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# STRATIGRAPHIC ARCHITECTURE OF UPPER CRETACEOUS GALLUP CLASTIC WEDGE. SHALLOW MARINE AND COASTAL PLAIN STRATA: GALLUP SANDSTONE, MANCOS SHALE AND CREVASSE CANYON FORMATION, SAN JUAN BASIN, NEW MEXICO

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## ABSTRACT

A 3-D stratigraphic architecture and facies distribution framework of upper cretaceous coastal plain and shallow marine strata was established in the Western San Juan basin, New Mexico. Strata are represented by the Turonian-Coniacian Gallup Sandstone, Mancos shale and Crevasse Canyon Formations. This high-resolution genetic stratigraphic study was conducted in a 1000 km2 area, and used 2000 m of measured section calibrated with 1200 m of outcrop gamma ray from 25 sections and 85 plugs. Twenty short-term cycles account for the internal distribution of facies within five facies tracts and reveal a large degree of compartmentalization. Seven intermediate-term cycles compose a long-term cycle. The basal four cycles account for deposition of seaward-stepping shoreface/tidal couplets and the coeval bay margin to intertidal flat strata during the long-term base level fall. These cycles are fully asymmetrical to symmetrical. Three landward-stepping cycles containing tidal influenced open bay, tidal dominated inner shelf and bay-margin/intertidal flat strata occur in the long-term base-level rise. These cycles are rise asymmetrical. The Gallup Sandstone consists of seaward-stepping shoreface/tidal couplets. The landward-stepping Tocito Member of the Mancos Shale overlies the Gallup and no major stratigraphic dislocation is observed at the contact between them. Those changes are expressions of sediment volume partitioning and facies differentiation accompanying changes in accommodation and sediment supply (A/S).

**Key words:** Stratigraphy, Genetic, Sedimentology, Facies, Successions, Associations, Modeling, Simulation, New Mexico, Gallup, Tidal, Reservoirs.

## ARQUITECTURA ESTRATIGRAFICA DE LA CUÑA CLASTICA DEL GALLUP. ESTRATOS MARINOS SOMEROS Y DE PLANICIE COSTERA DEL CRETACEO SUPERIOR: GALLUP SANDSTONE, MANCOS SHALE AND CREVASSE CANYON FORMATION, SAN JUAN BASIN, NEW MÉXICO.

## RESUMEN

Un marco de distribución de facies y una arquitectura estratigráfica de estratos marinos someros y de llanura costera del Cretaceo Superior fue establecida en la cuenca de San Juan en Nuevo Méjico, USA. Los estratos están representados por las formaciones Gallup Sandstone, Mancos shale y Crevasse Canyon de edad Turoniano-Coniaciano. Este estudio de estratigrafía genética de alta resolución fue realizado en un área de 1000 km2, y uso 2000 m de sección estratigráfica medida y calibrada con registros gamma ray de afloramiento en 25 secciones y con 85 plugs tomados en afloramiento. Veinte ciclos de corto termino permiten explicar la distribución interna de facies dentro de cinco facies tracts y permiten evidenciar un alto grado de compartimentalización en estas unidades. Siete ciclos de termino intermedio constituyen un ciclo de largo termino. Los cuatro ciclos basales explican la depositacion de dupletas shoreface/tidal con patrón de apilamiento (stacking pattern) hacia el mar y de los estratos coevales de margen de bahia a llanuras intermareales durante el hemiciclo de caida del ciclo de nivel base de gran escala (long-term base level fall). Esos ciclos son completamente asimétricos a simétricos. Los restantes tres ciclos muestran patrón de apilamiento hacia el continente y contienen estratos de bahía abierta influenciados por marea, plataforma interna dominada por marea y planicies intermareales/margen de bahía. Estos ciclos son asimetricos hacia arriba y se ubican en el hemiciclo de subida del ciclo de nivel base de gran escala (long-term base level rise). La formación Gallup Sandstone consiste de dupletas shoreface/tidal que se desplazan hacia el mar. El Miembro Tocito de la formación Mancos Shale, el cual se desplaza hacia el continente suprayace al Gallup y no se observa ninguna dislocación estratigráfica importante en el contacto entre estos. Los cambios en la arquitectura estratigráfica arriba mencionados son expresiones de la partición volumétrica de sedimento y la diferenciación de facies que acompaña a los cambios en acomodación y suministro de sedimento (A/S).

**Palabras clave:** Estratigrafía Genética, Sedimentología, Arquitectura, Cretaceo, Gallup, Dupletas, Mancos, Crevassse Canyon, Reservorios, Nuevo Méjico, Mareas.

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[1] Dirección actual: Occidental de Colombia

## INTRODUCTION

This paper discuses concepts and associated methodology for correlating stratigraphic cycles containing coastal plain, bay-margin/intertidal flat, shoreface, tidal influenced open bay and tidal dominated inner shelf strata. The scientific and philosophical basis for constructing the architecture of a clastic wedge is that stratigraphic base level oscillates basinwide, and that this oscillation describes how accommodation is created and how sediment is distributed spatially and temporally in an organized and predictable way.

In the following, a methodology of architectural restoration is presented. This methodology consists of several steps such as: 1. Interpreting the origin of individual facies and mapping lateral facies transitions and vertical facies successions. Identification of stratigraphic base-level cycles at different scales as product of changing conditions of accommodation space and sediment supply (A/S). 2. 1-D analysis of stratigraphic stacking patterns (i.e., how facies tracts within a cycle are displaced geographically relative to those in the preceding cycle). This provides a frame of reference for conducting 2-D analysis. 3. 2-D stratigraphic analysis between measured sections. This is the basis for correlating time-significant stratigraphic cycles. As a final result, this analysis provides a better understanding of how laterally linked and genetically related depositional environments migrated along a depositional profile, how time is recorded as rock or as surfaces of discontinuity, and how sediment volumetric partitioning impact the architecture and facies distribution in the Gallup clastic wedge.

Upper Cretaceous (Late Turonian-Early Coniacian) marine to continental deposits of the San Juan basin, New Mexico, USA, were selected for this study. Outcrops in this basin consist of 2-D exposures of strata deposited across laterally linked shoreface, bay-margin/intertidal flat, coastal plain, open bay and inner shelf environments. Continuous outcrops across multiple environments with accessible sections allow testing and extension of the cycle correlation method to areas and situations where strata and their correlations are not physically mappable. FIGURES 1 to 2 show the study area, four corners, New Mexico, USA and location of measured stratigraphic sections. FIGURE 3 shows schematically the occurrence of Gallup, Torrivio and Tocito, litho-stratigraphic units relevant to this study, within a genetic stratigraphic as representation of the results as derived from this study.

## FACIES SUMMARY AND ENVIRONMENTAL INTERPRETATION OF THE GALLUP SANDSTONE, CREAVASSE CANYON FORMATION AND MANCOS SHALE

In the following, a summary of facies tracts, facies within them, and their correspondent interpretation is presented. In this study, facies names consist of adjectives modifying the dominant texture. Name codes consist of capital letters designating five facies tract: S for shoreface, T for tidal influenced open bay, B for bay-margin/intertidal tidal flat, C for coastal plain and ST for tidal dominated inner shelf. This study recognizes facies previously described by Nummedal and Molenaar (1995), Valasek (1995), and Jones et al. (1991), separates some facies that were grouped in previous studies and redefine previous environmental interpretations related with formations such as Gallup, Crevasse Canyon and Mancos Shale. Detailed information dealing with Facies and facies tract characterization and environmental interpretation is presented in Alvarez (2002), Alvarez (2003), Alvarez (2004).

**Shoreface Facies Tract (S):** The shoreface facies tract underlies the tidal influenced open bay and the bay-margin/intertidal flat facies tracts and is seaward (NE) of coeval bay-margin/intertidal flat facies tract. This facies tract is composed of eight facies. FIGURE 4 summarizes the main characteristics of facies in this facies tract and their correspondent environmental interpretation. Details and discussion on environmental interpretation is discussed in Alvarez (2002 and 2003).

**Tidal Influenced Open Bay Facies Tract (T):** The tidal influenced open bay facies tract occupies a position between the shoreface and the bay-margin/intertidal flat facies tracts. It also may overlie the bay-margin/intertidal flat facies tract. This facies tract consists of seven facies. FIGURE 5 summarizes the main characteristics of facies in this facies tract and their correspondent environmental interpretation. The tidal origin of this facies tract is discussed in Alvarez (2002 and 2004).

**Bay-Margin/Intertidal Flat Facies Tract (B):** The bay-margin/intertidal flat facies tract occupies positions between the tidal influenced open bay and the coastal plain facies tracts, between the coastal plain and tidal dominated inner shelf facies tract, and between units of the tidal influenced open bay facies tract. It is located landward of coeval shoreface, tidal influenced open bay and tidal dominated inner shelf facies tracts. The bay-margin/intertidal flat facies tract is not recognized in previous studies.

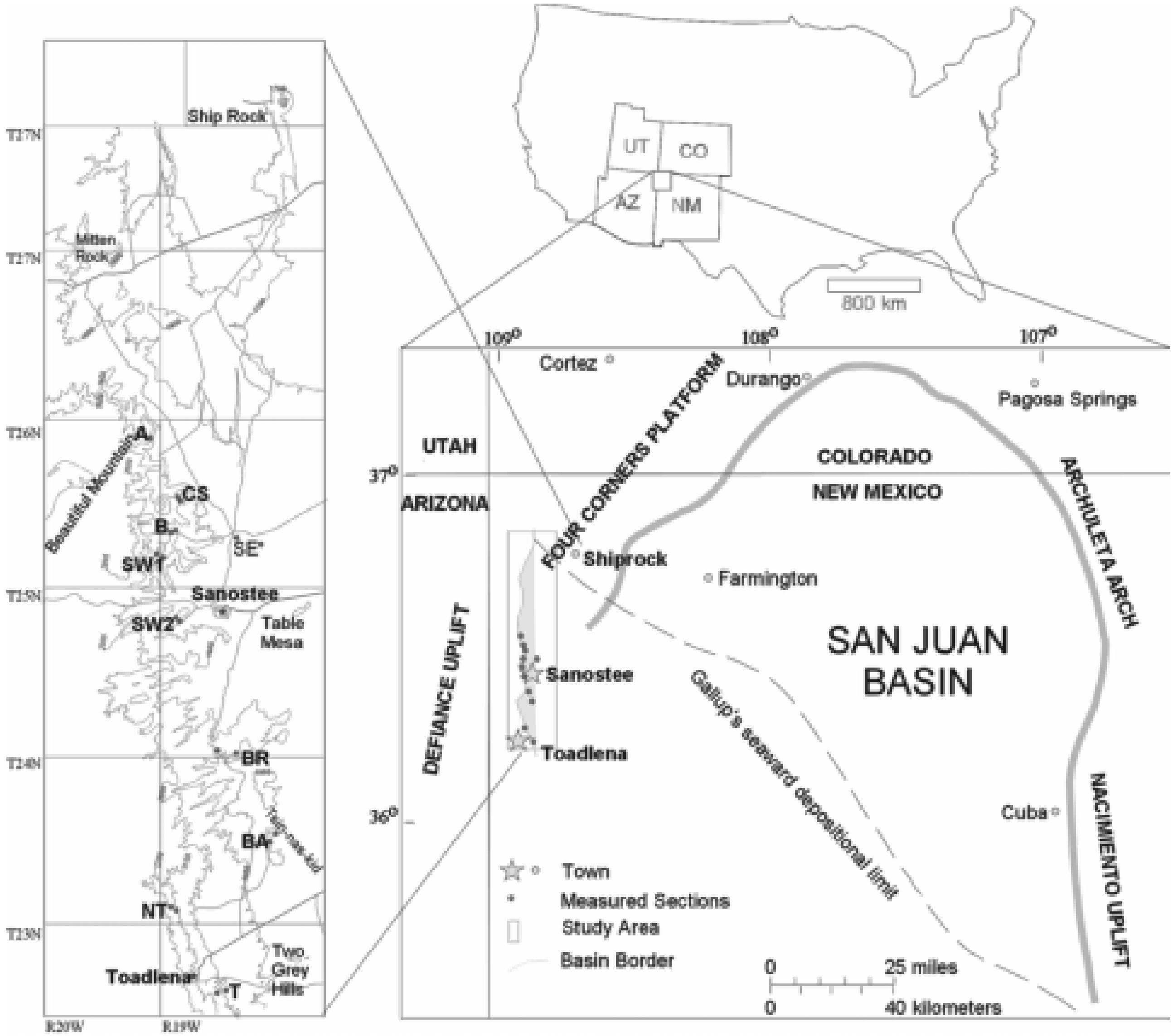


**FIGURE 1.** Location of the San Juan basin and the study area.

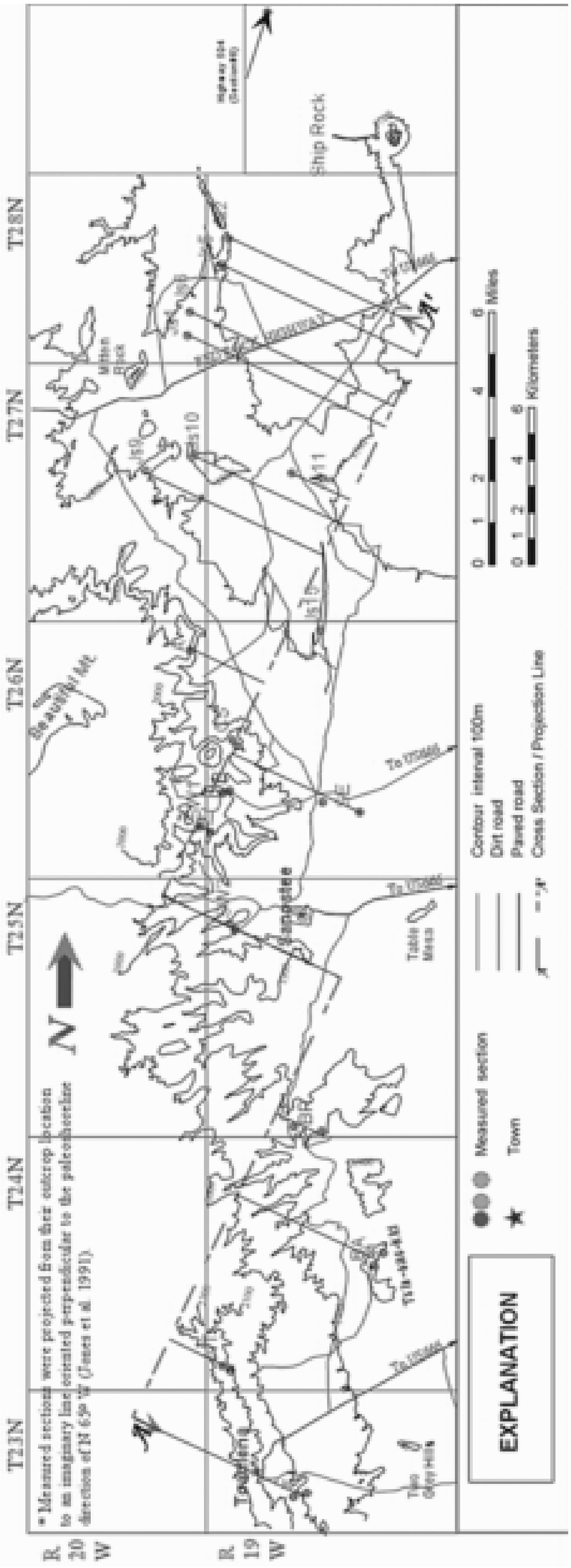


**FIGURE 2.** Location of measured sections in the study area.

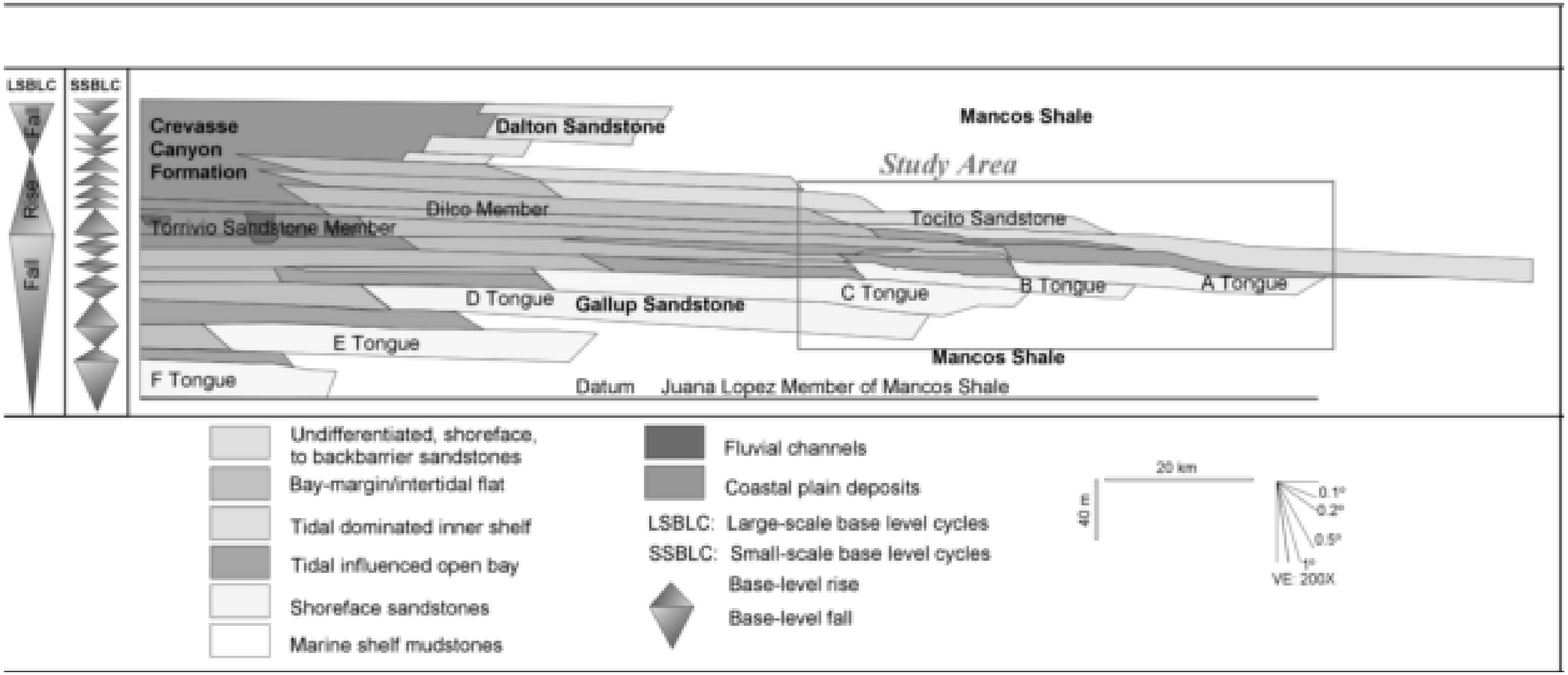


**FIGURE 3.** Schematic lithostratigraphic cross section of the Gallup Sandstone and genetically associated units showing interfingering relationships. In this study Dilco and Torrivio are considered members of the Crevasse Canyon Formation.

This facies tract is composed of twelve facies. FIGURE 6 summarizes the main characteristics of facies in this facies tract and their correspondent environmental interpretation. Tidal influence of this facies tract is discussed in Alvarez (2002 and 2004).

**Coastal Plain Facies Trac (C):** Bay-margin/intertidal flat facies tracts lie above, below and seaward of the coastal plain facies tract. The coastal plain facies tract records the maximum seaward progradation in the study area. The environmental interpretation for the coastal plain facies tract is widely recognized by previous studies, although in many cases it is overestimated and extended into the bay-margin/intertidal flat facies tract presented in this report. This facies tract is composed of four facies. FIGURE 7 summarizes the main characteristics of facies in this facies tract and their correspondent environmental interpretation. Details and discussion on environmental interpretation is discussed in Alvarez (2002, 2003).

**Tidal Dominated Inner Shelf Facies Tract (TS):** The tidal dominated inner shelf facies tract overlies in a landward direction the shoreface, tidal influenced open bay, and the bay-margin/intertidal flat facies tracts. The environmental interpretation for the tidal dominated inner shelf facies tract has been controversial. See Alvarez (2002 and 2004). This facies tract is composed of four facies. FIGURE 8 summarizes the main characteristics of facies in this facies tract and their correspondent environmental interpretation.

## FACIES SUCCESSIONS AND FACIES ASSOCIATIONS

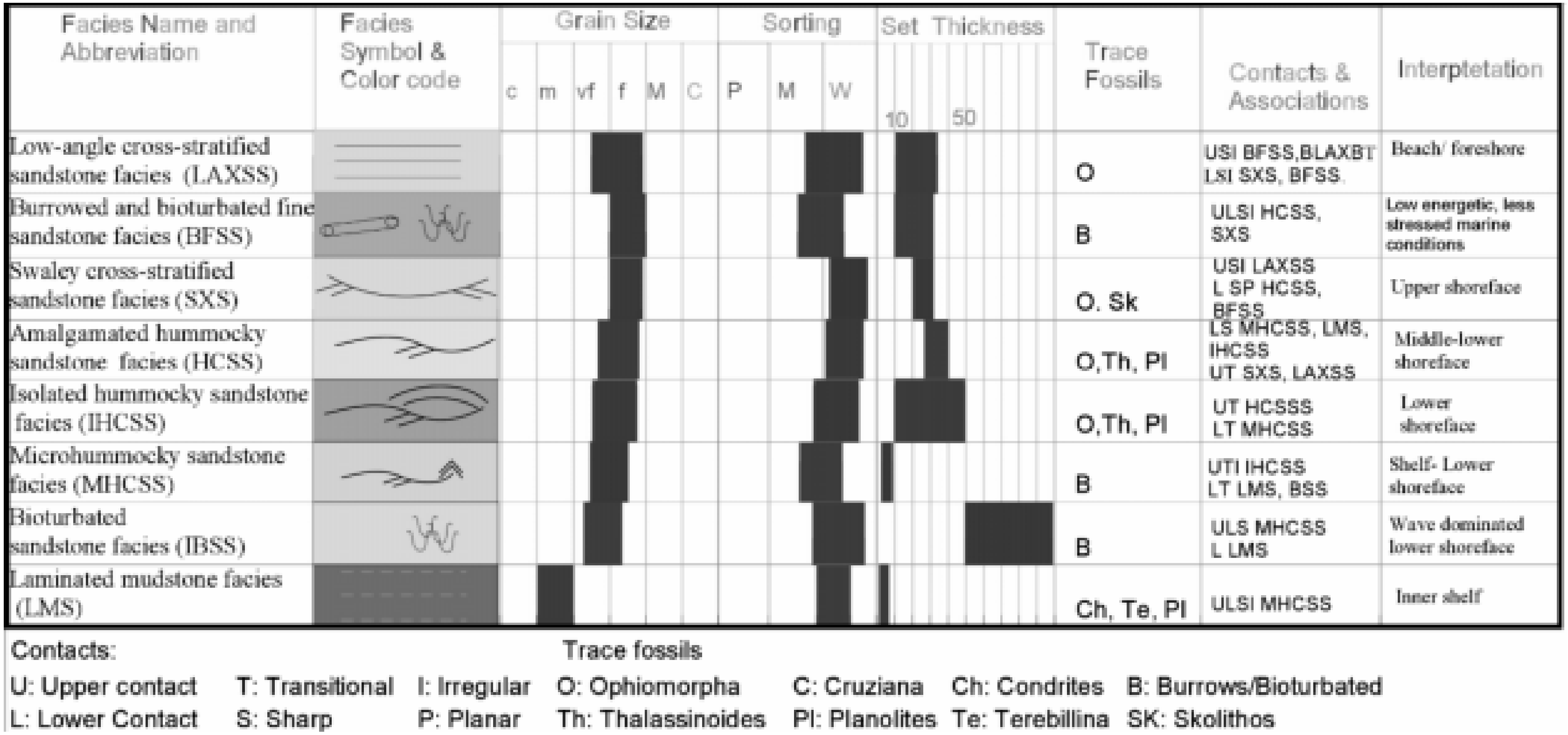
Geomorphic elements may migrate, disappear or form during progradation or aggradation. Within the same environment, their occurrence at specific positions varies along depositional strike and dip. The A/S regime, and therefore the stratigraphic position of an environment at a particular time can control the types and attributes of geomorphic elements that occur along a depositional profile. Dynamic replacement (substitution) of geomorphic elements during base-level cycles is considered responsible for generating different vertical facies successions for the same depositional environment. The proportion and diversity of facies incorporated in the stratigraphic record are a function of the original area occupied by specific geomorphic elements and their degree of preservation.

**Associations and Successions Among Facies Tracts:** In the following, six facies tract transitions are discussed: 1. shoreface to bay-margin/intertidal flat; 2. shoreface to tidal influenced open bay; 3. tidal influenced open bay to bay-margin/intertidal flat; 4. bay-margin/intertidal flat to coastal plain; 5. tidal dominated inner shelf to tidal influenced open bay; and 6. shelf to tidal dominated inner shelf. General relationships were obtained by mapping the spatial relationships between main facies tracts in the study area and using knowledge of similar relationships found in the Mesaverde Group of the San Juan basin (Cross, personal communication).

Under decreasing A/S conditions, the coastal plain changes seaward to bay-margin/intertidal flat and the bay-margin/intertidal flat to the shoreface facies tract. Under unidirectional increasing A/S conditions the tidal dominated inner shelf facies tract changes landward to tidal influenced open bay and the tidal influenced open bay to the bay-margin/intertidal flat facies tract. At a large scale, the shoreface, the bay-margin/intertidal flat and the coastal plain facies tracts are overlain by the tidal dominated inner shelf and coeval tidal influenced open bay and bay-margin/intertidal flat facies tracts. At an intermediate scale lateral changes and vertical successions described above are also observed. This allows us to identify a self-similarity at two different scales that is described in the following.

**Shoreface to Bay-margin/Intertidal flat:** Transitions between the bay-margin/intertidal flat and the shoreface facies tracts occur over distances of 1-2 km and vertically over 4-8 m (FIGURE 9). Shorefaces are sharply separated from the bay-margin/intertidal flat strata. Bay-margin/intertidal flat deposits occur behind shoreface deposits. These strata record the progressive filling of a bay, after the deposition of underlying tidal influenced open bay sediments. Once the bay is filled, the paleoshoreline was less embayed and a shoreface formed and began to prograde under decreasing A/S conditions.

FIGURE 9 compares two examples of the shoreface to bay-margin/intertidal flat transition. FIGURE 9 A shows the transition in a progradational/aggradational unit that steps seaward with respect to the underlying unit shown in FIGURE 9 B. Paleodepo-sitional profiles are inferred from the lower and upper boundaries limiting the bay-margin/intertidal flat unit and its associated shoreface unit. The steeper slopes for these depositional surfaces are shown in FIGURE 9 A and occur at the lowest A/S conditions. Lateral transitions between shoreface and bay-margin/intertidal flat strata conform to Walther's law.



| Facies Name and Abbreviation | Trace Fossils | Contacts & Associations | Interptetation |
|---|---|---|---|
| Low-angle cross-stratified sandstone facies (LAXSS) | O | USI BFSS,BLAXBT<br>LSI SXS, BFSS. | Beach/ foreshore |
| Burrowed and bioturbated fine sandstone facies (BFSS) | B | ULSI HCSS, SXS | Low energetic, less stressed marine conditions |
| Swaley cross-stratified sandstone facies (SXS) | O. Sk | USI LAXSS<br>L SP HCSS, BFSS | Upper shoreface |
| Amalgamated hummocky sandstone facies (HCSS) | O,Th, Pl | LS MHCSS, LMS, IHCSS<br>UT SXS, LAXSS | Middle-lower shoreface |
| Isolated hummocky sandstone facies (IHCSS) | O,Th, Pl | UT HCSSS<br>LT MHCSS | Lower shoreface |
| Microhummocky sandstone facies (MHCSS) | B | UTI IHCSS<br>LT LMS, BSS | Shelf- Lower shoreface |
| Bioturbated sandstone facies (IBSS) | B | ULS MHCSS<br>L LMS | Wave dominated lower shoreface |
| Laminated mudstone facies (LMS) | Ch, Te, Pl | ULSI MHCSS | Inner shelf |

Contacts:

U: Upper contact T: Transitional I: Irregular

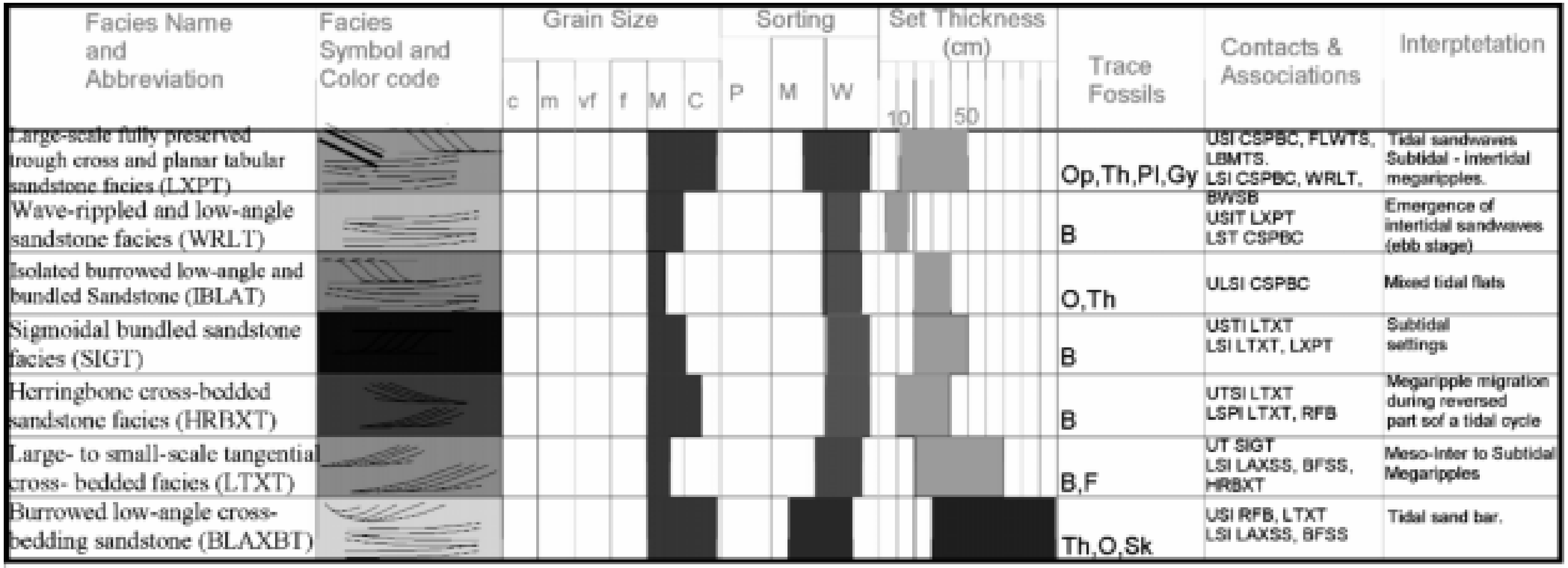
L: Lower Contact S: Sharp P: Planar

Trace fossils

O: Ophiomorpha C: Cruziana Ch: Condrites B: Burrows/Bioturbated

Th: Thalassinoides Pl: Planolites Te: Terebillina SK: Skolithos

**FIGURE 4.** Summary of characteristics of facies in the shoreface facies tract



| Facies Name and Abbreviation | Trace Fossils | Contacts & Associations | Interptetation |
|---|---|---|---|
| Large-scale fully preserved trough cross and planar tabular sandstone facies (LXPT) | Op,Th,Pl,Gy | USI CSPBC, FLWTS, LBMTS.<br>LSI CSPBC, WRLT, BWSB | Tidal sandwaves Subtidal - intertidal megaripples. |
| Wave-rippled and low-angle sandstone facies (WRLT) | B | USIT LXPT<br>LST CSPBC | Emergence of intertidal sandwaves (ebb stage) |
| Isolated burrowed low-angle and bundled Sandstone (IBLAT) | O,Th | ULSI CSPBC | Mixed tidal flats |
| Sigmoidal bundled sandstone facies (SIGT) | B | USTI LTXT<br>LSI LTXT, LXPT | Subtidal settings |
| Herringbone cross-bedded sandstone facies (HRBXT) | B | UTSI LTXT<br>LSPI LTXT, RFB | Megaripple migration during reversed part sof a tidal cycle |
| Large- to small-scale tangential cross- bedded facies (LTXT) | B,F | UT SIGT<br>LSI LAXSS, BFSS, HRBXT | Meso-Inter to Subtidal Megaripples |
| Burrowed low-angle cross-bedding sandstone (BLAXBT) | Th,O,Sk | USI RFB, LTXT<br>LSI LAXSS, BFSS | Tidal sand bar. |

| Contacts: | | | Trace fossils | | | |
|---|---|---|---|---|---|---|
| U: Upper contact | T: Transitional | I: Irregular | O: Ophiomorpha | C: Cruziana | Ch: Condrites | B: Burrows/Bioturbated |
| L: Lower Contact | S: Sharp | P: Planar | Th: Thalassinoides | Pl: Planolites | Te: Terebillina | SK: Skolithos |

**FIGURE 5.** Summary of facies described as part of the tidal influenced open bay facies tract

Shorefaces may be capped by heterolithic and carbonaceous strata. This is interpreted as follows. After a shoreface reaches its seaward depositional limit, there is an increase in A/S conditions which causes first shoreface aggradation and then transgression. Vegetated zones farther landward are flooded and rapidly covered by prograding sediments that begin to fill the space.

**Shoreface to Tidal Influenced Open Bay:** Tidal influenced open bay deposits are discrete from and landward of the landward depositional limit of the shoreface FIGURE 10. They are overlain by shoreface units at their seaward depositional limits. The transition between these facies tracts is an irregular, seaward inclined and somewhat sharp contact between shoreface facies generated by waves and facies generated by tidal currents. Transitions occur over a distance of 2-3 km and vertically over 4-10 m.

FIGURE 10 A shows the transitions in a younger, seaward-stepping unit over an older unit shown in FIGURE 10 B. The slope of the contact between facies tracts is less steep than the slope of the steepest clinoform at the landward depositional limit of the shoreface. The slope of the contact between the facies tracts is steeper in A (0.21o) than in B (0.15o). These variations are related to changes in A/S conditions.Tidal influenced open bay units are deposited in embayments where tidal currents are reinforced. As embayments are filled with tidal strata the coastline changes into more rectilinear coasts affected by waves.

Lateral transitions for the tidal influenced open bay and the shoreface indicate that shoreface units seaward of and overlying tidal influenced open bay units are always younger. Shorefaces are separated from overlying younger tidal units by a transgressive surface. This relationship is referred as the shoreface/tidal couplet. Shoreface to tidal influenced open bay vertical transitions consist of finer storm-dominated facies (e.g., HCSS, and SWS) changing abruptly into coarser tidal influenced open bay facies. Vertical successions through shoreface and tidal influenced open bay facies represent genetic units. A vertical transition from tidal to shoreface facies tracts is considered a facies offset FIGURE 10.

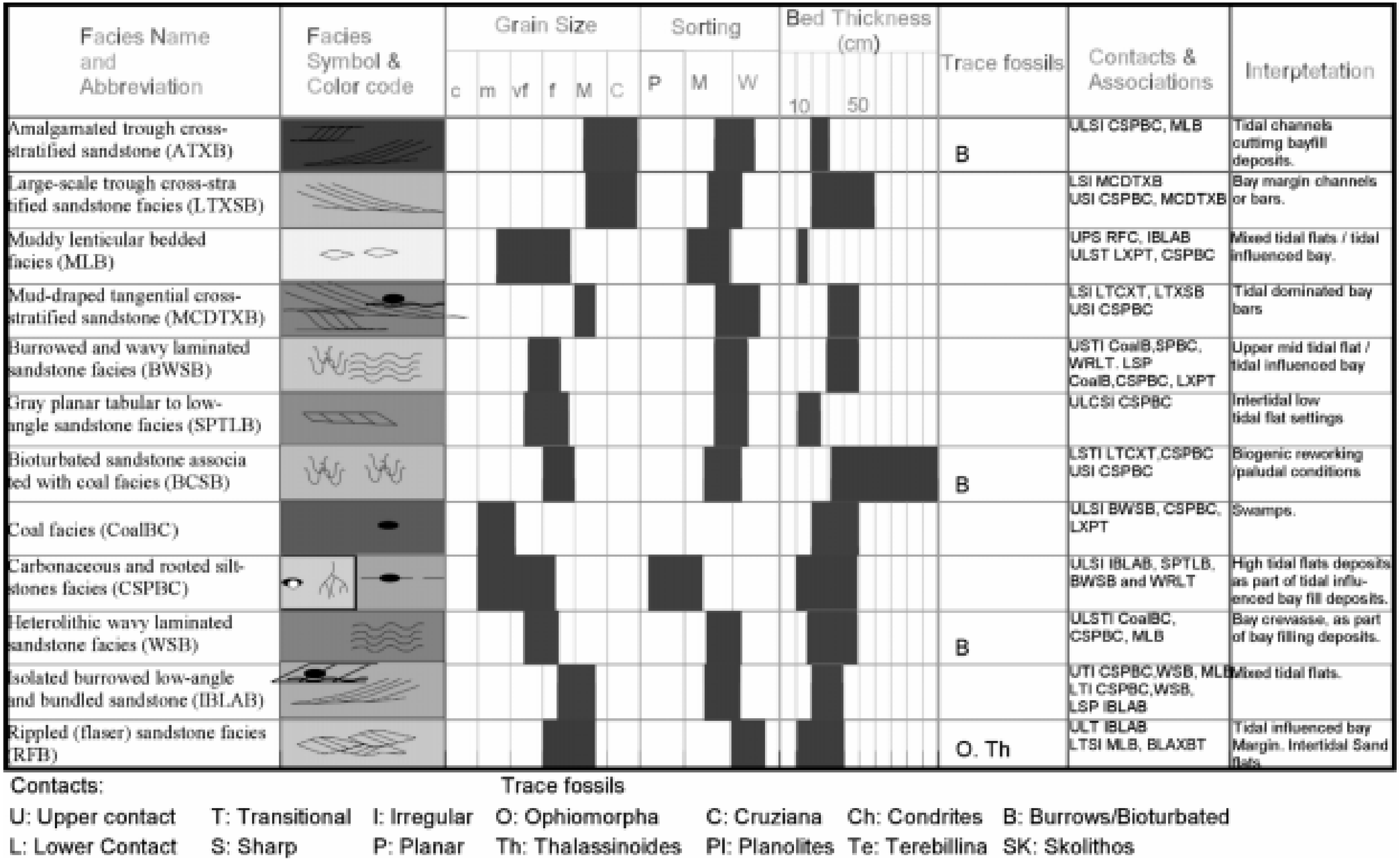
**Tidal Influenced Open Bay to Bay-Margin/Intertidal Flat:** Bay-margin/intertidal flat deposits underlie and are landward of tidal influenced open bay strata. Bay-margin/intertidal flat deposits aggrade and then tidal influenced open bay deposits expand landward with transgression, covering the older bay-margin facies. The transition is a somewhat sharp contact between the two facies tracts (FIGURE 11) in which coarser sand-rich tidal influenced open bay facies underlie or overlie mud-rich bay margin facies. The contact between the two facies tracts extends laterally about 2-5 km and vertically over 5-12 m. Slopes at the base of these units vary between 0.01o and 0.05o. Surfaces on which tidal influenced open bay units were deposited are steeper in long-term increasing A/S conditions (FIGURE 11 A) than in long-term decreasing A/S conditions (FIGURE 11 B).

In vertical successions, a bay-margin/intertidal flat facies succession overlying tidal influenced open bay strata is interpreted as a facies offset, since shallow bay-margin strata are displaced farther seaward and cap deeper open bay strata. Conversely, a bay-margin/intertidal flat facies succession underlying tidal influenced open bay facies is interpreted as a normal succession (FIGURE 11).

**Bay-Margin/Intertidal Flat to Coastal Plain:** The transition from bay-margin/intertidal flat to coastal plain facies tracts consists of interfingering relationships (FIGURE 12). Coastal plain deposits aggrade behind bay margin deposits. An interfingering geometry results from episodic depositional events when the coastal plain aggrades and expands seaward covering progressively older bay margin deposits.

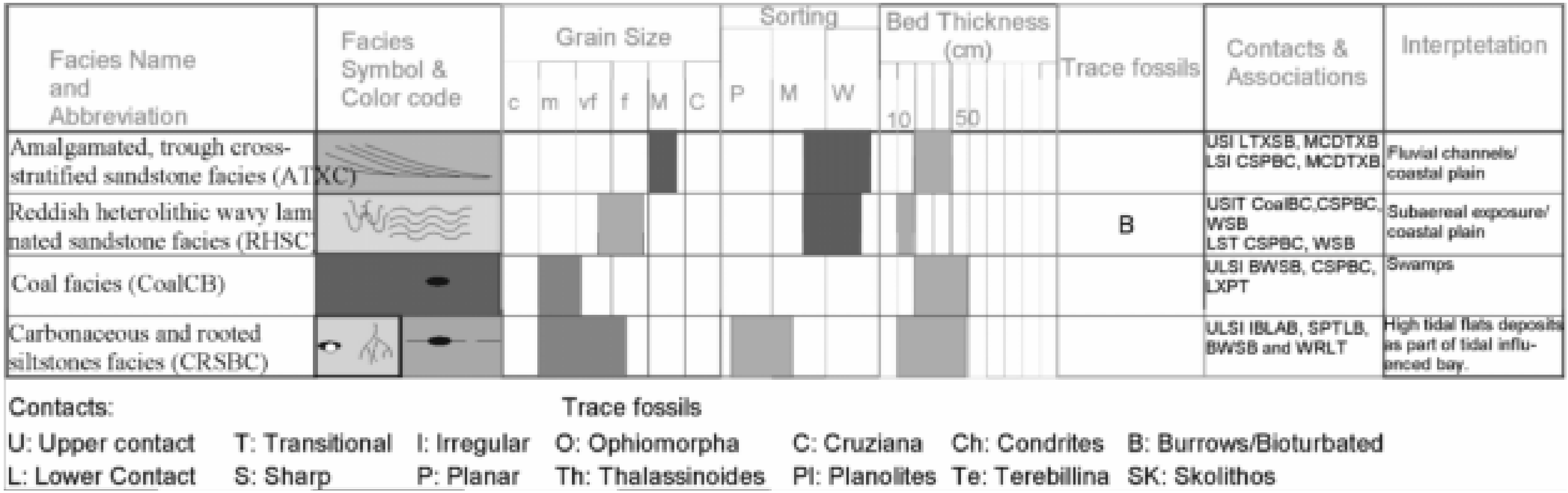
The transition from coastal plain to bay margin facies tracts occurs over a distance of 7 km and vertically between 2 to 5 m. Due to the interfingering transition, lithologic heterogeneity and poor exposure is typical. The transition is mapped based on presence of reddish heterolithic facies, suggesting subaerial exposure, interbedded with heterolithic and wavy facies, suggesting subaqueous conditions. This transition also shows a lateral change from highly amalgamated trough cross-stratified facies into heterolithic facies (Figure 3.29). The transition occurs at nearly the lowest A/S conditions in the study area and is roughly at the same stratigraphic position of the maximum progradation of the time equivalent shoreface.

Bay-margin/intertidal flat to coastal plain transitions consist either of sharp contacts between heterolithic strata and highly amalgamated channelforms, or transitions between muddy and heterolithic subaqueous facies and reddish and muddy subaerial facies. Vertical succession of subaerial facies overlying subaqueous facies is interpreted as a normal succession. Conversely, vertical succession of subaqueous facies overlying subaerial facies is interpreted as a facies offset. This offset is associated with the maximum progradational event in the study area and the lowest A/S conditions.



| Facies Name and Abbreviation | Trace fossils | Contacts & Associations | Interptetation |
|---|---|---|---|
| Amalgamated trough cross-stratified sandstone (ATXB) | B | ULSI CSPBC, MLB | Tidal channels cuttimg bayfill deposits. |
| Large-scale trough cross-stratified sandstone facies (LTXSB) | | LSI MCDTXB<br>USI CSPBC, MCDTXB | Bay margin channels or bars. |
| Muddy lenticular bedded facies (MLB) | | UPS RFC, IBLAB<br>ULST LXPT, CSPBC | Mixed tidal flats / tidal influenced bay. |
| Mud-draped tangential cross-stratified sandstone (MCDTXB) | | LSI LTCXT, LTXSB<br>USI CSPBC | Tidal dominated bay bars |
| Burrowed and wavy laminated sandstone facies (BWSB) | | USTI CoalB,SPBC, WRLT. LSP CoalB,CSPBC, LXPT | Upper mid tidal flat / tidal influenced bay |
| Gray planar tabular to low-angle sandstone facies (SPTLB) | | ULCSI CSPBC | Intertidal low tidal flat settings |
| Bioturbated sandstone associated with coal facies (BCSB) | B | LSTI LTCXT,CSPBC<br>USI CSPBC | Biogenic reworking /paludal conditions |
| Coal facies (CoalBC) | | ULSI BWSB, CSPBC, LXPT | Swamps. |
| Carbonaceous and rooted siltstones facies (CSPBC) | | ULSI IBLAB, SPTLB, BWSB and WRLT | High tidal flats deposits as part of tidal influenced bay fill deposits. |
| Heterolithic wavy laminated sandstone facies (WSB) | B | ULSTI CoalBC, CSPBC, MLB | Bay crevasse, as part of bay filling deposits. |
| Isolated burrowed low-angle and bundled sandstone (IBLAB) | | UTI CSPBC,WSB, MLB<br>LTI CSPBC,WSB,<br>LSP IBLAB | Mixed tidal flats. |
| Rippled (flaser) sandstone facies (RFB) | O. Th | ULT IBLAB<br>LTSI MLB, BLAXBT | Tidal influenced bay Margin. Intertidal Sand flats |

**FIGURE 6.** Summary of facies described as part of the bay-margin/intertidal flat facies tract

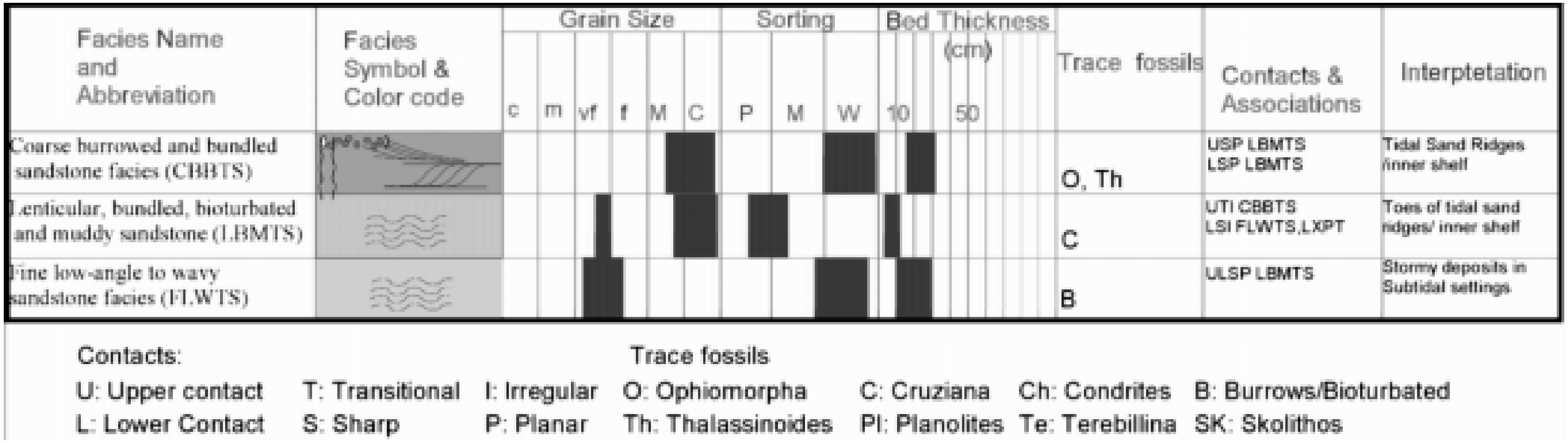


| Facies Name and Abbreviation | Facies Symbol & Color code | Grain Size c | m | vf | f | M | C | Sorting P | M | W | Bed Thickness (cm) | Trace fossils | Contacts & Associations | Interptetation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Amalgamated, trough cross-stratified sandstone facies (ATXC) | | | | | | ■ | | | | ■ | ■ | | USI LTXSB, MCDTXB<br>LSI CSPBC, MCDTXB | Fluvial channels/ coastal plain |
| Reddish heterolithic wavy laminated sandstone facies (RHSC) | | | | ■ | ■ | | | | | ■ | ■ | B | USIT CoalBC,CSPBC, WSB<br>LST CSPBC, WSB | Subaereal exposure/ coastal plain |
| Coal facies (CoalCB) | | | ■ | | | | | | | | ■ | | ULSI BWSB, CSPBC, LXPT | Swamps |
| Carbonaceous and rooted siltstones facies (CRSBC) | | | ■ | ■ | ■ | | | ■ | | | ■ | | ULSI IBLAB, SPTLB, BWSB and WRLT | High tidal flats deposits as part of tidal influenced bay. |

Contacts:
U: Upper contact T: Transitional I: Irregular
L: Lower Contact S: Sharp P: Planar

Trace fossils
O: Ophiomorpha C: Cruziana Ch: Condrites B: Burrows/Bioturbated
Th: Thalassinoides Pl: Planolites Te: Terebillina SK: Skolithos

**FIGURE 7.** Summary of facies described as part of the coastal plain facies tract.



| Facies Name and Abbreviation | Facies Symbol & Color code | Grain Size c | m | vf | f | M | C | Sorting P | M | W | Bed Thickness (cm) | Trace fossils | Contacts & Associations | Interptetation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coarse burrowed and bundled sandstone facies (CBBTS) | | | | | | ■ | ■ | | | ■ | ■ | O, Th | USP LBMTS<br>LSP LBMTS | Tidal Sand Ridges /inner shelf |
| Lenticular, bundled, bioturbated and muddy sandstone (LBMTS) | | | | ■ | | | ■ | ■ | | | ■ | C | UTI CBBTS<br>LSI FLWTS,LXPT | Toes of tidal sand ridges/ inner shelf |
| Fine low-angle to wavy sandstone facies (FLWTS) | | | | ■ | ■ | | | | | ■ | ■ | B | ULSP LBMTS | Stormy deposits in Subtidal settings |

Contacts:
U: Upper contact T: Transitional I: Irregular
L: Lower Contact S: Sharp P: Planar

Trace fossils
O: Ophiomorpha C: Cruziana Ch: Condrites B: Burrows/Bioturbated
Th: Thalassinoides Pl: Planolites Te: Terebillina SK: Skolithos

**FIGURE 8.** Summary of facies described as part of the tidal dominated inner shelf facies tract

**Tidal Dominated Inner Shelf to Tidal Influenced Open Bay and Bay-margin/intertidal flat:** Transitions from tidal dominated inner shelf to tidal influenced open bay facies tracts, and from open bay to bay-margin/intertidal flat consist of interfingering relationships. FIGURE 13 B shows interfingering relationships where tidal influenced open bay deposits aggrade and prograde landward of tidal dominated inner shelf deposits. Landward expansion of the tidal dominated inner shelf facies tract during base-level rise results in a landward directed stair case pattern. Tidal influenced open bay deposits expand landward behind the tidal dominated inner shelf successions, and interfinger with the bay-margin/intertidal flat facies tract. The transition occurs over a distance of 34 km and vertically over 2-10 m.

A similar relationship is observed between the tidal dominated inner shelf and the bay-margin/intertidal flat facies tracts. Where tidal dominated inner shelf strata strongly expand landward, the bay-margin/intertidal flat facies aggrades and interfingers with them. This transition occurs over a distance of about 11 km and vertically over 17 m. FIGURE 13 A and B the landward-stepping stacking pattern of units in A with respect to units in B. Tidal dominated inner shelf transitions consist of coarse tidal influenced open bay megaripples and sands waves overlain by sigmoidal bundled sandwaves, interbedded with muddy and rippled sandstone facies. Vertical transition from tidal influenced open bay to tidal dominated inner shelf facies is interpreted as a normal transgressive replacement.

**Shelf to Tidal Dominated Inner Shelf:** Shelf to tidal dominated inner shelf transitions consists of interfingering relationships (FIGURE 14). Tidal dominated inner shelf deposits aggrade and prograde landward of shelf mudstones. Tidal dominated inner shelf strata expand progressively landward during base-level hemicycles. This pattern results in a stair case geometry in which tidal dominated inner shelf deposits migrate landward above bay margin/intertidal flat strata. As mentioned before tidal dominated inner shelf strata also interfinger with tidal influenced open bay and bay-margin/intertidal flat facies strata. This transition occurs over 5 to 7 km laterally and vertically over 11 m.

Tidal dominated inner shelf to shelf transitions consist either of storm-dominated marine sandstones underlying sandy and muddy heterolithic tidal influenced open bay strata, or muddy marine strata underlying sandy and muddy heterolithic tidal dominated inner shelf strata. In any case, vertical transitions through these strata are considered a normal transgressive succession.

## STACKING PATTERNS

Stacking patterns are the geometric description of geographic shifts of facies tracts and the direction of offset within successive genetic sequences (Cross, 1988). Stacking patterns are described as landward-stepping, seaward-stepping and vertically stacked. In this study the first two are recognized. Seaward-stepping stacking patterns (SS) correspond to a geometrical arrangement where the shoreface, bay-margin/intertidal flat, and tidal influenced open bay facies tracts in one genetic sequence are displaced in a seaward direction relative to identical facies tracts of the underlying genetic sequence. Landward-stepping stacking patterns (LS) correspond to a geometrical arrangement where the bay-margin/intertidal flat, tidal influenced open bay, tidal dominated inner shelf facies tracts in one genetic sequence are displaced in a landward direction relative to identical facies tracts of the underlying genetic sequence. Stacking pattern analysis is important in defining stratigraphic cycles.

**Stacking Patterns of Shoreface Strata:** Shorefaces within genetic sequences show seaward-stepping stacking patterns (SS) across the study area. Successive arrows pointing to the right (NE) marked with the SS symbol indicate the progressive seaward-stepping between adjacent shoreface units (FIGURE 15).

In a shoreface unit with a SS stacking pattern, the proportion of shallower facies within it is greater than that in the underlying unit at the same geographic position. The shoreface unit at the lowest position consists exclusively of MHCSS and IBSS facies (FIGURE 15). This unit is overlain by another shoreface unit composed of a lower proportion of MHCSS, and a higher proportion of IHCSS, and HCSS facies indicating shallower depositional conditions. The slope of shingle breaks in seaward-stepping units tends to increase seaward within the same shoreface, and vertically through successive shoreface units. The shingles break slope in the basal shoreface unit is 0.08o to 0.09o, which is less steep than that of the upper SS shoreface unit of 0.1o to 0.17o. The aggradation /progradation ratio of Gallup shorefaces is about (0.0001 to 0.0033).

**Stacking Patterns of Tidal Influenced Open Bay Strata:** The tidal influenced open bay facies tract occurs in two seaward-stepping (SS) and one landward-stepping (LS) genetic sequences (FIGURE 16). On a small-scale herringbone cross-stratified (HRBXT) facies in T2 shift landward (FIGURE 16A). We believe that facies are younger to the southwest because they are

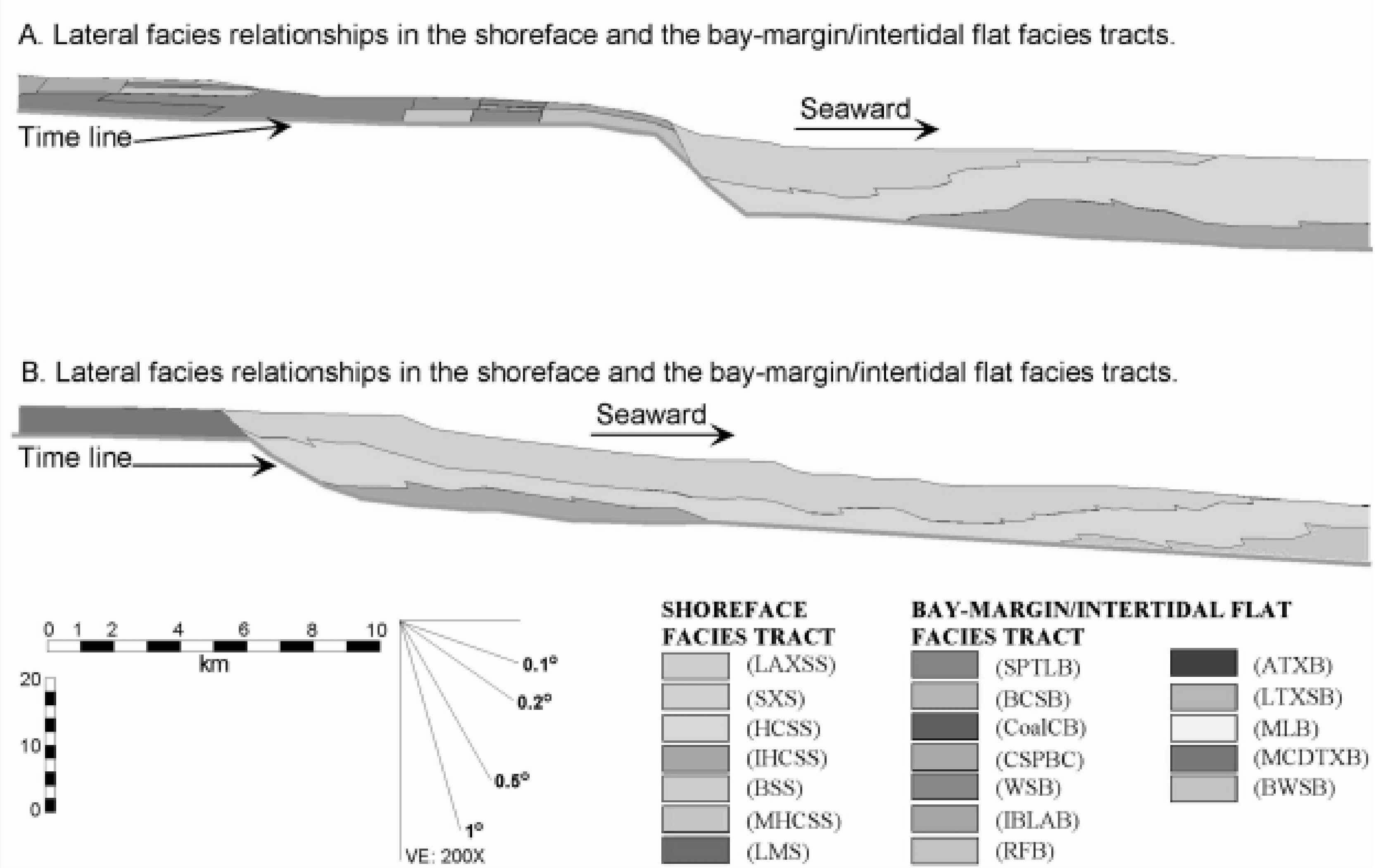


**FIGURE 9.** Dip stratigraphic cross-section showing lateral facies relationships between shoreface and bay-margin/intertidal flat strata. A. Relationships shown for a seaward-stepping PAU that underlies the PAU in B. B. Observe lateral extension of facies in B and compare them with those in A. These changes are associated with temporal long-term decreasing A/S conditions.

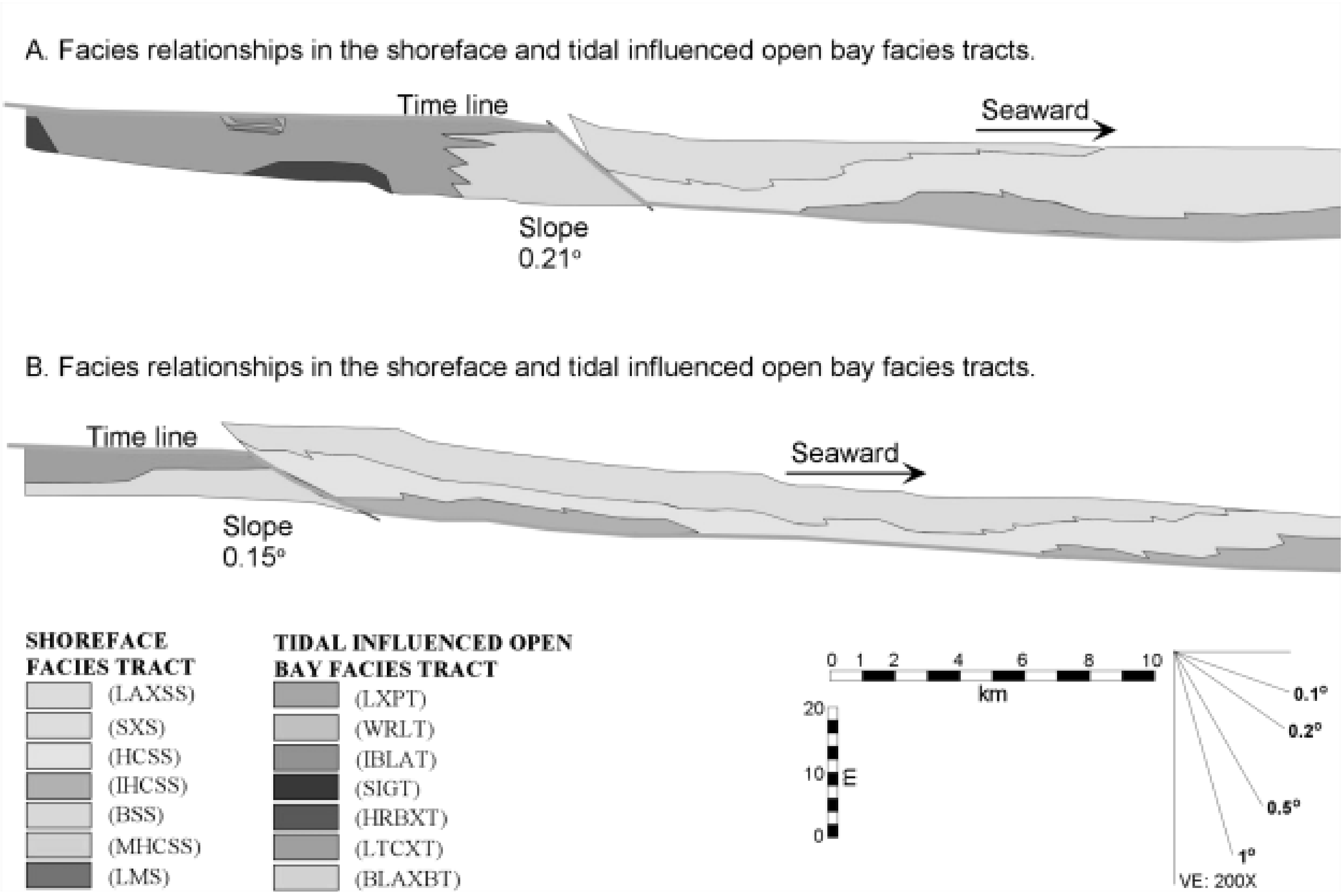


**FIGURE 10.** Dip stratigraphic cross section showing facies relationships between shoreface and tidal influenced open bay strata. A. Observe PAU in A stepping seaward relative to the underlying PAU shown in B. B. Contact between facies tracts is steeper in A than in B. In Both case the shoreface facies tract is younger than the tidal influenced open bay facies tract.

stratigraphically higher. Units T2 and T3 labeled with arrows pointing to the right (NE) and a SS symbol indicate the seaward-stepping stacking pattern (FIGURE 16). Unit T4 labeled with an arrow pointing to the left (SW) and a LS symbol is landward stepping (FIGURE 16 and 19). T4 overlies tidal influenced open bay and bay-margin/intertidal flat units in increasing A/S conditions. At large-scale (FIGURE 16), tidal influenced open bay and tidal dominated inner shelf facies tracts overlie and are displaced landward of the SS shoreface units. This large-scale offset is considered to be self-similar to the offset observed at the intermediate scale for the shoreface/tidal couplets (FIGURE 16).

The distribution of tidal influenced open bay units changes with stratigraphic position. Under long-term decreasing A/S conditions, tidal influenced open bay units are separated from each other and are encased between shoreface and bay-margin/intertidal flat strata (e.g., T1 and T2 in FIGURE 16 and 19). Under long-term increasing A/S conditions tidal influenced open bay units are in contact and encased between shelf, bay-margin/intertidal flat, and tidal dominated inner shelf strata (e.g., T3 and T4 in FIGURE 16 and 19). Stacking pattern analysis of tidal influenced open bay units is easy because of the clear geographic offsets. Offsets between T1 and T2, and between T2 and T3 are clear because they are seaward-stepping and paired with a shoreface unit. Offsets between T3 and T4 are less apparent. T4 is not paired with a shoreface unit. This is explained by the clear landward-stepping event. This case offers the only example of stacking pattern analysis between tidal influenced open bay units physically in contact with one another.

Facies offset analysis within tidal influenced open bay units is difficult since there are no good cases where tidal facies successions show sufficient diversity to identify offsets within tidal strata. Facies offsets within units of the tidal facies tract can be observed in two dimensions by shifts of identical facies associated with specific geomorphic elements (FIGURE 15 A). Later, we will show that in a vertical profile, facies offsets and stacking patterns can be characterized by changes in facies proportions within successive tidal influenced open bay units.

**Stacking Patterns of Bay-Margin/Intertidal Flat:** Stacking patterns for the bay-margin/intertidal flat facies tract are characterized by seaward and landward displacements of bay-margin/intertidal flat facies tracts in seven genetic sequences (FIGURE 17). A seaward-stepping stacking pattern is characterized by a seaward displacement of the bay-margin/intertidal flat unit BM2 with respect to BM1. Unit BM2 also overlies tidal influenced open bay strata of the older genetic unit. Landward-stepping stacking patterns are characterized by a landward displacement of the bay-margin/intertidal flat unit BM3 with respect to BM2. Bay-margin/intertidal flat strata of unit BM2 are overlain by tidal influenced open bay strata at seaward (NE) positions. Units BM4 and BM5 also are landward stepping. Strata within seaward-stepping bay-margin/intertidal flat units, consist of amalgamated, laterally continuous and less heterolithic strata. Strata within landward-stepping bay-margin/intertidal flat units, consists of less amalgamated, less continuous and more heterolithic strata. For example, channels and bars are progressively better preserved and more associated with heterolithic strata. Explanation for these observations is a consequence of sediment volume partitioning and facies differentiation.

**Stacking Patterns of Tidal Dominated Inner Shelf Strata:** Stacking pattern for the tidal dominated inner shelf facies tract is characterized by landward displacements of the four tidal dominated inner shelf units shown in FIGURE 18. Episodic landward migration of geomorphic elements composed of CBBST facies (i.e., tidal sand ridges) and associated heterolithic facies is the 2-D expression of the landward-stepping stacking pattern in tidal dominated inner shelf strata. The 1-D expression of this stacking pattern consists of the progressive upward increase of LBMST facies replacing CBBST facies. In general, each landward-stepping tidal dominated inner shelf unit shows a higher proportion of deeper water facies than in the underlying unit. These changes in facies proportions suggest are associated with volume partitioning accompanying base level cycles. In the landward-stepping stacking pattern, the tidal dominated inner shelf facies tract overlies shoreface, tidal influenced open bay and bay-margin/intertidal flat facies tracts.

**General Stacking Patterns of Shoreface, Tidal Influenced Open Bay, Bay-Margin/Intertidal Flat, and Tidal Dominated Inner Shelf Strata:** The seaward-stepping stacking pattern of the shoreface facies tract always coincides with seaward-stepping stacking pattern of the bay-margin/intertidal flat facies tract. Seaward stepping of the tidal influenced open bay facies tract is also accompanied by a seaward stepping of the bay-margin/intertidal flat facies tract. Landward stepping of the tidal influenced open bay and tidal dominated inner shelf facies tracts coincides with the landward stepping of the coeval bay-margin/intertidal flat facies tract. Deposition of tidal influenced open bay units landward of underlying older shorefaces restricts the seaward advance of bay-margin/

intertidal flat and coastal plain strata. Consecutive landward-stepping stacking patterns of tidal dominated inner shelf facies tract coincide with progressively more restricted landward positions for tidal influenced open bay and bay-margin/intertidal flat facies tracts (FIGURE 19). Stacking patterns are also revealed by proportions of facies or facies tracts composing genetic units. For example, the proportion of facies tracts indicating deeper conditions are larger in landward-stepping genetic units, compared with seaward-stepping genetic units FIGURE 19.

## STRATIGRAPHIC CYCLES

Regardless of scale, a complete stratigraphic cycle is considered to record the sedimentary response to a base-level cycle. It consists of base-level fall (FH) and base-level rise (RH) hemicycles. RH describes a condition where facies tracts shift landward or uphill, accommodation space increases across the depositional profile and new accommodation is created in uphill positions, and sediment supply and transport energy in downslope positions decreases. FH describes a condition where facies tracts shift seaward, accommodation space decreases across the depositional profile and accommodation is reduced in uphill positions, and the sediment supply and transport energy in downslope positions increases.

The hemicycle boundaries are "turnaround" positions from base-level rise-to-fall (RTF) and from base-level fall-to-rise (FTR). Turnarounds record the culmination of unidirectional trends of increasing or decreasing A/S conditions. Turnarounds are points of reference to be correlated from one geographic position to another through adjacent facies tracts and throughout the spatial extent of each stratigraphic cycle. Robust chronostratigraphic correlations are possible when the initiation points for stratigraphic cycles of all scales are picked consistently at the same turnaround position.

Expressions of these base-level cycles are stratal stacking patterns and/or similar facies succession motifs appearing at different stratigraphic positions and at different scales throughout stratigraphic cross sections. Triangles are used conventionally to describe stratigraphic cycle hierarchy, geologic time and A/S conditions accompanying base-level cycles. FIGURE 20 shows the use of triangle notation. Symmetric cycles represent continuous sedimentation at a constant geographic position through time. In asymmetric cycles strata corresponding to the "missing" hemicycle are interpreted as initially deposited and later eroded or never deposited, either because of bypass or starvation. Slightly asymmetric cycles are represented by FH and RH triangles in which either of them is substantially thinner than the other. The smaller hemicycle is considered to represent less sediment accumulation per unit of time than the other hemicycle. It may be associated with minor erosion after deposition, bypass or starvation surfaces. Conventionally, cycles are denoted as slightly rise-asymmetric or fall-asymmetric if RH or FH are dominantly preserved (FIGURE 20). In the following, a way of describing and analyzing cycles is presented. This paper only shows information dealing with analysis of the large scale, lower frequency cycle represented by the Gallup clastic wedge and associated strata. Analysis of higher frequency and lower scale cycles is discussed in detail in Alvarez (2002) and will be summarized in the conclusions of this paper.

**Characterization of Large-Scale Cycles:** Large-scale base-level cycles around 100 to 130 m thick record the migration of depositional environments over several 100s of kilometers. They consist of fall and rise hemicycles defined by staking patterns of 7 to 9 constituent intermediate-scale cycles (FIGURE 23). Large-scale cycles are easy to identify on two-dimensional map areas encompassing tens of km2 and in one-dimensional sections measured through tens to hundreds of meters of strata. In this study, one large-scale cycle is recognized and correlated through all facies tracts (FIGURES 21 y 22).

**Large-Scale Cycle Identification: Long-Term Fall Hemicycle (FH):** The large-scale FH consists of three to four intermediate-scale seaward-stepping cycles culminating at a large-scale FTR turnaround (FIGURES 21 and 23). During long-term FH, tidal influenced open bay environments appear overlying shoreface environments (FIGURE 22). At early stages in the FH, we observe shoreface toes encased in microhummocky sandstones and mudstones of the inner shelf (FIGURE 22). Bay-margin/intertidal flat facies are behind shorefaces and tidal influenced open bay facies tracts. In the late FH, we observe Gallup shorefaces reaching their seaward depositional limits (FIGURE 20). The extension of the bay-margin/interidal flat across the tidal influenced open bay facies tract in the late FH is characterized by an intermediate- scale cycle (FIGURE 21).

Intermediate-scale cycles within the long-term FH begin with a RTF turnaround in shoreface strata, and culminate at a FTR turnaround in bay-margin/intertidal flat, coastal plain and shallow shoreface facies. Within large-scale FH, intermediate-scale cycles seaward-stepping and record decreasing A/S conditions (FIGURE 21). In North Toadlena, Breached Anticline and Amphitheater sections, the fall hemicycle 1F record SS stacking pattern of shoreface cycles and coeval bay-margin/intertidal flat strata. They are followed by SS of tidal influenced open bay and coeval bay-margin/intertidal flat strata and culminate at the FTR turnaround of intermediate-scale cycle 4F in coastal plain and bay-margin/intertidal flat strata (FIGURE 21).

**Long-Term Rise Hemicycle (RH):** Large-scale RH consists of three to four intermediate-scale cycles and culminates at a large-scale RTF turnaround. During long-term base-level rise, the tidal influenced open bay and tidal dominated inner shelf facies tracts advance landward as the bay-margin/intertidal flat facies tract displace landward (FIGURES 22, 23).

During the early long-term RH, the bay-margin/intertidal flat facies tract do not extend as far seaward as at the long-term FTR turnaround (FIGURE 21), and tidal influenced open bay deposits overlie shoreface strata. The tidal influenced open bay facies tract advances landward, while the coeval bay-margin/intertidal flat facies tract progressively displaces landward. At landward locations, channel sandstones appear at the base of landward-stepping bay-margin strata. In the early RH, intermediate-scale rise hemicycles consist of stacks of large-scale, fully preserved cross-stratified facies changing laterally into stacked low-angle coarse tidal influenced open bay facies. Tidal influenced open bay facies dominate FTR turnarounds of intermediate- scale cycles.

During the late long-term RH, tidal influenced open bay and tidal dominated inner shelf units step landward over the underlying, low-gradient bay-margin/ intertidal flat facies tract. This produces interfingering transitions between bay-margin/intertidal flat and tidal influenced open bay facies tract. Pinchout transitions are most characteristic of FTR long-term turnaround. Intermediate-scale cycles of bay-margin/intertidal flat strata display LS stacking patterns. Successions commonly end in tidal influenced open bay facies suggesting a small-scale base-level rise (FIGURE 21).

Bay-margin/intertidal flat strata occur throughout the early and most of the late, long-term RH (FIGURE 22). Intermediate-scale bay-margin cycles are completely rise-asymmetric as a result of nondeposition during base-level fall time. Maximum seaward advance of bay-margin/ intertidal flat strata at intermediate- scale coincides with that of FTR turnarounds.

**Large-Scale Cycle Turnarounds:** Large-scale turnarounds occur within or at contacts between beds and facies tracts. The large-scale FTR turnaround coincides with an intermediate-scale FTR turnaround and represents minimum long-term A/S conditions. It corresponds to the maximum seaward extent of the coastal plain, bay-margin/intertidal flat and shoreface facies tracts (FIGURE 21). The tidal influenced open bay facies tract occurs immediately above the turnaround position and over shoreface strata (FIGURE 22). Minimum progradation of the bay-margin/intertidal flat facies tract occurs during base- level rise.

Topographic expression of large-scale turnarounds is subtle. A change in color from gray to beige shoreface strata, to lighter beige to white tidal influenced open bay strata suggests the location of this turnaround. Sometimes a recessive horizon, which is represented by bay-margin/ intertidal flat and/or coastal plain strata between the shoreface and tidal influenced open bay strata, indicates the position of the turnaround (FIGURE 21, sections Big Reentrant to Amphitheater and FIGURE 25, 26 and 27). This criterion is difficult to apply, especially at Toadlena and N Toadlena sections, where bay-margin/intertidal flat and coastal plain successions are 30-40 m thick.

Within bay-margin/intertidal flat and coastal plain facies tracts, large-scale FTR turnarounds are characterized by the decreased proportions of heterolithic subaqueous strata, fully preserved channelforms, and thin gray channels (e.g., facies, WSB, LTXSB, ATXB) relative to subaerial reddish and muddy facies and highly amalgamated reddish facies (e.g., facies RHSC, ATXC). For example, in Toadlena and North Toadlena measured sections, the large-scale FTR turnaround is placed at the intermediate-scale turnaround of cycle 5, where an upward change from ATXC to LTXSB and a change from RHSC to WSB and ATXB, respectively, is identified for each of the sections (FIGURE 26).

Topographic expression of the large-scale RTF turnaround is very good. At lower positions, calcareous sandstones constituting the shelf at the base of the long-term base-level fall hemicycle are overlain by distal shoreface mudstones. Beds at the top of the long-term base-level rise hemicycle pass from tidal dominated inner shelf strata that become mud rich and pass into inner shelf mudstone facies (FIGURE 27).

**Large-Scale Cycle Resolution:** The large-scale cycle comprises the lowest stratigraphic resolution but the most certain cycle scale in the study area. Definition of the large-scale hemicycle and turnarounds is easy to moderately difficult. The large-scale FTR turnaround commonly consists of coastal plain, bay-margin/intertidal flat and tidal influenced open bay strata that correlate across the study area. Large-scale FTR turnaround definition is less robust than that of RTF turnarounds. Large-scale cycle definition is certain because large-scale cycles laterally record the migration of depositional environments over several kilometers.

**Cycle Symmetry:** The long-term cycle of this study is slightly fall-asymmetric across the study area and through all the facies tracts (FIGURE 21). This asymmetry could suggest the slight possibility to have a regional unconformity and predicts our observation of lack of regional erosional surface.

Throughout a long-term FH, intermediate-scale cycles containing the shoreface/tidal couplets show symmetry changes from slightly fall asymmetric at landward positions to symmetric and/or slightly rise asymmetric at seaward positions. These symmetry changes are associated with a progressive reduction in depositional gradient, contact between the shoreface and tidal influenced open bay facies tracts. This symmetry changes abruptly farther seaward to fall asymmetric cycles within shoreface strata. At a fixed geographic location (e.g., Big Reentrant or Breached Anticline sections), intermediate-scale cycle symmetry changes from completely fall asymmetric to slightly fall asymmetric, to symmetric cycles. This vertical change in symmetry is associated with progressive change from lower gradient environments to higher gradient environments, as result of progradation of shoreface units.

**Large-Scale Cycles in 2-D Example:** The thickness of the long-term cycle decreases slightly seaward (FIGURE 21). Lines connecting large-scale cycle turnarounds generally cross several facies tracts (FIGURE 21). For example, coastal plain, proximal to distal bay-margin/intertidal flat and then tidal influenced open bay facies occur at large-scale FTR turnarounds. Shoreface strata at the FTR turnaround display maximum seaward progradation across the study area. The turnarounds occur at positions within beds and at contacts representing stratal and cycle stacking pattern changes (FIGURE 21). Regional erosion surfaces are absent at these positions. Lines connecting large-scale RTF turnarounds are dominated by zones of deep shoreface facies up to few meters thick. Regional surfaces of starvation were not observed. Large-scale RTF cycle turnarounds coincide with maximum landward advance of deepest facies of the shoreface facies tract. Resolution of the large-scale turnarounds in the study is very good. Uncertainty is reduced because turnarounds can be traced by following turnarounds from more confident to less confident sections. FTR turnaround uncertainties in the study area is around < 5% (1-5 m in 100-120 m).

**Large-Scale Cycles in 1-D Measured Sections:** This discussion summarizes the interpretation of large-scale base-level cycles using the Amphiteater section example, based on stacking patterns of intermediate-scale cycles. The Amphitheater measured section (FIGURE 21 and 24) consists of five intermediate-scale cycles each composed of two to four small-scale cycles (FIGURE 21, 23 and 25). One cycle is composed of bay-margin/intertidal flat strata, one of shoreface strata, one of shoreface-tidal influenced open bay, one of tidal influenced open bay-tidal dominated inner shelf strata, and one of tidal dominated inner shelf strata.

Intermediate-scale cycles range from 10 to 20 m thick and average 9 m. The thinnest cycle (i.e., cycle 7) is at the top of the section within tidal dominated inner shelf successions (FIGURE 24). Cycle 2 is the thickest and is composed of shoreface and tidal influenced open bay facies successions and occurs at the base of the clastic wedge.

Long-term cycle definition within alternating successions of multiple facies tracts is moderately easy. A combination of seaward- and landward-stepping stacking patterns, large number of facies, and many facies attributes help in the cycle interpretation process.

Uncertainty for placement of RTF turnaround ranges between 1% to 2% (1 to 2 over cycles 100 m thick), whereas uncertainty for placement of FTR turnaround ranges between 1% to 4% (1-4 m over cycles 100 m thick).

## CONCLUSIONS

Five facies tracts were recognized: shoreface, bay-margin/intertidal flat, coastal plain, tidal influenced open bay, and tidal dominated inner shelf. Under long-term decreasing A/S conditions, the shorefaces of the Gallup Sandstone were deposited under wave-dominated conditions probably along straight coastlines. They are capped by the coasrser tidal components of Gallup shoreface/tidal couplets. Embayed geomorphology reinforced tidal currents responsible for reworking continental bedload and marine sediments. Under long-term increasing A/S conditions, the tidal influenced open bay and tidal dominated inner shelf facies tracts (Tocito Lentil of Mancos Shale) were deposited. Streams feeding embayed areas were progressively more flooded than those feeding shoreface and coeval bay-margin/intertidal flat units. These units were deposited in open bays along embayed coastlines affected by tidal currents. Bay-margin/intertidal flat units (Dilco Member of the Crevasse Canyon Formation) were deposited landward of Gallup shoreface/tidal couplets. In these environments, tidal currents were slightly important.

Small-scale cycle definition is based on facies successions. Small-scale base-level cycles are the highest resolution cycles in this study and have the highest degree of uncertainty for turnaround placement. Small?scale cycles can be correlated for hundreds of meters within facies tracts. Intermediate-scale cycle definition is based on facies succession trends and stacking patterns of small-scale cycles. Intermediate-scale cycles have high-resolution and an intermediate level of uncertainty in turnaround definition. They are considered the basic correlation unit in the study area, and can be correlated across multiple facies tracts for tens of kilometers.

Intermediate-scale cycles consisting of shoreface and tidal influenced open bay strata are dominantly symmetric. These cycles change landward from a completely fall asymmetry to a slightly rise asymmetry. For their coeval bay-margin/intertidal flat and coastal plain facies tracts, cycle symmetry changes landward from slightly rise asymmetric cycles to fairly symmetric cycles. Intermediate-scale cycles consisting only of shoreface facies tract are slightly to completely fall asymmetric. They occur at basal stratigraphic positions within the large-scale cycle. Intermediate-scale cycles consisting of tidal influenced open bay and tidal dominated inner shelf facies tracts are slightly rise asymmetric. They occur at higher stratigraphic positions within the large-scale cycle.

Intermediate and large-scale cycles are defined by mapping maximum and minimum progradation shorefaces and coeval bay-margin/intertidal flat units along with other sedimentological attributes such as bed thickness, degree of bioturbation, and degree of heterogeneity (i.e., S/Sh ratio).

Large-scale cycle definition is based on stacking patterns of intermediate-scale cycles. The large-scale cycle has the lowest resolution and represents the lowest degree of uncertainty in turnaround definition. It can be correlated over hundreds of kilometers.

The large-scale cycle in the study area is slightly fall asymmetric. It contains subequal proportions of landward- and seaward-stepping intermediate scale cycles. Symmetric cycles imply approximately continuous sediment accumulation during a base level cycle. Asymmetry of certain cycles is associated with sediment volume partitioning. Continuous base-level cycles dominate stratigraphic architecture at intermediate and large scales. Cycle symmetry and our observations explain and confirmed the absence of regional erosion and starvation surfaces. The lack of regional erosional unconformities within cycles at all scales suggests the improbability of base-level transits in the study area.

Base-level changes correspond with stacking patterns and relative movement of depositional units within a facies tract, or between different facies tracts. During a long-term fall hemicycle (FH), shoreface and tidal influenced open bay units step seaward with respect to equivalent facies tracts within the underlying genetic unit. During the long-term rise hemicycle (RH), tidal influenced open bay and tidal dominated inner shelf units step landward with respect to equivalent facies tracts within the underlying genetic unit.

Correlation from continental to marine strata is possible using base-level cycles as working tools that describe A/S variations in time and space. Analysis of facies successions and associations under a context of changing A/S conditions during stratigraphic base-level cycles leads to a high resolution and robust method to construct a confident chronostratigraphic and architecture framework.

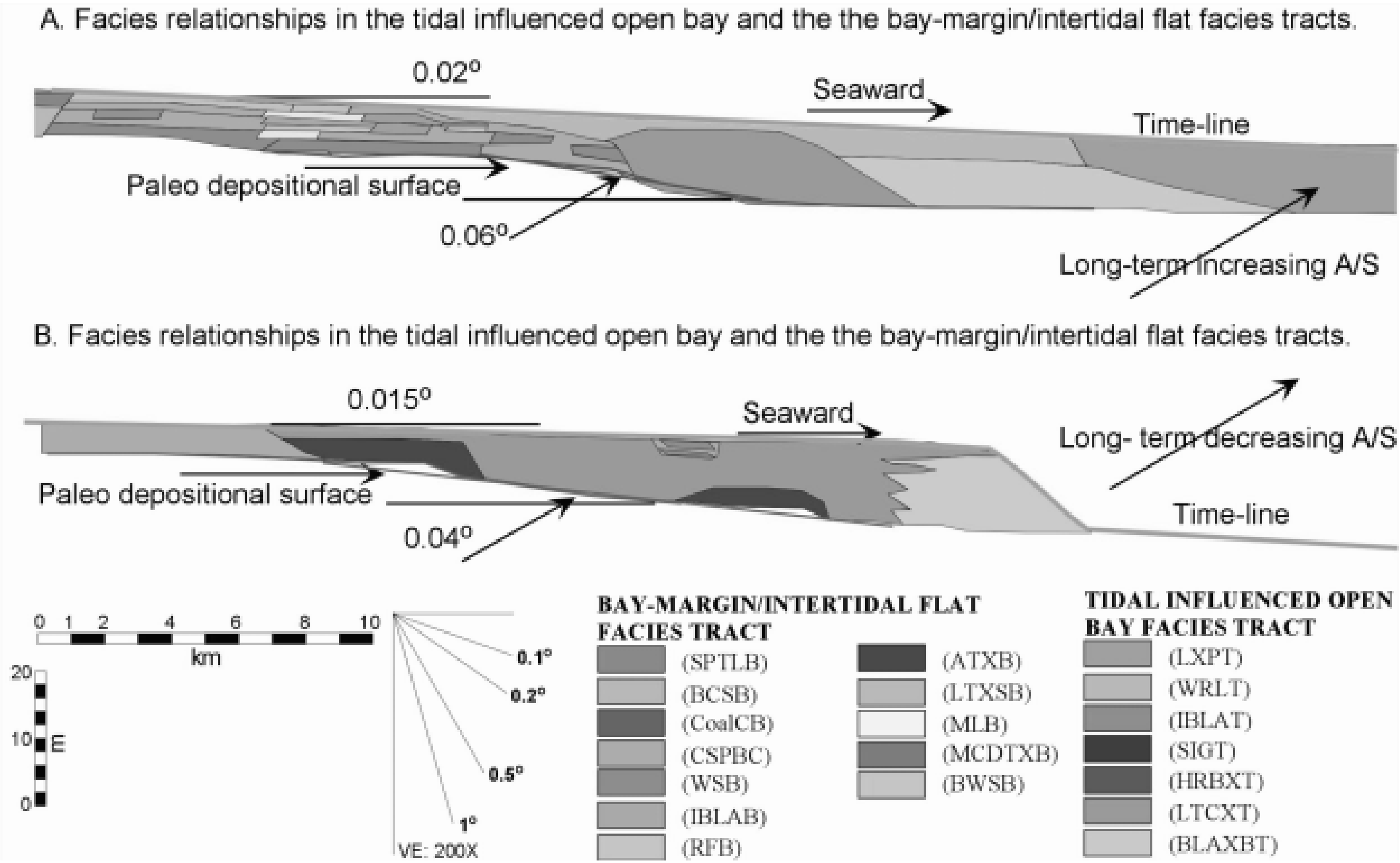


**FIGURE 11.** Dip stratigraphic cross-section showing facies relationships between bay margin and tidal influenced open bay strata. A. Lateral relationships for PAU deposited in unidirectional increasing A/S conditions. B. Lateral relationships for PAU deposited in unidirectional decreasing A/S conditions.

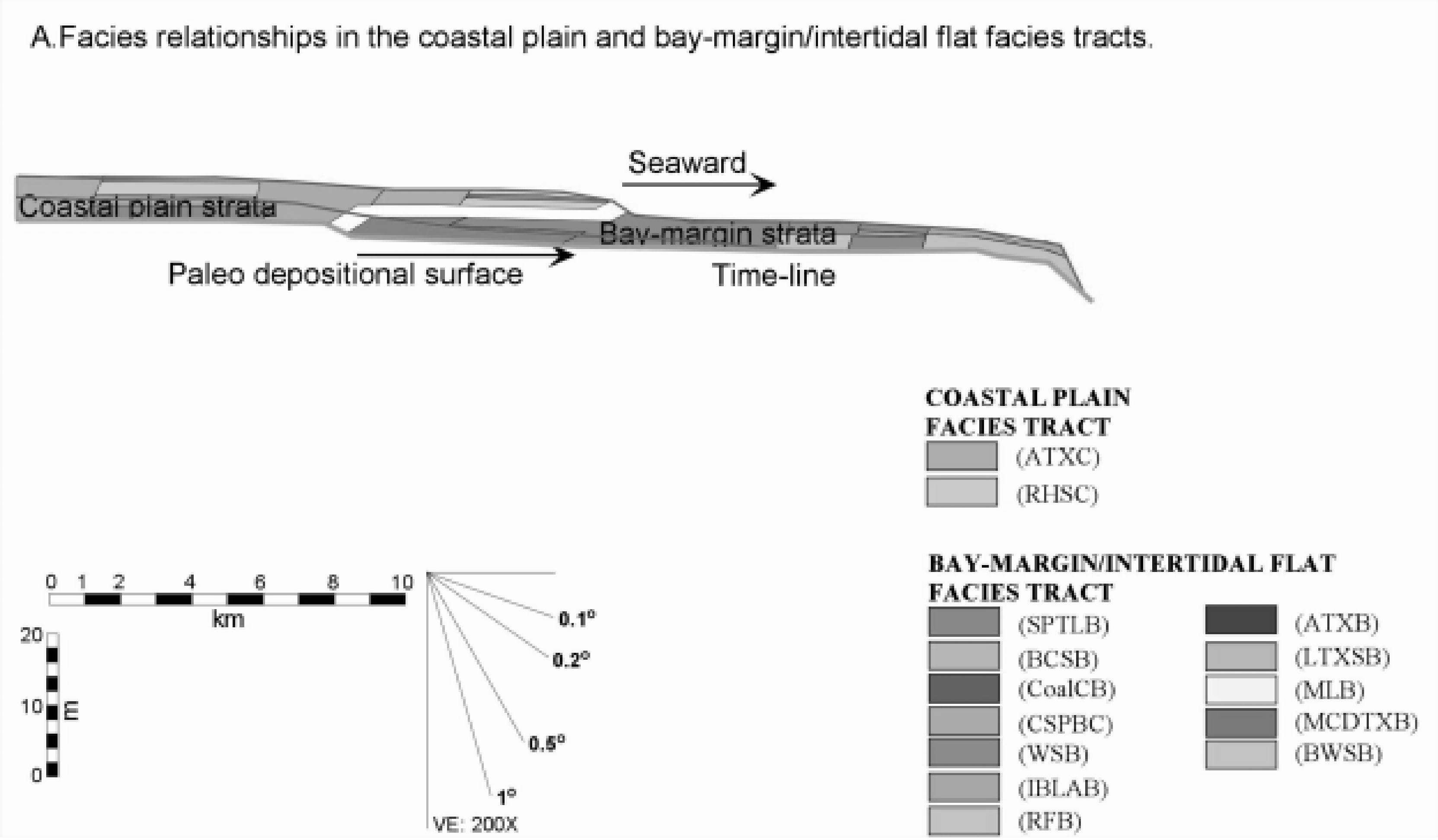


**FIGURE 12.** Dip stratigraphic cross-section showing facies relationships between bay-margin/intertidal flat and coastal plain facies tracts.

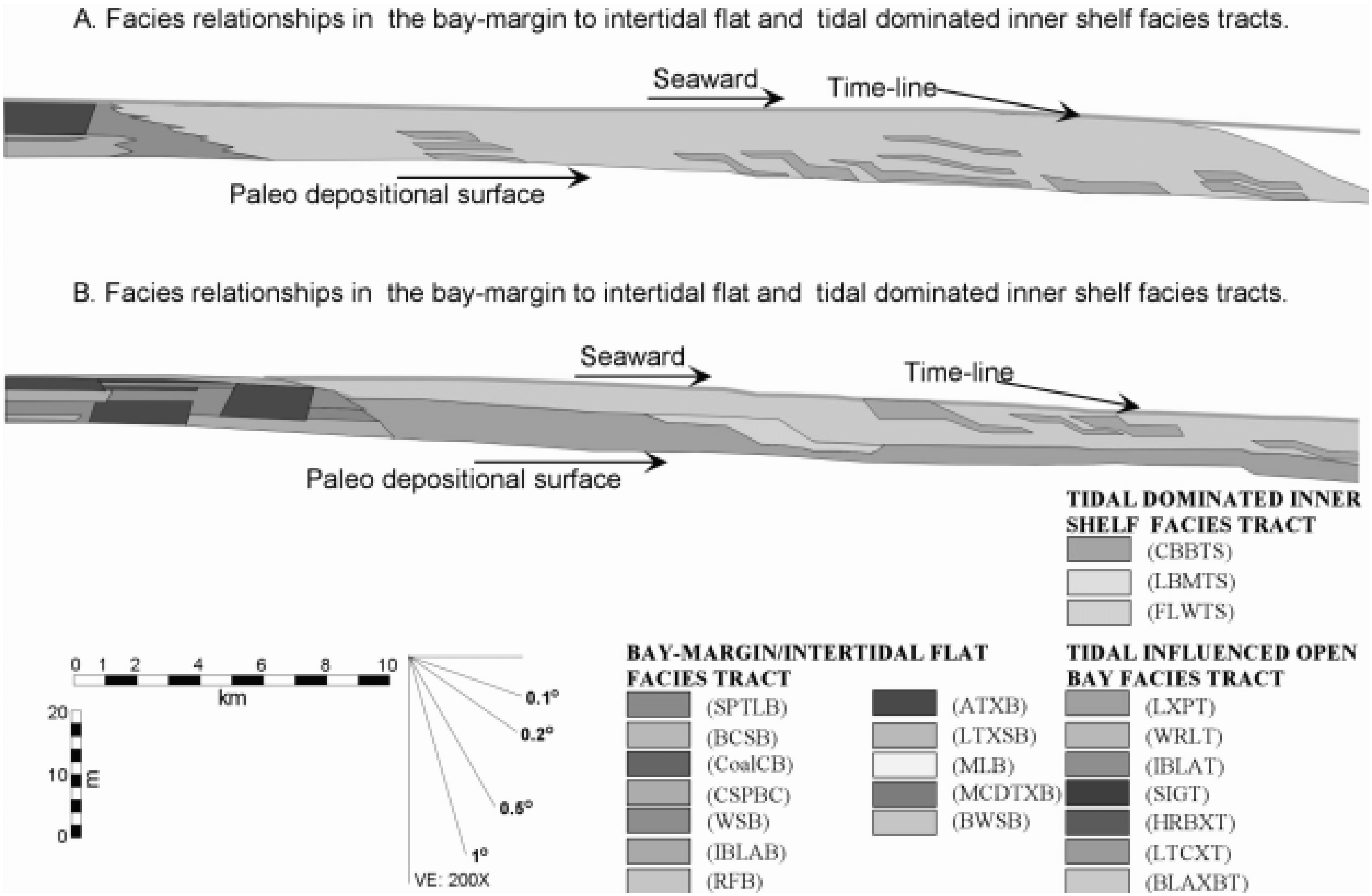
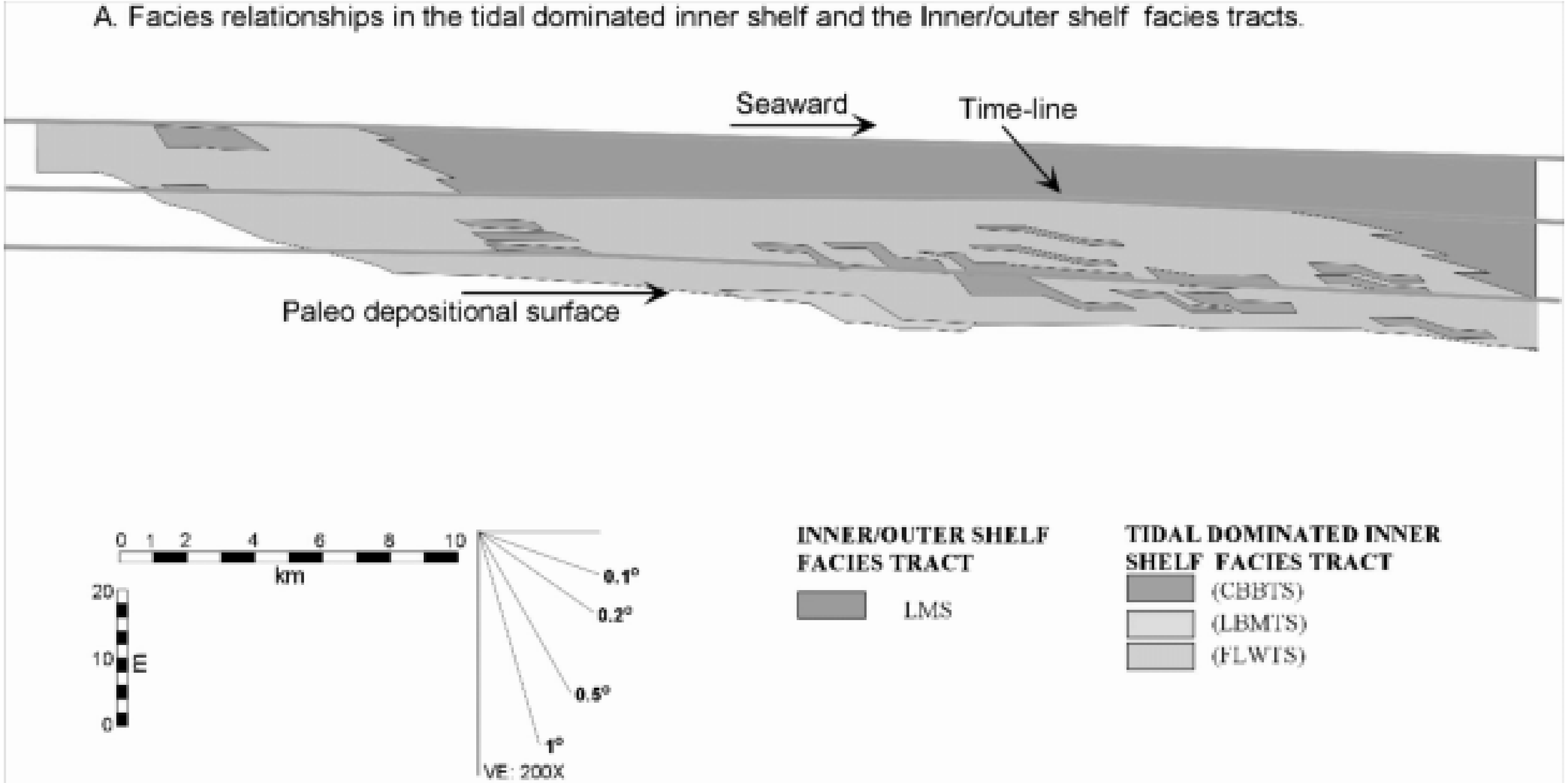


**FIGURE 13.** Dip stratigraphic cross-section showing detailed facies relationships among tidal dominated inner shelf, tidal influenced open bay, and bay-margin/intertidal flats strata.



A. Facies relationships in the tidal dominated inner shelf and the Inner/outer shelf facies tracts.

**FIGURE 14.** Dip stratigraphic cross section showing facies relationships between three genetic units composed of tidal dominated inner shelf and inner/outer shelf strata.

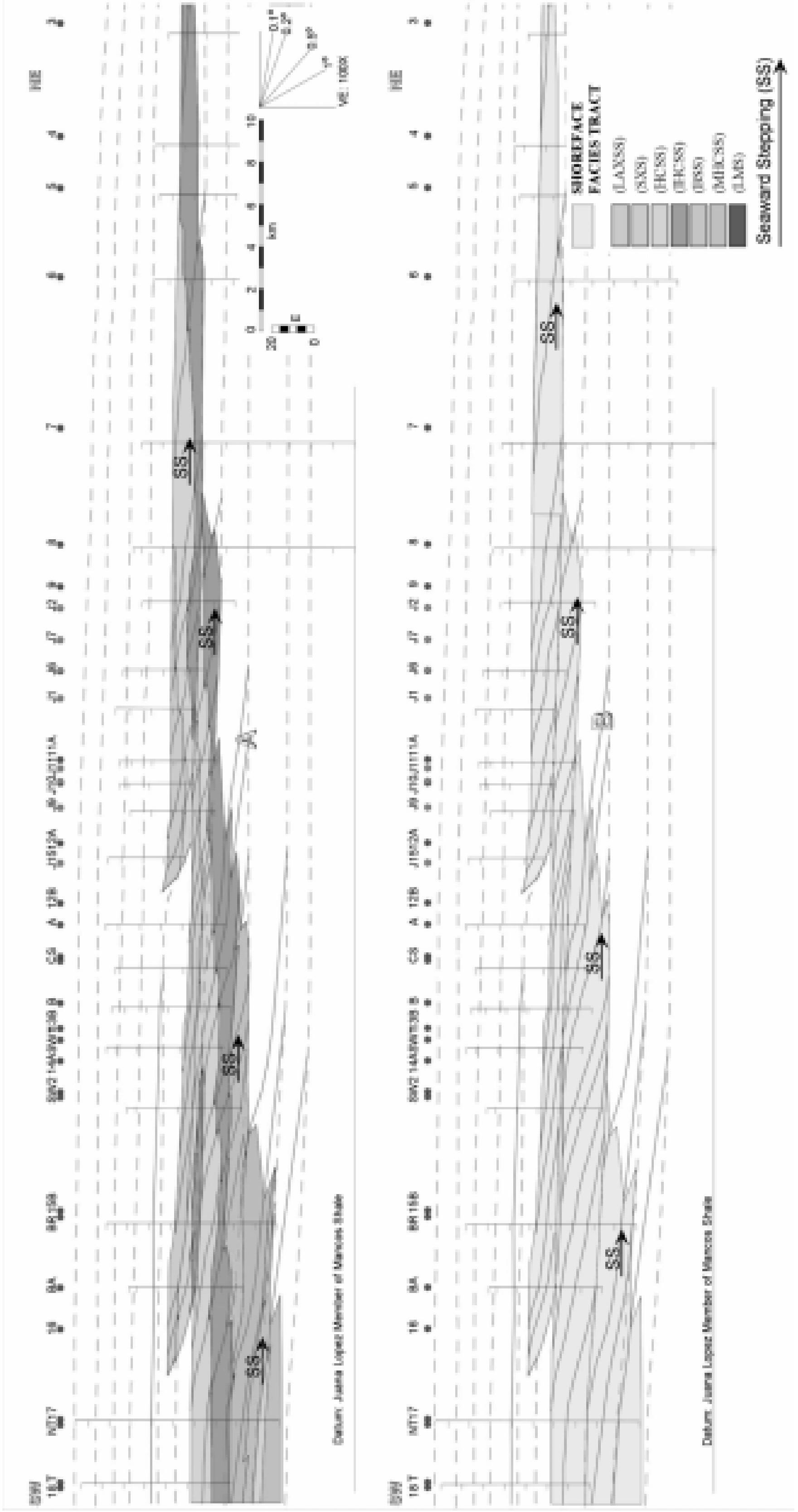


**FIGURE 15.** Dip stratigraphic cross section showing stacking patterns in shoreface strata. A. Map of facies associations within shoreface units. B. Intermediate scale stacking patterns between PAUs.

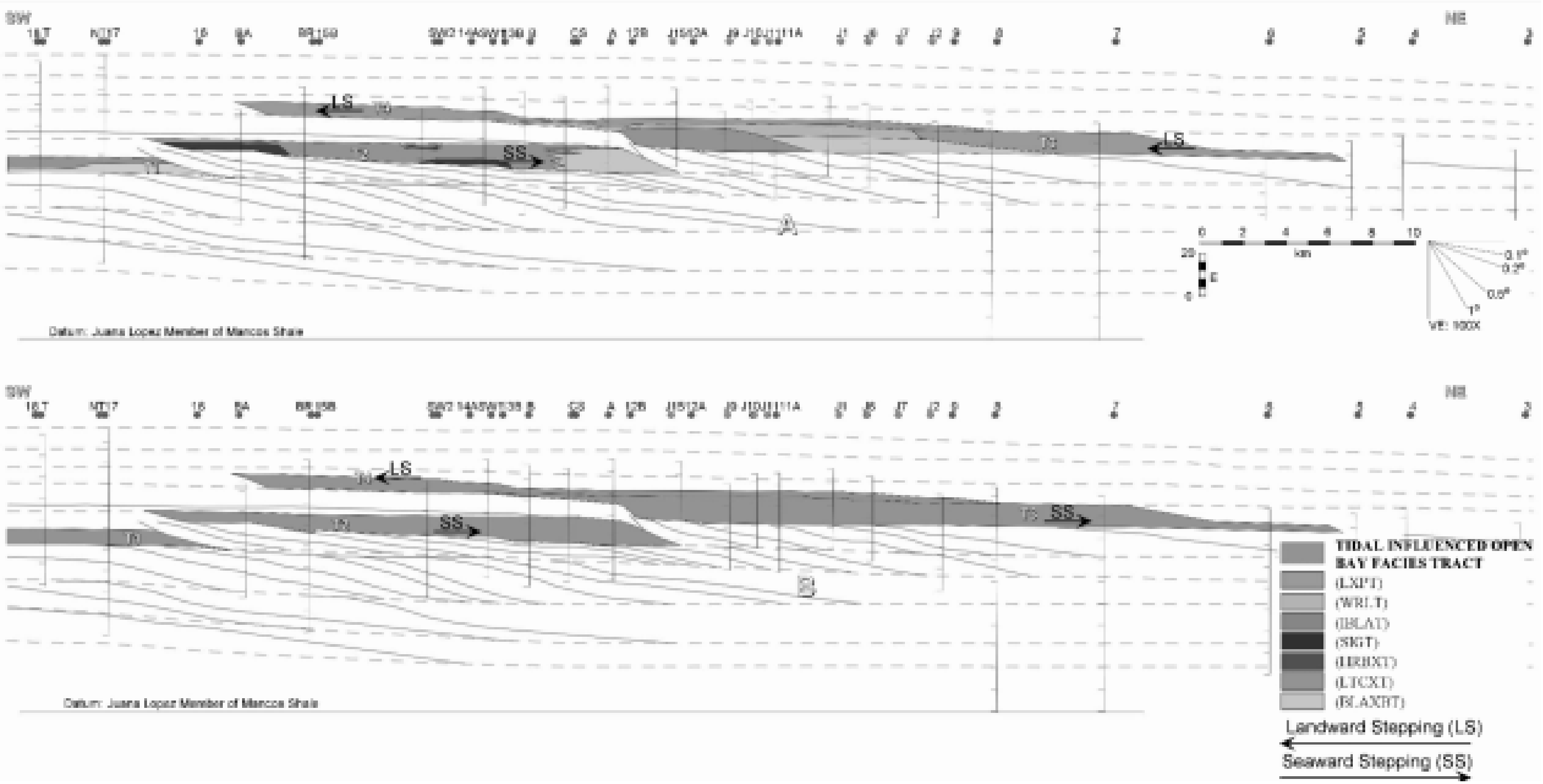


**FIGURE 16.** Dip stratigraphic cross-section showing stacking patterns in tidal influenced open bay strata. A. Map of facies associations within tidal influenced open bay units. B. Intermediate-scale stacking patterns of successive tidal influenced open bay facies tracts.

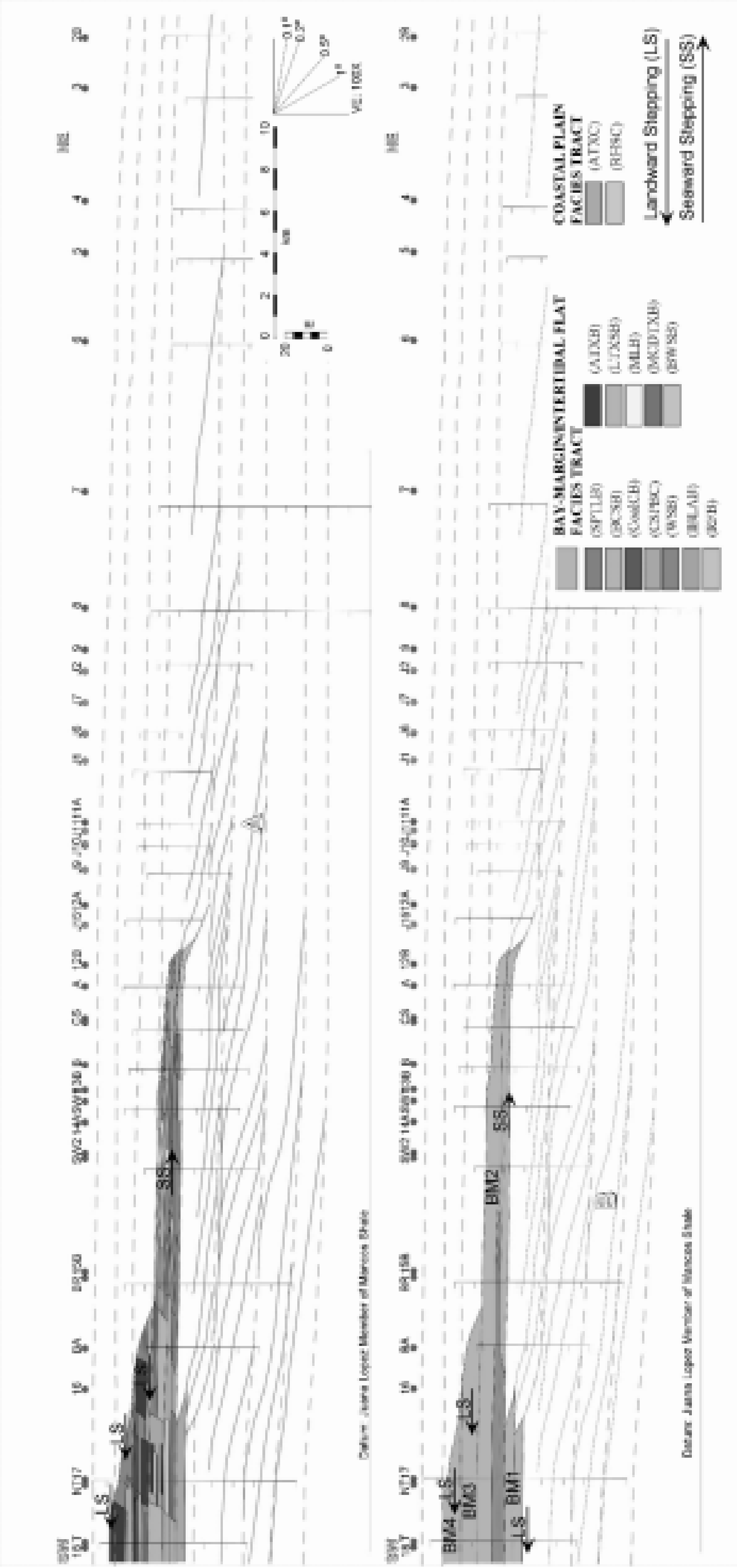


**FIGURE 17.** Dip stratigraphic cross-section showing stacking patterns in bay-margin/intertidal flat and the coastal plain facies tracts.

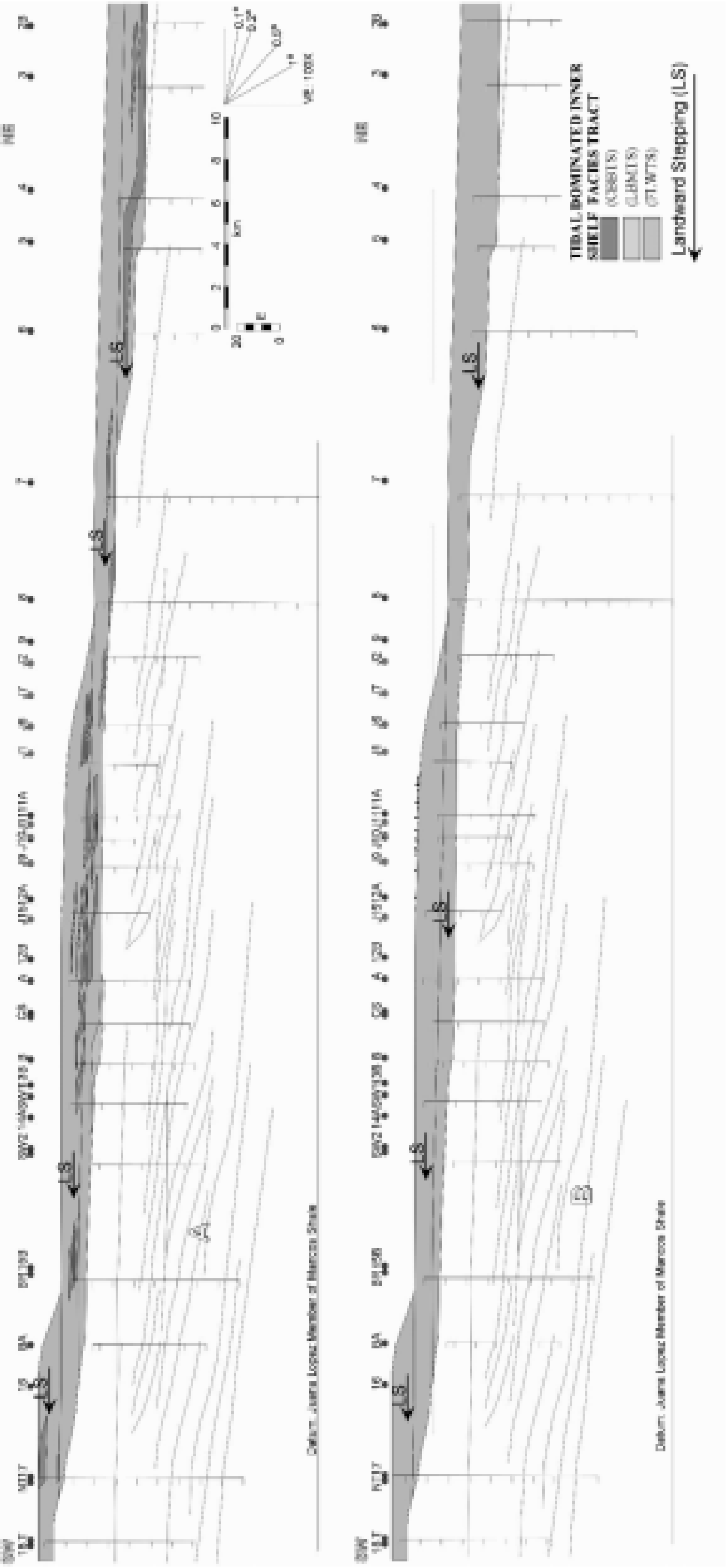


**FIGURE 18.** Dip stratigraphic cross section showing stacking patterns within the tidal dominated inner shelf faceis tract.

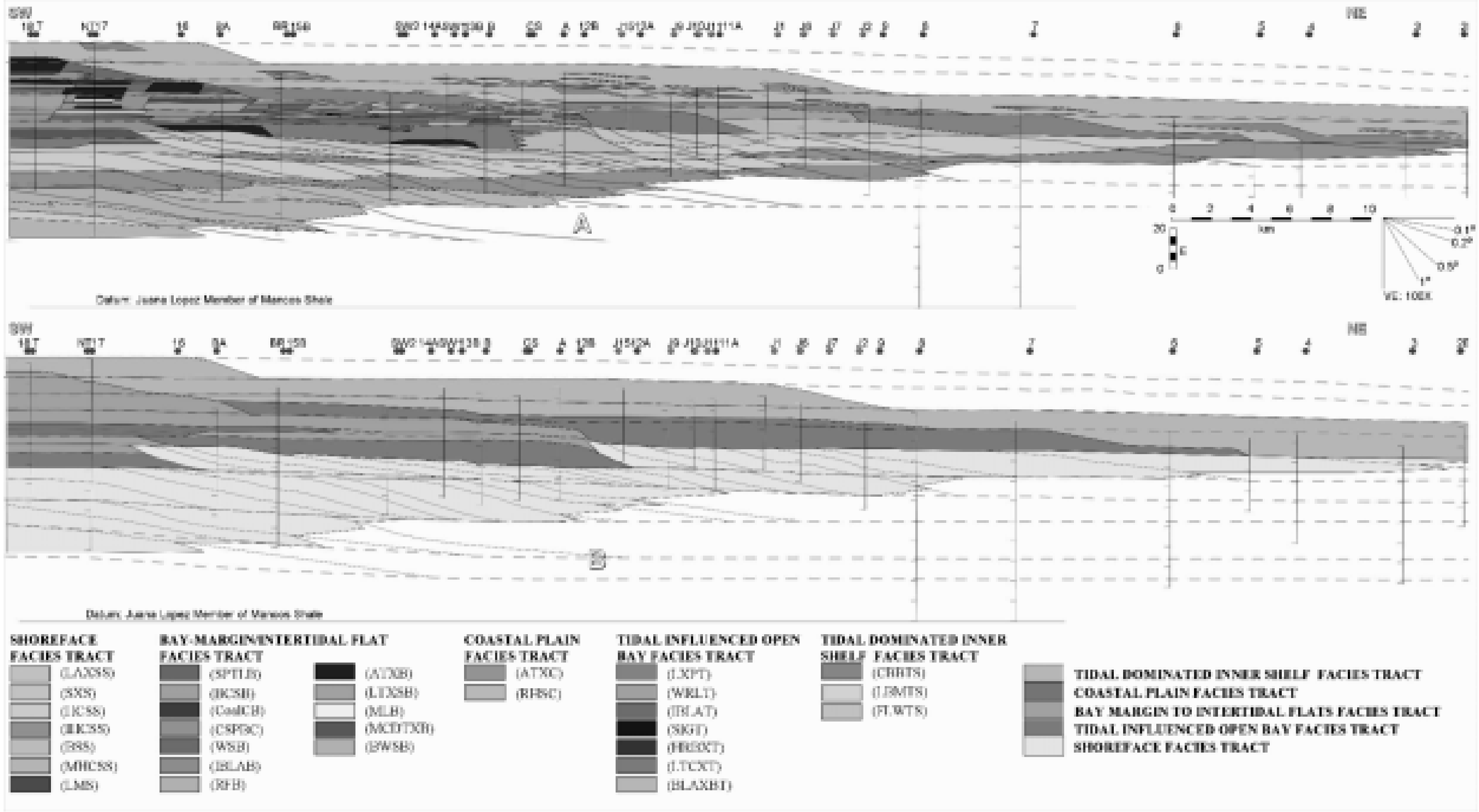


**FIGURE 19.** Dip stratigraphic cross-section showing mapping of facies associations within facies tracts and stacking patterns among shoreface, tidal influenced open bay, bay-margin/ intertidal flat, coastal plain, and tidal dominated inner shelf strata.

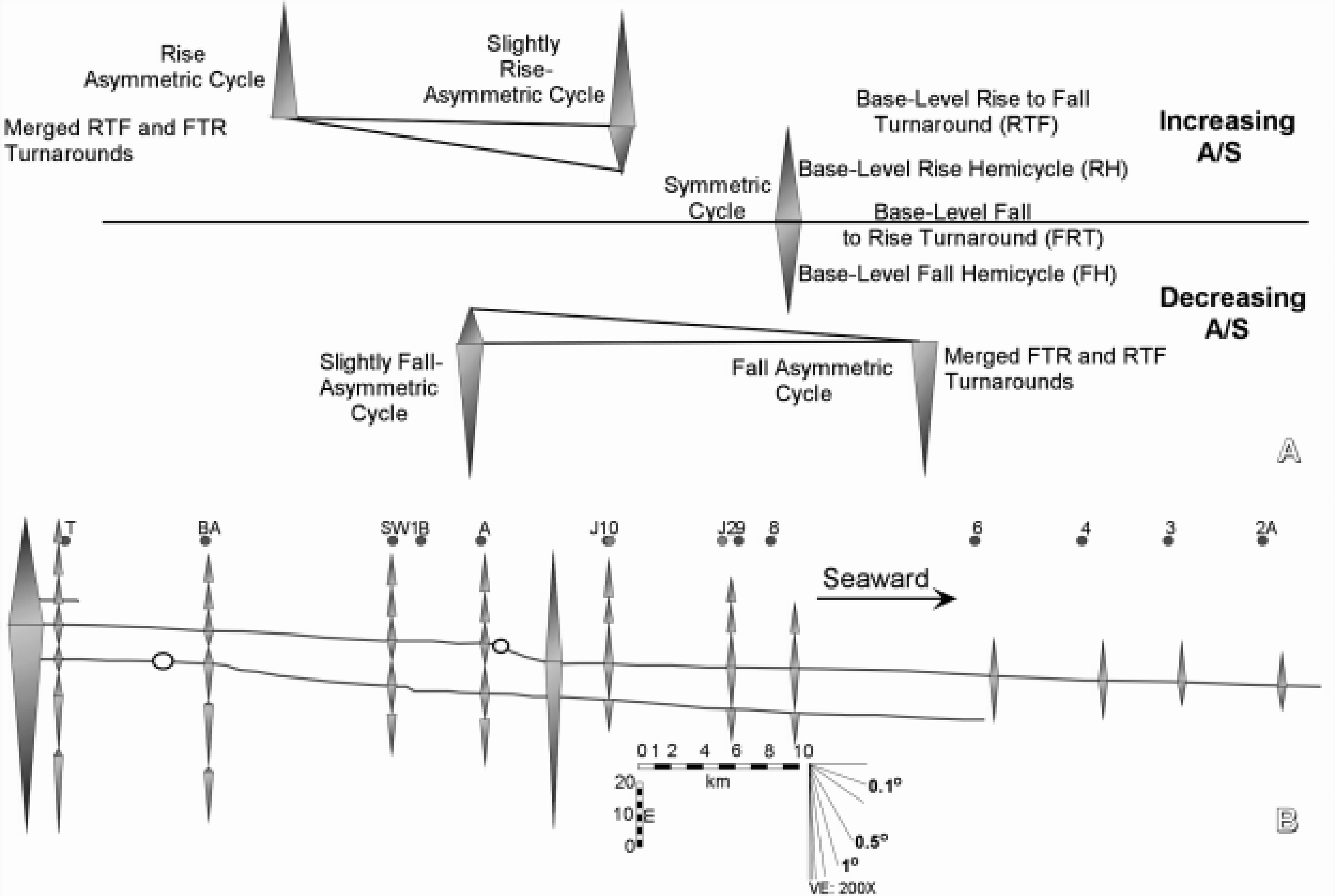


**FIGURE 20.** Cycle definition using triangle symbols. Changing conditions of A/S accompanying base-level cycles are indicated by triangles. A. Explanation of triangle notation. B. Example of symmety changes in intermediate-scale cycles along depositional profile (i.e., cycle along lower red line).

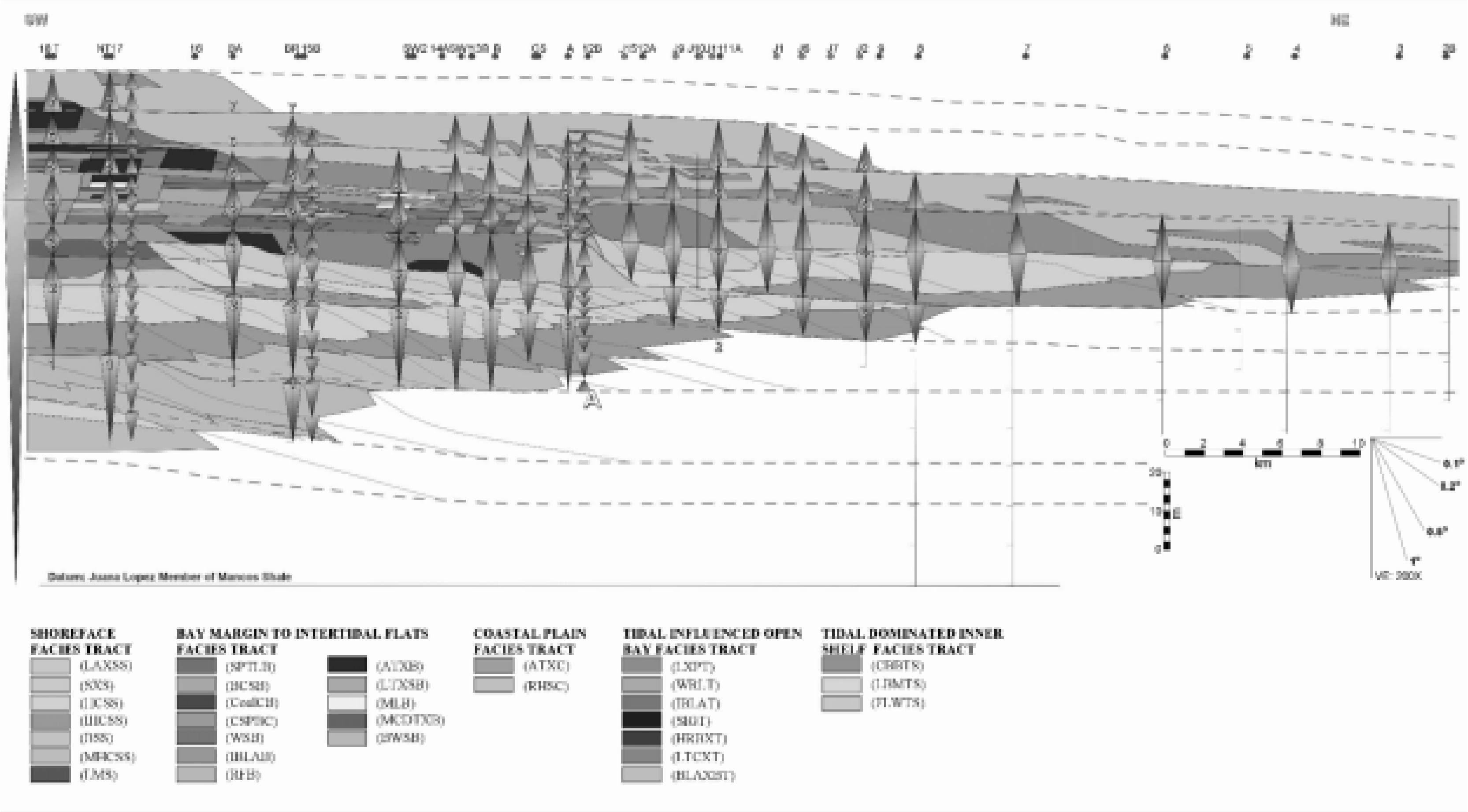


**FIGURE 21.** Dip stratigraphic cross section showing intermediate-scale base level cycles across the study area and among shoreface, tidal influenced open bay, bay-margin/intertidal flat, coastal plain, and tidal dominated inner shelf facies tracts.

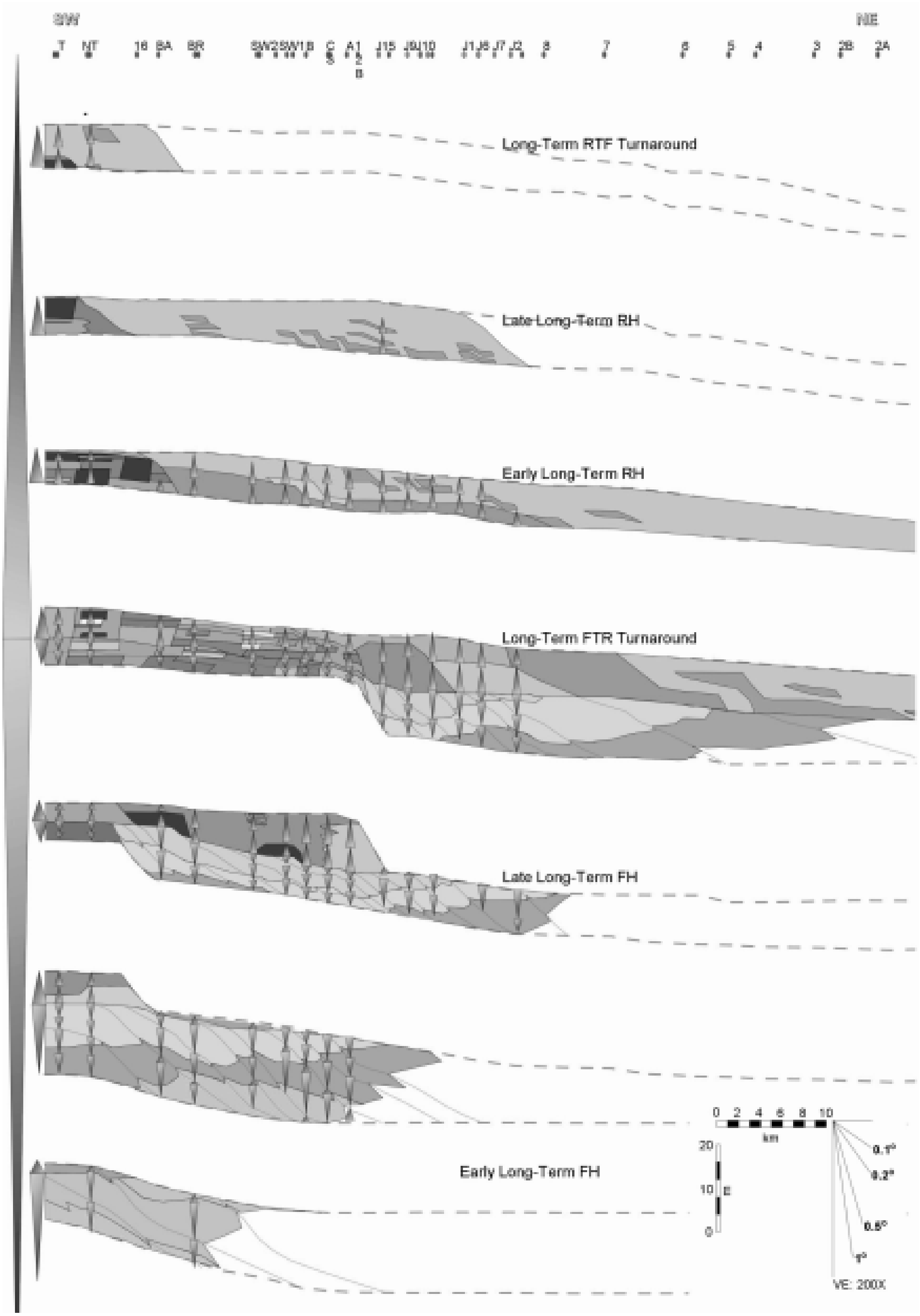


**FIGURE 22.** Architecture of the large-scale base-level cycle. A series of intermediate-scale and constituent small-scale cycles portrays changes through a long-term cycle. Architectural components such as FH, FTR turnaround, RH, and RTF turnaround are discussed in the text.

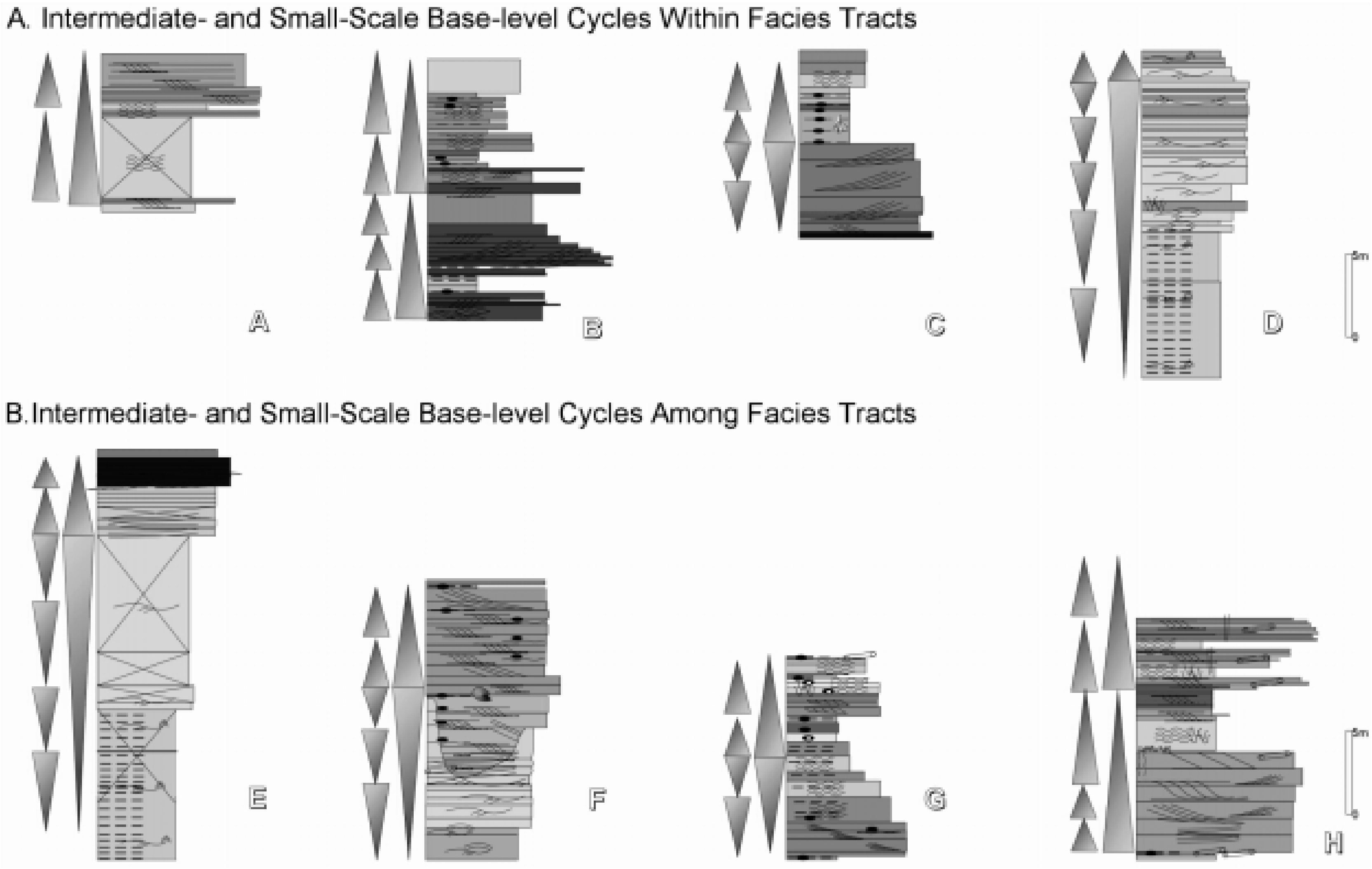


**FIGURE 23.** Intermediate-scale base-level cycles within and among facies tracts. Cycles are derived from facies successions and stratal stacking patterns.Letters show intermediate-scale cycles within tidal dominated inner shelf (A), bay-margin /interidal flat (B and C) and shoreface (D) facies tracts. They also show intermediate-scale among shoreface and tidal influenced open bay (E and F), bay margin and tidal influenced open bay (G), and tidal influenced open bay and tidal dominated inner shelf (H) facies tracts.All sections are at same scale, bar indicates scale.

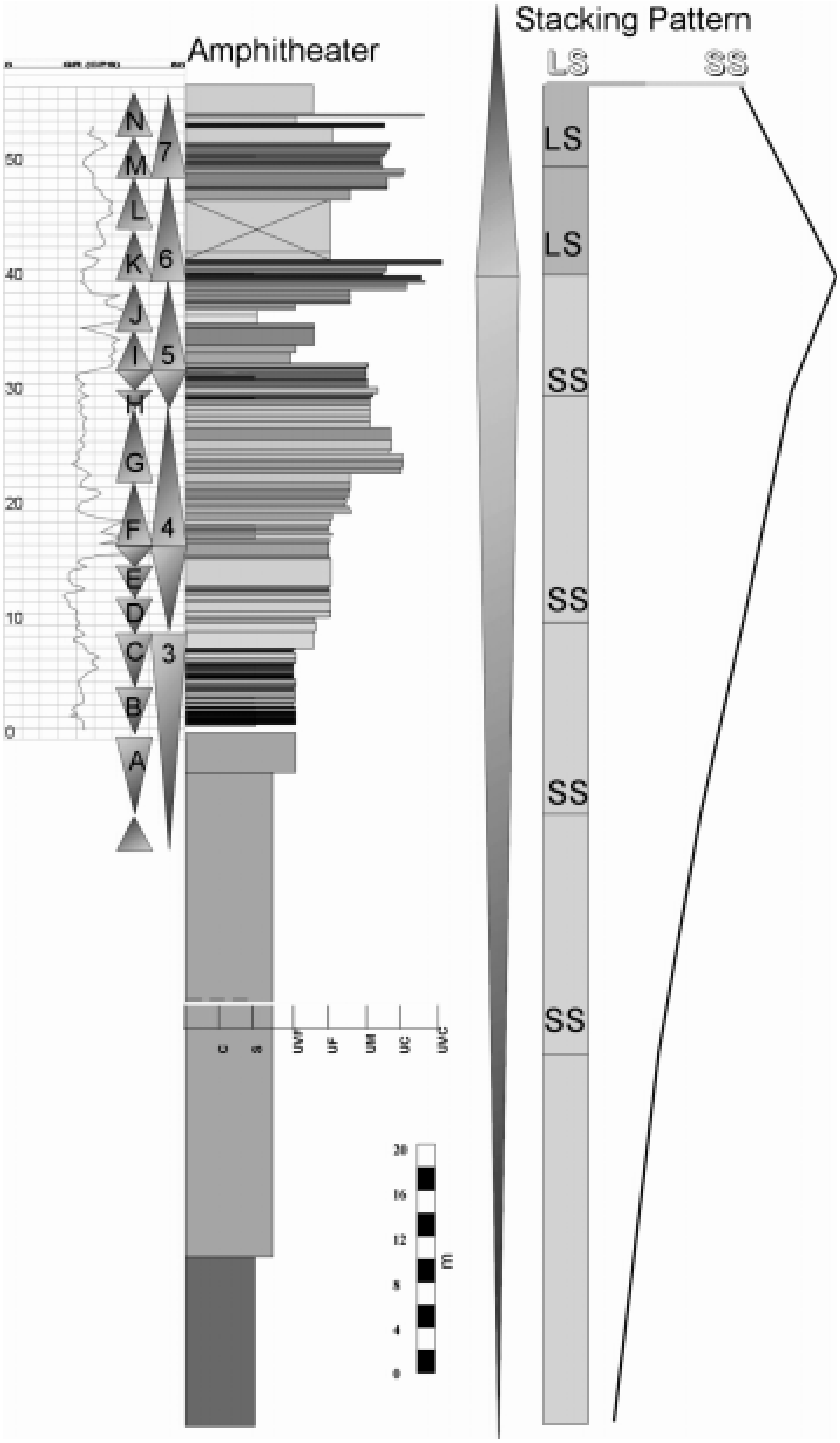


**FIGURE 24.** Intermediate scale base-level cycles in coastal plain, bay-margin/intertidal flat, shoreface, tidal influenced open bay, and tidal dominated inner shelf strata. Section includes a portion of Big Reentrant section in cycles 1 to 6.

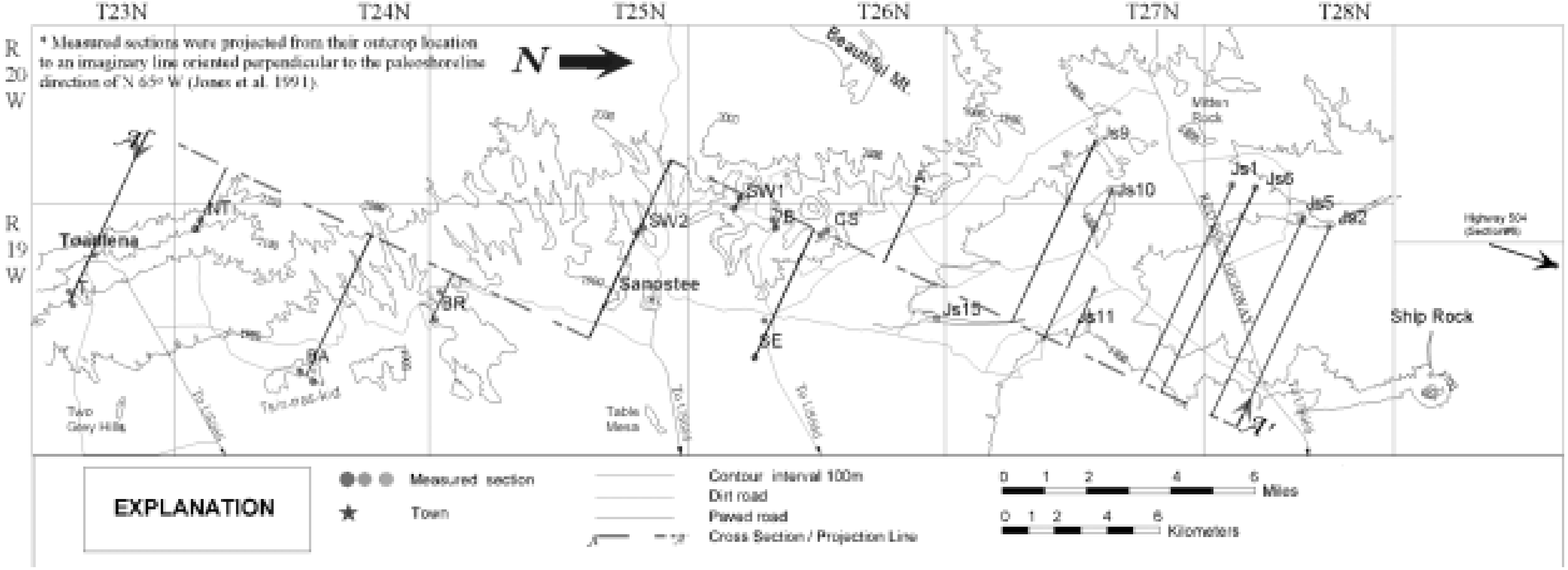


**FIGURE 24A:** Small-scale base-level cycles in bay-margin/intertidal flat, shoreface, tidal influenced open bay, and tidal dominated inner shelf strata. Section includes a portion of Amphitheater section in cycles 3 to 7.

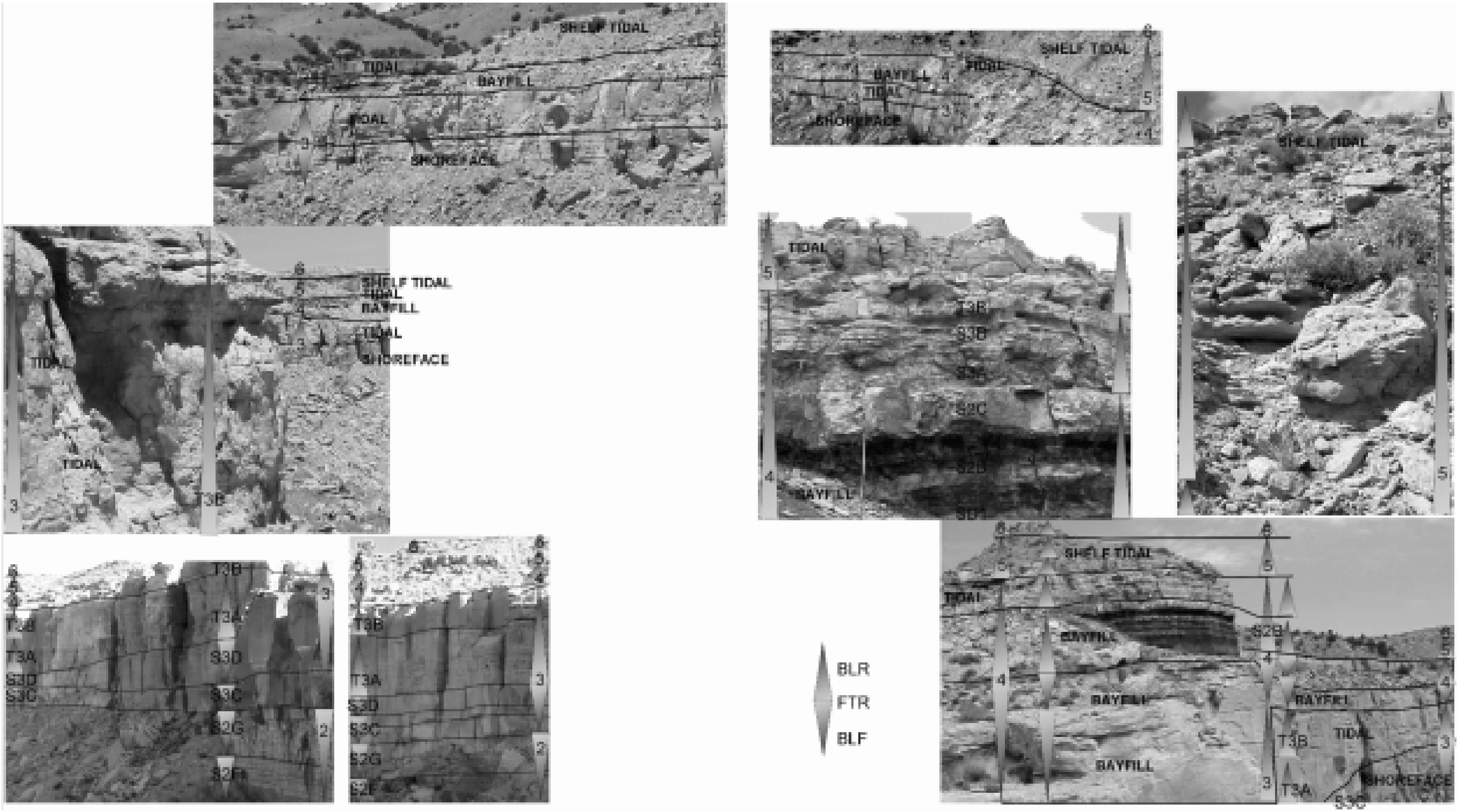


**FIGURE 25.** Identification of small- and intermediate-scale base-level cycles. Example from Cone Shape section. Numbers correspond to intermediate scale cycles, letters correspond to the following key: S for shingles within shoreface units, T for tidal influenced open bay, B for bay-margin/intertidal flat, and C for coastal plain.

**FIGURE 26.** Large-scale cycle turnarounds in the Beautiful Mountain area. A. Placement of FTR and RTF turnarounds for the large-scale cycle at SW1 section. B. Placement of FTR and RTF turnaround at Amphitheater section. Dashed line indicates turnaround.

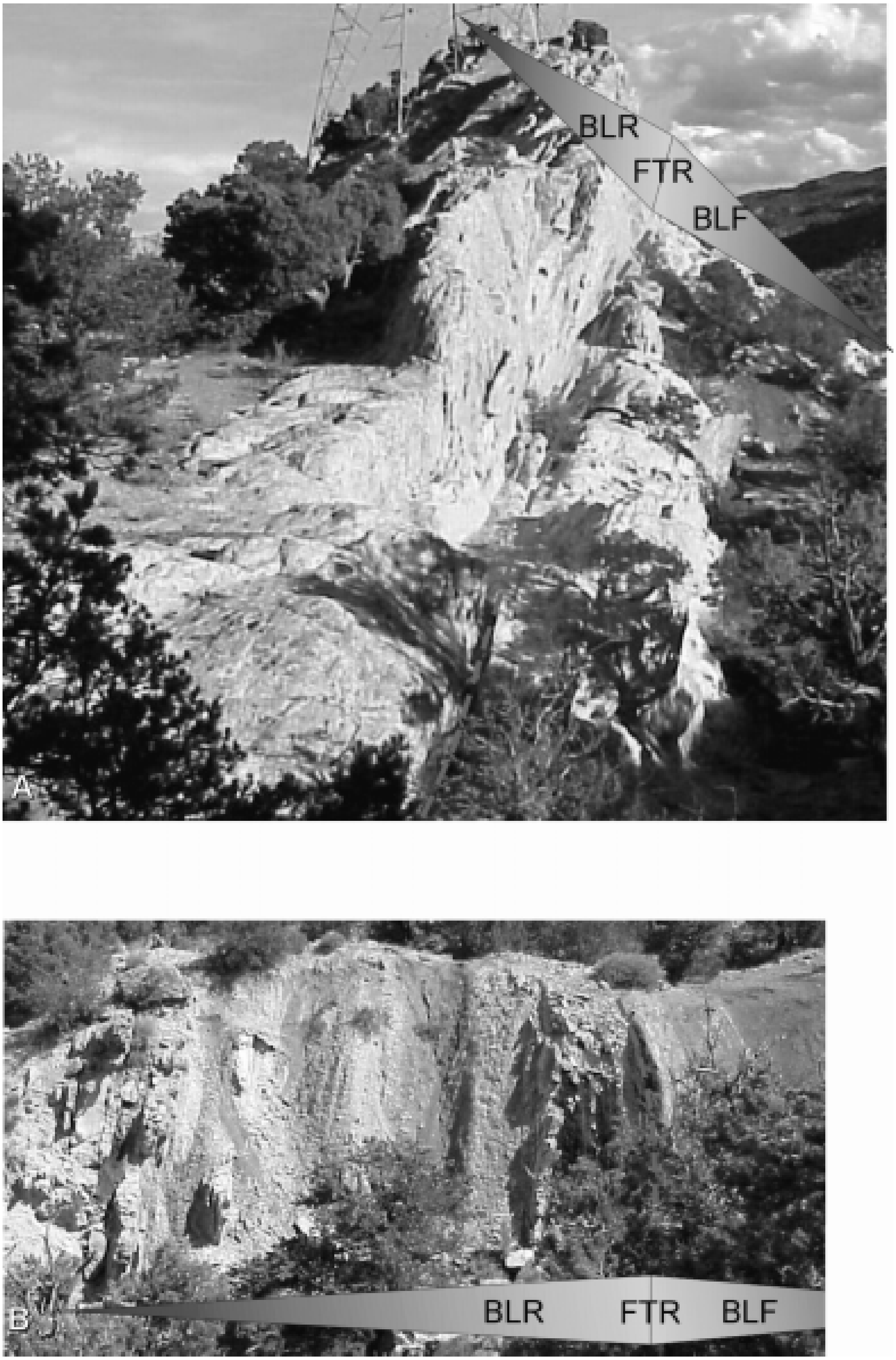


**FIGURE 27.** Large-scale turnarounds in the Toadlena area. A. Placement of FTR turnaround for large-scale cycle 1 at Toadlena section. B. Placement of FTR turnaround for large-scale cycle 1 at Toadlena section. Dashed line indicates turnaround.

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