Seismic Stratigraphy-A Primer on Methodology

By

John W. Snedden[1]; and and J. F. (Rick) Sarg[2]

Search and Discovey Article #40270 (2008)
Posted January 19, 2008

[1]ExxonMobil Upstream Research Company, Houston, Texas (john.w.snedden@exxonmobil.com)
[2]Colorado Energy Research Institute, Colorado School of Mines, Golden, Colorado (jsarg@mines.edu)

Abstract

Seismic stratigraphic methods allow one to interpret and map reservoir, source, and seal facies from reflection seismic data. Seismic stratigraphic methods have evolved since the first publications in the late 1970's. This document attempts to provide an update of these elementary principles, written as a "how-to" series of steps.

Introduction

Seismic stratigraphic techniques have evolved considerably since the underlying principals were first discussed over twenty years ago (e.g. Vail et al., 1977). Seismic stratigraphy methodology has proven quite successful in identifying plays on a regional basis, maturing leads to drillable prospect status, and exploiting field hydrocarbon resources (Greenlee, 1992; Duval et al., 1992).

In this document, we discuss some guidelines for conducting a seismic stratigraphic investigation and include guidelines for data preparation. This type of work should lay the foundation for later sequence stratigraphy (Van Wagoner et al. 1988), seismic attribute analysis (2D or 3D), volume interpretation (3D), and forward seismic and geological modeling.

However, these recommendations are meant to form a working approach rather than a series of subjective directions. Methodologies must always be adjusted to fit the data from a given area. Further reading is listed to support the information provided here.

Data Preparation

As regional seismic stratigraphic analysis often proceeds detailed 3D seismic mapping, it is assumed that the first stages of analysis involve 2D seismic or merged 2D/3D datasets with relatively long lines (>1-5 km line length). Preparing these data for analysis usually require the following six steps:

1. Plot regional base maps showing shot points and posted wells. These should be at an appropriate scale and size for later use in mapping. Bathymetry is also useful to have in offshore datasets. Base maps serve several functions, including places to mark seismic facies notations, areas of interest, anomalies to further investigate, checking line ties, etc.

2. From the base map, select key 2D or 3D seismic lines, emphasizing regional or sub-regional dip lines with important well-ties. Avoid, if possible, areas where wells must be extrapolated considerable distances (> 1 km) along strike or down structural dip to tie seismic lines. Select lines to allow loop ties in a progressively widening grid, avoiding severe tectonic deformation zones, if possible. Identify possible "hero" lines, often dip lines, which tie key wells and show clear stratigraphic trends and are good "show lines". Sometimes the best choices for hero lines emerge later on, following initial interpretation.

3. Plot paper copies of selected regional seismic lines at a reduced scale. **We highly recommend using wiggle trace paper sections at the first stages of an investigation** as this is usually the best way to see complex stratal relationships and terminations over long distances (**Table 1**). On the seismic workstation, such stratal observations are often obscured or masked by a high degree of vertical exaggeration. Long regional lines often require panning large back and forth on a workstation, whereas paper sections allow uninterrupted visual scanning for key terminations. In addition, wiggle trace sections, which allow for marking of often subtle stratal terminations, do not display well on the workstation screen.

Figures 1 and 2 illustrate the results of plotting a small portion of a seismic workstation view with wiggle trace and variable density displays at regional scales (1:50,000). Notice how onlap of the seismic reflections is more clearly displayed on the wiggle trace section (**Figure 1**) than the variable density plot (**Figure 2**).

This also holds true for the prospect or field scale at 1:25,000 (**Figures 3 and 4**). Variable density sections (as on seismic workstations) are more difficult to interpret stratigraphically than wiggle trace (variable area) sections because stratal terminations tend to be “smoothed out” by this type of display. In addition, the subtle brightening of adjacent reflections at a stratal termination, due in part to tuning effects, is often masked. If there is a desire to make the troughs stand out more, one can color these with a light shade of gray for greater contrast.

4. Avoid data which has trace-mixing that obscures stratal terminations. Avoid narrow AGC (automatic gain control) windows which tend to reduce differences in relative amplitude between stratigraphic units. Use migrated sections where possible, but this is not a requirement (sometimes non-migrated data is better for seismic stratigraphic interpretation).

5. Prepare well data for seismic ties. **We recommend that well ties be made paper to paper in the early phase of a seismic stratigraphy study**. One reason is that it is normal practice to tie synthetics to wiggle trace sections. Wiggle trace sections are preferred over variable density for other reasons as discussed above. Be sure to include the gamma ray or other critical logs. Time-based logs should be at the same scale as the seismic section (10 or 20 cm/sec). Time-based logs can also be used in various log correlation program cross-sections, for example. Seismic displays at 10 cm/sec offer an obvious advantage over 5 cm/sec while 20 cm/sec are good for detailed, prospect or field scale. Biostratigraphic and lithostratigraphic tops should be input into the synthetic seismogram program; this saves time by not having to do it by hand later. Check-shot surveys or VSP's (vertical seismic profiles), when available, should be used in generation of the synthetic. If these are not available, two other options can be employed:

1) Identifying a key reflection (typically a limestone/shale contact) with high acoustic impedance contrast and hanging the synthetic on it.

2) In some cases with limited or older velocity data, there is some utility in constructing a time-depth (T-Z) curve for the region using other checkshot surveyed wells. This empirical approach often yields a polynomial equation to predict depths from seismic TW time. Most check-shot data

can be fit with a second-order polynomial (y = 2x +b) where y is depth and x is TW time. Be careful of areas where overpressuring causes variations in T/Z plots.

Keep in mind that some bulk time-shifting can still be required to match the seismic (generally less than 100 ms).

6. **We highly recommend construction of a well-tie template** for illustrating the relationship between seismically-defined surfaces, time-based well log, biostratigraphic calibration, and global chronostratigraphy. This template can be prepared once horizons have been identified and well-ties are made with general agreement among interpreters. It also useful for project presentations as it provides a clear documentation of the stratigraphic age model used.

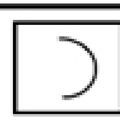
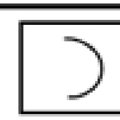
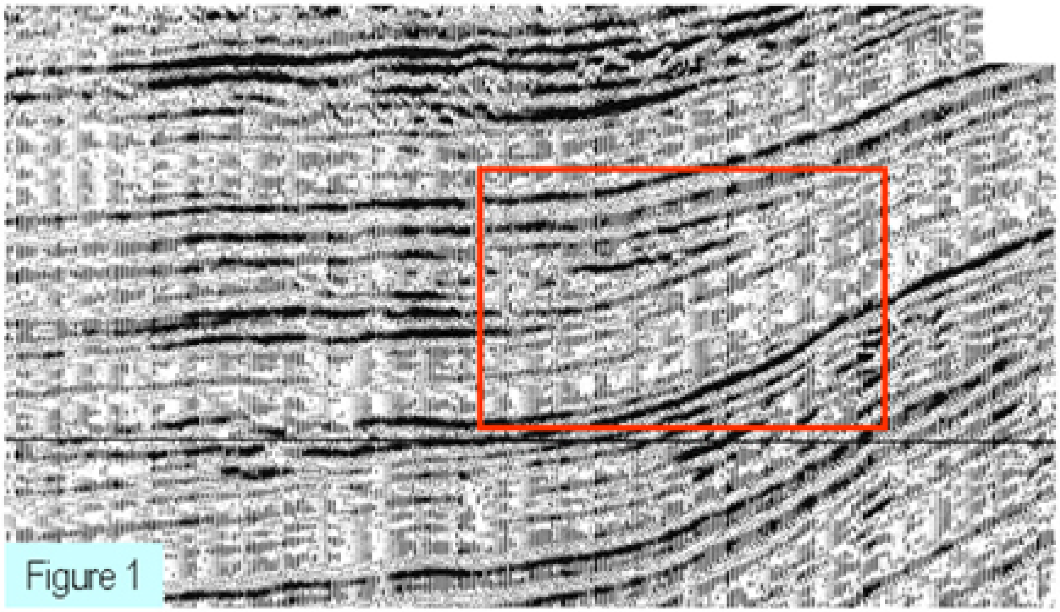
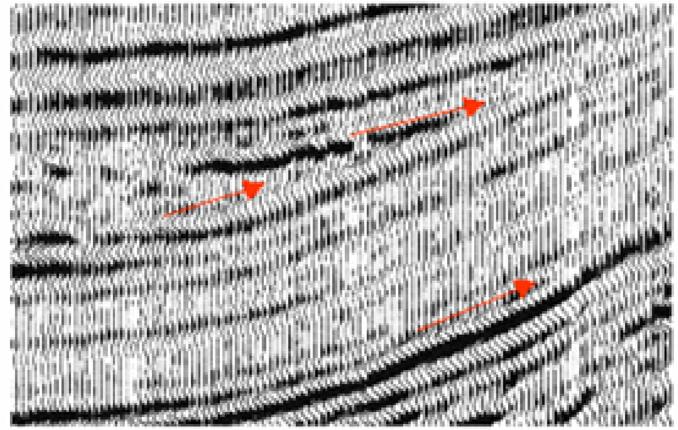
Type of Analysis	Regional	Field or Prospect-Specific
Display Specifications		
Trace Type	Wiggle (Variable Area)	Wiggle (Variable Area)
Gain Control:		
Type	RMS	RMS
Polarity	Normal/Reverse	Normal/Reverse
Amplitude	125-150	125-150
Wiggle Trace:		
Show Wiggle	Yes	Yes
Color	Black	Black
Style		
Scaled Plot Parameters		
Plot Units	Metric	Metric
Horizontal Units	1:50,000	1:25,000
Vertical Units	10 cm/sec	10 cm/sec or more
Trace Decimation	2	1

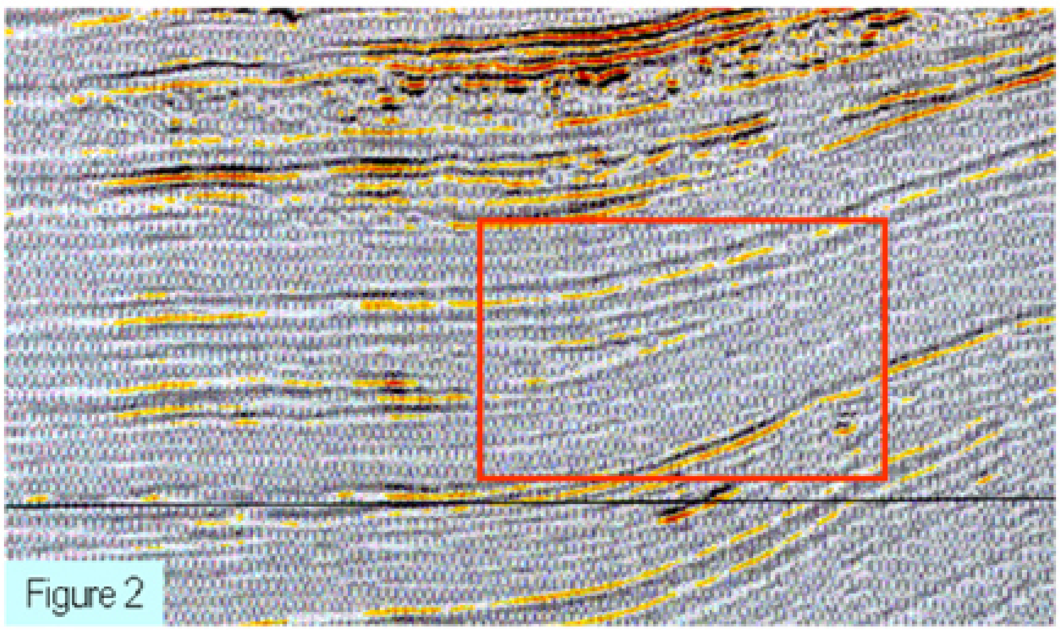
Table 1. Parameters for plotting seismic interpretation program sections in paper form. Some of the parameters listed above will need to be adjusted, depending on the data itself.



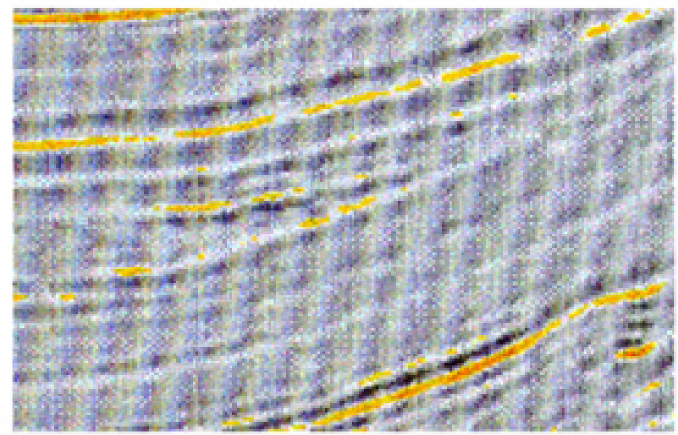
Wiggle trace, 10cm/sec, 1:50,000



Expanded inset with arrows indicating onlap

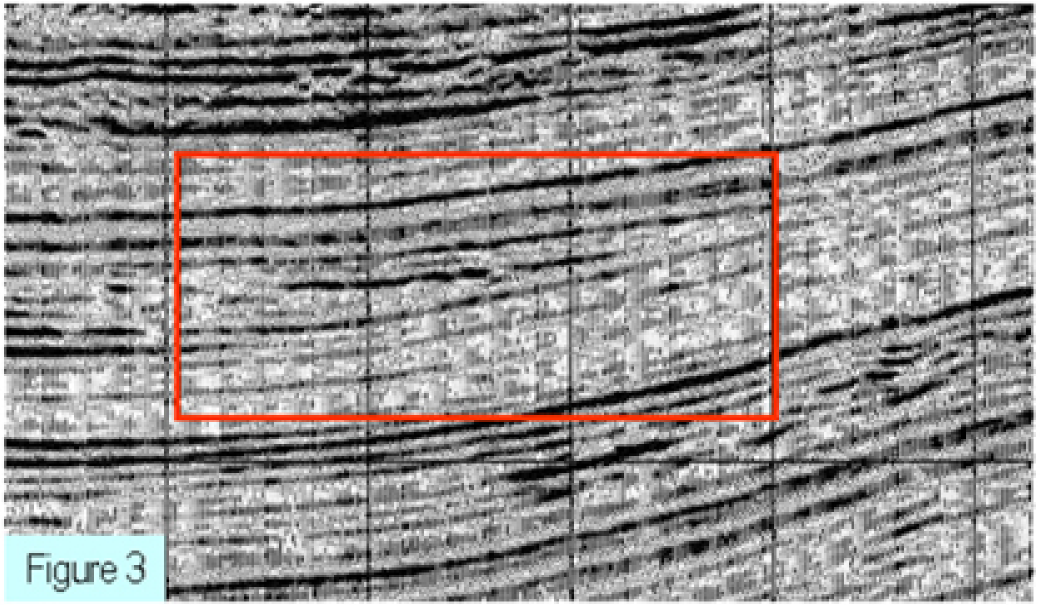


Variable density, 10cm/sec, 1:50,000

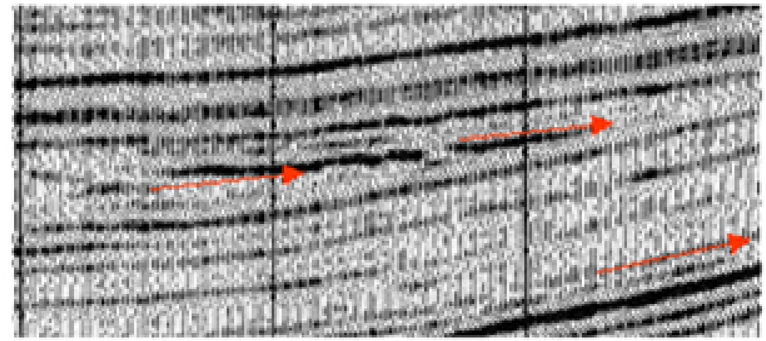


Expanded inset

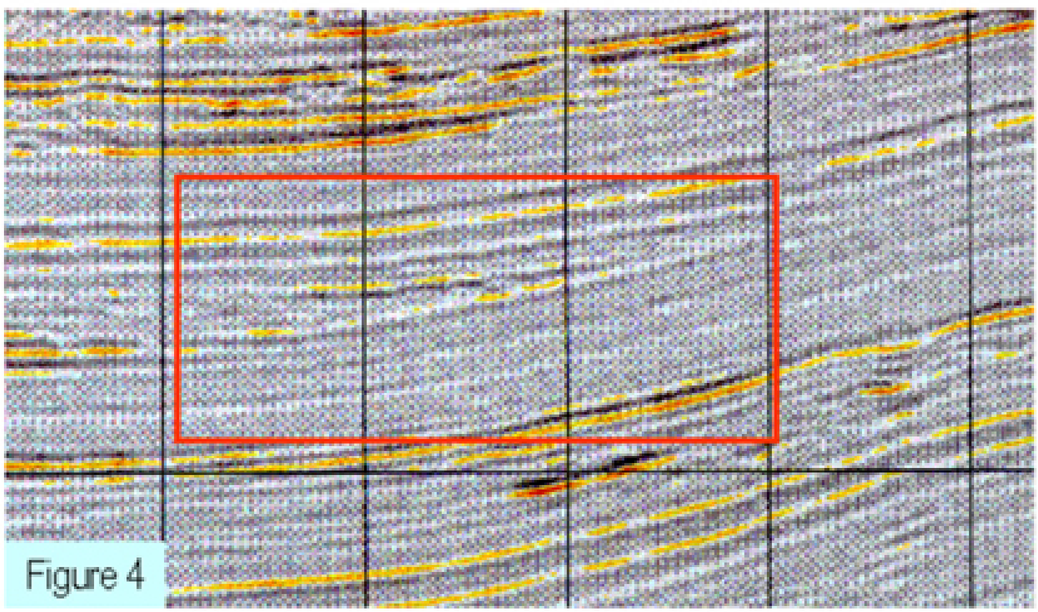
Figures 1 and 2. (1) Wiggle trace versus (2) variable density seismic displays at regional scale (1:50,000).



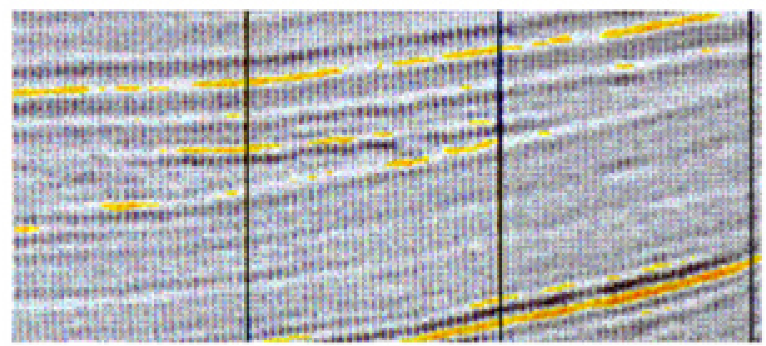
Wiggle trace, 10cm/sec, 1:25,000



Expanded inset with arrows indicating onlap



Variable density, 10cm/sec, 1:25,000



Expanded inset

Figures 3 and 4. (3) Wiggle trace versus (4) variable density seismic displays at prospect scale (1:25,000).

Seismic Stratigraphy Interpretation

Once data has been properly prepared, seismic stratigraphic interpretation begins, typically using colored pencils for different horizons. While the speed and ease of work-station correlation is far greater than hand interpretation, there always is a basic need to develop regional ‘hero lines” to illustrate key stratigraphic relationships. Having a hero line or series of hero lines is a useful way of reducing variations among interpreters, as these become the starting point for any new seismic workstation project.

Pencil-interpreted paper sections allow for some changes in correlation, especially when looping across other sections occurs. However, at some point the lead interpreter declares that the key horizons are “looped” and only limited significant subsequent alterations are allowed.

Interpretation Steps

1. Identify areas of major structural deformation and data artifacts (sideswipe and diffraction) on the seismic sections. One should have a sense of the general tectonic style, presence of structural decollements, or key deformational events from previous reports or the literature. Do not blindly adhere to conventional wisdom if seismic data dictates otherwise.

2. In structurally complex terrains, it may be useful to do an initial correlation of a few surfaces and then cut, flatten, and tape together sections to see key tectonic relationships. A few half-scale seismic displays at or near 1:1 vertical exaggeration may also be helpful if structure is not clear-cut. Interpret faults (with normal pencil) where obvious offsets can be identified. Be sure to differentiate between migrated and unmigrated seismic sections where identifying faults. Also be careful of pitfalls due to over- or undermigration of seismic data. In some cases, complete restoration of a series of seismic sections is necessary to fully understand the original depositional patterns and stratigraphic organization (e.g. Gulf of Mexico slope salt province).

3. Review key lines (especially dip lines) to identify major (second-order) shelf margins, if present in the region. Indicate by triangle or circular symbol. Get a feel for the scale of the seismic sequences (2^{nd} order, 3^{rd} order, etc.), and pre-, syn-, and post-orogenic sequences. Identify major angular truncations by bold top truncation arrows (in red).

4. Begin to identify major lapouts with red pencil marks. Do this BEFORE making seismic correlations. Stratal terminations are listed in order of importance and illustrated in **Figure 5**:

-angular truncation obvious erosional termination of dipping reflections up against a reflection of lesser dip)

-onlap (stratal termination up against a reflection of greater dip)

> **-downlap** (stratal termination down against a reflection of lesser dip)
>
> **-toplap** (termination of successively younger reflections against a reflection, passing downdip to prograding clinoforms (in some cases))

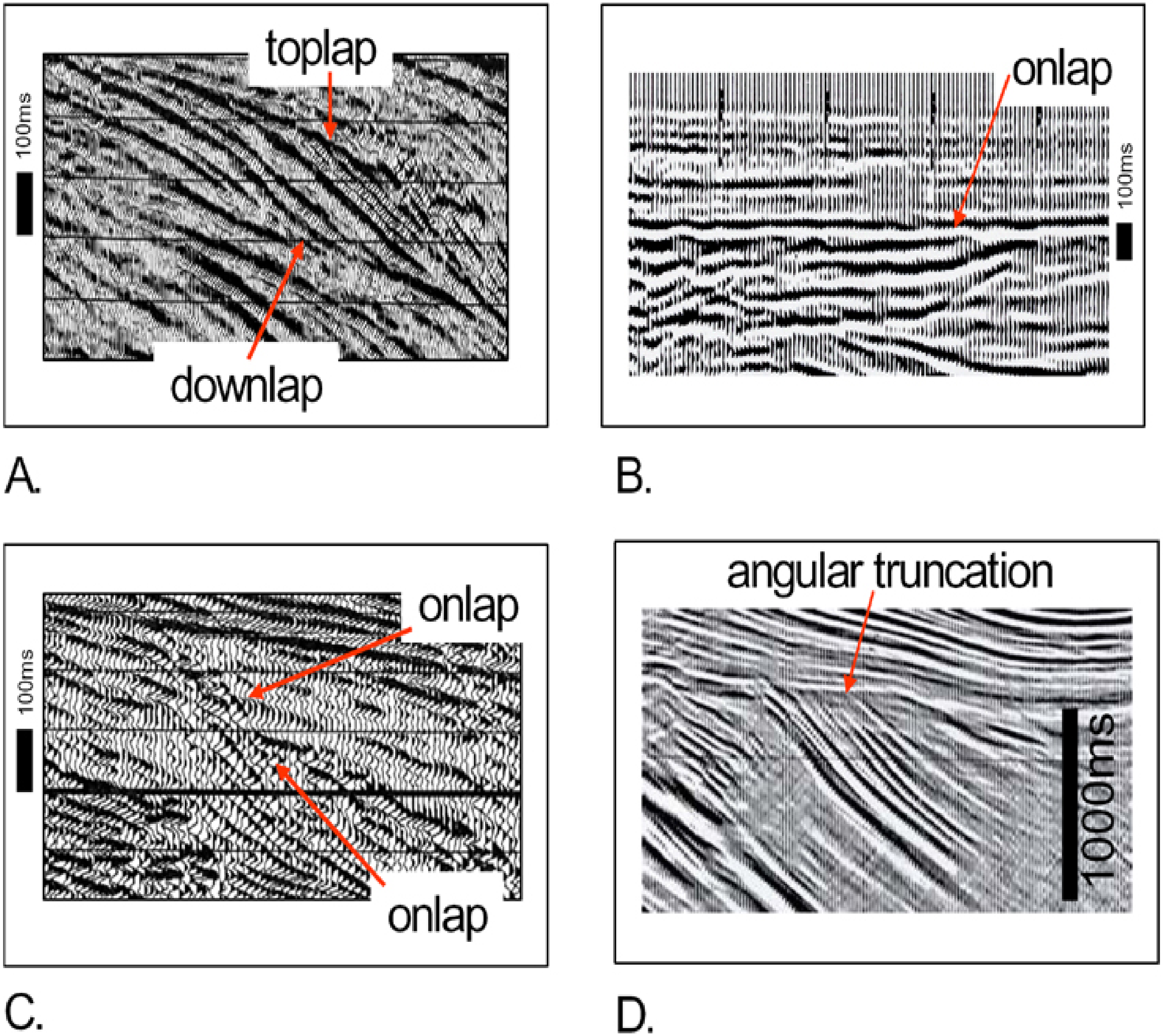


Figure 5. Examples of key stratal termination. Seismic data modified from Bally et al. (1982).

5. Connect onlap and angular truncation terminations as a candidate sequence boundary. Connect the downlaps as a candidate maximum flooding surface (MFS), keeping in mind the caveats listed above. Toplaps remain unconnected temporarily. Be careful when interpreting onlaps and downlaps in strike sections or in tectonically rotated and growth fault sections. Please note that listric fault planes or glide planes can be misinterpreted as onlaps.

6. Keep in mind that the **most important seismic stratigraphic surface is the sequence boundary** (SB), which is most easily identified by stratal **onlap,** especially in shelfal portions of the sequences. It will be most continuous throughout the area of interpretation. Both toplap and downlap surfaces can change reflection position for various reasons. For example, the toplap surface can drop below the sequence boundary in a lowstand systems tract (LST) or can be part of rising, shingled lowstand wedges (LSW's). The downlap surface can also rise as basinward progradation occurs in both highstand systems tract (HST) or LST. Toplap and downlap surfaces may step up stratigraphic section as well. Loop typing will help identify the regional downlap surface associated with a condensed section and maximum flooding. Also keep in mind that sections oblique or parallel to depositional dip will not yield classical downlap progradational direction.

7. Look in basinal positions for double downlap as an indicator of LST-basin-floor thick or (in slope) slope thicks or channels. The sequence boundary on the basin floor is by definition a correlative conformity and may not necessarily show much associated erosion. **However, in confined deepwater channel systems this surface will tie with significant erosion, collapse, or failure.**

8. Look in shelf-margin position for LSW's, which will often be indicated by detached, shingled toplap-downlap couplets. These should be colored separately from other systems tracts. The LSWpc (lowstand wedge prograding complex) is often identified where smaller clinoforms downlap the sequence boundary.

9. Carry through the correlations made by connecting stratal terminations marks. Loop-tie the sequence boundary (SB) and maximum flooding surface (MFS) in a progressively widening set of line ties, in order to gain confidence in the correlations. At least five or more surfaces need to be tied in multiple loops before correlations are considered more than "candidate" SB or MFS.

10. A good practice in seismic stratigraphic correlation is to drag your pencil on the black peak or at the zero crossing just above the peak. One reason for this is the ease in erasing the pencil line should a miss-tie occur. However, if the impedance characteristics of sand and shale are well established and the surface type and position are known, it is more important to correlate the surface in the appropriate peak or trough. Knowing whether seismic data is quadrature or zero phase is also important, as these will control surface position to some degree.

11. A general rule of thumb when correlating, either with pencil or with workstation cursor, is to stay low as possible without crossing reflections when correlating a SB in the basin. Conversely, it is wise to stay high when correlating on the shelf, without crossing reflections. A MFS surface may rise in the basin (due to sedimentation prior to downlap). As mentioned, low toplap is common and can be confused with a sequence boundary but may be an internal surface in the LSWpc. **This is why it is so important to understand the type of surface that is being correlated and the basin position of the area being interpreted.**

Integration with Other Data Types

After key stratigraphic surfaces have been identified and correlated, the next set of steps are undertaken to integrate any available well data.

1. Integrate with logs, cores, and biostratigraphic information.

--**Biostratigraphic data**: It is important when using biostratigraphic data to look for concentration/dilution cycles. In general terms, concentration cycles, zones where large numbers of microfauna and flora are condensed over short intervals, are often associated with maximum flooding surfaces (MFS). By contrast, dilution cycles are often associated with sequence boundaries. Keep in mind the potential for depressed fauna and displaced (transported) fauna. Be careful where data comes from wells with thin stratigraphic sections on structural or paleogeographic highs. Sequence boundaries sometimes are associated with high numbers of reworked older fauna, usually due to updip or local erosion of older strata. Biofacies and paleoclimatic inferences from paleontologic data should also be considered in this integration because latitude variations in faunal and floral content can also occur (Armentrout et al., 1991).

--**Logs**: Stacking patterns, log motifs, and lithology are keys to the intermediate scale of correlation which should support the seismic correlations**.** <u>In fact, the best log correlations are established when the seismic data is used as a guide to extending stratigraphic surfaces from well to well.</u> While seismic data does not often capture the high-resolution stratigraphic correlations possible in a log cross-section, it usually displays gross geometries (e.g., dipping clinoforms) which should be followed in log correlation. For example, experience has shown that clinoforming parasequences or stacked sequence architectures can be missed in log correlation if not first identified on seismic.

Stacking patterns seen on logs (and outcrops sections) are often indicative of key stratigraphic surfaces. For example, the change from retrogradational to progradational stacking often is associated with a maximum flooding surface, which can be checked against both seismic and biostratigraphic data.

Log motif interpretation of systems tracts is particularly well defined (e.g., Mitchum et al., 1994). Stacking patterns, log curve shape, vertical trends in sand content, and relationship to over- and underlying surfaces are keys to identifying the systems tracts. However, integration with seismic and other data is critical to validating these interpretations.

--**Lithologic relationships** can help identify systems tracts: 1) in mixed siliciclastic/carbonate systems, HST's are often dominated by carbonate rocks while sandstones are often found in the LSW’s and TST (e.g., Guadalupian strata of the Permian Basin; Sarg and Lehman, 1986). 2) In some LST’s, the carbonates can dominate the LSWpc, but sandstones onlap as basin-floor thicks. In-situ coals often reside in the HST’s and/or TST’s while transported terrestrial organic matter and coal spar (clasts) occur in the LST’s (e.g., North Sea Tertiary; Armentrout et al., 1993). Juxtaposition of contrasting lithologies and unlike facies types often signals a major basinward facies shifts (SB) or major transgressive event (parasequence set boundary (PSSB)).

--**Cores**: The best evidence for identification and validation of important stratigraphic surfaces often comes from cores. Sequence boundaries can be associated with basal lags or paleosols (on the interfluves of incised valley-fills (ivf’s)). Parasequence boundaries (PSB’s) can be associated with burrowed, wave rippled surfaces. The *Glossifungites* trace fossil assemblage is a firm or hard ground indicator and this can be associated with PSSB or PSB’s.

At this point, it is often helpful to take some of the sequence boundaries and maximum flood surfaces from the sequence stratigraphically interpreted seismic sections and post these on log cross-sections. The result is seismic-consistent well log correlation (as described in item #1). Such sections are good ways to illustrate how seismic geometries point to sand type, thickness, and distribution (shelf vs. basin, for example). Of critical importance is the need to pick a surface that is a good (flat) datum. The surface chosen should have been close to horizontal at the time of deposition. This is not easy, considering that virtually every surface has some stratigraphic dip. If the surface elevations are close, then perhaps hanging on subsea depth might work. Maximum flooding surfaces often work well in basinal settings while shelf top sequence boundaries in shelfal domains are favored. Flooding or transgressive surfaces work well locally, but are clearly diachronous at the regional scale.

Once surfaces are established, it is relatively easy to compute statistics like net/gross, etc., used in map overlays described below. Multiple datums may be necessary, particularly with long regional cross-sections, but many computer cross-section programs have some difficulty with this.

2. Color systems tracts: green = TST, Blue=HST, terra cotta (brown) = LST. Coloring lightly with pencil is particularly good for seismic sections which become the hero line and are used in the workroom as a "rosetta" stone for the group.

3. Use biostratigraphic information to date the sequence boundaries and MFS. It is very important to establish sequence boundaries ages at the narrowest lacuna (smallest hiatus). This is particularly critical for major angular or structural unconformities (e.g., Middle Miocene Unconformity (MMU) of SE Asia, Base Cretaceous in Northern Viking Graben). **Figure 6** illustrates how the MMU of Malaysia was definitively dated at 15.5 ma (Haq et al., 1987 terminology) by using biostratigraphic age dates where the gap between the oldest strata above and the youngest strata below the MMU was identified.

4. Compare to global chronostratigraphy: a) assign age and b) appropriate surface nomenclature. We recommend use of terminology following the European Basins Cenozoic and Mesozoic Chronostratigraphy (de Graciansky et al., 1998). This system and associated charts are gaining industry acceptance as a global reference standard. The surface is named using the European Basins nomenclature; e.g.:

Tor1_sb	Tortonian-1 sequence boundary (3^{rd} order)
Tor1_200fs	Tortonian-1 200 flooding surface (4^{th} order)
MioX1_100mfs	Miocene 4^{th} order surface, unknown stage or depositional sequence

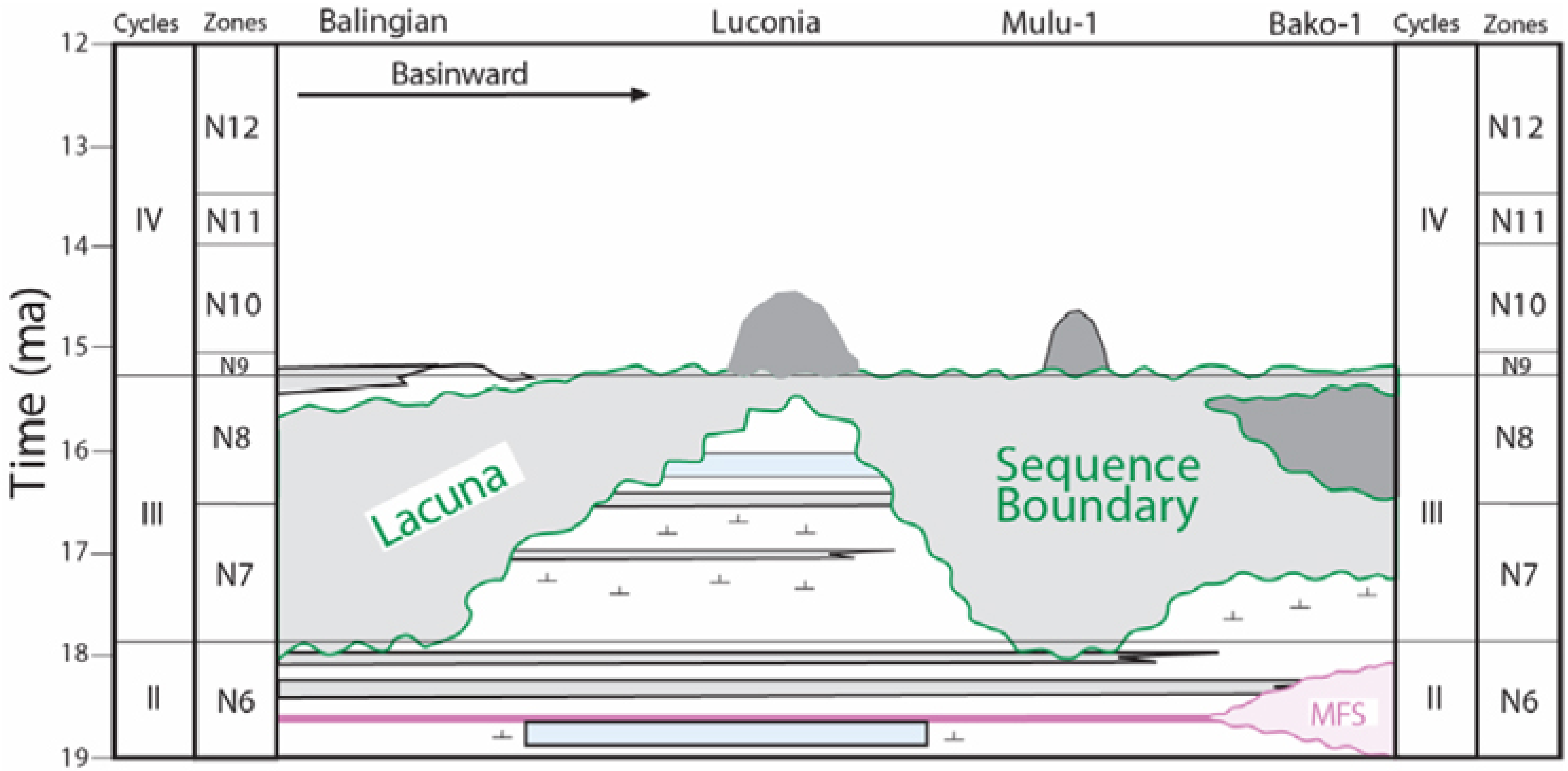


Figure 6. Dating an unconformity at its narrowest lacuna: Middle Miocene Unconformity (green sequence boundary) in Sarawak (about 15.5 ma). This is accomplished through a Wheeler diagram (time vs. distance). Note that the lacuna associated with the unconformity includes both hiatus (non-deposition) and the erosional vacuity (due to erosion). Modified from Mansor et al. (1999).

Seismic Mapping Based Upon Sequence Stratigraphy

Once a preliminary stratigraphic framework has been established, mapping based upon sequence and seismic stratigraphic interpretation is done to provide documentation to seismic observations. These also serve to help identify prospective petroleum plays, fairways for prospect generation, and evaluating acreage and development well opportunities. While amplitude-based mapping approaches are evolving rapidly with the computing and workstation technology, the traditional approaches discussed below still offer value to the interpreter.

Seismic Facies Mapping

Seismic facies mapping involves qualitative to quantitative analysis of seismic character to infer areal trends in either lithology, paleoenvironment, or both (e.g., outer shelf shales). Generally, seismic character is analyzed from two standpoints: external form (geometry) and internal character. Internal form includes the continuity, frequency, and amplitude of seismic reflections (**Table 2**). Many of these parameters relate to lithology or the processes responsible for deposition and thus are often used to interpret sand body origin and reservoir type. Others relate to the acoustic impedance contrast, tuning, etc., and thus seismic resolution plays a role in their discernible patterns of occurrence. Bed or stratal continuity is assumed to exceed the Fresnel zone width for a given seismic frequency.

Workstation- and some PC-based seismic analysis programs can provide quantitative measures of frequency, continuity, and amplitude to support mapping. Seismic amplitude mapping is particularly well advanced in industry today. Seismic volume interpretation allows seismic amplitudes "polygons" and 3D objects to be viewed in proper spatial and temporal relationships.

Feature	Significance
Amplitude	-Impedance contrast (significant stratal surfaces) -Bed spacing/tuning -Lithofacies -Fluid content
Continuity	-Lateral stratal continuity -Depositional processes
Frequency	-Bed Thickness -Fluid content
Geometry	-Depositional Processes

Table 2. Seismic reflection characteristics of seismically definable sand bodies.

External Form and Internal Geometry-A-B-C Mapping

Seismic facies mapping was definitively explained in Ramsayer's (1979), based upon 2D seismic sections interpreted prior to the advent of seismic workstations. This is referred to as the "A-B-C" mapping approach, as observations are made upon the upper boundary (A), the lower boundary (B), and internal reflection character (C). For example, a prograding seismic package with oblique clinoforms, toplap at its upper surface and downlap at its base would be noted as Top-Dwn/Ob (**Figure 7**).

The three categories (A-B-C) of Ramsayer's (1979) seismic facies codes each include five types, thus providing 15 different variations for a given seismic interval of interest (**Table 3**). Although the technique was developed largely from 2D seismic data, it can be used on modern 2D and 3D sections displayed on conventional industry workstations.

Figures 8 and **9** illustrate use of the Ramsayer (1979) A-B-C seismic facies mapping approach on a series of 2D sections interpreted using a workstation. In the Paleogene section of the North Sea, five or six depositional sequences were recognized, correlated, and mapped (Armentrout et al., 1993). The shelf margin break is denoted by a pink triangle. Thick lowstand wedge prograding complexes (orange) formed in the shelf margin position, seaward of the highstand systems tracts and thin embedded transgressive systems tracts (blue).

Four seismic facies were identified in sequence 30, as indicated in **Figure 8**. The workstation method is to assign each different seismic facies to different parts of the vertical time or depth scale (seisfac horizon in **Figure 8**). For example, the cross-section position of seismic facies C-C/P is assigned to time horizon 300ms, while C-Dn/Si is indicated along time 400ms, Tp-Dn/Ob along time 500ms, and On-C/P to 600ms, all above the interval of interest to avoid overlapping the key interpretation interval below 700ms. The horizontal distribution or geometry of the various seismic facies is seen on the corresponding seismic map view (**Figure 9**). It is also important to indicate areas of bad data or poor seismic reflectivity.

When placed in a map view, the interpreter infers patterns of similar seismic character as well as trends going from up-depositional dip to downdip (**Figure 9**). The intent is to make objective observations of seismic character and then interpret the meaning of these seismic facies in a regional and local depositional context.

In addition to A-B-C seismic facies maps, other observations include marking stratal terminations (e.g., arrows indicating downlap and toplap), isochron thickness, or depositional limits of the individual lobes and interpreted progradation direction or sediment input orientation. Different seismic facies sometimes correspond to different progradational lobes. It is useful to indicate paleoshelf margin location by symbols, such as triangles or filled circles.

Rather than mapping the entire sequence, it is recommended that individual maps be constructed for each depositional systems tract (**Figure 10**). These often have different seismic facies character and map geometry. Note how the interpreted highstand systems tract (HST) is characterized by offsetting lobes, which define the highstand shelf phase deltas, which in aggregate prograde the shelf margin from the maximum flooding position. The transgressive systems tract (TST) has a different map pattern than the overlying highstand systems tract. Few stratal terminations can be identified. The mapped seismic facies is located largely inboard of the shelf margin position. Only one seismic facies (largely parallel continuous reflections) can be recognized, in contrast to four facies mapped in the HST. The lowstand systems tract (LST) is largely formed seaward of the shelf margin position. Two distinct seismic facies are represented: 1) a large mounded to parallel seismic facies thought to be the basin-floor fans or thicks and 2) more lobate but areally limited packages near the shelf margin, interpreted as lowstand-wedge-prograding complexes (**Figure 10**).

Comparing these maps, one can see the variations in map pattern through one eustatic sea level cycle (**Figure 8**). Stacking all the systems tracts for one cycle, by contrast, leaves a very complicated map (**Figure 10**, inset).

Seismic facies mapping on the workstation can be done with both 3D and 2D seismic, although the latter case involves some interpretative interpolation between 2D lines (**Figure 11, A**). Using the map geometries and seismic facies characteristics tied to well control, interpretation of the depositional sand bodies is made (**Figure 11, B**).

Ramsayer (1979): $\dfrac{\text{A-B}}{\text{C}}$

Where A = upper boundary character (e.g. Top = toplap)

Where B = lower boundary character (e.g. Dwn = downlap)

Where C = reflection character (e.g. oblique)

$\dfrac{\text{Top-Dwn}}{\text{Ob}}$

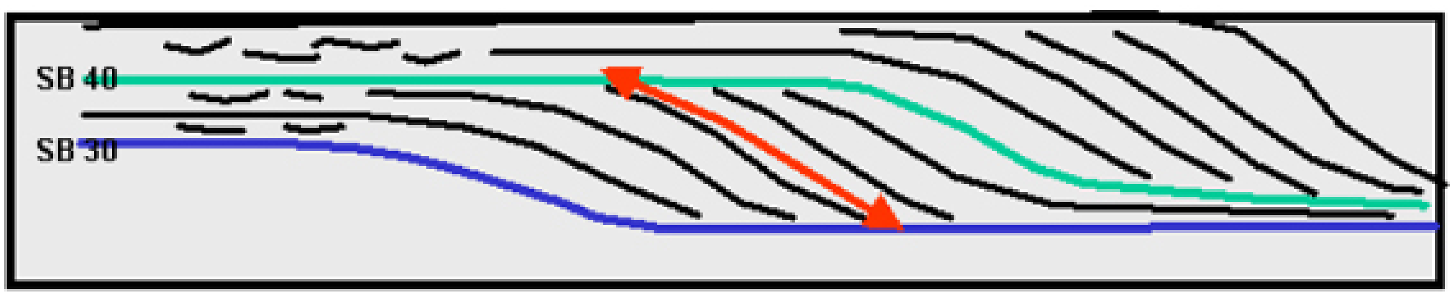


Figure 7. A-B-C seismic facies technique of Ramsayer (1979).

Descriptor	Position	Code	Explanation	Comments
Top	A	C	Concordant	often assoc'd with parallel internal reflections
		Top	Toplap	non-erosional, c.f. truncation
		Dwn	Downlap	double downlaps oc. assoc'd with mounding
		Di	Divergent	
		Tr	Truncation	associated with erosional unconformities
Base	B	C	Concordant	
		Top	Toplap	
		Dwn	Downlap	
		Di	Divergent	
		Tr	Truncation	
Internal	C	P	Parallel	
		Ob	Oblique	
		Si	Sigmoidal	assoc'd w/ clinoforms
		Mo	Mounded	shallow (deltas), deepwater
		Subp	Subparallel	rare, c.f. oblique

Table 3. Seismic facies mapping codes (modified from Ramsayer, 1979).

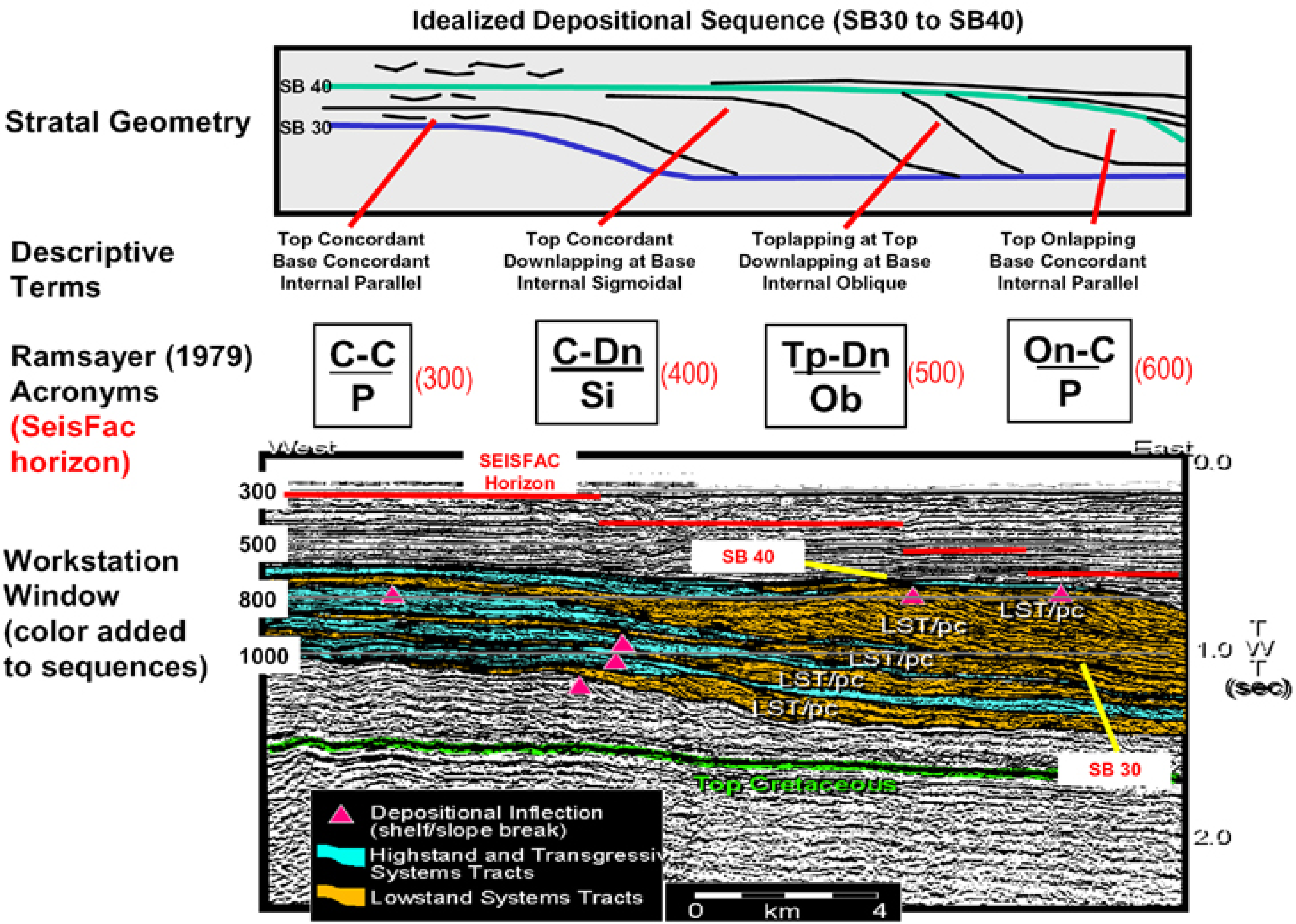


Figure 8. Using Ramsayer (1979) seismic facies code system on a workstation (seisfac horizons). Note color added to sequences for clarity. Shelf margin positions shown by pink triangles. Seismic section modified from Armentrout et al. (1993).

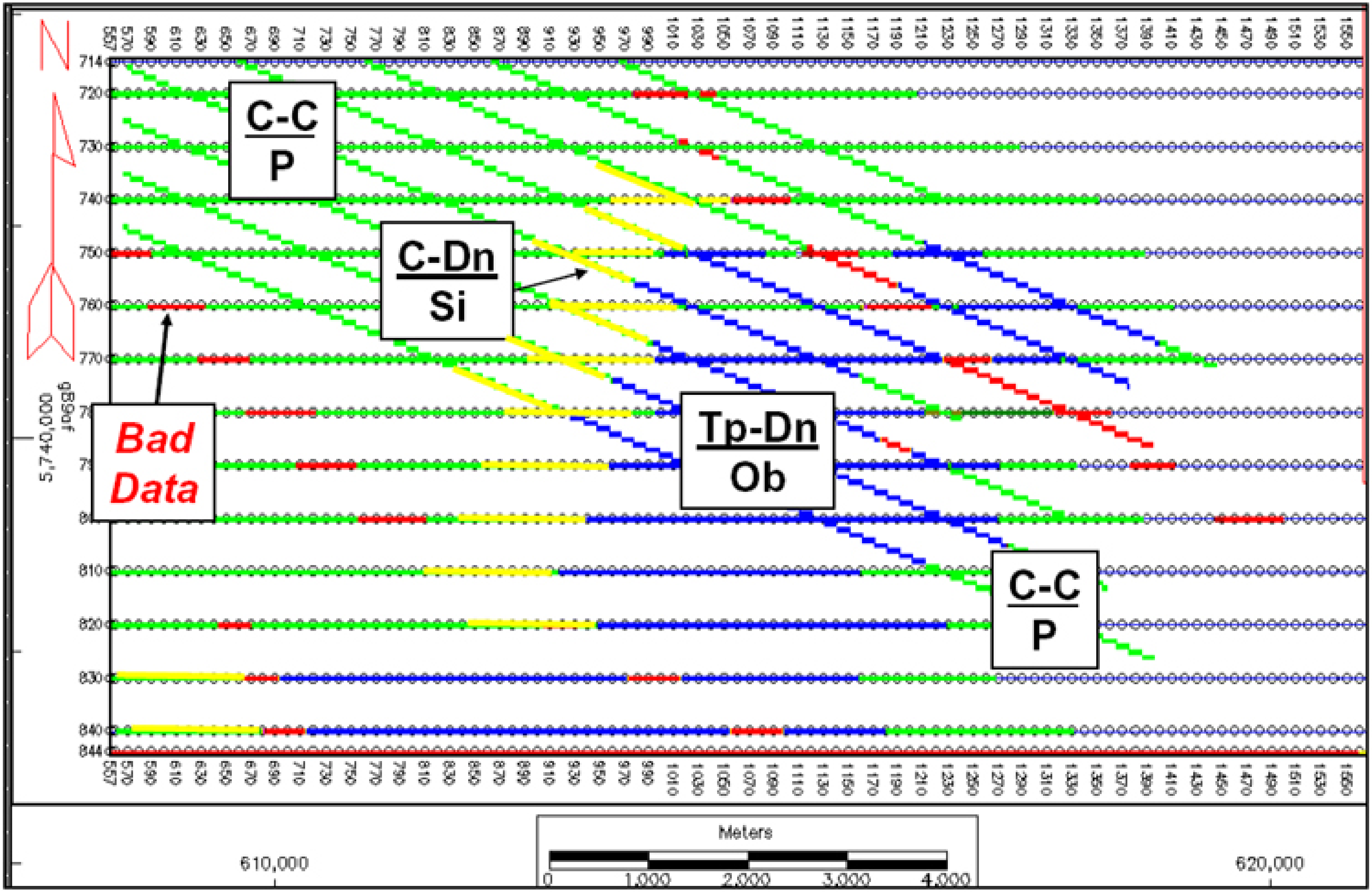


Figure 9. Workstation seismic map using Ramsayer (1979) seismic facies code system.

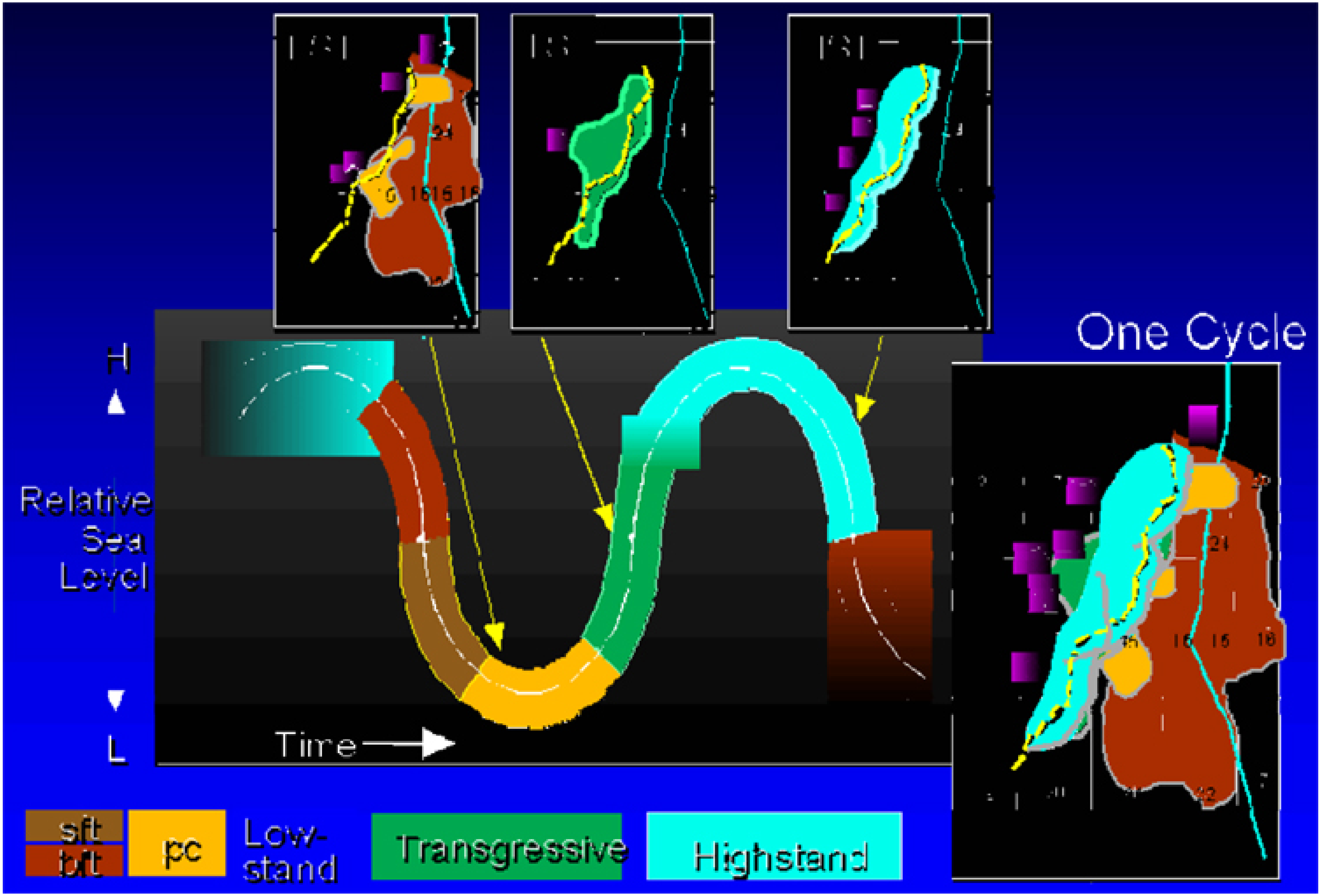


Figure 10. Importance of mapping seismic facis by systems tract (modified from Armentrout et al., 1993).

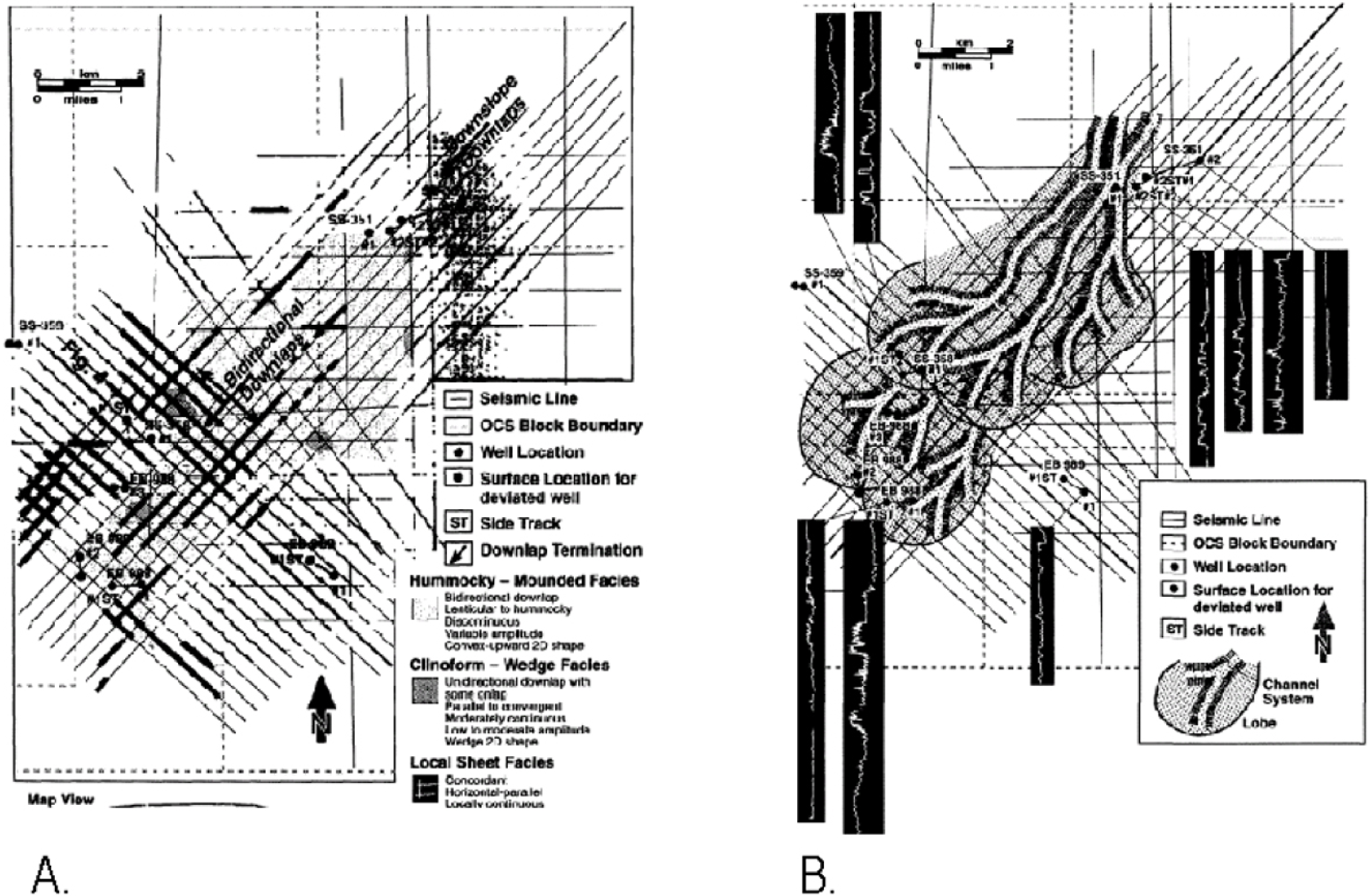


Figure 11. Interpretation of reservoir sand bodies from seismic facies (modified from Armentrout et al., 1996).

Seismic Facies with Emphasis on Amplitude Characteristics

Since Ramsayer's seminal paper in 1979, seismic facies techniques have evolved to include additional information on internal amplitude characteristics. Robust seismic facies information related to amplitude strength (high or low), continuity, and reflection frequency (**Figure 12**) can be described in qualitative terms or quantified using various software products and analysis techniques. This is particularly important in deepwater paleoenvironments as amplitude often provides critical lithologic and depositional facies information (e.g., channel axis vs. margin). Of course, the key is to calibrate seismic facies against available well control where possible (Garfield, 2000). Calibrated internal and external seismic observations provide a means of interpreting depositional systems directly from seismic in areas with little or no well control.

Seismic Facies by Trace Classification

Recent innovations in seismic facies involve use of programs that discriminate and classify seismic wavelet trace shape. The approach is used within a sequence or systems tract to differentiate seismic facies (**Figure 13**). The user defines a set of trace shapes from experience or iterative review of the data. These are plotted in map view, using color as a means of discriminating different facies. The map geometries often lend themselves readily to interpretation, in similar fashion to amplitude based maps. Once calibrated against well control, this technique can be a powerful tool and is considerably faster than maps created by hand.

Combining Seismic Facies Maps with other Maps

Confidence in seismic facies mapping can be gained by combining seismic facies maps with other types of displays such as isochron/isochore, etc., as explained below.

Isochron/Isochore Maps: These maps provide more quantitative information on the gross thickness of sequences or systems tracts and are particularly powerful when combined with overlays showing net sand, net/gross reservoir, etc. (e.g., Snedden et al., 1996). Conventional methods for isochron (seismic time) or isochore (depth-converted thickness) are employed. These thickness variations can indicate areal differences in accommodation, particularly related to differential subsidence. However, without some measure of net/sand or seismic facies, it is difficult to ascertain whether the "thicks" contain any reservoir rock. Overlays providing reservoir statistics or trends in nearby drilled areas allow inferences to be made about the depositional system (was the delta lobe nearby?). Combining this map with the stratal termination map provides a means of interpreting the observed map patterns. For example, an isochron or isochore thick located downdip of a submarine canyon and shelf-break may suggest the presence of a possible sandy submarine fan. However, such interpretations need to be referenced against regional trends and seismic amplitude maps.

Paleogeographic Maps: Traditionally, paleogeographic maps have been based on paleoenvironmental trends inferred from depositional systems analysis. Paleogeographic maps based on sequence stratigraphic correlations are truer representations of the paleogeography as they are based on stratal "timelines" observed in seismic sections. Paleogeographic maps are best constructed at the systems tract level (**Figure 10**). Mapping at the depositional sequence or level tends to average the highstand, transgressive, and lowstand systems tract trends. There can be considerable differences between the systems tracts, for example, differing shoreline trends at highstand and lowstand time. These maps are most useful when: 1) there is considerable well control (to support paleoenvironmental interpretations); and/or 2) combined with seismic facies mapping.

Paleogeographic maps are particularly useful when they represent the sum of other seismic maps. Combining seismic facies, isochron or isochore maps, and stratal observations (lapout maps) onto one map, if not too busy, provides an integrated basis for intepretation.

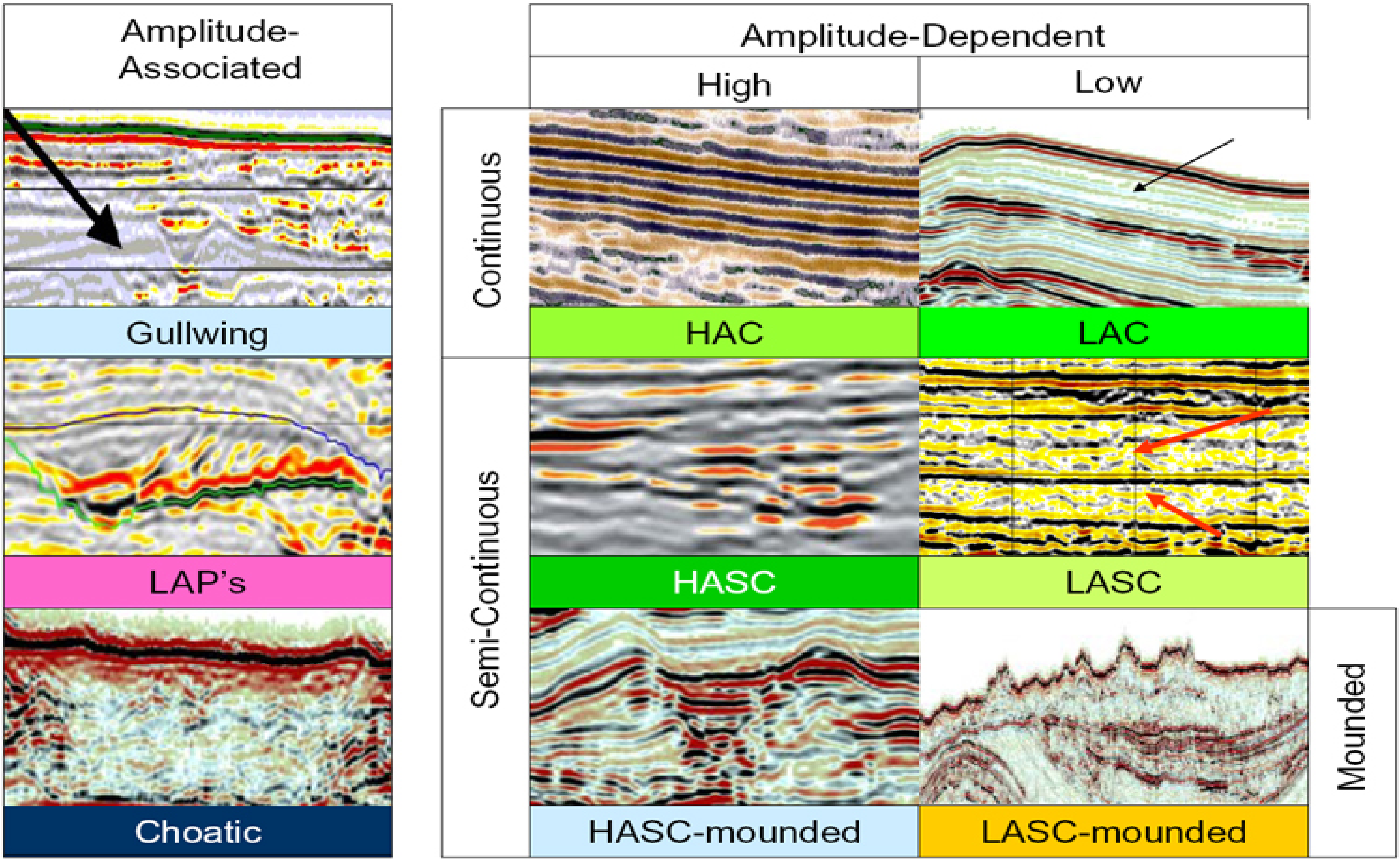


Figure 12. Examples of deepwater seismic facies types based on amplitude-associated and –dependent characteristics. Acronyms and sources: LAP's: lateral accretion packages, from Abreu et al. (2003); HAC: high amplitude continuous, from Posamentier (2002a); HASC: high amplitude semi-continuous, from Kolla et al. (2001); LASC: low amplitude semi-continuous and Gullwing, from Brami et al. (2000); LAC: low amplitude continuous, Choatic, HASC-mounded, LASC-mounded, from McGilvery and Cook (2003).

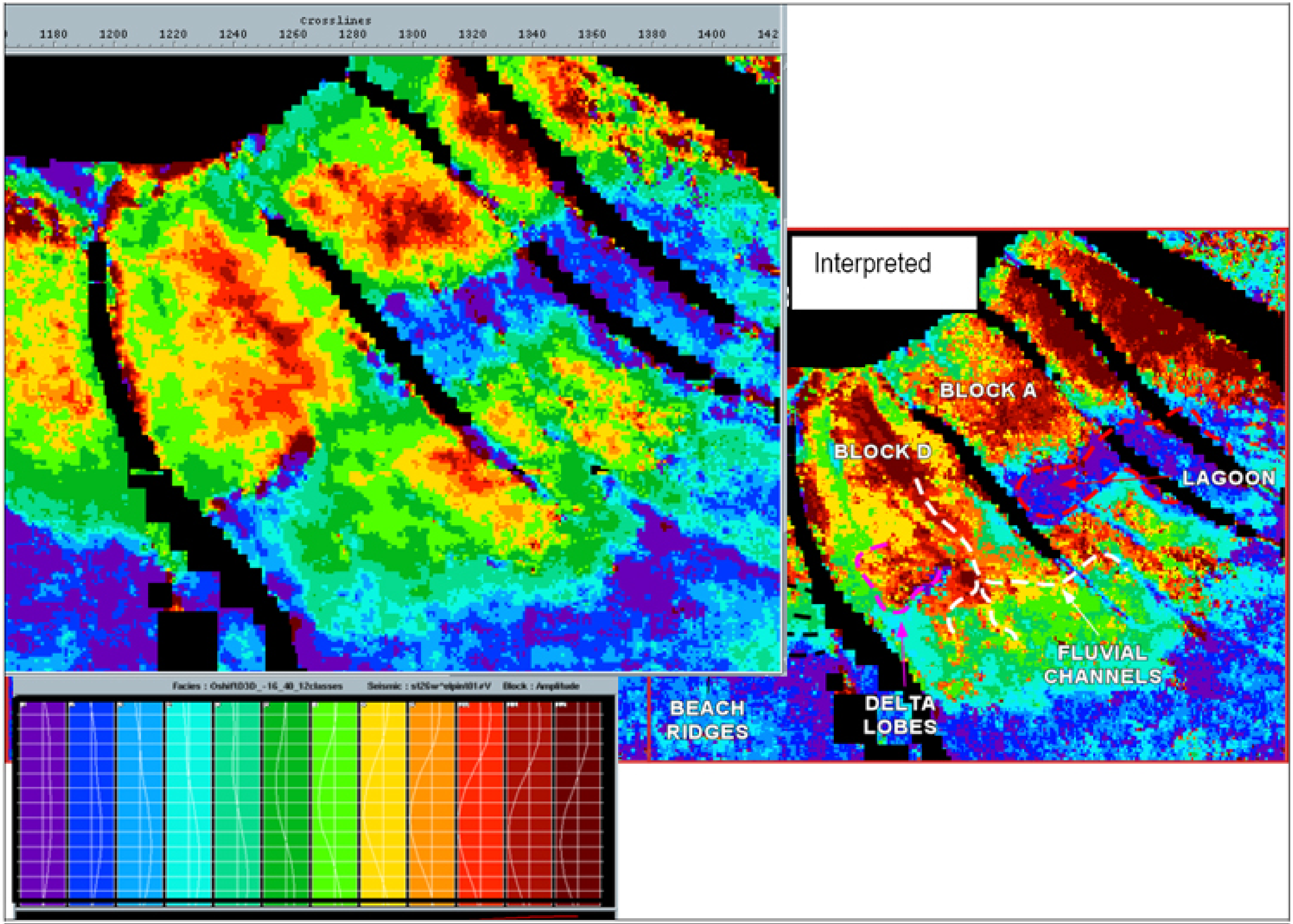


Figure 13. Example of trace classification approach to seismic facies mapping, South Timbalier-26 Field, Gulf of Mexico. Left image is uninterpreted; right shows interpretation of delta environments. Inset shows trace classification used in seismic facies mapping. Modified from Abreu et al. (2002).

Application to Petroleum Exploration and Exploitation

The major reason for developing seismic stratigraphic maps is to reduce critical risk in exploration and to extract benefit from hydrocarbon discoveries. Sequences and Sequence sets are large scale elements primarily used for global, regional, and local exploration (**Figure 14**) Field and compartment scale elements are found in parasequences, parasequence sets, and high frequency sequences (Mitchum and Van Wagoner, 1991), but these are not normally resolvable on conventional seismic data (Fulthorpe, 1991). Systems tracts (**Figure 15**) are the link between these two scales but are often under-utilized. The discussion below re-emphasizes systems tract as a part of the petroleum exploration and exploitation workflow using seismic stratigraphy.

Highstand Systems Tract (HST)

In many hydrocarbon exploration plays, many of the earliest discoveries are found in updip structural traps, which tend to be dominated by reservoirs of the HST or highstand sequence set (**Figure 16**; Snedden et al., 2002). In some high accommodation basins like West Africa or Gulf of Mexico, this scales up to the highstand sequence set level (**Figure 14**). Stratigraphic traps are less common in HSTs as strata often continue updip without significant barriers and hence are regionally "leaky" (**Figure 17**). Structural closure (anticlinal or fault-type) can provide the potential for entrapment, especially if sealed by overlying shaly TST's.

Transgressive Systems Tract (TST)

Transgressive systems tract (TST) and in high accommodation settings, the transgressive sequence sets (TSS), are the most overlooked hydrocarbon-bearing component of the sequence stratigraphic model (Posamentier, 2002b). TST's often provide lateral and top seal for LST reservoirs in the basin, when they are shale-prone, and for highstands on the shelf, when they comprise 2nd-order transgressive mudrocks. They also can contain significant source rocks facies, particularly at the second-order (Duval et al., 1998; green strata in **Figure 14**). When reservoirs are present, they tend to be more marine than those of the HST or LST, and thus more laterally continuous. Development of thick TST’s usually involves high local subsidence (e.g., growth fault wedges).

Lowstand Systems Tract (LST)

The lowstand systems tract (LST; **Figure 15**) and lowstand sequence sets (LSS; **Figure 14**) are the most controversial and yet often the most economically important elements of any sequence (Posamentier et al. 1992). Much attention has been devoted to LSTs as the greatest remaining potential in many plays lies in deeper and depositional downdip areas (**Figure 16**), where LST/LSSs are more common than HST/HSS’s and TST/TSS's (Snedden et al., 2002). The potential for stratigraphic entrapment is also greater, as strata do not generally continue updip (**Figure 17**).

The presence of a significant relative sealevel fall causes a major basinward shift in onlap, particularly when shifted seaward of the offlap break. Mid-shelf LST's can also occur (incised valley-fill of Van Wagoner et al., 1990). A common motif on seismic is often toplap/downlap couplets, with toe of clinoform debris wedges or sandstones. These are typically sand rich, although carbonates can also form (the downdip oolite play of the Permian basin).

The vertical succession in a LST prograding complex is (bottom to top): downlap, progradation, toplap, aggradation, and floodback (**Figure 17**). Earlier models for deepwater settings suggested that there may be three parts to the LST: the basin-floor systems (distributary channel and sheet), slope channel systems (confined to weakly confined), and the prograding complex (LSWpc; Mitchum et al., 1994). Basin-floor systems sometimes show double downlap while the prograding complex shows toplap/downlap lapouts. Slope systems exhibit incision, lateral truncation of reflections, and complex filling geometries. These can greatly impact the internal fluid connectivity of a deepwater reservoir within the LST.

More recent work suggests that deepwater systems are very complex arrangements reflecting shelf margin evolution, sediment load, climate, eustacy, and other factors. The methodologies for stratigraphic correlation, interpretation, and mapping in these complex, hierarchical deepwater channel systems are well defined and described in documents at these chapters.

The lowstand systems tract prograding complex (LSWpc) can be confused with the highstand systems tract, as both are progradational. However, there are ways to differentiate the two systems, which have important implications for hydrocarbon entrapment (**Figure 17**). The LSWpc typically is dip-restricted, with strata not continuing updip vs. the more continuous HST. As a result, all other factors being equal, the HST's tend to have less potential for lateral sealing than the LSWpc. Stratal terminations at the top of a HST tend to be tangential to non-terminated, versus toplap patterns in LSWpc's. The stacking patterns also differ, as LSWpc show early progradational and late aggradational patterns on logs, versus HST's with early aggradation and late progradational motifs

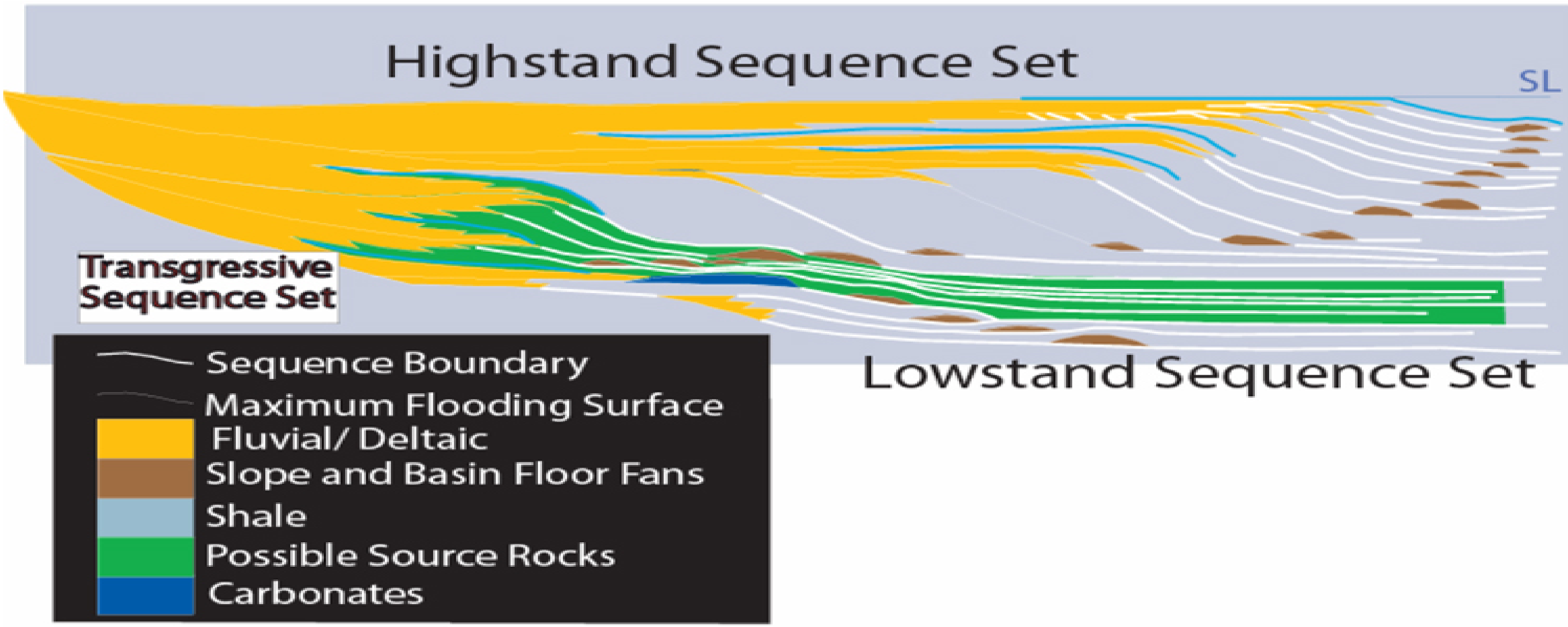


Figure 14. Sequence sets. Modified from Vail et al (1987).

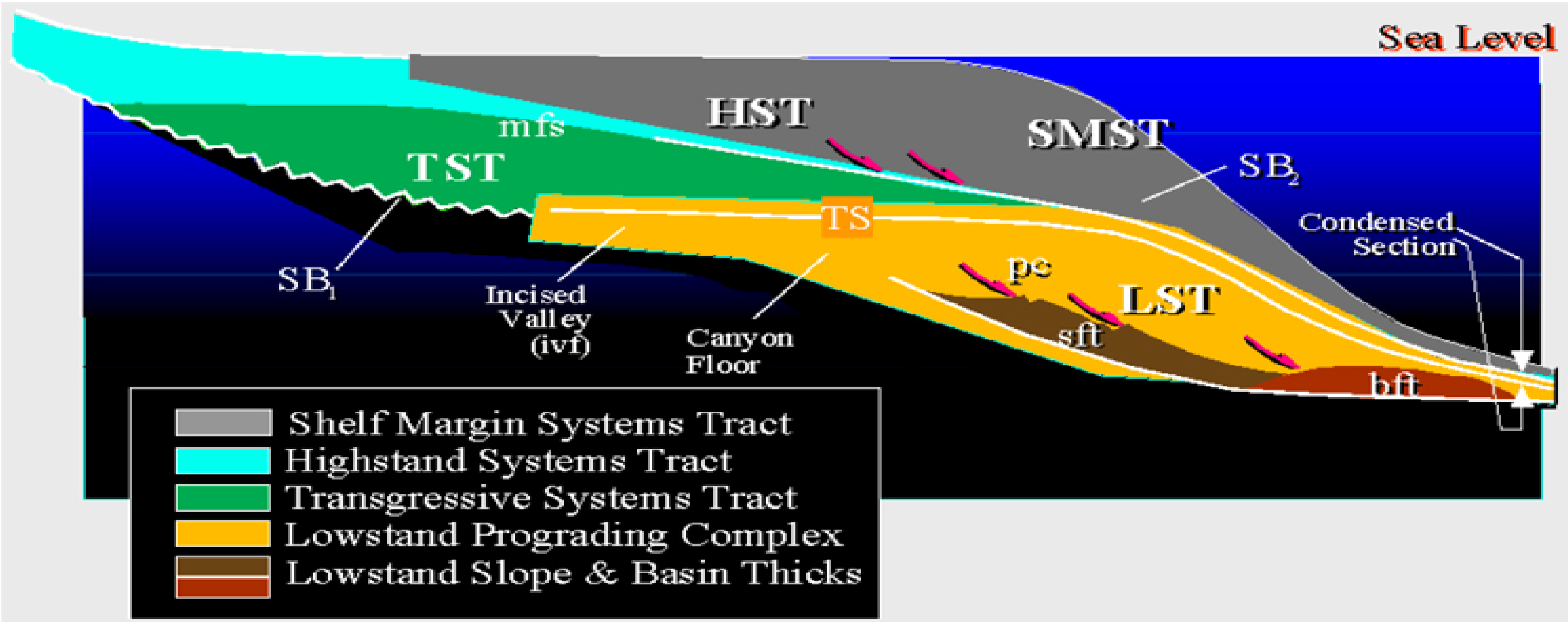


Figure 15. Systems tracts: Highstand, transgressive and lowstand. Modified from Vail et al. (1987).

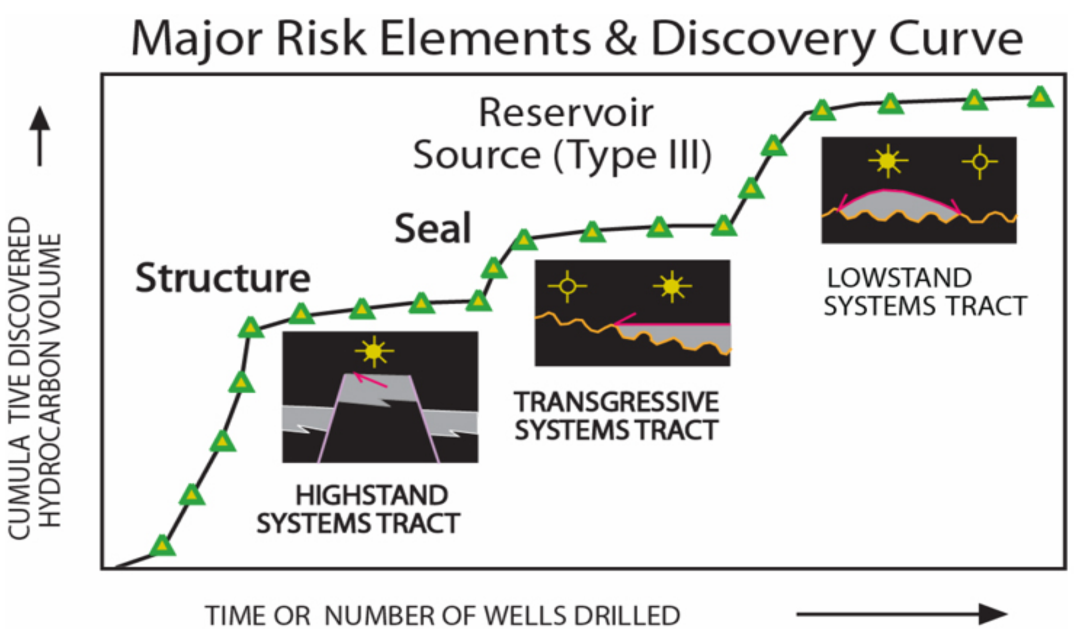


Figure 16. Creaming curve (cumulative discovered volumes vs. time) from a sequence stratigraphic standpoint (modified from Snedden et al., 2002). Major risk elements shown.

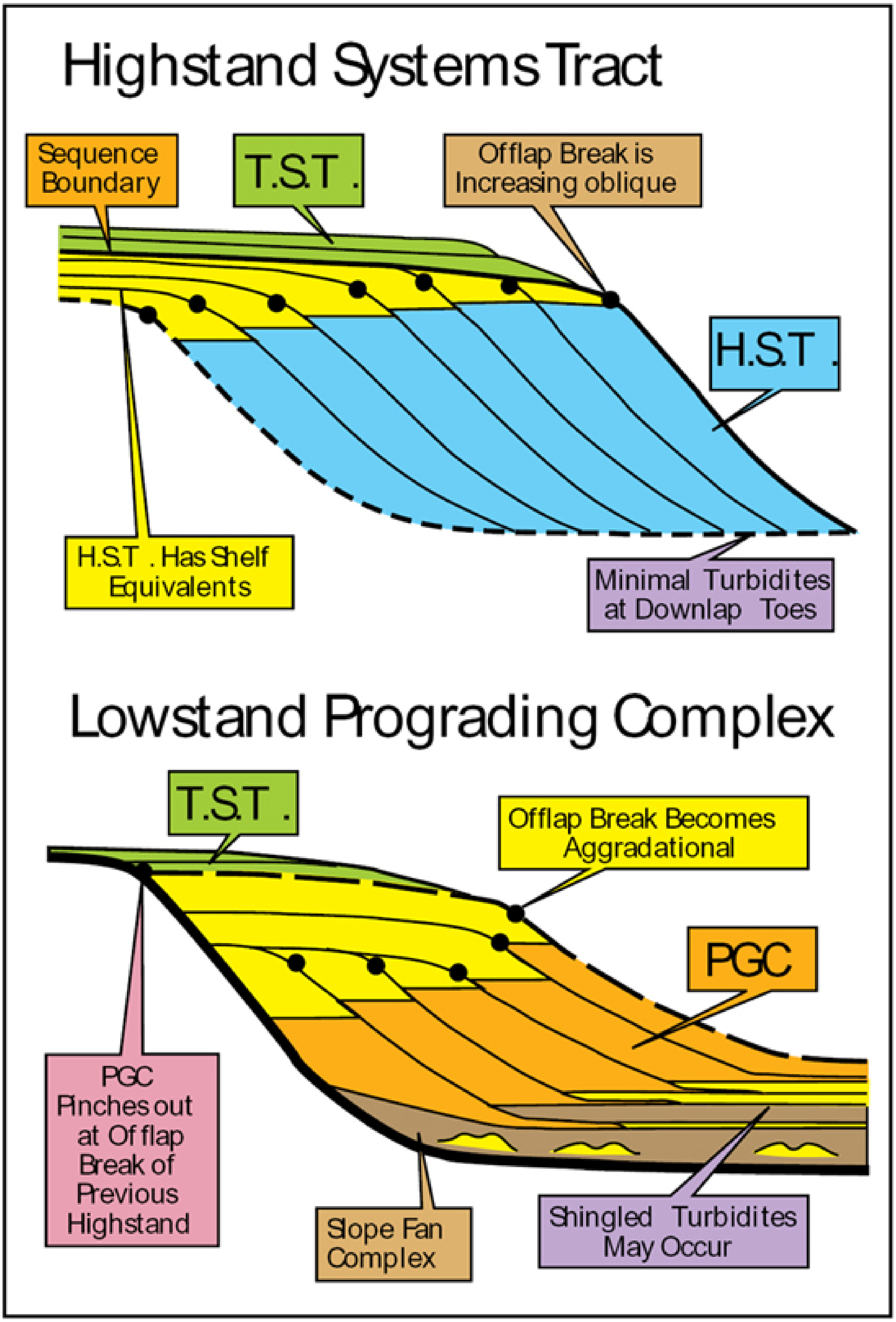


Figure 17. Highstand vs. Lowstand systems tract prograding complex (LSWpc). Modified from Mitchum et al. (1994). Note inherent differences in trapping potential between the HST, which usually requires a structural component, and the LSWpc, which is dip-restricted.

Key Questions

One measure of the value of a seismic stratigraphic mapping effort is seen in the ability to address and answer the following key questions:

a) **Is the petroleum system complete?** Is there a critical missing element which will fatally flaw the petroleum system and prevent discoveries in un- or under-explored basin?

It is recommended to use the resulting products (cross-sections and maps) to identify source and seals, not just reservoir rocks. For marine source rock mapping, recognition of the large scale, major downlaps (maximum flood) of major continental encroachment cycles is a good starting place (for more detail, see Duval et al., 1998).

It is also useful to relate to worldwide eustatic charts and known source bed events. For example, Klemme and Ulmishek (1991) determined that six stratigraphic intervals have provided 90% of the world's discovered original reserves of oil and gas (Silurian-9%, U. Devonian-Tournasian-8%, Pennsylvanian/Lower Permian-8%, Upper Jurassic (25%), Mid-Cretaceous-29%, Oligo-Miocene (12.5%)).

b) **Are certain systems tracts under- or unexplored?** In a recent survey of Texas onland plays, it was determined that nearly one-third of the plays produced from only one systems tract, with the highstand systems tract containing nearly 70% of the produced hydrocarbons (Snedden et al., 2002). It is evident that in many plays, the lowstand systems tract is underexplored

c) **Can the sequence stratigraphic model built here explain the present distribution of fields and dry holes?** Do the downdip dry-holes define a poorly developed lowstand systems tract, or just the distal limits of the highstand systems tract? In some basins, there is a zone of bypass between the HST and LST, which can be misinterpreted.

d) **If the lowstand system tract play corridor can be identified, are downdip prospects located in the major deltaic fairway or marginal to it?** Even the world's greatest basinward shift will fail to send sand into a basinal area of interest if no updip deltaic source is present or an appropriate conduit for sand delivery is not in proximity. It is critical to be in the sand "fairway"!!

e) Finally, **identify possible play types for prospectors**: e.g., pre-orogenic HST, if sealed by syn-orogenic shales; LST, if detached and sealed. TST, if sealed by MFS and sourced by 2nd-order TST shales.

Summary and Conclusions

This document is meant to be used as a working guide to seismic stratigraphic interpretation and not to be used as a strict set of best practices or conceptual basis for sequence stratigraphic interpretation. It is a gross representation of regional to lead level analysis, and is not meant to substitute for normal prospect definition or upgrading to RTD (ready-to-drill) status.

Much of the methodology described here and in this volume involves interpretation on paper sections and handmade well-ties (paper to paper). Much of any company’s seismic interpretation today is done on a seismic workstation. **The use of paper sections is most useful at the early stages of a**

project, as geoscientists seek to make correlations and establish criteria for identifying horizons. Once a seismic stratigraphic framework is established on some paper sections (hero lines), the geoscientists can make better interpretations and often faster ones, as no delays occur when multiple interpreters cannot agree on correlations, terminology, or ages. Interpretation is then taken to the workstation for efficient and optimized mapping.

Acknowledgements

The authors appreciate the assistance of Kurt Johnston (EMEC) in preparing seismic examples for this document. ExxonMobil is thanked for permission to publish this document. John Armentrout provided many insights on scale, hierarchy, and source rocks.

References and Further Reading

Abreu, V., M. Sullivan, C. Pirmez, and D. Mohrig, 2003, Lateral accretion packages (LAPs): an important reservoir element in deep water sinuous channels: Marine and Petroleum Geology, v. 20, p. 631-648.

Abreu, V., P. Teas, Thomas De Brock, Kendall Meyers, Williams Spears, Steve Pierce, and Dag Nummedal, 2002, Reservoir characterization of the South Timbalier 26 Field: The importance of shelf margin deltas as reservoirs in the Gulf of Mexico: AAPG Bulletin, v. 86, p. 212.

Armentrout, J. M., 1991, Paleontologic constraints on depositional modeling: examples of integration of biostratigraphy and seismic stratigraphy, Plio-Pleistocene, Gulf of Mexico, *in* Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems, p. 137-170.

Armentrout, J.M., S.J. Malecek, L.B. Fearn, C.E. Sheppard, P.H. Naylor, A.W. Miles, R.J. Demarais, and R. E. Dunay, 1993, Log motif analysis of Paleogene depositional systems tracts, Central and Northern North Sea: defined by sequence analysis, *in* J.R. Parker, ed., Petroleum Geology of Northwest Europe, Proceedings of 4th Conference. p. 45-57.

Armentrout, J.M., S.J. Malecek, V.R. Mathur, G.L. Neuder, and G.M. Ragan, 1996, Intraslope basin reservoirs deposited by gravity-driven processes: Ship Shoal and Ewing Banks areas, Offshore Louisiana: GCAGS Transactions, v. 46, p. 443-448.

Bally, A.W., 1982, Atlas of Seismic Stratigraphy, AAPG Studies in Geology no. 27, 300 p.

Brami, T. R., C. Pirmez, C. Archie, S. Heeralal, and K.L. Holman, 2000, Late Pleistocene deep-water stratigraphy and depositional processes, Offshore Trinidad and Tabago: GCS-SEPM, v. 20, p. 104-115.

de Graciansky, P. et al., 1998, Mesozoic and Cenozoic Sequence Stratigraphy of European Basins: SEPM Special Publication no. 60, 786 p.

Duval, B.C., C. de Janvry, and B. Loiret, 1992, Detailed geoscience reinterpretation of Indonesia's Mahakam delta scores: Oil and Gas Journal, p. 67-72.

Duval, B.C., C. Cramez, and P.R. Vail, 1998, Stratigraphic cycles and major marine source rocks, *in* P. de Graciansky et al., eds., Mesozoic and Cenozoic Sequence Stratigraphy of European Basins: SEPM Special Publication no. 60, p. 43-52.

Fulthorpe, C. S., 1991, Geological controls upon seismic sequence resolution: Geology, v. 19, p. 61-65.

Garfield T R., 2000, New insight into the three-dimensional architecture of deep-water facies; the product of a multidisciplinary approach**.** Anonymous, *in* Brazil 2000; 31st international geological congress; abstract volume. International Geological Congress Abstracts = Congres Geologique International, Resumes. 31; unpag.

Greenlee, S.P., 1992, Integrated sequence stratigraphy of Neogene deposits, New Jersey continental shelf and slope: comparison with Exxon model: GSA Bulletin, v. 104, p. 1403-1411.

Haq, B.U., J. Hardenbol, and P.R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156.

Klemme H.D., and G.F. Ulmishek, 1991, Effective petroleum source rocks of the world; Stratigraphic distribution and controlling depositional factors. AAPG Bulletin, v. 75, p. 1809-1851.

Kolla, V., Ph. Bourges, J-M. Urruty, and P. Safa, 2001, Tertiary sinuous channels, offshore Angola,(West Africa) and implications for reservoir architecture: AAPG Bulletin, v. 85, no. 8, p. 1373-1405.

Mansor, Y., J.W. Snedden, J.F. Sarg, B.S. Smith, T.H. Kolich, and M.H. Carter, 1999, Pre-drill predictions versus post-drill results: Use of sequence stratigraphic methods in reduction of exploration risk, Sarawak deep-water blocks, Malaysia: Journal of Asian Earth Sciences, v. 17, p. 247-254.

McGilvery, T.A., and D.L. Cook, 2003, The influence of local gradients on accommodation space and linked depositional elements across a stepped slope profile, Offshore Brunei, 2003, GCS-SEPM; v. 23, p. 387-420.

Mitchum, R.M., Jr. and J.C. Van Wagoner, 1991, High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency eustatic cycles: Sedimentary Geology, v. 70, p. 131-160.

Mitchum, R.M., Jr., J.B. Sangree, P.R. Vail, and W.W. Wornardt, W. W., 1994, Recognizing sequences and systems tracts from well logs, seismic data, and biostratigraphy: Examples from the Late Cenozoic of the Gulf of Mexico, *in* P. Weimer and H. W. Postamentier, eds, AAPG Memoir 58, p. 163-197.

Posamentier, H.W., G.P. Allen, D.P. James, and M. Tesson, 1992, Forced regressions in a sequence stratigraphic framework: Concepts, examples, and exploration significance: AAPG Bulletin, v. 76, p. 1687-1709.

Posamentier, H.A., 2002a, Sequence stratigraphy: Past, present, future and the role of 3D seismic: GCS-SEPM, p. 37-54.

Posamentier, H.W., 2002b, Ancient shelf ridges-a potentially significant component of the transgressive systems tract: Case study from offshore northwest Java: AAPG Bulletin, v. 86, p. 75-106.

Ramsayer, G.R., 1979, Seismic stratigraphy, a fundamental exploration tool: 11th Annual Offshore Technology Conference Proceedings, p. 101-109.

Sarg J.F.; and P.J. Lehmann., 1986, Lower-middle Guadalupian facies and stratigraphy, San Andres / Grayburg formations, Permian Basin, Guadalupe Mountains, New Mexico, *in* George E. Moore and Garner L. Wilde eds., J.F.Sarg, leader, Lower and Middle Guadalupian Facies, Stratigraphy, and Reservoir Geometries; San Andres / Grayburg Formations, Guadalupe Mountains, New Mexico and Texas: Permian basin Section – SEPM Symposium and Guidebook 86-25, p. 1-8.

Snedden, J.W., J.F. Sarg, M.J. Clutson, M. Maas, T.E. Okon, M.H. Carter, B.S. Smith, T.H. Kolich, and Md. Y. Mansor, 1996, Using sequence stratigraphic methods in high-supply deltas: examples from the ancient Mahakam and Rajang-Lupar deltas: Proceedings, Indonesian Petroleum Association, 25th Annual Convention, p. 281-295.

Snedden, J.W., J.F. Sarg, and Xudong Ying, 2002, Exploration play analysis from a sequence stratigraphic perspective: GCS-SEPM Foundation Research Conference Proceedings, p. 79-97.

Thompson, L.B., and J.W. Snedden, 1996, Geology and reservoir description of 1Y1 reservoir, Oso Field, Nigeria, using FMS and dipmeter, in J.A. Pacht, and R.E. Sheriff, eds., Stratigraphic Analysis Utilizing Advanced Geophysical, Wireline, and Borehole Technology for Petroleum Exploration and Production: GCS-SEPM 17th Annual Research Conference, p. 1-11.

Van Wagoner, J.C., et al., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* C.K. Wilgus et al., eds., Sea-level Changes, An Integrated Approach: SEPM Special Publication no. 42, p. 39-46.

Van Wagoner, J.C., et al., 1990, Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for High-Resolution of Correlation of Time and Facies: AAPG Methods in Exploration Series no. 7, 55 p.

Vail, P.R., R.M. Mitchum, Jr., and R.G. Todd, 1977, Seismic stratigraphy and global changes of sealevel, *in* Seismic Stratigraphy--Applications to Hydrocarbon Exploration: AAPG Memoir 26, p. 49-212.

Vail P R., 1987, Seismic stratigraphy interpretation using sequence stratigraphy; Part 1, Seismic stratigraphy interpretation procedure, *in* A.W. Bally, ed. Atlas of Seismic Stratigraphy: AAPG Studies in Geology no. 27; v. 1, p. 1-10.