GEOLOGIC NOTE

Site-specific sequence-stratigraphic section benchmark charts are key to regional chronostratigraphic systems tract analysis in growth-faulted basins

L. Frank Brown Jr., Robert G. Loucks, and Ramón H. Treviño

ABSTRACT

Subbasins composing a larger basin can have similar appearing sediment fills that are diachronous. It is important to construct a chronostratigraphic section for each subbasin to correctly correlate between subbasins. A methodology is presented that incorporates the sequence-stratigraphic interpretation of each subbasin, which improves correlation of systems tracts between adjacent and widely separated subbasins. The growth-faulted subbasins in the Corpus Christi Bay area along the western margin of the Gulf of Mexico are used to demonstrate this methodology.

A composite wire-line log created by splicing unfaulted and relatively conformable log segments from the deepest wells in an area provides a stratigraphic record that captures a complete succession of depositional and cyclic history. Site-specific sequence-stratigraphic section (S^5) benchmark charts are composite logs containing additional data that summarize available geologic information for a subbasin, site-specific area. Color-coded sequences and component systems tracts are basic information displayed on S^5 benchmark charts. This physical framework can then be calibrated with ages (Ma) of sequences and bounding surfaces. Ages are based on geologic time charts representing latest consensus from isotopic, polarity, and microfossil integration. Sequence-bounding unconformities and internal maximum flooding surfaces delineated on S^5 benchmark charts, when correlated with other wire-line logs and placed into the seismic time domain, produce a chronostratigraphic

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framework for an area. Comparison of S^5 benchmark charts among adjacent, widely spaced, or isolated sites facilitates correlation of diachronous lithostratigraphic units.

INTRODUCTION

Many published examples of the value of sequence stratigraphy have documented its validity; nevertheless, full appreciation of the scope and value of the routine application of sequence stratigraphy is still evolving. In this article, we highlight a subsurface, sequence-stratigraphic methodology for describing subbasins, which has emerged from several decades of interpreting and constructing chronostratigraphic and depositional systems frameworks for use in applied and basic research.

A key stratigraphic methodology or product that has evolved from our studies is a composite wire-line log that places the lithofacies into a chronostratigraphic sequence framework for the specific subbasin or site under investigation. Known as a site-specific sequence-stratigraphic section benchmark chart, or S^5 benchmark chart (Figures 1, 2), it is a valuable tool for integrating all available stratigraphic information in a specific area or subbasin (Brown et al., 2004). For example, lithofacies, sequences, systems tracts, stratigraphic surfaces, relative sea level cycles, biozones, petrophysical properties, and age data can be placed in chronostratigraphic context and correlated basinwide. Site-specific sequence-stratigraphic section benchmark charts are based on composites of wire-line-log sections of several key wells spliced to display the most complete stratigraphic succession. Consequently, the S^5 benchmark chart captures the record of maximum depositional history and cyclicity recorded in the rocks of a particular basin or subbasin.

Site-specific sequence-stratigraphic section benchmark charts do not represent a major advance in stratigraphic interpretation. The charts do, however, offer a method of integrating different kinds of basin information within a lithogenetic and chronostratigraphic framework. Consequently, preparation of such charts requires a thorough analysis of sequences, systems tracts, depositional systems, and their application in preparing sequential paleogeographic time slices, with or without complementary seismic information. Reference to an S^5 benchmark chart permits selection of key surfaces and stratigraphic intervals, which leads to more precise mapping and reconstruction of (lithogenetic) depositional systems and structural history. With the use of an S^5 benchmark chart, any data set (e.g., the parameters of a hydrocarbon system) can be extrapolated throughout a basin in a precise time-stratigraphic context. Finally, cycles, systems tracts, unconformities, and maximum flooding surfaces composing a stratigraphic succession can be readily correlated in geologic time with those of other areas. We have been able to successfully use these charts to demonstrate the diachronous nature of lowstand systems tracts in a series of growth-faulted subbasins in the Corpus Christi Bay area along the northwestern margin of the Gulf of Mexico.

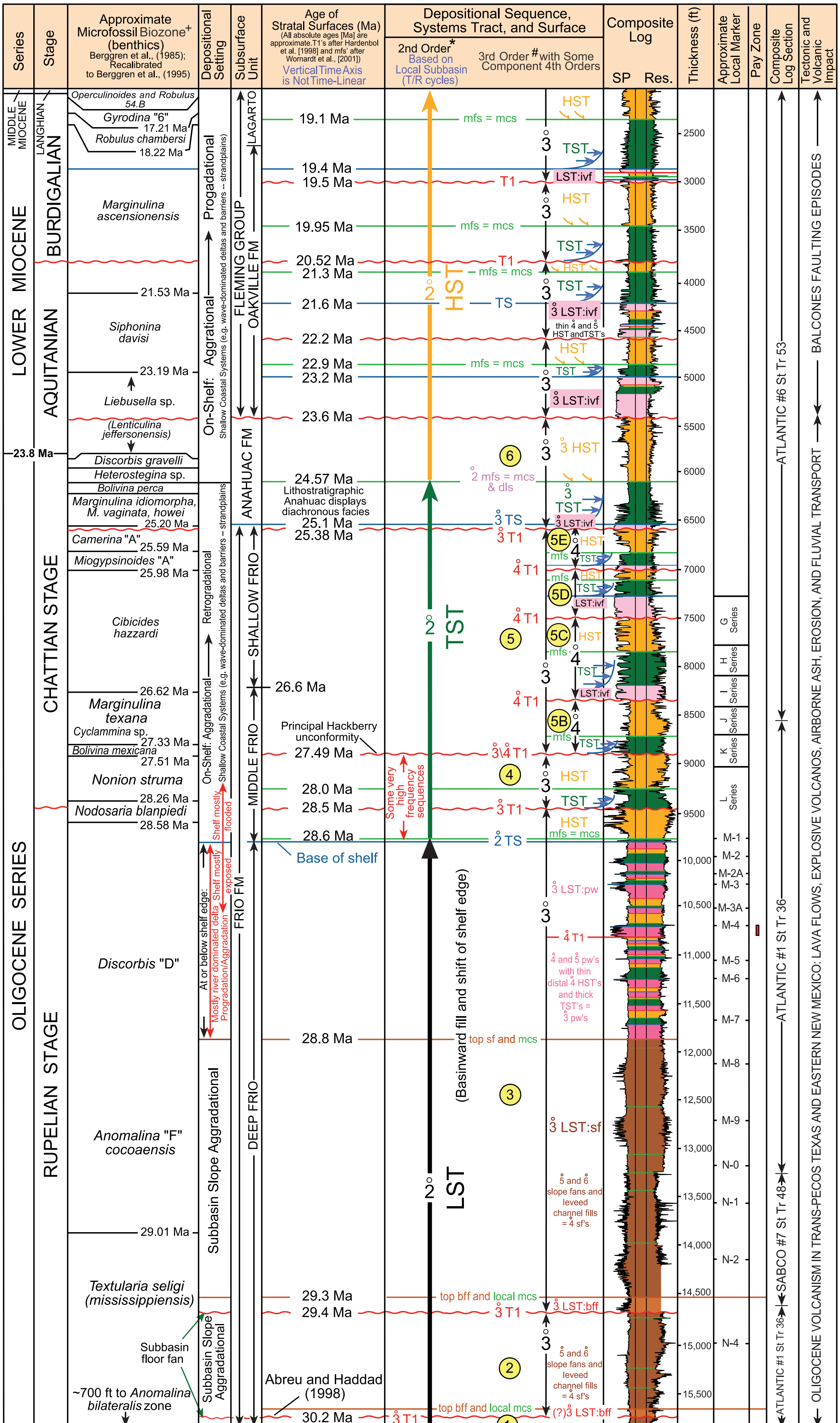

Figure 1. S[5] benchmark chart, Encinal Channel subbasin, Corpus Christi Bay, Texas. Six third-order sequences compose the Oligocene Frio and Anahuac formations. Sequence 5 comprises four fourth-order sequences (5B–5E) in this region (modified from Brown et al., 2004). Sequence 5A (LST) exists only in subbasin 5. See Figure 4 for location of subbasins, and see Figure 2 for legend.

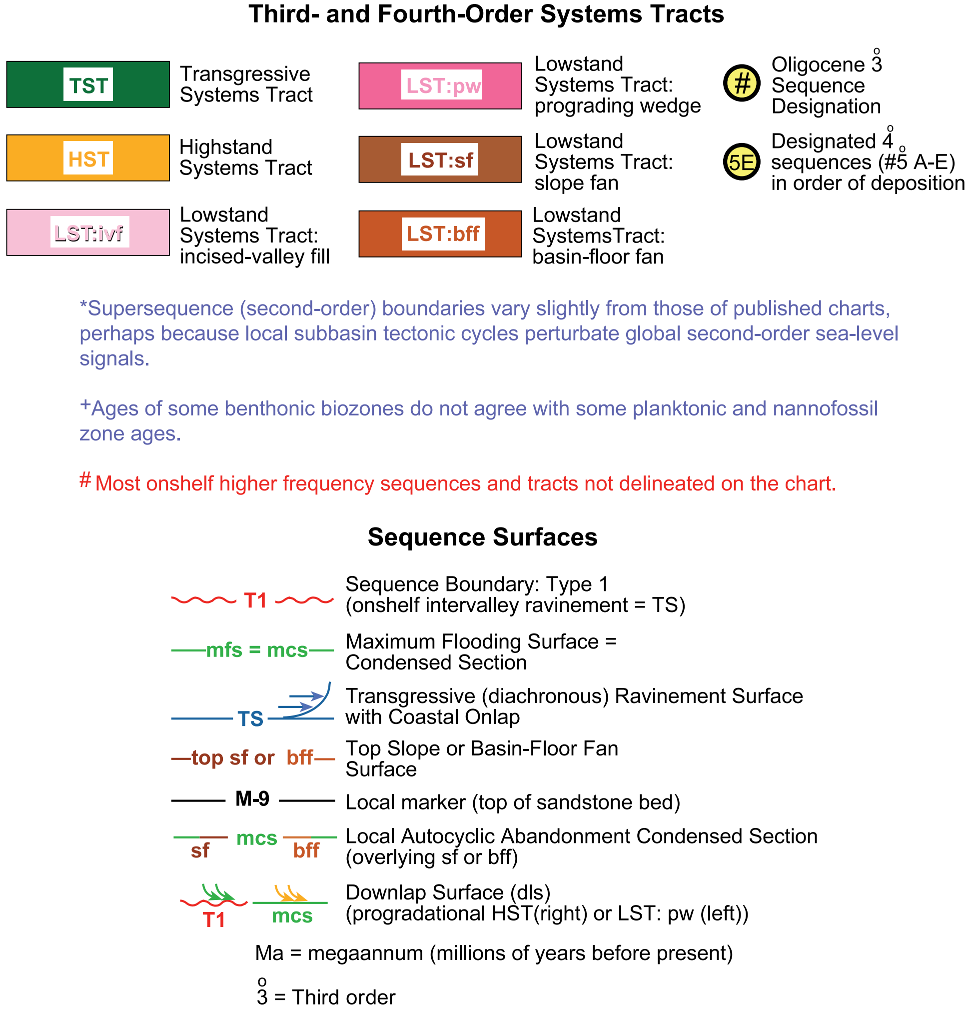

Figure 2. Legend for S^5 benchmark charts and sequence-stratigraphic, wire-line-log cross sections.

CONSTRUCTION OF S^5 BENCHMARK CHARTS

For decades, geologists have created composite wire-line logs during conventional subsurface studies. Such logs have been used primarily to depict sections missing by normal faulting. Other so-called type logs have been designated for many subbasins and petroleum-field areas because the well in question penetrated what was considered a typical stratigraphic succession. Using the compositing technique, as presented in this article, to display and interpret the sequence stratigraphy of a basin or subbasin, however, significantly extends the application of composite wire-line logs.

This increased value derives primarily from the many advantages of applying sequence stratigraphy. For example, sequence-bounding unconformities and internal maximum flooding surfaces of various frequencies are sequence-stratigraphic surfaces (Vail et al., 1977). Except for diachronous ravinement surfaces at the base of transgressive systems tracts, highstand and lowstand tracts are bounded by chronostratigraphic unconformities and maximum flooding surfaces. Although systems tracts internally comprise diachronous lithostratigraphic successions (i.e., facies tracts), they can link depositional processes and systems to cycles of relative sea level change. The chronostratigraphic nature of sequence-bounding surfaces and systems-tract stacking patterns can thus be used to correlate across widely separated areas.

Introduction to Sequence-Stratigraphic Wire-Line-Log Analysis

Sequence-stratigraphic analysis of wire-line logs has been discussed and demonstrated by several geologists. For example, Van Wagoner et al. (1990) provided an outstanding source of information for those unacquainted with such interpretations. Inferred mechanisms and processes related to cyclic stratigraphy

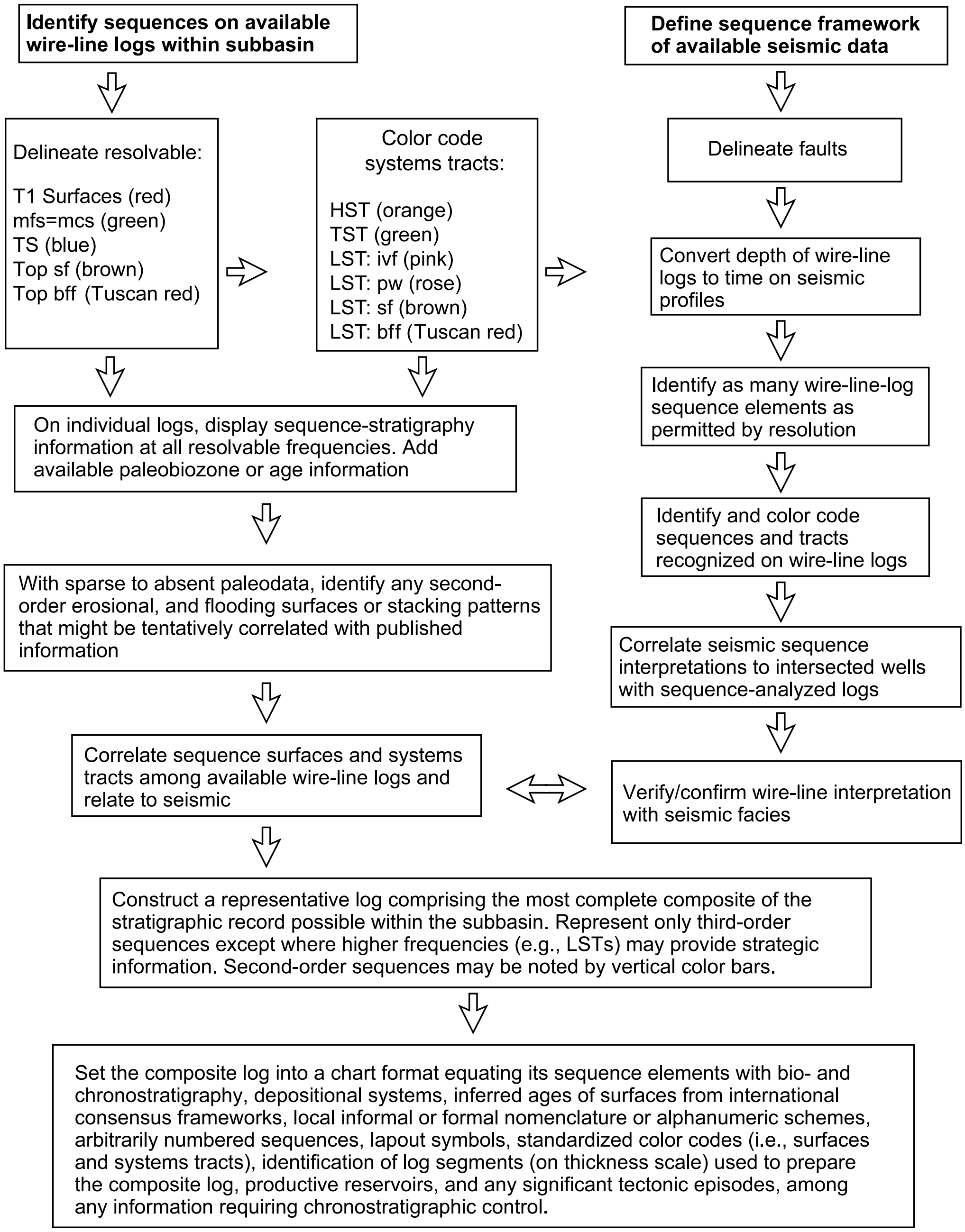

Figure 3. Flow diagram showing steps and tasks for creating an S^5 benchmark chart. Sequence-stratigraphic analysis can be performed without seismic control, and in frontier basins, analyses can be carried out with only seismic data. Integration of seismic and wire-line geophysical data, however, allows for extraction of maximum geologic information from a stratigraphic succession.

were examined by authors of *Sea-Level Changes: An Integrated Approach*, edited by Wilgus et al. (1988). These and many other publications address various aspects of sequence stratigraphy. We do not intend to repeat the basic elements of identification and interpretation of stratigraphic surfaces, sequences, or systems tracts. Our goal is to outline procedures for constructing composite wire-line logs that serve as the basis for S^5 benchmark charts, a useful tool in sequence-stratigraphic interpretation and correlation.

The following are general steps for sequence-stratigraphic analysis (Figure 3) necessary to select, interpret, and chart segments of wire-line logs that compose the most complete succession of sequences and systems tracts in a site-specific area. Refer to the legend in Figure 2 for color code, abbreviations, and symbols. The color code used in this article is the generally accepted code (Van Wagoner et al., 1990). Some of the major steps for sequence-stratigraphic wire-line-log analysis are presented below:

1. Select wire-line logs of wells that penetrate a maximum thickness of the stratigraphic section of interest and that exhibit minimum faults or major

erosional unconformities. It is critical that missing sections caused by large-scale faults be recognized.
2. Select several of these logs and undertake a typical sequence-stratigraphic analysis at all resolvable frequencies:
   a. Mark all sequence-bounding unconformities with a red line. Label type 1 (T1) or type 2 (T2) unconformities.
   b. Mark all maximum flooding surfaces (mfs) (=marine-condensed sections [mcs]) with a green line. Label mfs and/or mcs.
   c. Mark all transgressive surfaces (TS) with a blue line. Label TS. (Remember, TSs are diachronous.)
   d. Mark top of slope fans (sf) with a brown line, top of basin-floor fans (bff) with a Tuscan red line, local autocyclic abandonment mcs's with a green line.
   e. Color each systems tract (and lowstand system) delineated by the above stratigraphic surfaces as follows: highstand tracts (HST = orange); transgressive tracts (TST = green); lowstand tracts (LST: ivf [incised valley fill] = pink; LST: bff [basin-floor fan] = Tuscan red; LST: sf [slope fan] = brown; and LST: pw/pc [prograding wedge/prograding complex] = rose).
3. Construct a cross section using the analyzed wire-line logs. Select a maximum flooding surface near the top of the section of interest to serve as a datum.
4. Delineate candidates for third-order stratigraphic surfaces, sequences, and systems tracts.
5. Correlate third-order surfaces among the analyzed wire-line logs. Use fourth- and fifth-order surfaces and systems tracts to support correlation of third-order sequences and systems tracts. Stacking patterns exhibited by parasequences and parasequence sets or sequence sets are principal criteria for recognizing systems tracts. Stacking patterns can be marked on logs with vertical progradational or retrogradational symbols.

Site-specific sequence-stratigraphic section benchmark charts can be constructed without complementary seismic data, but when available, the seismic data provide strong support of sequence interpretations and correlations.

Basics of S^5 Benchmark Chart Construction

Interpretation of wire-line logs and coincident seismic data is the basis for constructing S^5 benchmark charts (Figure 3). Segments of analyzed wire-line logs can be selected and spliced to record the thickest and most complete stratigraphic succession in the basin (Figure 1). Seismic profiles can corroborate fault cuts in wells whose wire-line logs will form part of the S^5 benchmark chart's composite log.

A variety of descriptive information can be plotted on an S^5 benchmark chart (Figures 1, 2). Any information from a well may be linked to geologic time and approximate depth (i.e., thickness; number 3-h below). The following list presents some data types that can be readily plotted on S^5 benchmark charts:

1. Generally, only third-order tracts and surfaces are plotted by color on S^5 benchmark charts to avoid clutter. It is useful, however, to delineate surfaces and tracts of any frequency resolved in third-order LSTs because of the prospective nature of LSTs. A vertical scale of 500 ft/in. (387 m/cm) is typically appropriate.
2. Systems tracts are coded by color between spontaneous potential and resistivity curves. All stratigraphic surfaces are color coded and labeled. Only third-order surfaces are extended horizontally to intersect vertical information columns (Figure 1).
3. Vertically graphed columns may include the following (see Figure 1 for examples of items discussed below):
   a. Composite log data from selected wells: Vertical lines delineate labeled segments of the different wells that were used to construct the composite log.
   b. Depositional sequences, systems tracts, and surfaces: Divided into second- and third-order columns. Color-coded systems tracts, geologic age, and approximate thickness are labeled on vertical lines. Higher frequency LST information is plotted to the right within third-order columns.
   c. Age of stratal surfaces (Ma): Color-coded horizontal lines and symbols show ages of T1 erosion, TSs, and mfs's that can be based on radiometric, oxygen isotopic, or micropaleontologic dates (Berggren et al., 1985, 1995; Hardenbol et al., 1998; Wornardt et al., 2001).
   d. Subsurface units: Vertical arrows delineate geologic time and approximate thickness range of formal or informal lithostratigraphic units.
   e. General depositional setting: Vertical arrows denote geologic time and approximate thickness range of depositional systems and tract locations.
   f. Approximate microfossil biozones: Age-defined horizontal lines mark geologic time and approximate thickness range of zones. The top of the

zone is typically the last occurrence; the base of the zone marks the first occurrence (in time, not in drilling penetration).

g. Stage and series: Geologic time and approximate thickness range of formal chronographic and chronostratigraphic units. The nontime-linear age scale for the chart includes ages of biozones (Berggren et al. 1985, 1995), sequence boundaries (Hardenbol et al., 1998), and maximum flooding surfaces (Wornardt et al., 2001) that are calibrated with international consensus scales.
h. Thickness (not precise depth because of splicing of logs) and local markers: Local colloquial lithostratigraphic names or numbering systems plot to the right of the wire-line log.
i. Tectonic and/or volcanic impact: Vertical lines mark geologic time and approximate range of events that affected the composition of sediments and deposition.
j. Analytical results: For example, chronostratigraphic correlation of porosity, permeability, and seismic-velocity values; log-depth location of values for petrographic, chemical, isotopic, and source-bed analyses; cored intervals; and petrophysical plots, among others (e.g., see pay zone, Figure 1).
k. Legend: This contains conventional sequence-stratigraphic color codes and symbols (Figure 2).

S^5 BENCHMARK CHARTS SUPPORT CHRONOSTRATIGRAPHIC ANALYSIS BETWEEN GROWTH-FAULTED SUBBASINS

The Frio and subjacent Vicksburg formations in the Corpus Christi Bay area (Figure 4) along the western margin of the Gulf of Mexico comprise the basal lowstand and transgressive supersequence in a Tertiary ~30-m.y. supersequence set (Greenlee and Moore, 1988; Haq et al., 1988). The area is composed of a series of growth-faulted subbasins that become younger basinward (Brown et al., 2004).

High-quality, three-dimensional (3-D) seismic data (courtesy of WesternGeco) in Corpus Christi Bay permitted seismic-stratigraphic support of wire-line-log interpretations. Consequently, analysis of each subbasin involved the use of seismic, wire-line-log, biostratigraphic, and other data, which provided the basis for constructing S^5 benchmark charts to characterize the stratigraphy. Five S^5 benchmark charts have been constructed in several fields located in growth-faulted, intraslope subbasins (Figure 4): upper Nueces Bay subbasin (1), Nueces Bay subbasin (2), Encinal Channel subbasin (3A), Corpus Christi Channel subbasin (3B), Red Fish Bay subbasin (4), and Mustang Island subbasin (5). Three sequence-stratigraphically interpreted composite logs from three S^5 benchmark charts are presented in Figure 5 to provide insight into the application of S^5 benchmark charts in regional correlations.

Tectonics and deposition during successive Frio cyclic, relative sea level lowstands were genetically repetitious and resulted in the deposition of almost identical but diachronous lithostratigraphic successions. Sequence-stratigraphic elements and biozones (where available) were applied to determine correct chronostratigraphic relationships among basins. Correlating only on the basis of wire-line-log patterns between the subbasins aligned along different growth-fault systems can result in major miscorrelations. Consequently, 3-D seismic profiles and sequence-stratigraphic cross sections have revolutionized the precision of intraregional correlation of genetically similar but temporally distinct cyclic-stratigraphic successions.

Constructing sequence-stratigraphic wire-line cross sections using S^5 benchmark charts (Figure 5) in the Corpus Christi Bay areas placed respective growth-faulted subbasins in proper chronological order and permitted precise correlation of essentially time-stratigraphic surfaces. Stratigraphic interpretations between the subbasins in Figure 5 can now be confidently viewed in a geologic time domain, leading to improved applications of digital simulations and animation.

For an example of the application of S^5 benchmark logs for intraregional correlation, refer to Figure 5. This figure illustrates chronostratigraphic correlation between three adjacent, dip-aligned growth-faulted subbasins. Note that a full lowstand section in subbasin 3 (basin-floor fan, slope fan, and prograding deltaic wedge) of Frio third-order sequence 3 is represented only by an unconformity in subbasin 2 and a partial section of slope fan in subbasin 4. A lithostratigraphic correlation of the prograding complex of sequence 2 in subbasin 2 with the genetically similar prograding complexes of sequence 3 in subbasin 3 and sequence 4 in subbasin 4 would result in incorrect correlation of highly diachronous units. Only by using sequence-stratigraphic surfaces, such as those delineated in the S5 benchmark charts of Figure 5, can true chronostratigraphic relationships be resolved. For another example of the utility of S^5 charts in

Figure 4. Corpus Christi region and location of six, growth-faulted, intraslope, Oligocene subbasins (numbering system after Brown et al., 2004). Subbasins shown in red denote those for which S^5 benchmark charts were generated. These and many other equivalent-aged subbasins are located along the basinward, downthrown side of extensive regional fault systems and are filled with third-order Oligocene lowstand systems tracts. Fault systems are generalized and are based on seismic data. The center of the map is located at long. 27°46′33″N, lat. 97°16′56″W. Figure modified from Brown et al. (2004).

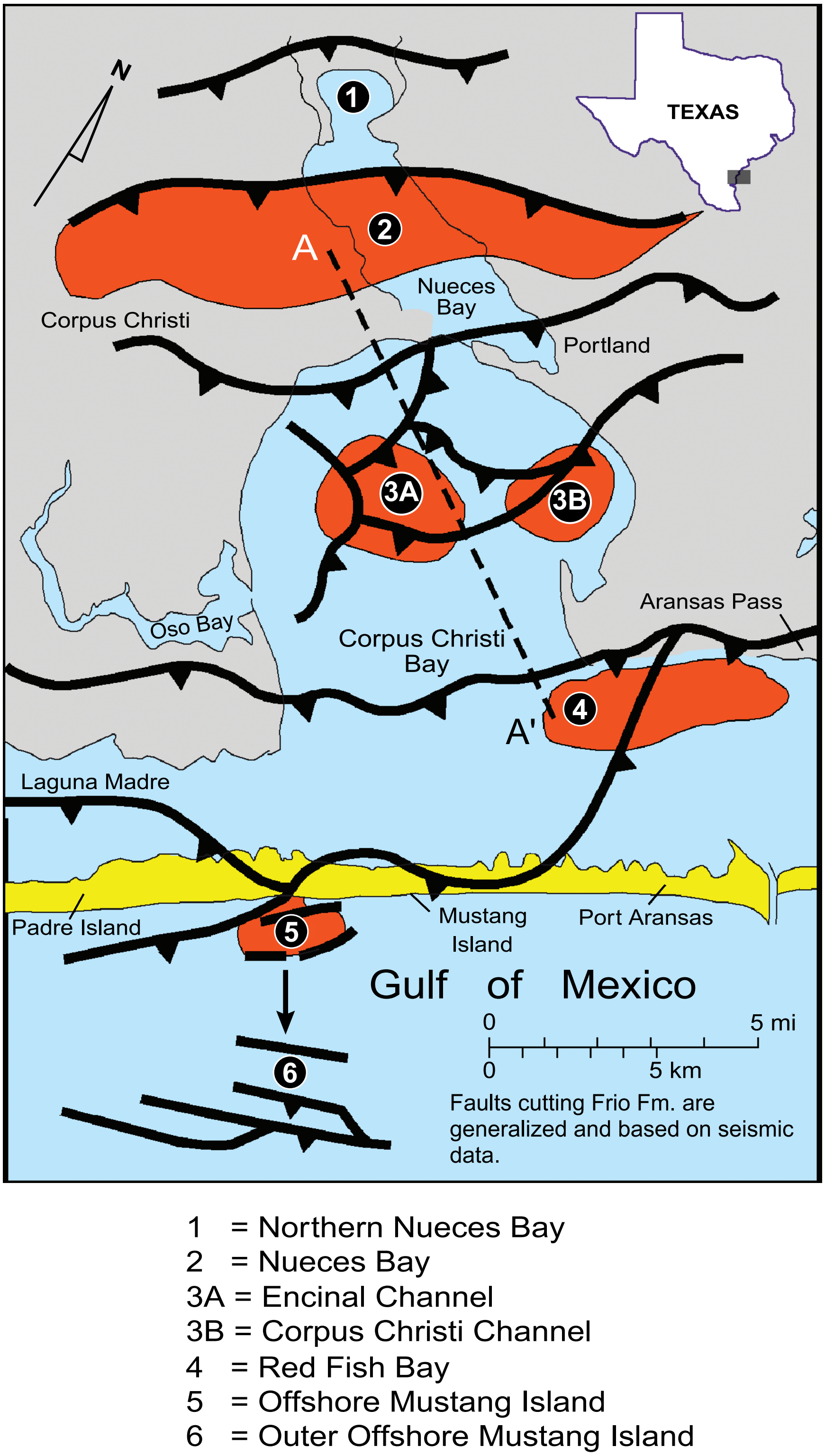

Figure 5, trace the rocks overlying the T1 unconformity (27.49 Ma) in subbasin 4 updip (to the left), and notice that no strata of that age occur in subbasin 3, whereas in subbasin 2, an incised-valley-fill facies overlies the unconformity. The temptation is great to correlate horizontally by linking similar wire-line-log patterns and lithostratigraphic successions in different growth-faulted subbasins, but such correlations will produce an incorrect regional stratigraphic architecture.

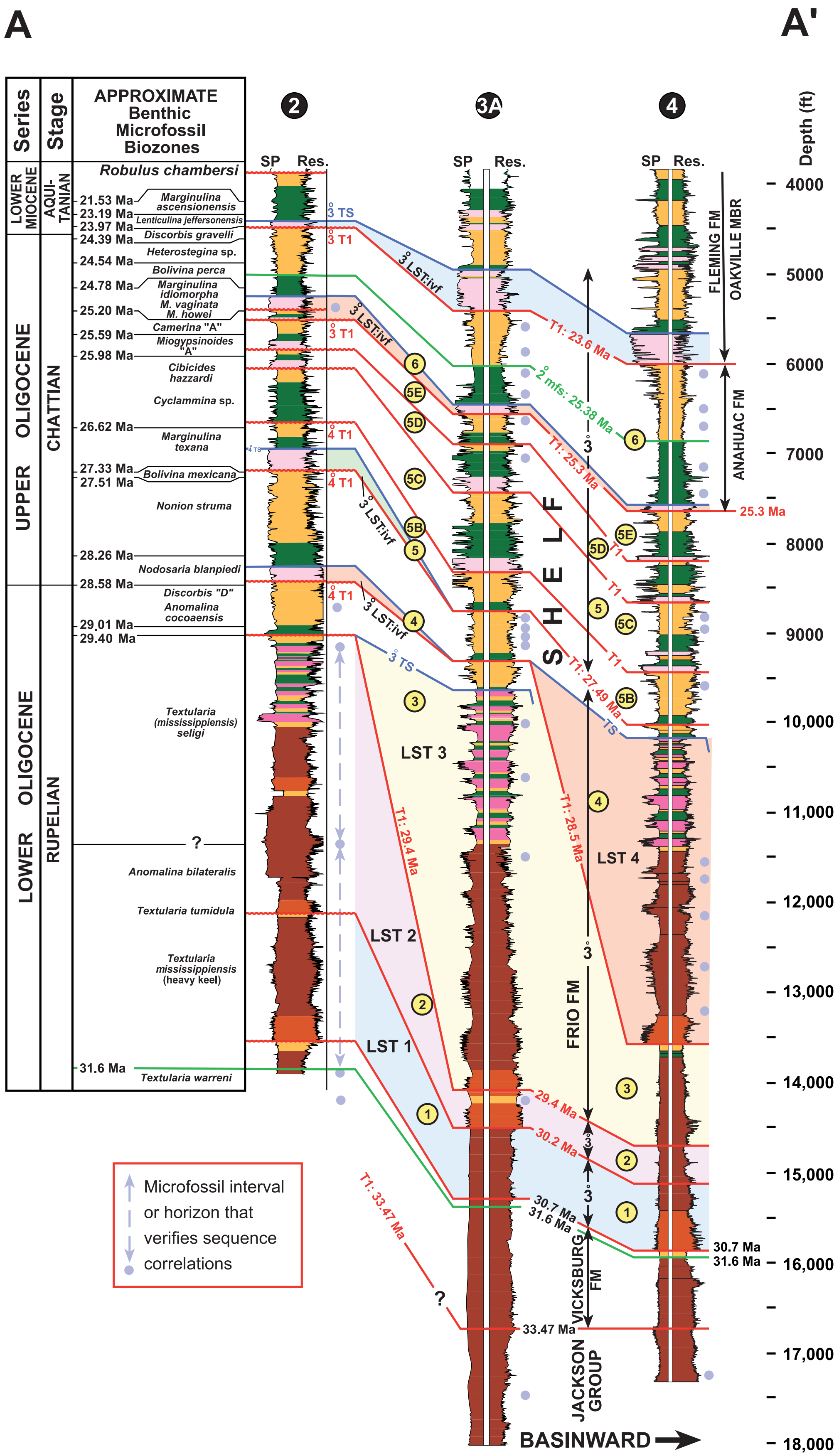

Figure 5. Dip-aligned cross section AA′ (see Figure 4 for location) composed of S^5 benchmark charts of Oligocene Frio and Anahuac formations, Corpus Christi region, Texas, correlated using sequence-stratigraphic surfaces. Section extends downdip from Nueces Bay, through Encinal Channel, and Red Fish Bay subbasins. Physical correlation of sequences, systems tracts, and stratigraphic surfaces agrees with available microfossil biozones. See Figure 2 for legend.

DISCUSSION AND SUMMARY

Long-distance and even global correlations are facilitated when S^5 benchmark charts are used because they can also display biozone, magnetic reversal, and isotope ranges. Even without adequate microfossil data, site-specific sequences can be empirically and reliably calibrated to global cycle charts by comparing erosional intensity of unconformities, magnitude of flooding events, third-order sequence-stacking variations at second-order frequencies, and third-order durations per estimated depositional rates, among other criteria. Incorporating known tectonic events in the S^5 benchmark can help to further calibrate sequences to global cycle charts by highlighting events other than eustasy, which may have influenced local deposition. A single, age-documented surface or microfossil marker within a major stratigraphic succession will link a site-specific sequence succession to an accepted age-dated cycle chart. Even without age calibration, an S^5 benchmark chart will still support empirical regional time-stratigraphic applications.

Color-coded sequences, systems tracts, and bounding surfaces on S^5 benchmark charts can be expanded into informational benchmark charts that temporally integrate biozones, ages of sequence surfaces, depositional settings and systems, stratigraphic nomenclature, sequence frequencies, related tectonism, identification of composite well segments, petroleum pay zones, local marker horizons, and sequence-stratigraphic symbols. Myriad data sets can be compared throughout a basin using the S^5 benchmark chart as a chronostratigraphic reference. Site-specific sequence-stratigraphic section benchmark charts do not provide inherently unique information. These charts, however, convey an interpreter's view of the rocks and present a graphic system for displaying any specific data with chronologic accuracy.

Stratigraphy has reached the threshold of dynamic and quantitative science. Site-specific sequence-stratigraphic section benchmark charts provide a useful tool that can help organize and accurately display available elements of relative sea level cyclicity, depositional-systems processes, and hydrocarbon systems. Digital simulations of depositional and tectonic evolution of a basin have, for many years, offered the potential for synthesizing sequential sedimentary dynamics that generated the observed stratigraphy of a basin. Such simulations, however, lack strong chronostratigraphic control with which to test fully such digital manipulations. Integration of all aspects of basin fill using chronostratigraphic sequence and depositional-systems reconstructions now permits rapid evaluation of myriad sequential paleogeographic scenarios to produce best fit dynamics to match observations.

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