-bedded sandstone facies. This facies was interpreted as being the bottom sets of large migrating dunes in environments involving higher sedimentation rates.

The structureless sandstone rich in clay content and organic matter interbedded with lenticular beds of beige coarse to very coarse sandstone that commonly show bundling described above is interpreted as toes of landward migrating tidal sand ridges or dunes. The association with facies FLWTS exclusively underlying LBMTS facies suggests that wave action was weak and that tidal currents dominated.

Coarse Burrowed and Bundled Sandstone (CBBTS)

CBBTS consists of white to beige upper medium to upper coarse sandstone with dispersed granules. It is well cemented by silica, contains numerous bundles and is mud free (FIGURE 18). *Ophiomorpha* and *Thalassinoides* dominate burrowing (FIGURE 18). Shark teeth and shells (*Inoceramids*) also occur.

Beds range from 15-30 cm thick and bedsets may be 2-4 m thick. This facies is laterally continuous and may be followed laterally for 100s of meters.

This facies occurs at the highest stratigraphic positions. It is commonly interbedded with lenticular, bundled bioturbated, muddy sandstone facies (LBMTS). It underlies LBMTS facies and marine siltstone similar to the ones described as laminated mudstone facies (LMS). Contacts between beds are sharp and irregular. Contacts with LBMTS facies are sharp and slightly irregular.

Paleocurrent data obtained at Cone Shape and Sanostee East sections show a change in paleocurrent trends. For this facies SE to NE paleocurrent trends correspond to seaward and landward directions (FIGURE 19). The change in the characteristic paleocurrent direction, NE trend for underlying LXPT facies to SE trend for this facies, suggests a change on the coastline due to embayment and the deposition of sand-ridges parallel to the embayed shoreline. This interpretation agrees with characteristics of this deposits documented by studies of modern shoreface sand ridge fields on tide-dominated shelves.
Nummedal and Riley (1999) reported a similar facies as their cross-bedded sandstone. It is associated with the *Skolithos* ichnofacies and is interpreted as a combination of straight crested dunes and large-scale sinuous crested dunes (tidal sand bars).

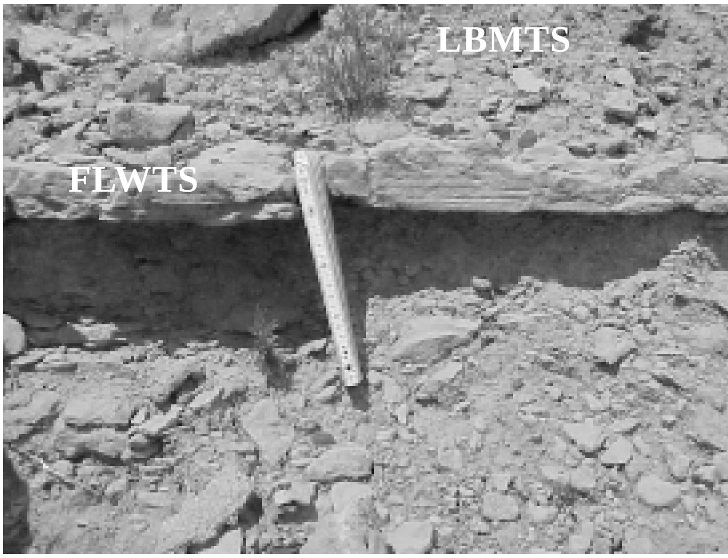

FIGURE 16. Fine low-angle to wavy sandstone facies (FLWTS). Observe low-angle laminae interbedded within LBMTS facies. Location: Sanostee West 1 section.

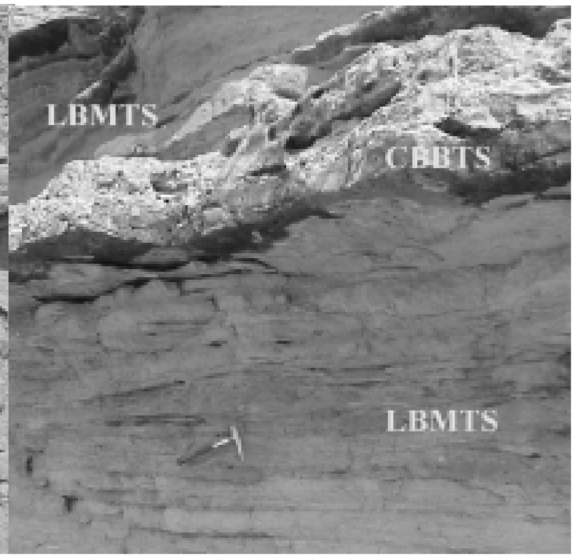

FIGURE 17. Lenticular, bundled bioturbated and muddy sandstone facies (LBMTS). Observe isolated lenticular beds within muddy to bioturbated beds, and sharp contact between LBMTS and CBBTS facies. Hammer is 35.7 cm. Location: Sanostee East section.

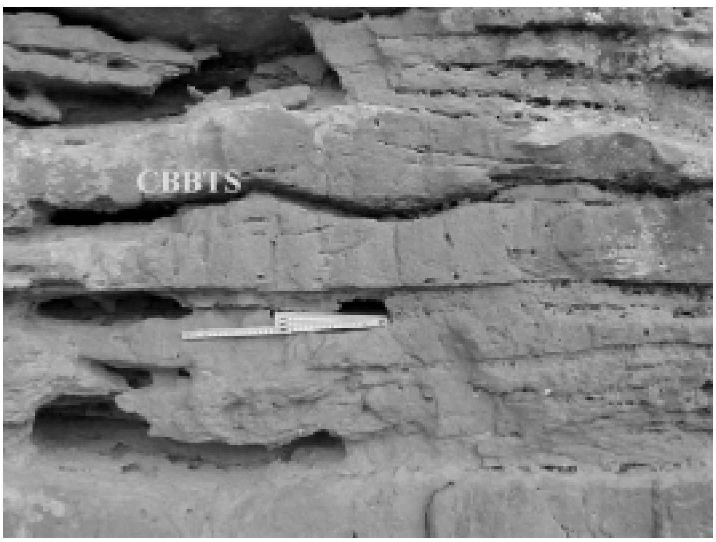

FIGURE 18. Coarse burrowed and bundled sandstone facies (CBBTS). Observe shape of foresets, dimensions of scours and beds, and irregular shape of bounding surfaces. Location: Amphitheater section.

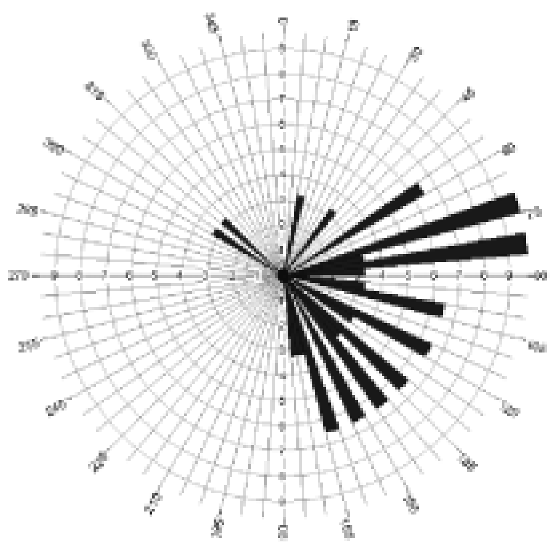

FIGURE 19. Paleocurrent rose diagram indicating preferential migration direction of Tocito sandwaves facies (CBBTS) at Sanostee West 1 section.

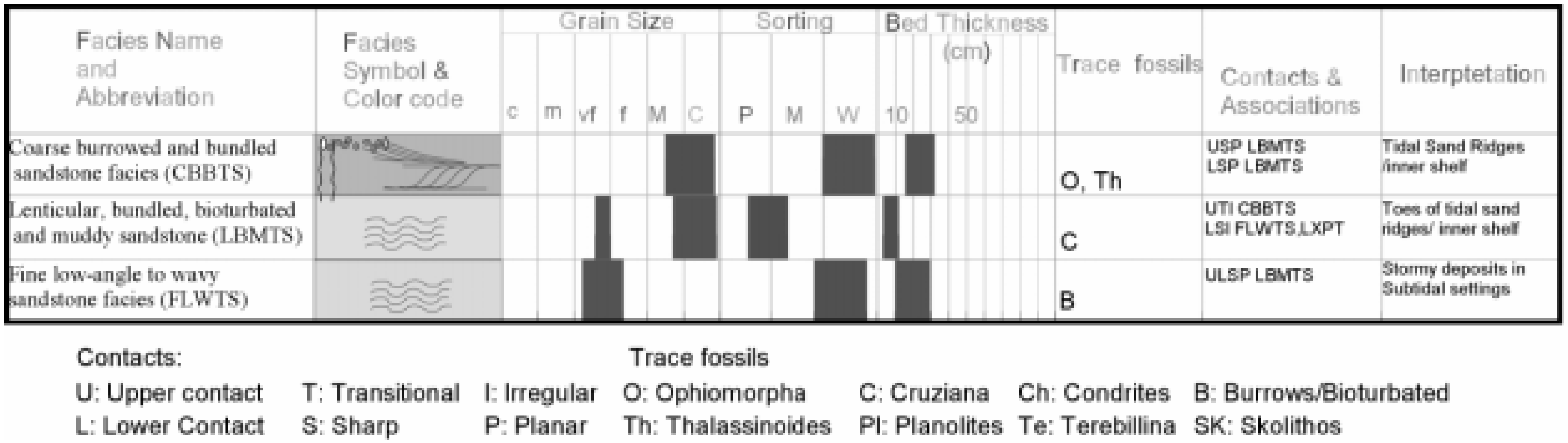

FIGURE 20. Summary of facies described as part of the tidal dominated inner shelf facies tract.

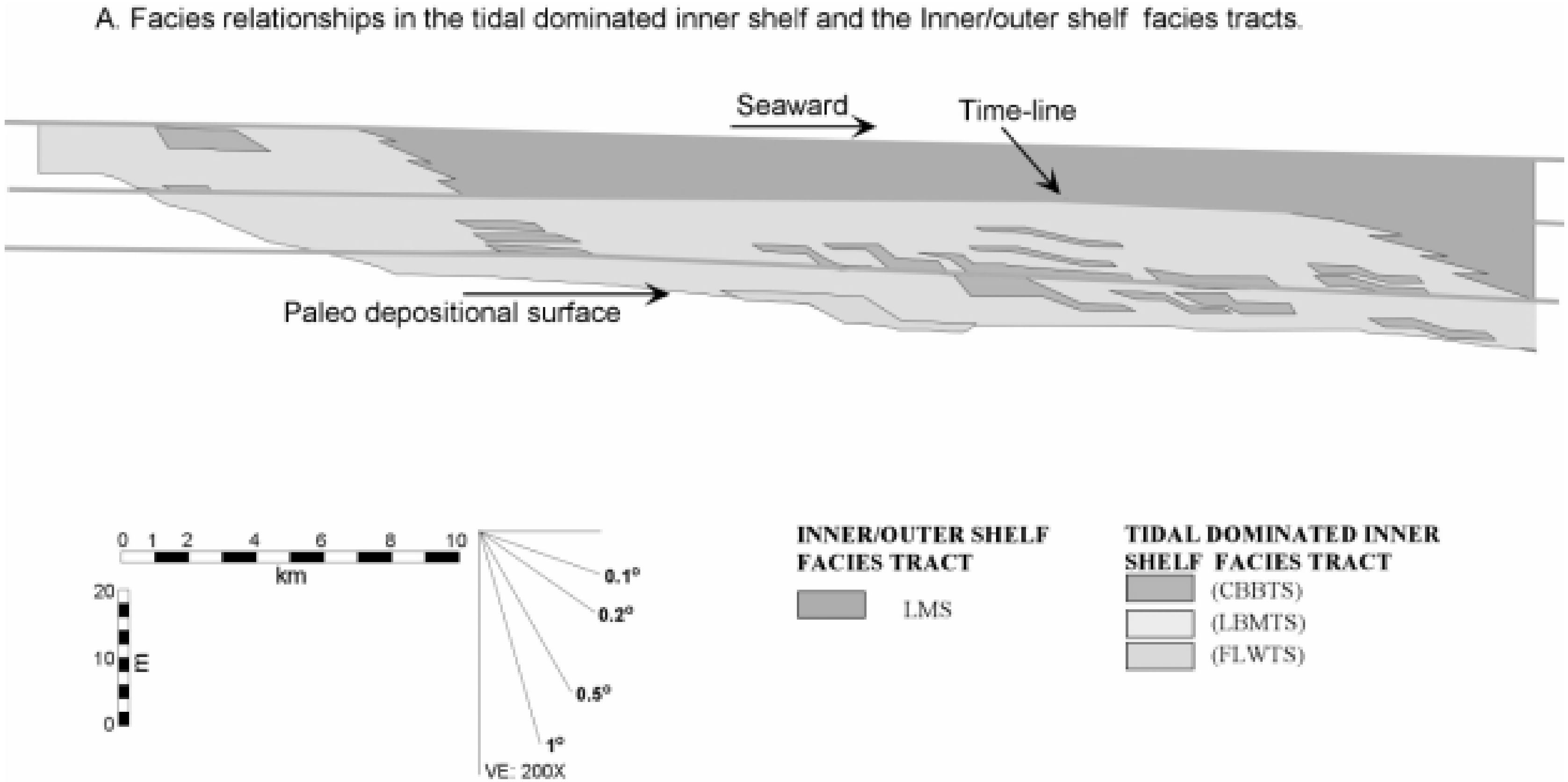

FIGURE 21. Dip stratigraphic cross section showing facies relationships between three genetic units composed of tidal dominated inner shelf and inner/outer shelf strata.

The bundles and close association with facies described above suggest this facies was deposited by migrating sandwaves or tidal ridges on a tidal dominated inner shelf.

Tidal Dominated Inner Shelf, Facies Association and Succession

The tidal dominated inner shelf facies tract occurs between marine shelf mudstones and either the bay-margin/intertidal flat or the tidal influenced open bay facies tracts. It only occurs at the top of landward-stepping cycles. Facies distributions within this facies tract suggest tidal influenced open bay sandwaves or ridges migrated landward and seaward (FIGURE 20). These are characterized as a progressive landward and vertical change from the lenticular bundled, bioturbated and muddy sandstone (LBMST) to the coarse burrowed and bundled sandstone (CBBST). This facies transition is interpreted as tidal sand ridges deposited on tidal dominated inner shelf settings. Locally, LBMST facies changes to fine low-angle to wavy sandstone facies (FLWST).

This facies tract changes landward into either the tidal influenced open bay facies tract or the bay-margin/ intertidal flat facies tract. This facies may extend over shorefaces, the tidal influenced open bay, and the bay margin to intertidal facies tract for 40-90 km. This facies tract is 10-20 m thick.

Sandy beds within this facies tract are generally isolated. Landward, there is a progressive increase in the sand/mud ratio, fewer tidal influenced open bay features, and thinner, more amalgamated beds.

Vertical sections though this facies tract display alternation of the three facies previously mentioned. Vertical successions in measured sections (FIGURE 21) recapitulate lateral transitions. The facies succession motif describes a fining and thinning upward facies succession. FIGURE 22 C to E shows close-ups of the facies constituting this facies succession. Gamma ray signatures for this facies succession are blocky to slightly bell shaped (FIGURE 22).

This facies succession motif always occupies the top of measured sections and always overlies the fully preserved tidal influenced open bay facies motif . These motifs represent continuous landward-stepping tidal units deposited under increasing A/S conditions. Lateral and vertical facies changes and relationships are summarized by a facies substitution diagram in FIGURE 23.

CONCLUSIONS

Sedimentary structures, fossils and paleocurrent data allow us to characterize the studied facies tracts as a tidal influenced open bay facies tract and a tidal dominated inner shelf facies tract, respectively.

Avalanching typical of the tidal bundled beds suggest high accommodation conditions and continuous drowning events. Reactivation surfaces represent current reversals, or current or depth changes under unidirectional flow. Distinct couplets reflect semidiurnal tidal inequality. Mud drapes along pause planes and associated burrowing indicate slack water periods. Rippled toes of sand waves represent lower current velocity. Opposed cross beds represent current reversals between ebb and flood tidal currents. Strong tidal action is indicated by the landward migration of large sandwaves (strong flood current). Thick sand waves reflect deposition during dominant tides, whereas the thin units are products of subordinate tides.

Bioturbation is inferred as periods of strong tidal currents followed by minor shifting of the substrate and periods of subordinate currents that favored preservation of trace fossils. Burrowing also reflects marine conditions, and low rates of sediment transport. Finally, paleocurrent data show bidirectional current distribution NE, SW, perpendicular to paleoshoreline, which are associated with ebb/flood tidal currents. NW and SE paleocurrent trends parallel to paleoshoreline are associated with longshore drift currents.

Facies located at more seaward positions were deposited under higher A/S conditions. Tidal processes are expressed by low-angle cross bedded facies and well preserved sandwaves.

Facies located at more landward positions were deposited under lower A/S conditions. Tidal processes are expressed by amalgamated, laterally continuous and less heterolithic strata.

Over time, facies associated with specific geomorphic elements (i.e., fully preserved sandwaves) migrate laterally landward as a consequence of a longterm increasing A/S conditions.

FIGURE 22. Tidal-dominated inner shelf facies motif. The basic pattern for tidal shelf facies succession consists of the following: fine low-angle to wavy sandstone (FLWST), lenticular bundled bioturbated and muddy sandstone (LBMST), and coarse burrowed and bundled sandstone (CBBST). These facies describe a fining and thinning upward facies succession where, typically, LBMST facies change laterally into toes of CBBST facies. This facies association is interpreted as tidal sand ridges deposited in tidal dominated inner shelf settings. GR signature for this facies succession shows blocky to slightly bell shape.

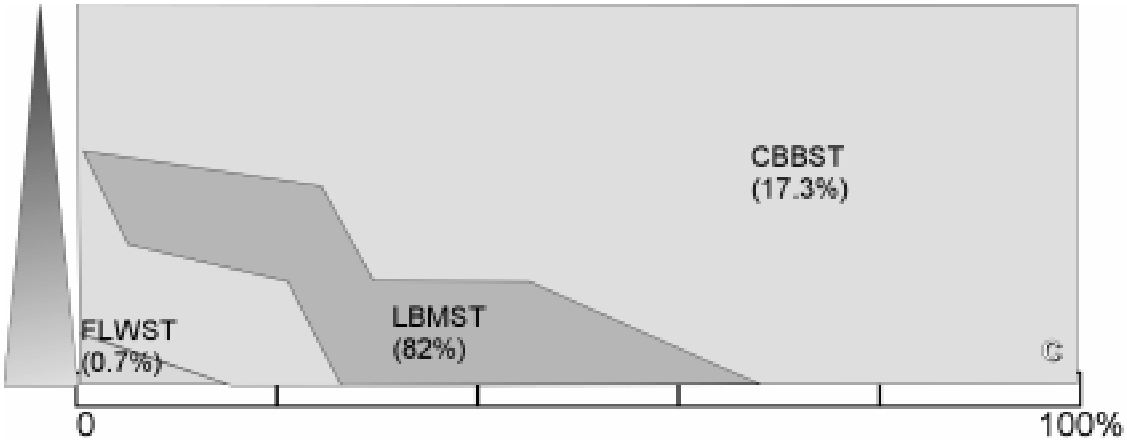

FIGURE 23. Facies succession and substitution diagram within the tidal dominated inner shelf facies tract.

Tidal influenced units are the result of processes of migration and aggradation that result in partial removal and reworking of previously deposited sediments. For example, trains of migrating megaripples or sandwaves are partially or fully preserved depending on the A/S conditions.

As a consequence of the preferential landward accumulation of tidal influenced open bay sediments during intermediate-term increasing A/S, more space is available near the seaward limits of tidal units. In seaward-stepping units, this space is eventually filled by the deposition of a younger shoreface unit of the next genetic sequence.

Physical sedimentary structures such as sigmoidal bundles and conspicuous burrowing suggest an important influence of tidal processes.

Tidal influenced deposits, related with large scale base level fall trends are more amalgamated, less wide, and more homogeneous that tidal dominated deposits, associated to large scale base level rise conditions.

This study recognizes a change in sedimentary processes operating in Gallup's sedimentation and the evolution of its contemporaneous paleoshoreline. Processes changed from wave dominated to tidal dominated. Wave dominated environments corresponded to a fairly straight paleoshoreline. This paleogeomorphology is associated to Gallup's shoreface. Tidal influenced open bays corresponded to embayed shorelines where amalgamated or fully preserved sand waves of the Torrivio Member were deposited. Bay margin and intertidal flats deposits of Dilco Member were coeval and located landward of Gallup shorefaces and the tidal influenced open bay deposits. Finally, shorelines became fully embayed and processes were tide dominated when Tocito sandwaves and sand ridges were deposited.

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