RECOGNITION OF ANCIENT SHOREFACE DEPOSITS. FACIES, FACIES SUCESSIONS, AND ASSOCIATIONS. AN EXAMPLE FROM THE CRETACEOUS GALLUP CLASTIC WEDGE, NEW MÉXICO

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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 geométricas y faciales detalladas hechas en la Formación Gallup Sandstone permitieron aprender acerca de: (1) como un ambiente paleodepositacional de shoreface es incorporado en el registro estratigráfico, (2) como este ambiente antiguo se expresa en afloramiento, (3) la manera como el tiempo es registrado dentro del mismo y (4) las dimensiones y geometrías asociadas con el Shoreface facies tract.

Ocho facies principales fueron usadas para caracterizar una sucesión de facies típica del Shoreface facies tract. Esas facies son depositadas pendiente abajo y reflejan la coexistencia de subambientes lateralmente unidos y un tren de energía que decrece desde posiciones mas someras a las mas profundas. Esas facies son reflejadas en un perfil vertical como consecuencia de la progradación: la migración de subambientes lateralmente unidos (observados como shingles) a lo largo de un perfil depositacional (observado como clinoformas). La aplicación de observaciones realizadas por Gressly y Walther son usadas para ejemplificar la forma de identificar los depósitos de Shoreface en el registro estratigráfico y sus líneas de tiempo asociadas. La cuantificación de los atributos geométricos y dimensiónales provee información valiosa que debe ser tenida en cuenta en la caracterización el modelamiento y en la simulación de reservorios.

Palabras clave: Estratigrafía, Genética, Sedimentología, Facies, Sucesión, Asociación, Modelamiento, Simulación, Nuevo Méjico, Gallup, Shoreface, Yacimientos.

ABSTRACT

A high-resolution genetic Stratigraphic study was conducted on the four corners area, New Mexico, USA. Detailed geometric and facial observations made on the Gallup Sandstone allowed to learn about 1. how a Shoreface paleo-depositional environment is incorporated into the stratigraphic record, 2. how it looks like in outcrops, 3. the way time is recorded within it, and 4. dimensions and geometry associated with a shoreface facies tract.

Eight main facies were used to characterize a typical facies succession of the shoreface facies tract. These facies are deposited down slope and reflect coexistence of laterally linked subenvironments and an energy trend that decreases from shallow positions to the deeper ones. These facies are reflected in a vertical profile as a consequence of progradation: a lateral migration of laterally linked subenvironments (observed as shingles) along a depositional profile (observed as clinoforms). Application of seminal observations made by Gressly and Walther are used to exemplify the way of identifying shoreface deposits in the stratigraphic record and their associated time lines. Quantification of the geometric and dimensional attributes give us worthy information to be taken into account in reservoir characterization, modeling and simulation.

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

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INTRODUCTION

The Gallup clastic wedge represents a natural laboratory that allow us to study and understand basic issues about paleo-depositional environments trapped within it. FIGURES 1 and 2 show the study area and the locations of the measured stratigraphic sections.

In this study, the Gallup Sandstone is the lithostratigraphic unit of interest (FIGURE 3). This paper exemplify a meticulous way to describe and charactrize facies. It also suggest ways to deal with environmental interpretations of individual facies and facies associations. Finally, characterization of the facies tract is exemplified with outcrop pictures, diagrams, and a summary of the main observations and features.

Characterization of a Shoreface Facies Tract (S)

The shoreface facies tract is composed of the following eight muddy to upper fine sand facies: laminated mudstone (LMS), microhummocky sandstone (MHCSS), bioturbated sandstone (BSS), isolated hummocky sandstone (IHCSS), amalgamated hummocky sandstone (HCSS), swaley cross-stratified sandstone (SXS), low-angle cross-stratified sandstone (LAXSS), and burrowed or bioturbated fine sandstone (BFSS).

Laminated Mudstone Facies (LMS)

The laminated mudstone facies (LMS) consists of wavy or planar mm- to cm-scale laminated black to dark brown siltstone and mudstone. Organic matter occurs in the dark laminae (FIGURE 4). Facies LMS contains trace fossils including *Chondrites, Terebellina* and *Planolites,* as well as rare to locally common body fossils of Inoceramids and oysters. Facies LMS is occasionally interbedded with 1-2 cm thick beds of beige to dark brown or gray, lower to upper very fine, wave-rippled sandstone (FIGURE 4). Beds of facies LMS range in thickness from one to several meters and are laterally continuous over several 10s to 100s of meters.

Facies LMS occurs at the bottom of the shoreface facies succession. It is interbedded with and overlain by microhummocky sandstone facies (MHCSS). Transition to MHCSS facies occurs over a 5-10 m interval by a progressive decrease in the proportion and thickness of the LMS facies and a corresponding increase in abundance and thickness of MHCSS facies. This facies differs from overlying MHCSS facies in that sandy laminae are thin (<2 cm), isolated and constitute <<20% through a stratigraphic interval of LMS facies.

This facies weathers as blocky chips and forms small topographic promontories with smooth relief. Soils developed on this facies expand when wet.

The LMS facies is interpreted as deposits of low energy inner shelf below storm wave base because of the high organic content, wavy and planar laminae, burrows and near absence of wave-generated sedimentary structures.

Microhummocky Sandstone Facies (MHCSS)

The microhummocky sandstone (MHCSS) facies consists of interbedded black to light gray laminated mudstone and light green, lower very fine to upper fine, wave-rippled and microhummocky cross-stratified sandstone (FIGURE 5). Microhummocks consist of elliptical to circular lenses of sand 5 to 10 cm thick and decimeter scale in diameter. Low-angle laminae are concave up at the base, concordant with the basal scour surface, and convex up at the top. Wave ripples are commonly associated with microhummocks as waning flow caps (FIGURE 5). This facies progressively increases in sand content through a stratigraphic transition to overlying isolated hummocky sandstone facies (IHCSS). Beds of facies MHCSS range from a few to more than 11 m in thickness. Laterally, they extend 10s to 100s of meters (FIGURE 5).

Burrowing is conspicuous and dominated by *Chondrites, Thalassinoides, Cruziana,* and *Planolites.* Some thin intervals are bioturbated. Pelecypods occur occasionally in this facies.

This facies occurs above laminated mudstone facies (LMS), and is interbedded with bioturbated sandstone facies (BSS); It is always below IHCSS facies.

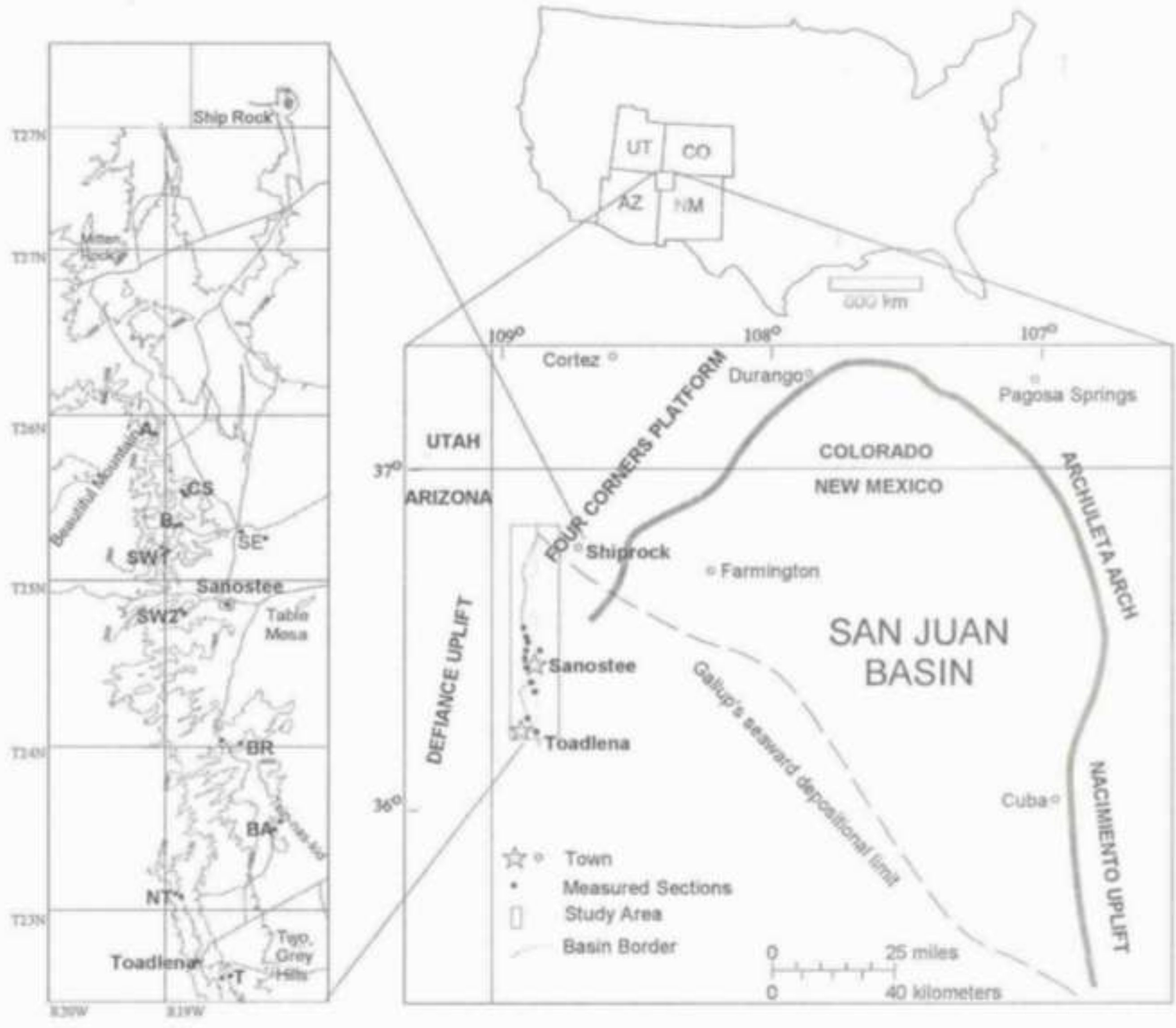

FIGURE 1. Location of the San Juan basin and the study area.

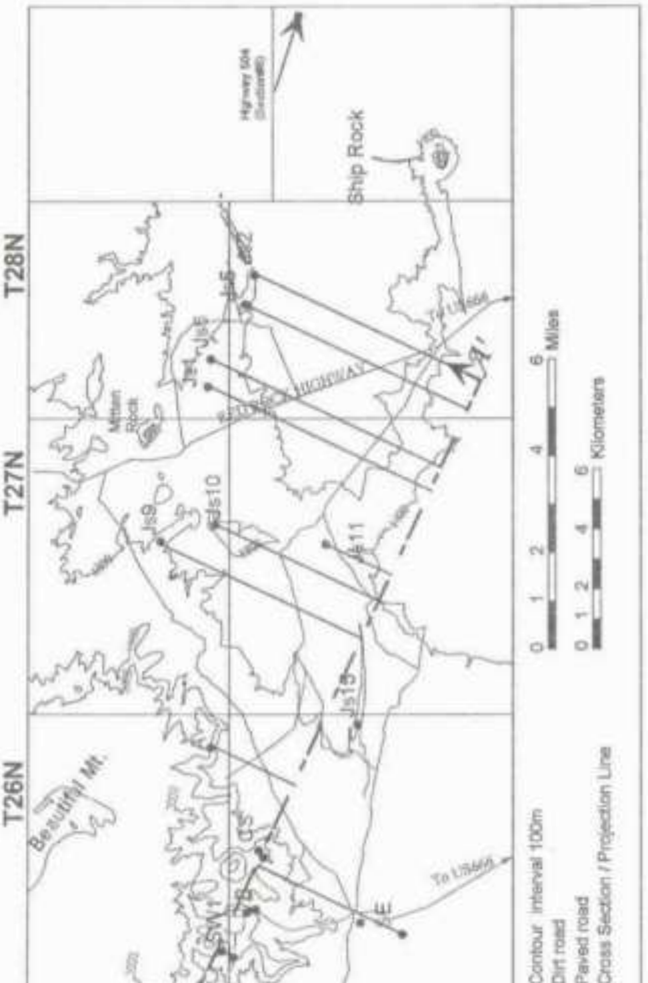

FIGURE 2. Location of measured sections in the study area.

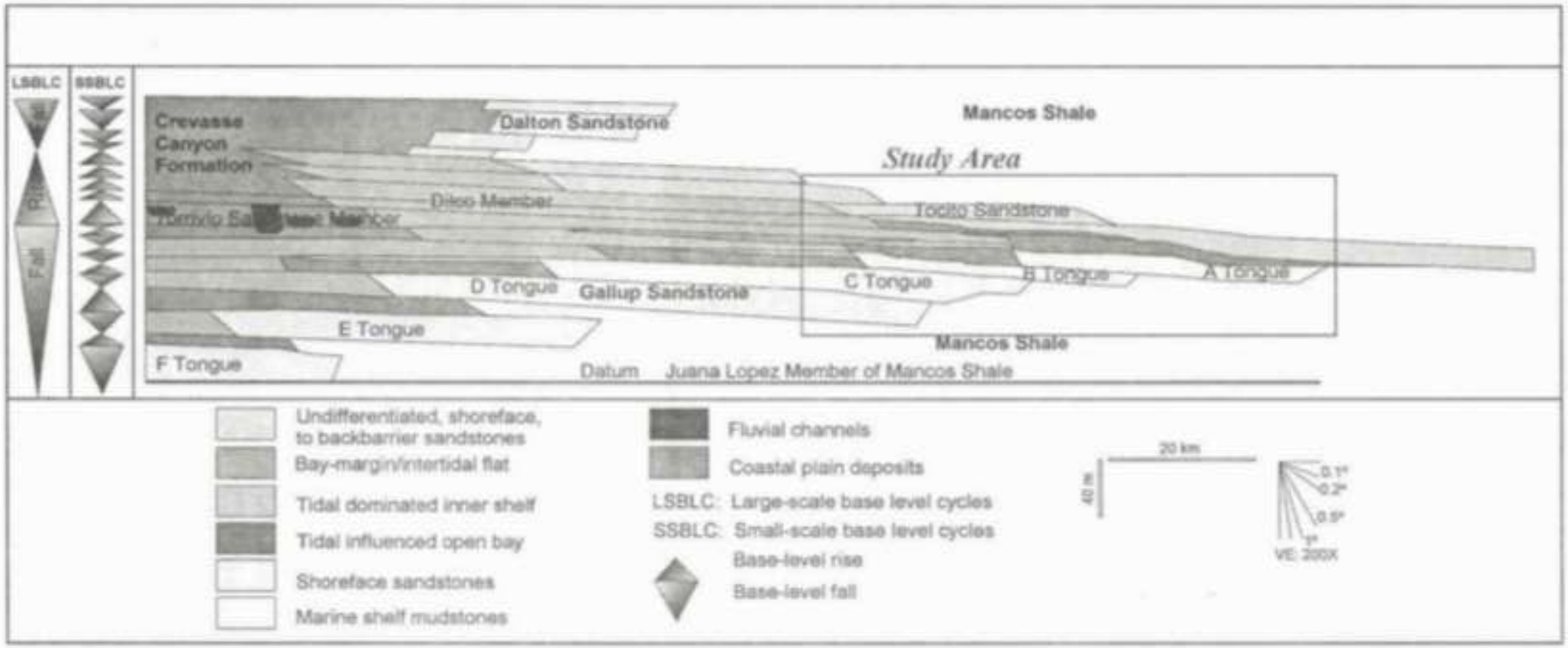

FIGURE 3. Schematic lithostratigraphic cross section of the Gallup Sandstone and genetically associated units showing interfingering relationships. In this study Dilco and Torrivio are considered members of the Crevasse Canyon Formation.

Contacts with overlying IHCSS facies are either sharp (irregular or scooped) or gradational. Gradational contacts consist of a transition zone typically 1 to 2 m thick from MHCSS facies to interbedded MHCSS and IHCSS facies, to just IHCSS facies (FIGURES 5 and 7). Contacts with underlying LMS facies and bioturbated sandstones (BSS) are transitional and sharp, respectively (FIGURE 5). Contacts with overlying amalgamated hummocky sandstone facies (HCSS) are sharp and irregular (FIGURE 5). This facies forms gentle slopes to steeper, resistant cliffs.

MHCSS facies contains sedimentary structures formed by weak wave action (i.e., wave ripples and microhummocks). During deposition, sediment is brought in as small gravity flows or resuspended locally from the seafloor. It is then reworked by storms waves to form wave ripples and microhummocks. MHCSS facies are interpreted as sediments deposited on the inner shelf or in the lower shoreface below fair-weather wave base but deep within storm wave base. This facies may represent a transitional zone between the shelf and lower shoreface).

Bioturbated Sandstone Facies (BSS)

The bioturbated sandstone facies (BSS) consists of gray to beige, lower very fine to lower fine sandstone (FIGURE 6). Carbonaceous debris occurs either disseminated or as wavy discontinuous laminae. This facies is usually bioturbated but sometimes only heavily burrowed. At the top of a succession of beds of this facies, more organic rich, faint laminae and burrows are observed.

Facies BSS occurs in beds 0.5 m to 10 m thick that extend 10s to 100s of meters This facies is poorly exposed in outcrop.

Facies BSS is usually interbedded with the microhummocky sandstone facies (MHCSS) and it is always above facies LMS. This facies differs from other sandy facies by lacking wave-generated sedimentary structures and mudstones. This facies outcrops as fairly resistant promontories between MHCSS facies. The BSS facies is interpreted as to represent lower shoreface toes.

Isolated Hummocky Sandstone Facies (IHCSS)

The isolated hummocky sandstone facies (IHCSS) consists of light green to beige, upper very fine to upper fine sandstone. Isolated to slightly amalgamated hummocky cross-stratified sandstones alternate with mud-rich, wave-rippled microhummocky sandstone facies (MHCSS) (FIGURE 7).

Hummocks consist of meter-scale concave-up scours draped with sand laminae that are concave-up and concordant with the scour, flat in the middle and convex-up at the top This facies contains 3 to 5% clay. Locally, hummocky beds have conspicuous fine laminae enriched with dark flaky material (e.g., carbonaceous detritus and biotite). Towards the top of a bed, the proportion of organic material decreases, and hummocky beds become thinner as the hummocks begin to amalgamate. Beds of facies IHCSS range from 10 cm to more than 50 cm thick. Although beds of this facies can be followed for 10s to 100s of meters, they are usually discontinuous and grade landward into HCSS facies.

Traces fossils are predominantly *Ophiomorpha*, *Thalassinoides* and *Planolites*. Body fossils such as *Inoceramids* are rare.

Contact with overlying amalgamated hummocky sandstone facies (HCSS) is gradational over a couple of meters. Isolated hummocky beds become more amalgamated and laterally more continuous in their transition to HCSS facies. Contacts with underlying facies MHCSS are transitional over a distance of 1-2 m. The gradational contact between IHCSS and HCSS facies is topographically expressed as sharp, heterolithic, resistant cliffs.

IHCSS facies contains sedimentary structures formed by waves. IHCSS facies is interpreted as deposited on the lower shoreface beyond the breaker zone below fair-weather wave base but within storm wave base. Interbedding of hummocky beds and mud-rich beds suggest an alternation of stormy weather sedimentation and fairweather sedimentation. Heavily burrowed sandstones are interpreted as the biologic reworking of the sediment between storms.

FIGURE 4. Laminated mudstone facies (LMS). Black to dark brown finely laminated organic-rich mudstone. Laminae are 1 - 2 cm thick weather as flakes or blocks. Folding ruler segment is 21.7 cm. Location: Breached Anticline section.

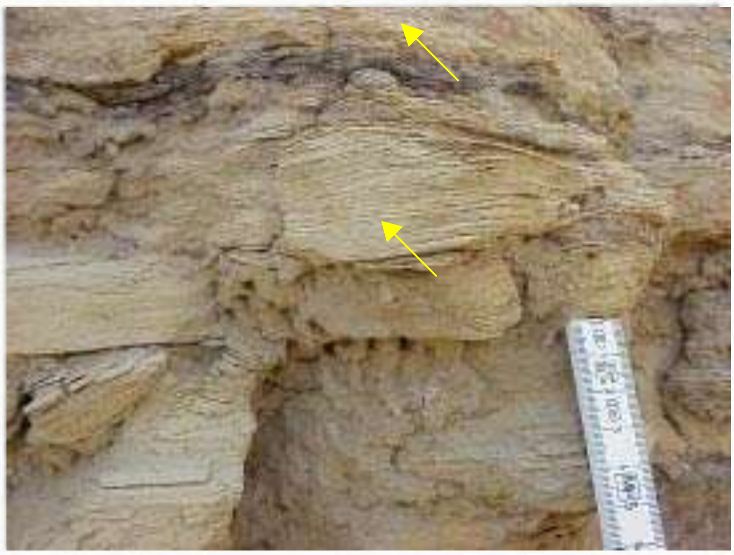

FIGURE 5. Microhummocky sandstone facies (MHCSS). Yellow arrows indicate interbedding of beige lower very fine to lower fine microhummocky and wave-rippled sandstone (laminae 1- 5 cm) within mudstone. Folding ruler is 2m. Location: Beautiful Mountain section.

FIGURE 6. Bioturbated sandstone Facies (BSS). Beige lower very fine to lower fine sandstone. Internally, structureless, organic-rich, wavy discontinuous laminae. It can be heavily burrowed or structureless. Folding ruler segments are 21.7 cm. Location: Big Reentrant section.

Amalgamated Hummocky Sandstone Facies (HCSS)

The amalgamated hummocky sandstone facies consists of light green to beige, upper very fine to upper fine sandstone. This facies contains concretions and interstitial clay (FIGURE 8). Amalgamated hummocks are formed by cannibalization of hummocks by subsequent storms. The convex-up tops of some older hummocks are partially or totally removed, and replaced by another convex-down scour. The degree of preservation of hummocks changes stratigraphically through the shoreface: scoop curvature increases (from isolated hummocks to swales), set thickness decreases from 50 cm to 30-20 cm, the degree of amalgamation increases, and beds thicken and become more homogeneous. Bedsets of this facies are up to 5 m thick on average. This facies can be followed laterally for 100s of meters.

Hummocky beds occur in slightly inclined lenticular sand bodies called shingles or clinothems between clinoforms, which are depositional surfaces with slopes of 0.01-0.1 degrees. When progradation of a shingle temporally stops, due either to insufficient sediment supply, to a pause between storms, or to a high-frequency base-level-rise hemicycle, it forms a stratigraphic surface called a shingle break. Shingles breaks are topographically expressed as recessive intervals (<1 m thick) within thicker beds of amalgamated hummocky sandstone. Finely laminated mud-rich amalgamated hummocks below the shingle break pass into isolated and mud-rich microhummocks cap ped by wave ripples within the recessive interval. Traces fossils are predominantly *Ophiomorpha*, *Thalassinoides* and *Planolites*. Body fossils, such as *Inoceramids*, occur locally.

This facies overlies isolated hummocky facies (IHCS) or microhummocky sandstone facies (MHCSS), and underlies swaley cross-stratified sandstone facies (SXS) or planar- low-angle stratified sandstone facies (LAXSS). Contacts with underlying IHCSS facies and with overlying SXS facies are usually transitional over 2 to 3 meters. This facies forms blocky, steep, resistant cliffs.

Facies HCSS is interpreted as being deposited near fair-weather wave base, under turbulent and combined flow conditions during storms. This is typical of middle to lower shoreface environments.

Swaley Cross-Stratified Sandstone Facies (SXS)

The swaley cross-stratified sandstone facies (SXS) consists of light green to beige, lower to upper fine sandstone. Swales consist of concave-up to horizontal laminae that concordantly fill meter-scale concave-up scour bases. Lamination curvature decreases from the scour surface to horizontal, just like the lower part of hummocks (FIGURE 9). Amalgamated hummocks progressively change to swales as amalgamation increases upwards. Swales are cannibalized HCS where only convex-up laminae are preserved. Bed thickness is commonly 20-50 cm to meter scale. This facies is continuous laterally for 10s to 100s of meters. *Ophiomorpha* and *Skolithos* are common near the base of this facies.

Facies SXS usually overlies hummocky cross-stratified sandstone facies (HCSS) or burrowed fine sandstone facies (BFSS), and underlies low-angle laminated sandstone facies (LAXSS). Contacts with underlying HCSS facies and BFSS facies are sharp. Contacts with overlying LAXSS facies are sharp and sometimes irregular. This facies forms steep, resistant cliffs.

Swaley cross-stratified sandstone is indicative of upper shoreface environments. This facies is interpreted as having been formed in the surf zone under turbulent, combined flow conditions.

Low-Angle Stratified Sandstone Facies (LAXSS)

The low-angle stratified sandstone facies (LAXSS) consists of light green to beige, upper very fine to upper fine sandstone. Laminae are planar parallel, dipping sub- horizontally at very low angles (0° to 5°). Laminae contain little interstitial clay, may be oxidized and may be burrowed (FIGURE 10). Laminae are usually 0.5 to 6 cm thick. Beds of facies LAXSS range from decimeter to meter scale, and are laterally continuous over 10s to 100s of meters. Trace fossils are dominated by *Skolithos* and *Ophiomorpha*. Body fossils (i.e., *Inoceramids* and small pelecypods) are rare.

FIGURE 7. Isolated hummocky sandstone facies (IHCSS). Isolated to slightly amalgamated hummocky cross-bedded sandstones. Folding ruler is 1.8m. Location: Sanostee West 1 section.

FIGURE 8. Amalgamated hummocky cross-stratified sandstone facies (HCSS). Folding ruler is 1.2m. Location: Cone Shape section.

FIGURE 9. Swaley cross-stratified sandstone facies (SXS). Beds are approximately 1m . Location: Breached Anticline section.

FIGURE 10. Low-angle cross-stratified sandstone facies (LAXSS). Observe faint lamination obscured by burrowing or weathering. Folding ruler is 1m. Location: Amphitheater section.

FIGURE 11. Burrowed to bioturbated fine sandstone facies (BFSS). Folding ruler is 1 m. Location: Cone Shape section.

Facies LAXSS usually overlies swaley cross-stratified sandstone facies (SXS) at the top of the shoreface facies succession. It may be interbedded with the burrowed to bioturbated fine sandstone facies (BFSS). It underlies burrowed and low-angle cross-bedded sandstone facies (BLAXBT) and BFSS facies. It can be partially or totally replaced by overlying coarser facies. Contacts with underlying and overlying facies are sharp and usually irregular.

LAXSS facies are interpreted as high-energy environments characteristic of the beach or swash zone.

Burrowed to Bioturbated Fine Sandstone Facies (BFSS)

The burrowed to bioturbated fine sandstone facies consists of light green, lower to upper fine sandstone. Relict plane parallel to slightly wavy lamination is occasionally visible through the bioturbation. Laminae are finely oxidized and rich in green clay matrix. The green clay is usually associated with carbonaceous detritus (FIGURE 11). Beds of this facies are 0.3 m to 1 m thick, and are laterally continuous over 10s to 100s of meters.

This facies occurs below HCSS and SXS facies. Contacts with these facies are sharp, irregular and oxidized (FIGURE 11). Topographically, this facies is expressed as light colored recessive intervals due the clay matrix.

Facies BFSS is interpreted as being generated by burrowing of hummocky or low-angle laminated sandstones. Bioturbated beds represent biologic reworking between storms.

SUMMARY

An association of wave ripples, furrows and microhummocks encased in laminated mudstone characterize the lower part of this facies tract. The association of laminated mudstone facies (LMS), microhummocky sandstone facies (MHCSS) and bioturbated sandstone facies (BSS) suggests deposition below fair-weather wave base but within, and sometimes below, storm wave base (FIGURE 12). This facies association is interpreted as the transition from lower shoreface to inner shelf.

The upper part of this facies tract has a vertical facies succession from isolated hummocky (IHCS) to amalgamated hummocky (HCS) to swaley (SXS) to low-angle stratified (LAXSS) facies. The association of IHCS and HCS suggests deposition beyond the breaker zone and near fair-weather wave base, under turbulent and combined flow conditions during storms (FIGURE 12). This is interpreted as the lower shoreface. The association of SXS and LAXSS facies suggests deposition in the surf zone under turbulent, combined flow conditions and beach or swash zone, respectively. These are interpreted as upper shoreface and foreshore. Strata are more amalgamated and laterally more continuous, and thickness of laminaesets decreases upwards. In general, these vertical successions are characterized by progressively higher sand/shale ratios. FIGURE 13 summarizes main features observed and quantified for the shorefaceies tract.

Shoreface Association and Succession

Shoreface units are 8-14 m thick and extend in dip direction 40-43 km. In this study, shorefaces change up depositional dip (SW) into heterolithic successions of the bay-margin/intertidal flat facies tract, and down depositional dip (NE) into inner shelf mudstones. Cycle conventions is explined by FIGURE 14.

From base to top of a shoreface, facies successions are as follows (FIGURE 15): microhummocky sandstone facies (MHCSS); interbedded bioturbated sandstone facies (IBSS); isolated hummocky sandstone facies (IHCSS); amalgamated hummocky sandstone facies (HCSS); swaley cross-stratified sandstone facies (SXS); and, low angle stratified sandstone facies (LAXSS). This is the same succession that can be mapped along a single bed or clinoforms. Heavily burrowed or bioturbated fine sandstone (BFSS) can be interbedded with any of the cross-bedded facies.

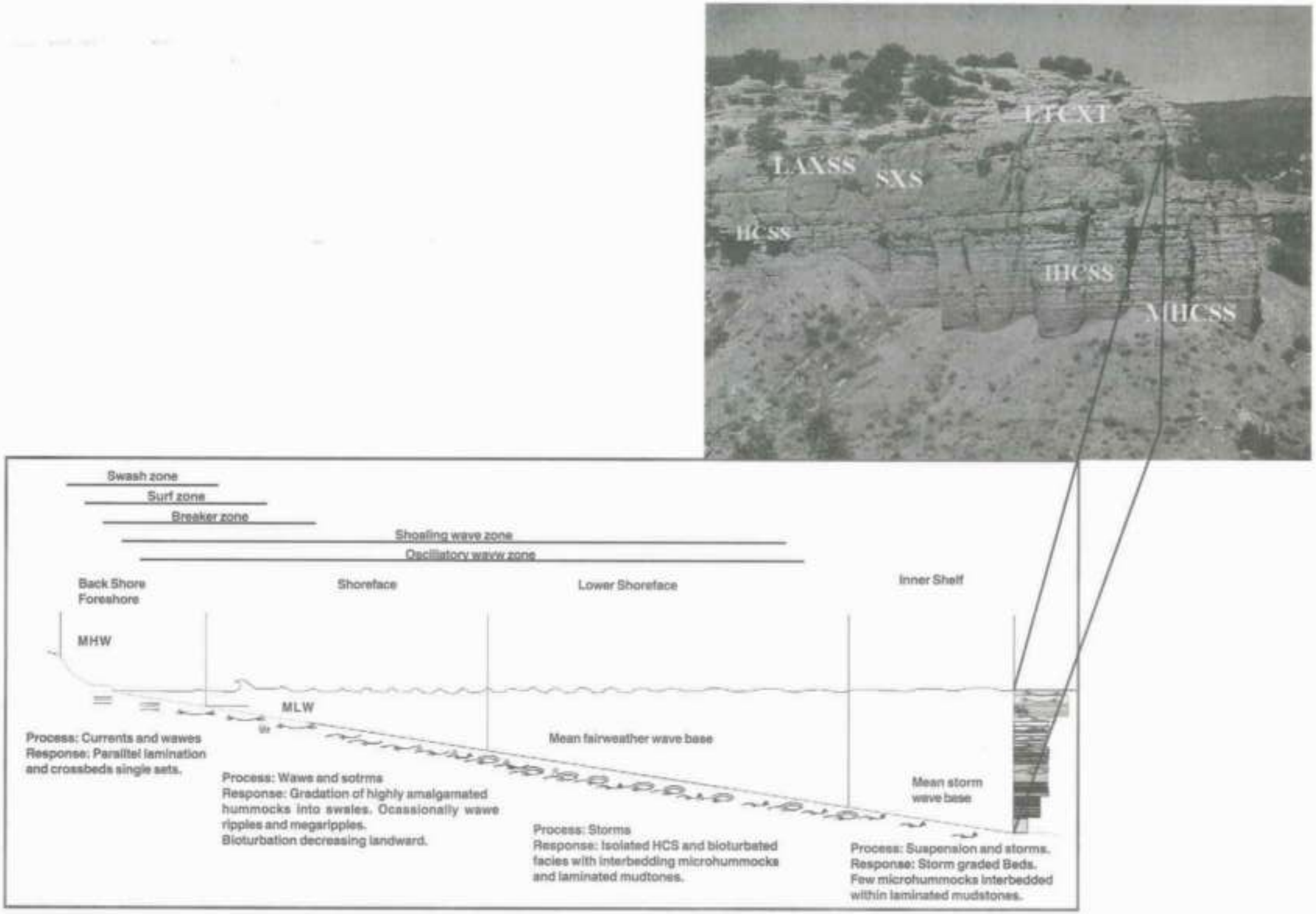

FIGURE 12. Generalized shoreface depositional profile showing environments, processes, and facies (Modified from Elliot, 1986). Observe the cliff-forming character of facies succession from MHCSS facies to LAXSS facies and the resulting transitional change from one facies to another. Location: Beautiful Mountain section.

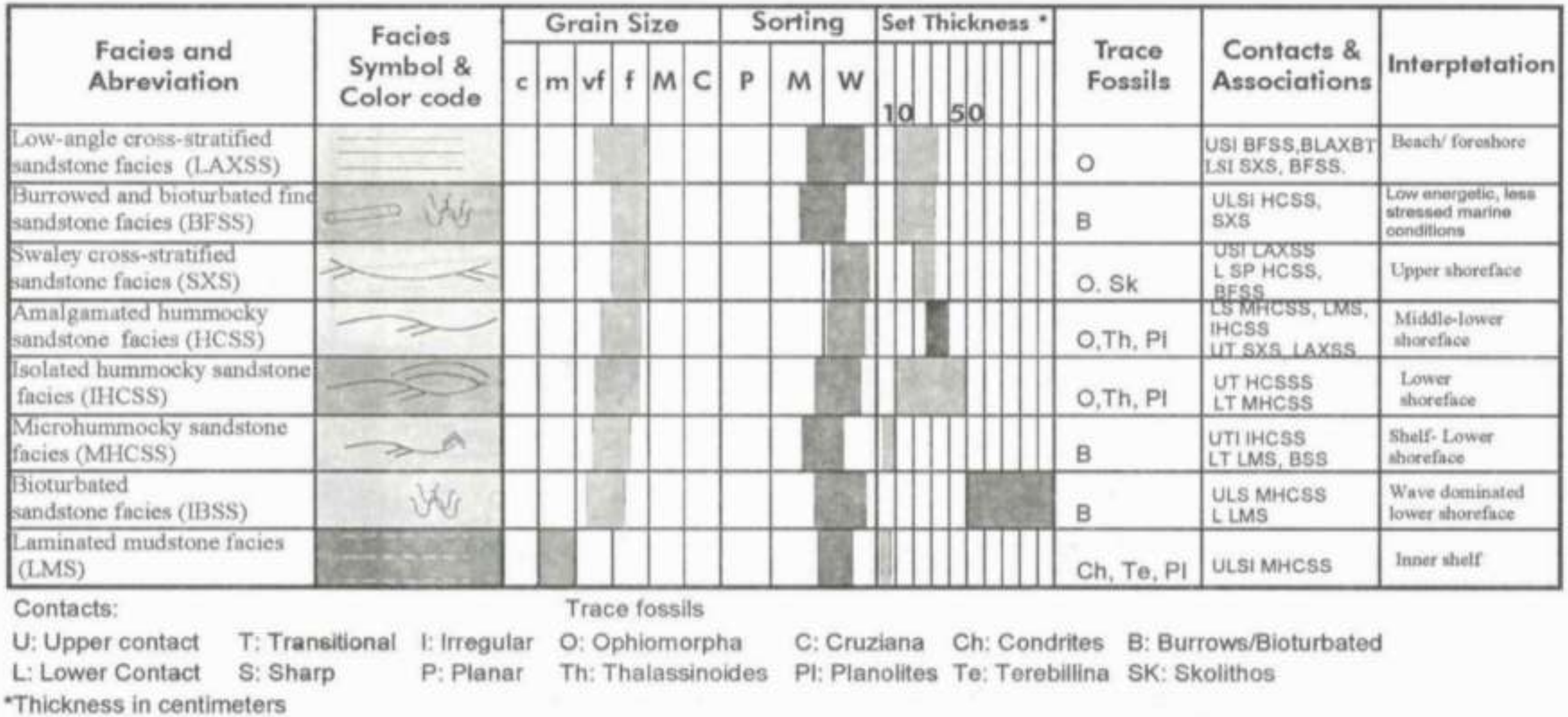

FIGURE 13. Summary of characteristics of facies in the shoreface facies tract

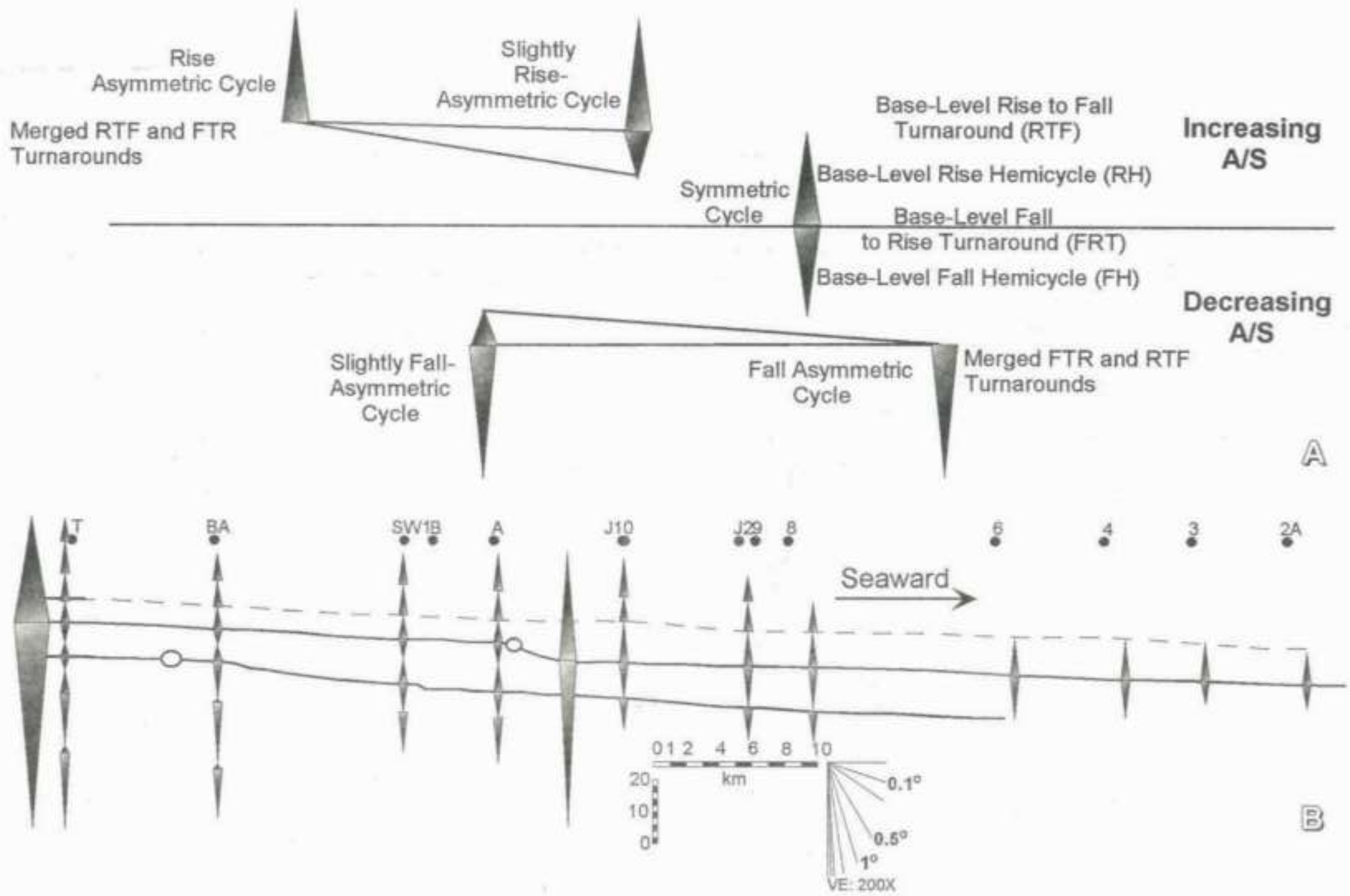

FIGURE 14. Cycle definition using triangle symbols. Changing conditions of A/S accompanying base-level cycles are indicated by triangles. A. Explanation of triangle notation. B. Example of symmety changes in intermediate-scale cycles along depositional profile (i.e. cycle along lower red line).

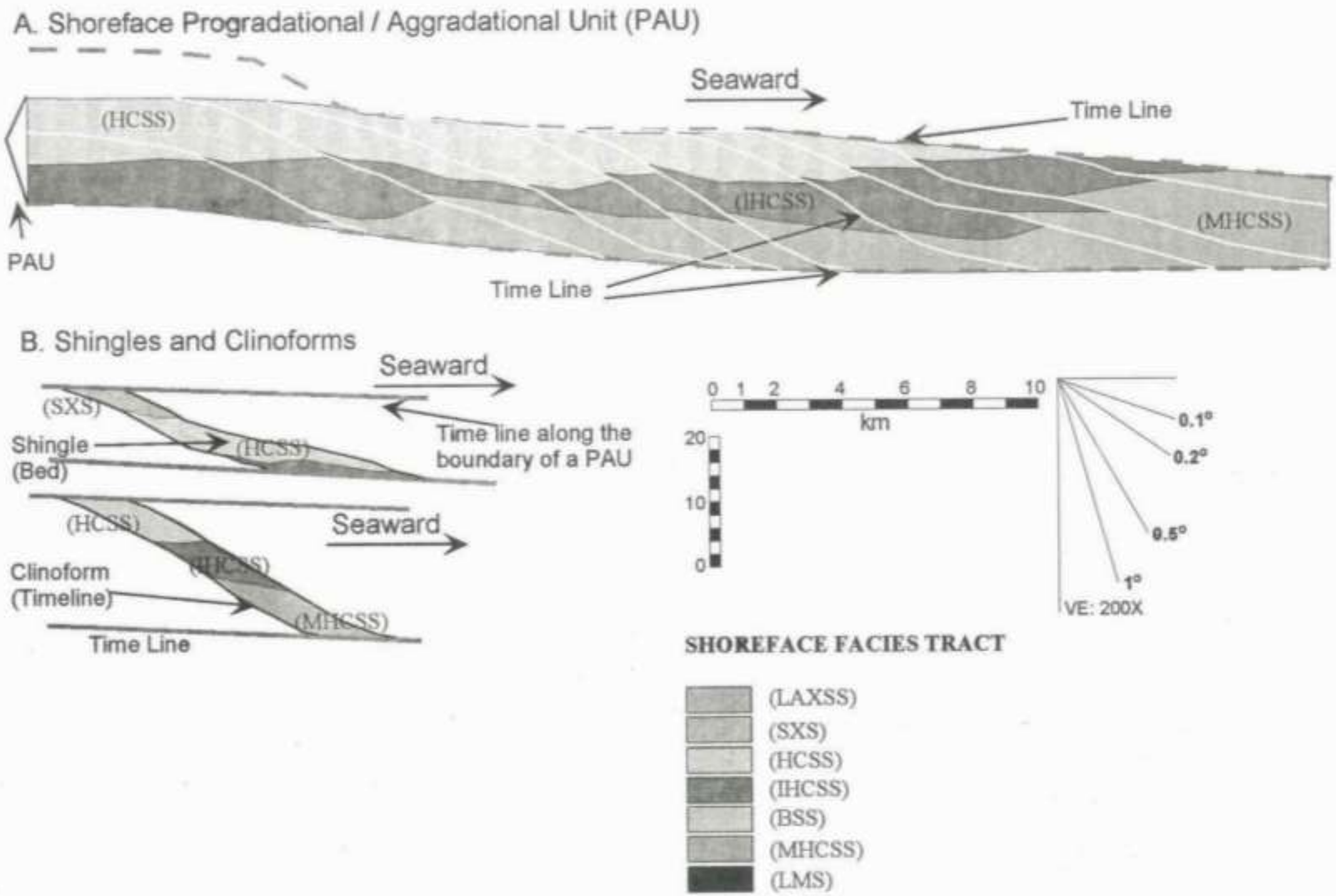

FIGURE 15. Stratigraphic dip cross-section showing lateral facies associations within shingles and progradational/aggradational units (PAU) composing the shoreface facies tract. A. Facies change laterally (from shingle's toes to top) from deeper to shallower facies. In each PAU, the proportion of deeper facies decreases landward. B. Observe dimensions, timelines (red and green lines), angles and nomenclature for shingles.

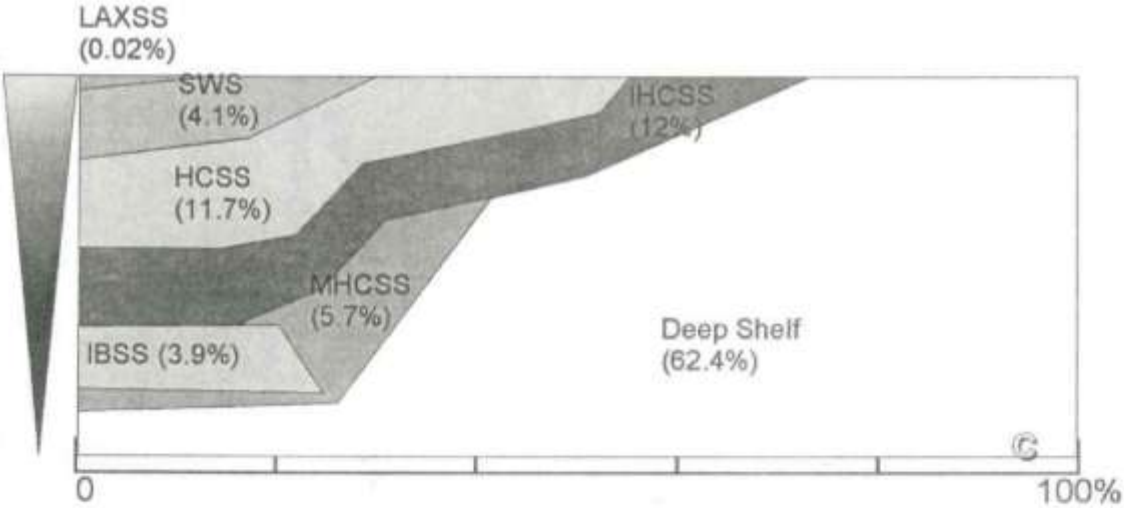

FIGURE 16. Facies succession and substitution diagram within the shoreface facies tract.

A shoreface unit is composed of a series of shingles. Shingles are composed of several beds that shoal upward and which are time-significant at a small scale. Mapping clinoforms within shorefaces demonstrates how shoreface units prograded. Clinoforms were mapped by identifying shingles and shingle breaks (i.e., time lines in FIGURE 15 A) and tracing them between sections (FIGURE 15). Within shoreface units there is a progressive seaward shift between successively deposited shingles. Shingles extend laterally 9-22 km, and the inclination of clinoforms ranges from 0.2° to 0.1°.

FIGURE 15 is a stratigraphic dip cross section showing lateral facies transitions within a shoreface and component shingles. Shingles and shoreface units change landward from deeper to shallower facies (FIGURE 15).

Lower and upper boundaries of a shoreface unit represent time lines where two or more shoreface units are superposed without intervening facies.

Lateral changes of facies along shingles are evident on a kilometer scale, although locally clear lateral changes can be observed within 100s of meters. Lateral facies changes within shoreface units are observable on a kilometer scale and are even more evident on a scale of 10s of kilometers. Lateral facies transitions within shorefaces are indicated by shazams. Shazams are characterized by cutting time lines and run diagonally across shoreface units (FIGURE 15).

FIGURE 16 is a facies succession and substitution diagram that allow to quantify and visualize how one facies is replaced by another downdip and the preferential location of facies according to Stratigraphic position within the shoreface facies tract. Measured sections though the shoreface facies tract display a shallowing upward facies succession motif containing the five facies previously described (FIGURES 17 and 18). FIGURE 17 shows a general view of the basal portion of the motif at Big Reentrant section. The basal portion is typically found at the toes of distal shingles and has a serrated, blocky GR signature. Sometimes, the top of these signatures has high GR values and shape resembling a rise cap. FIGURES 18 A to G show details of facies in the upper portion of the facies succession motif. FIGURE 18 A shows a general view of this motif at the Breached Anticline section. The upper portion of the facies succession motif usually shows a shallowing up, funnel GR signature. This GR signature can be observed at scales of shoreface units and shingles, and is used along with facies for defining intermediate and small-scale base-level hemicycles, respectively. FIGURE 18 shows stratigraphic variations of this motif.

Patterns in vertical successions correspond to progradation of shingles, the progradation of the shoreface within a single genetic sequence, and the stacking pattern and consequent facies tract offsets from one genetic unit to the next.

In the shoreface facies tract substitutions between LAXSS and SWS, SWS and HCSS, HCSS and IHCSS, and IHCSS and MHCSS are common. Substitution of IBSS and MHCSS is less commonly observed but very likely exists preferentially at seaward depositional limits of shoreface units.

CONCLUSION

This paper exemplify key aspects to be used by geologist in the recognition of ancient shoreface deposits. Geometries and quantitative data should be taken into account and incorporated in reservoir modeling and characterization. Meticulous work and key observations in outcropt and cores and their association with well log respond will ensure robustness on the proposed stratigraphic architectural models. This will result in risk reduction and ultimately in saving money in oil and gas exploration and development projects.

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