Exploration Play Analysis from a Sequence Stratigraphic Perspective

By

John W. Snedden[1], J. F. (Rick) Sarg[1], and Xudong (Don) Ying[2]

Search and Discovery Article #40079 (2003)

[1]ExxonMobil Exploration Company, P.O. Box 4778, Houston, Texas 77210-4778
(john.w.snedden@exxonmobil.com; rick.sarg@exxonmobil.com)

[2]ExxonMobil Upstream Research Company, P.O. Box 2189 · Houston, TX. 77252-2189
(don.ying@exxonmobil.com)

Abstract

Examination of exploration drilling histories for many different global basins indicates a counter-intuitive temporal and spatial pattern in the way hydrocarbons are sometimes discovered. Conventional wisdom holds that for any given basin or play, a plot of cumulative discovered hydrocarbon volumes versus time or number of wells drilled usually show a steep curve (rapidly increasing volumes) early in the play history and a later plateau or terrace (slowly increasing volumes). Such a plot is called a creaming curve, as early success in a play is thought to inevitably give way to later failure as the play or basin is drilled-up. It is commonly thought that the "cream of the crop" of any play or basin is found early in the drilling history.

By examining plays or basins with sufficiently long drilling histories and range of reservoir paleoenvironment and trap types, one actually finds two or three "terraces" to the creaming curve. The first string of successes in a given basin usually corresponds to exploitation of the highstand systems tract or sequence set reservoirs developed in updip structural traps. These reservoirs are typically marginal to shallow marine "shelfal" deposits, laterally continuous but lacking internal sealing facies and are seldom self-sourcing. The second or third terrace in the creaming curve usually involves the lowstand reservoir component (systems tract or sequence set), which is often developed in downdip deepwater or slope paleoenvironments. Transgressive (systems tract or sequence set) reservoirs, typically shallow marine shelfal sandstones that are sometimes self-sourced, are variably developed and may or may not occupy the second terrace of the creaming curve. These trends hold true for both 2nd-order (3-10 my) and/or third-order (1-3 my) stratigraphic cycles, depending upon the scale of the basin or play.

This analysis fits well with the definition of an exploration play provided by Magoon and Sanchez (1995): a fully developed play is the simple volume difference between the petroleum system capability and the current discovered hydrocarbon volumes (commercial or not). Where the difference is large, either the petroleum system has significant leakage problems (e.g., Barents Sea Mesozoic play) or the lowstand systems tract or sequence set has not been fully exploited.

Examples supporting these ideas are drawn from several global basins (Gulf of Mexico Miocene, Norway Upper Jurassic, Mahakam Delta, Texas Wilcox). Case studies demonstrate how critical elements of exploration risk shift from trap and seal in highstand plays to reservoir and source in lowstand components of these plays.

Introduction

One of the most critical tasks faced by petroleum industry geoscientists relates to the decision to enter into an exploration play or basin. Equally important is the timing of entry and if, unsuccessful, the timing of an exit from the play or basin. These judgments are as important as the decision to drill individual prospects in a play or basin (Brown and Rose, 2002).

Explorationists use a variety of methods to evaluate oil and gas plays. One of these is the "creaming curve", basically a graph of cumulative discovered hydrocarbon volumes versus time or number of wells drilled (Figure 1). This type of plot, formalized by Meisner and Demirmen (1981), is used to forecast future exploration success in a petroleum province by determining if discoveries are on a general rising trend (immature play) or a constant trend of cumulative volumes (mature play). Implicit in this analysis is the assumption that the largest discoveries in a play are made first and later exploration drilling tends to find progressively smaller volumes. The key to economic success is to enter the play and find the "cream" or exit the play once the largest and most economically attractive fields have been delineated by drilling (terrace of Figure 1).

One example of the diminishing effectiveness of exploration effort with advancing drilling is illustrated by the Middle Jurassic play of the United Kingdom, Norway, and Denmark (Figure 2). The creaming curve is quite steep in the years 1970 to 1980 when the giant oil fields of Brent, Beryl, Statfjord, Oseberg and others were discovered. Hydrocarbons are primarily trapped in large structural closures and non-marine to shallow marine sandstone reservoirs of the Brent Group (Johannessen *et al*., 1995). Success in this Middle Jurassic play slowed after 1980 as indicated by the plateau in the creaming curve. The first eight years of exploration in this play yielded about 77% of the reserves, on a estimated ultimate reserve basis (Berge, 1997).

However, this simple creaming pattern of a rising limb (immature phase) and a long, final plateau (mature phase) is not universal. Some plays exhibit more complex histories of drilling success, with multiple rising limbs and plateaus, suggesting that other factors are at work (Figure 3).

One could explain more complex play histories from a sequence stratigraphic standpoint. In fact, the sequence stratigraphic model predicts that an ideal creaming curve for an exploration play should actually have two or three-paired rising limbs and plateaus (Figure 4; Snedden *et al*., 1996a). The first set of discoveries (first rising limb) often are the highstand (sequence set or systems tract) structural traps which tend to be the first targets of exploration, typically onshore or in shelfal waters, reservoired in shallow marine siliciclastics. Often, the hydrocarbons are found in a stacked series of shallow water sandstones forming highstand systems tract assemblages or larger scale highstand sequence sets (Figure 5).

The sequence stratigraphic paradigm (Figure 4) would also explain or predict a second set of paired rising limb and plateau as exploration advances basinward, possibly discovering reservoirs in the transgressive systems tract (TST) or transgressive sequence set (TSS). However, experience has shown that the TST or TSS may or may not be well developed in thickness or extent. The transgressive component can be thin in passive margins, shale-prone in muddy depositional systems or eroded during subsequent lowstands (Greenlee *et al*., 1992; Mitchum *et al*., 1994)

The second or third pair of rising limbs and plateaus (Figure 4) often come from discoveries in lowstand systems tract (LST) or lowstand sequence set (LSS) reservoirs and traps. There are several reasons for this observed pattern. Exploration for lowstand reservoirs often involves: 1) more subtle, stratigraphic traps; 2) more complex, laterally discontinuous (over large areas) deepwater siliciclastic reservoirs; 3) deeper water drilling depths; or 4) areas with complex slope salt tectonics, uncertain source rocks, and higher overall exploration risk.

After providing definitions of key terms, this paper will describe several exploration plays which display more complex histories on creaming curve graphs. Analysis of these plays will demonstrate that the sequence stratigraphic paradigm can explain such patterns, which could alternatively be attributed to non-natural factors like progressive technology development, government policy-making, oil and gas pricing trends, etc. By understanding the scientific basis for such patterns, one may be able to predict similar trends in the future, which is an important goal for any geoscientist faced with the decision to enter or exit an exploration play or basin.

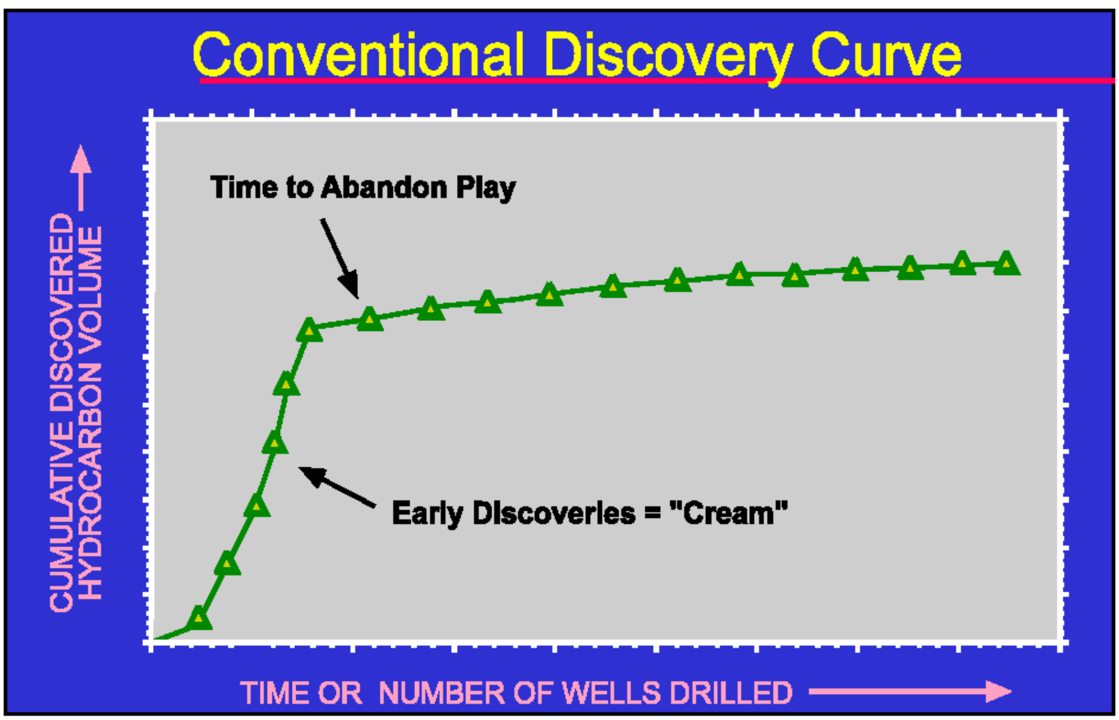

Figure 1. Idealized simple creaming curve (cumulative discovered volumes versus time).

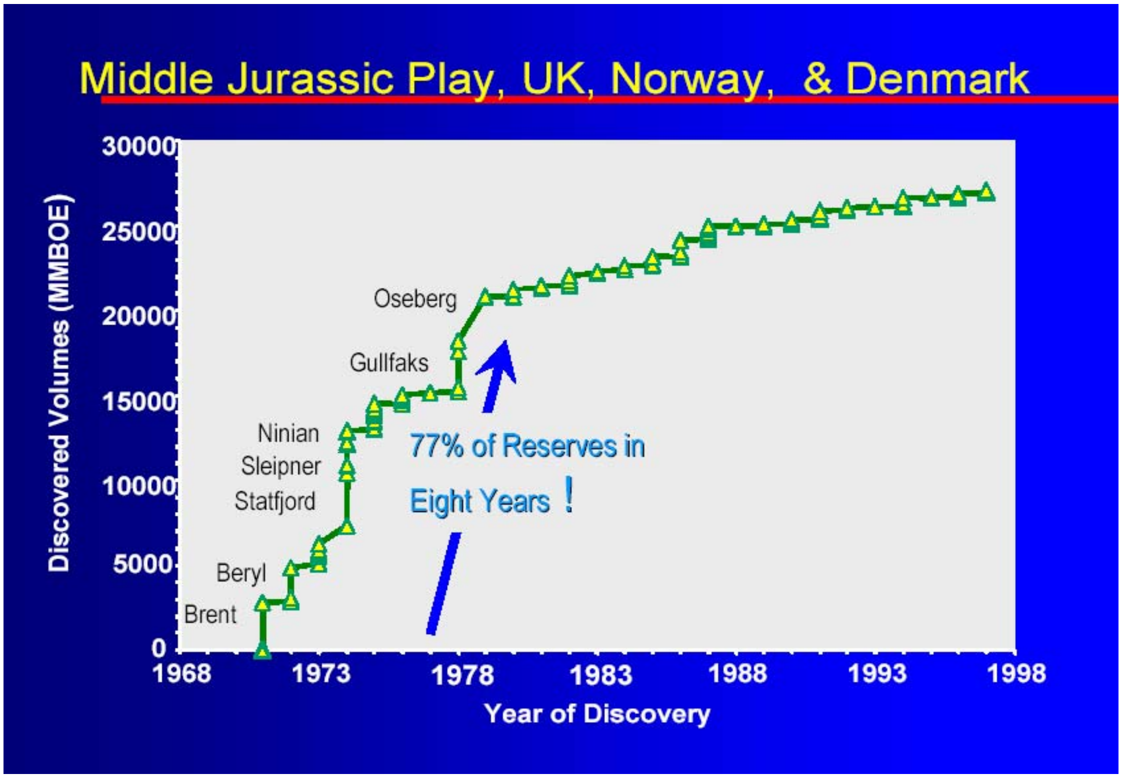

Figure 2. Creaming curve for the Middle Jurassic Play, United Kingdom, Norway, and Denmark. Data from Berge (1997). MMBOE=million barrels oil equivalent.

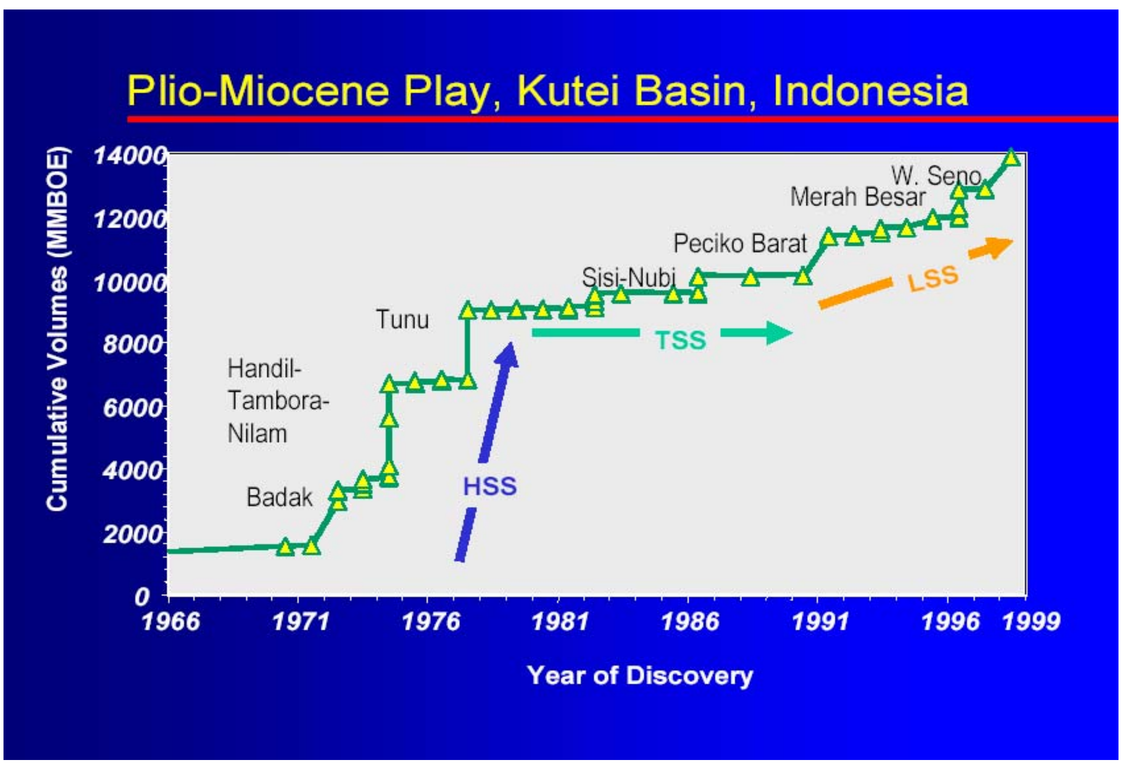

Figure 3. Creaming curve for the Kutei Basin. Data from Ahlbrandt (2000), Petroconsultants (1998), and Steinshouser et al. (1999). MMBOE=million barrels oil equivalent. HSS= highstand sequence set; TSS=transgressive sequence set; LSS=lowstand sequence set. Stratigraphic model in Figure 14.

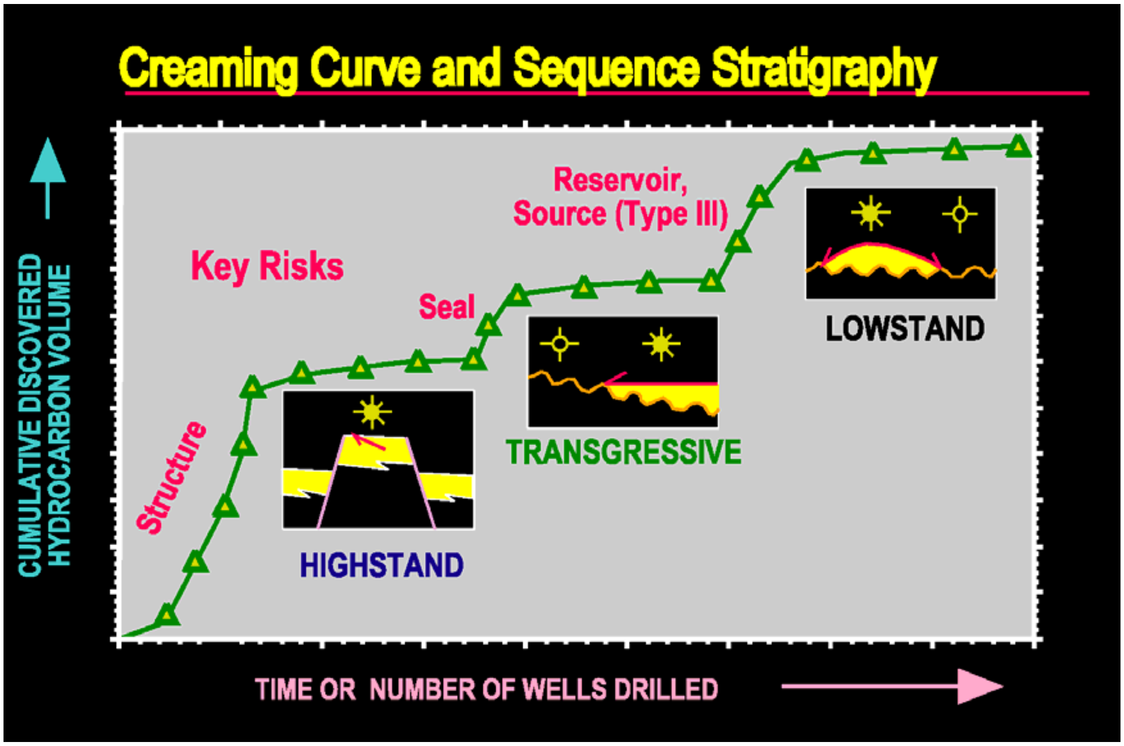

Figure 4. Idealized creaming curve from a sequence stratigraphic perspective. The components of the creaming curve refer to systems tract or sequence set, depending upon the size and scale of the play being considered.

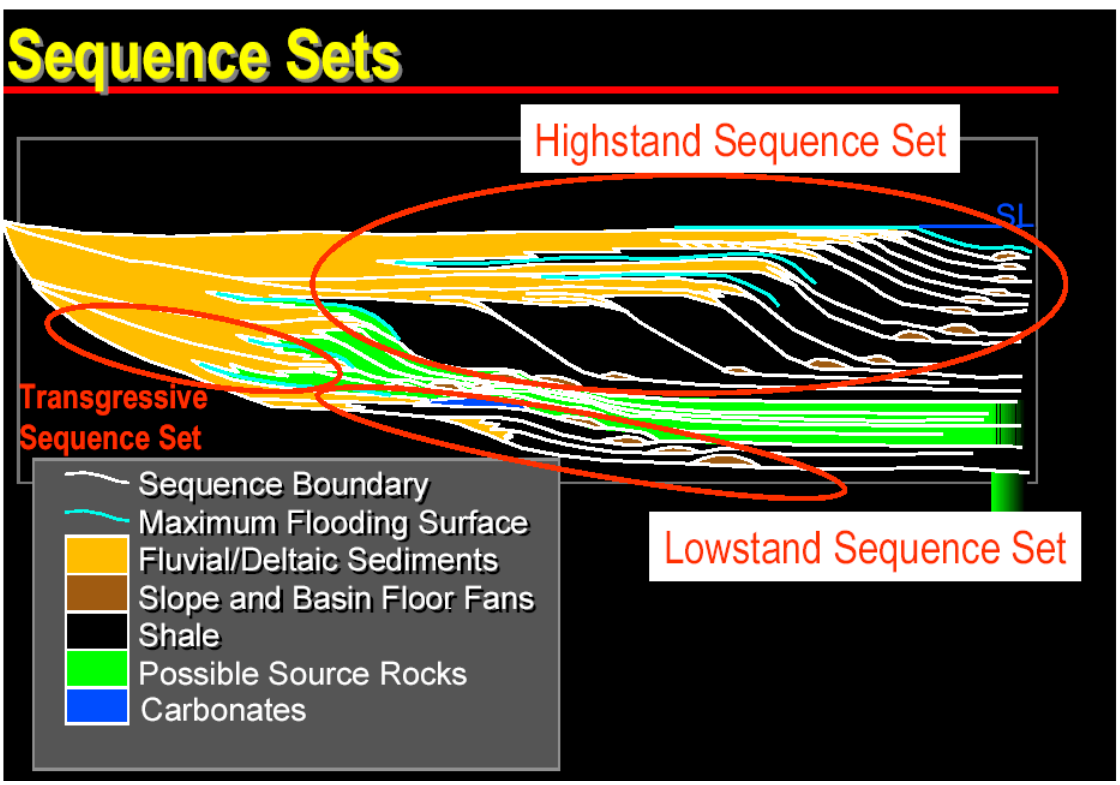

Figure 5. Idealized succession of lowstand, transgressive, and highstand sequence sets, each made up of sequences with embedded third-order lowstand, transgressive, and highstand systems tracts. Modified from Bartek *et al.* (1991).

Definitions

The creaming curve method of analysis focuses upon a petroleum province in a given geographic area with known commercial accumulations. The petroleum province being analyzed need not have distinct geologic, tectonic, or oil-accumulation properties or boundaries (Meisner and Demirmen, 1981). In practice, the creaming method is typically applied to exploration plays, following the definition of an exploration play as provided by Magoon and Sanchez (1995): a play emphasizes traps but also includes hydrocarbon charge and timing. This expanded definition for an exploration play aligns the concept with that of a petroleum system, an assemblage of elements such as reservoir, source, trap, seal, migration pathway, etc. that allow accumulation of oil and gas (Magoon and Dow, 1994).

In relatively large petroleum provinces like the U. S. Gulf of Mexico Basin, one could argue that exploration plays like the Miocene trend are actually assemblages of several plays, each with unique characteristics of reservoir, entrapment, etc. However, we have stayed at a fairly general level when considering exploration plays in order to meet the original criteria set forth by Meisner and Demirmen (1981) for creaming curve analysis: a sufficiently large data set of drill wells and discovered field sizes. Breaking an exploration play down to a relatively small subset of plays obviously reduces the number of wells and fields and thus greatly limits the historical range needed to do creaming analysis. For example, the Gulf of Mexico sub-salt play could be divided into five different trapping configurations but with very limited drilling histories (Lawrence, 1997). We have also combined oil and gas into barrels oil-equivalent, in order to avoid biasing the trends toward gas which tends to increase as drilling moves deeper into the subsurface.

Many of the plays discussed in this paper cover thick stratigraphic intervals where interpretations are made at the 2nd-order level, as per the definitions of Mitchum and Van Wagoner (1991). In these thick successions, stacked packages of sequences make up individual highstand, transgressive, or lowstand sequence sets (Figure 5). Embedded within these sequence sets and sequences are the individual systems tracts where stacked reservoirs form the main field pay zones. For example, the lowstand systems tract in progradational (highstand) sequence sets often contains a high percentage of the net reservoir thickness (e.g., Hentz *et al*., 2002). These lowstand systems tract reservoirs (incised valley-fill, slope channels, etc) are often located within the shelf domain for the lower-order sequence set, giving rise to some confusion when discussing the depositional position on the shelf to basin profile (Figure 5). The vertical stacking patterns of these successions give some hint as to the long-term trend of relative sea level and accommodation. These criteria are used to define the sequence sets and systems tracts in the cases described. In some cases, global charts (e.g., de Gracianksy *et al*., 1999) can used to define the sequence sets, where biostratigraphic data is convincing.

Miocene Play, Gulf of Mexico, USA

The Miocene play of the Gulf of Mexico clearly meets the criteria for creaming curve analysis as it has a sufficiently long exploration history, extending back as far as the 1940’s (Figure 6). In addition, The Miocene play encompasses a wide range of reservoir paleoenvironments, from non-marine to marginal marine to deepwater (Armentrout, 1991; Diegel *et al*., 2001).

Stratigraphic subdivisions of highstand, transgressive, and lowstand systems tracts or sequence sets are easily delineated from available published statistics and classifications. The most complete database is that of the Bureau of Economic Geology (Seni *et al*., 1994, 1995). While this published database did not use precise sequence stratigraphic terminology, their architectural terminology is easily translated into the sequence stratigraphy nomenclature:

- Progradational: highstand systems tract (HST) or highstand sequence set (HSS)
- Retrogradational: transgressive systems tract (TST) or transgressive sequence set (TSS)
- Submarine Fan: Lowstand systems tract (LST) or lowstand sequence set (LSS)
- Aggradational: HST-HSS or LST-LSS

While the aggradational classification spanned several sequence stratigraphic divisions, it did not represent significant volumes in comparison to other groupings.

The Gulf of Mexico Miocene play spans about 15 to 18 million years of geologic time, thus it encompasses at least one 2nd-order cycle. While the play can be discussed from the perspective of the sequence set on the gross scale, clearly smaller components (sequences and systems tracts) contain the actual reservoirs at the individual field and discovery scale.

The Miocene play displays the pattern expected from progressive exploration of a play with reservoirs in multiple sequence sets (Figure 6). The Miocene HSS was explored first (beginning in the 1950's) and discovered volumes reach a plateau by the 1970's. These discoveries were typified by relatively thick and laterally continuous shallow water (fluvial, shoreline, deltaic) reservoirs trapped in large structural closures. Growth faulted anticlines, downthrown traps, and salt dome flank traps were defined in several structural trends using a combination of seismic, gravity, and even "trendology" (Peel *et al*., 1995). Cumulative reserves in the Gulf of Mexico Miocene HSS represent about 3.0 BBOE, with relatively little volume added since the end of the 1980's.

The Miocene TSS has not really yielded significant hydrocarbon volumes in the Miocene, as it is normally quite shale-prone in all stratigraphic levels in the high subsidence regime of the Gulf of Mexico (Armentrout, 1991; Diegel *et al*., 2001). Thinning landward in these passive margin settings often makes the embedded TST's look eroded, though this apparent truncation is clearly a function of the seismic resolution (Mitchum *et al*., 1994).

However, the cumulative discovery curve for the Miocene play shows an abrupt increase beginning in the 1980's as the deepwater sandstones of the LSS were penetrated. Beginning in the early 1980's, there is a pronounced increase in discovered volumes as reservoirs of the paleo-deepwater slope channels, and basin floor amalgamated channels and sheets were drilled in progressively deeper water (Lawrence, 1997). With the Thunder Horse field discovery in 1999, cumulative discovered volumes for the LSS component of the Miocene play now exceeds that of the HSS component.

Thus, the suggested pattern of multiple rises and plateaus is quite apparent in the creaming curves for the three stratigraphic components of the Gulf of Mexico Miocene. The HSS plateau is followed by the LSS rising limb, which apparently is still in the "immature" phase of exploration (definition of Meisner and Demirmen, 1981).

Alternatively, one could argue that the Thunder Horse discovery could be a different play type (turtle structure) than many of the other deepwater Miocene fields (salt mini-basin traps of Lawrence, 1997). However, the number of wells targeting Thunder Horse type traps is relatively small, and these are plotted on the same plot, following the guidelines of Meisner and Demirmen (1981).

It is illuminating to consider the causes for the mid-1980's jump in exploration success in the LSS component of the Miocene play. This increase in discovered volumes was preceded by major enhancements in the water depth capability of exploration drilling and deepwater producing technology (Bourgeois *et al*., 1998). Other influences include significant improvements in seismic imaging, changes in offshore lease sale processes, and, importantly, advances in sequence stratigraphy as an exploration tool (e.g., meetings and symposia leading up to Wilgus *et al*., 1988).

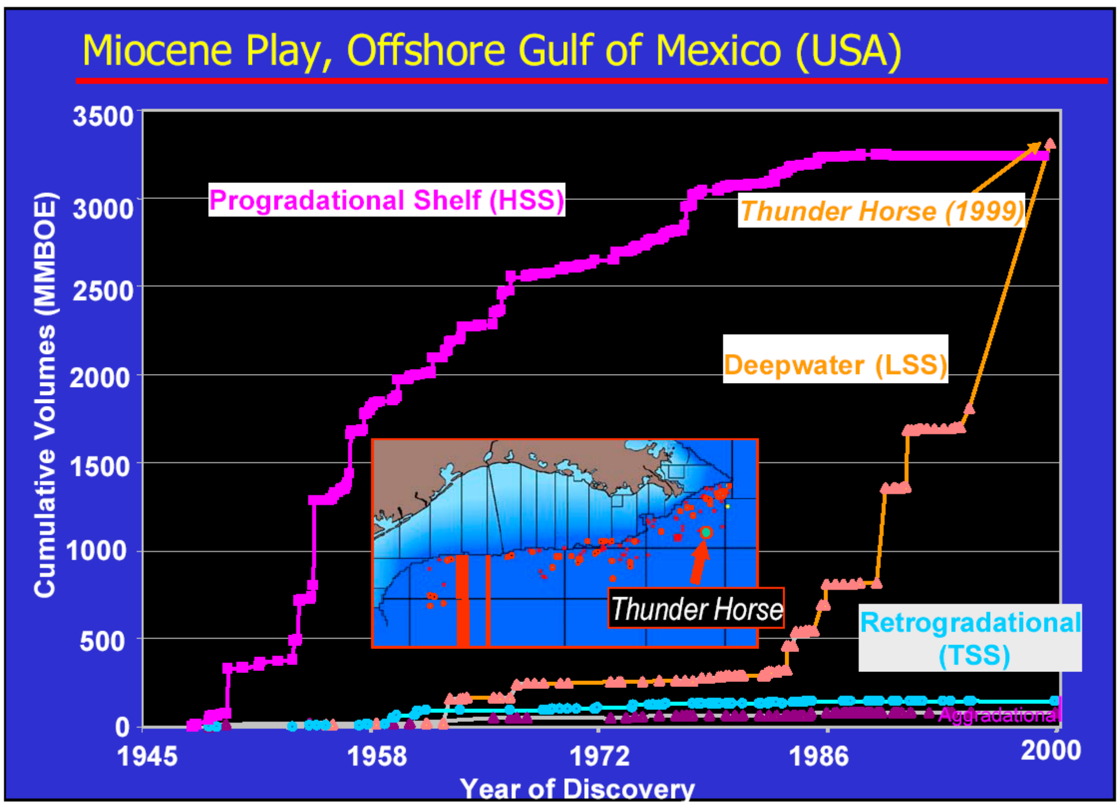

Figure 6. Creaming Curve for Miocene Play, Gulf of Mexico, with individual components plotted separately. MMBOE=million barrels oil equivalent. Thunder Horse discovery volumes from Antosh (2001). HSS= highstand sequence set; TSS=transgressive sequence set; LSS=lowstand sequence set.

Upper Jurassic Play, Norway

The Upper Jurassic of the Horda Platform and adjacent Norwegian Sea of Norway is a well-established producer of both oil and gas (Figure 7). Hydrocarbons in the Upper Jurassic were identified initially in 1975, but giant accumulations of gas were found with the discovery of Troll West in 1978 and Troll East in 1983 (Gray, 1987).

Hydrocarbons in the Upper Jurassic of the Troll Field (West and East) are trapped in a large fault-bounded, horst structure (Figure 8). A large gas column and smaller oil column extends across a stacked series of HST and TST shallow marine sandstone reservoirs of the Sognefjord and Fensfjord Formations (Gibbons *et al*., 1993). This composite succession of HST's and TST's forms a classic Highstand Sequence Set (HSS), with an overall progradational stacking pattern. Thus, the first portion of the creaming curve for the Upper Jurassic follows the expected early pattern for play development: discoveries in the highstand component of the 2nd order cycle (sequence set) in large structural closures (Figure 4). Reservoirs of the Sognefjord and Fensfjord do extend laterally a considerable distance and thus would not trap hydrocarbons without a significant structural closure (Van der Zwan, 1989).

A smaller (by comparison) discovery came a few years later in 1984 at the Draugen Field, which reservoired in similar age sandstones on the Trondelag Platform much further north (Figure 7). Unlike Troll Field, Draugen Field does not exhibit a large pronounced structural closure. A stratigraphic component for entrapment is provided by the lateral pinchout of the sandstone reservoirs (Provan, 1993). Sandstones are also shallow marine in origin, with obvious shelfal indicators like ammonite shells and marine dinocysts (Van der Zwan, 1989). The Draugen Field thus represents the second of the three sequence stratigraphic tiers: transgressive shallow marine sandstones in stratigraphic traps (c.f. Figure 4).

The third tier to the Upper Jurassic Play came over twenty years later in 1996, with discovery of the Fram Field in Block 35/11 (Figure 7). Initial tests of the Sognefjord Formation reservoirs yielded over 4400 BOPD with associated oil (AAPG Explorer, 1996). Sandstone reservoirs are interpreted to be paleo-deepwater high-density turbidites deposited in a lowstand submarine fan system (S. Setterdahl, personal communicaton). The discovery was made with the eighth well drilled in the block. Fram is currently waiting on field development, with first oil expected in 2003.

The discovery of the Fram Field proved that a third component to the Upper Jurassic play exists and additional drilling has pursued this component. Thus, this play fits the sequence stratigraphic prediction for 1) highstand structural component (Troll); 2) transgressive stratigraphic (Draugen); and 3) lowstand deepwater (Fram).

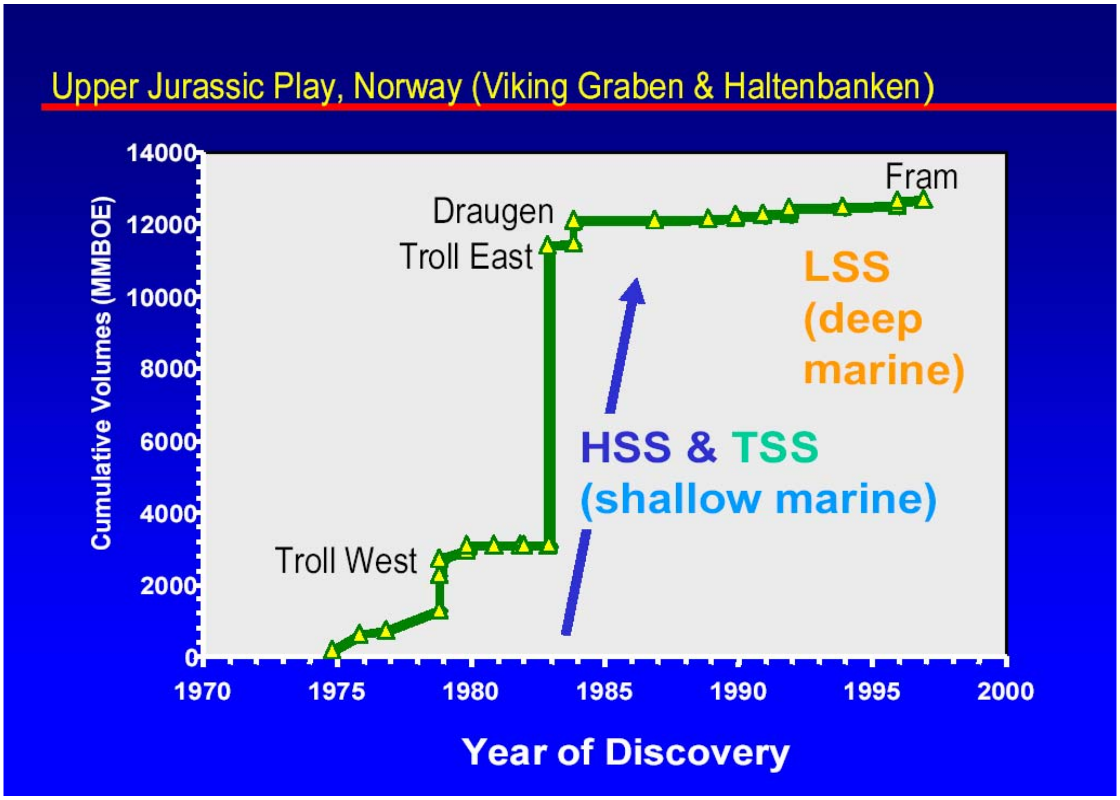

Figure 7. Creaming curve for the Upper Jurassic Play, Norway. MMBOE=million barrels oil equivalent. Data from Berge (1997). HSS= highstand sequence set; TSS=transgressive sequence set; LSS=lowstand sequence set.

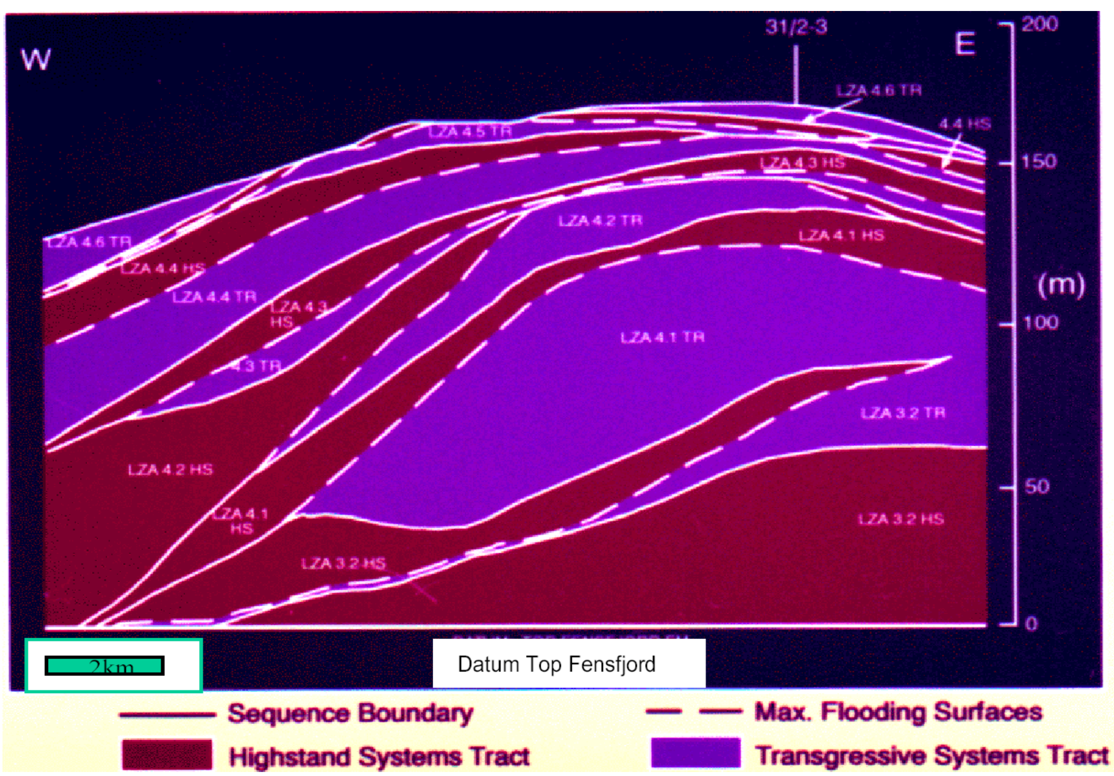

Figure 8. Cross-section through Troll West Field, Norway. Modified from Gibbons *et al.* (1993).

Wilcox Play, Lower Coastal zone, Texas, USA

The Wilcox Play of Texas also has a long exploration history, extending as far back as 1942 (Figure 9). Both oil and gas are found in the Wilcox, but gas dominates, probably due to source rock type and maturity, and the tendency for reduced permeability in more deeply buried reservoirs (Kosters *et al*., 1989). Like several plays discovered previously, the first rising limb of the creaming curve is represented by fields developed in fluvial to marginal marine sandstones in well-defined structural traps. An example is the downthrown trap at the Lake Creek gas field of Montgomery County (Figure 10, A). The main reservoir section includes a highstand sequence set of stacked fluvial, distributary channel, and mouth bars sandstones in a fault-bounded anticlinal structural trap (Figure 10, B and C).

The second set of discoveries in the Wilcox play of Texas began in the mid-1960's with discovery of the Laredo Field (1.0 TCFG OGIP) in South Texas. Laredo and other fields in the immediate area produce from a transgressive succession of shallow marine sandstones known informally as the "Lobo" series. Lobo sandstones harbor gas in a combination structural-stratigraphic trap with small scale faults and sealing by unconformities at the upper and lower Lobo levels (Figure 11). These subtle traps are typical of the second tier or "transgressive" component of the creaming curve.

The third tier of the Wilcox came over 15 years later as the downdip (lowstand) Wilcox component began to be exploited by South Texas majors and independents (Figure 9). Deeper drilling and higher gas prices in the late 1970's led to discoveries in the Seven Sisters, East (Duval County) and Fandango Fields (Zapata County). These fields are different in terms of structural style: thick growth wedges developed on the downthrown side of major listric faults (Edwards, 1981). Structural closure is provided by rollover into the faults (Stricklin, 1994).

However, detailed stratigraphic analysis of the Wilcox in South Texas area reveals that conventional log correlation sometime fails to discern the presence of lowstand packages of older Wilcox Group sandstone reservoirs (Figure 12). Assumptions about growth in younger Wilcox strata are sometimes refuted by biostratigraphic information and sequence stratigraphic correlations (Snedden *et al*., 1991; Snedden *et al*., 1996b). In the East Seven Sisters Area of Duval and McMullen counties, for example, this information confirms the presence of thick, Paleocene-age, lowstand wedge prograding complexes which pinchout updip onto a coeval sequence boundary, forming a bypass surface (Figure 13). The sequence stratigraphic model predicts that detached sandstone packages (lowstand wedge prograding complex) will sometimes be located downdip of coeval unconformities due to bypass during relative sea level lowstands (Posamentier *et al*., 1993).

Follow-up to the downdip Wilcox discoveries occurred in the middle 1990's with major gas finds like the Bob West Field in Zapata and Starr Counties (Jones, 1994), but these basically follow the same trap and reservoir type as the Seven Sisters East Field. Since the first plateau in the 1950's, about 6.0 TCFG (OGIP) has been discovered in the Wilcox play.

One key difference between the Wilcox play and other examples discussed thus far is the fact that Wilcox reservoirs, even in the lowstand sequence set, do not develop significant deepwater reservoir elements (Stricklin, 1994). Reconstructions suggest that the Wilcox Group in South Texas represents a progradation of shallow water siliciclastics into a major depocenter seaward of the Cretaceous shelf margin, an area of massive accommodation due to collapse of an autochthonous Mesozoic salt massif (Diegel *et al*., 2001). Sediment supply kept pace with subsidence, thus limiting bypass to basinal paleoenvironments and accommodating most sediment in lowstand, shelf-margin deltaic complexes (Edwards, 1981). Retrogradational failure of the shelf margin has also created accommodation in this strike-trending depocenter (Edwards, 2001). The few, well-documented deepwater sandstones encountered in fields like Northeast Thompsonville in Jim Hogg County have been relatively poor producers due to low net/gross and limited reservoir quality (Snedden *et al*. 1996b).

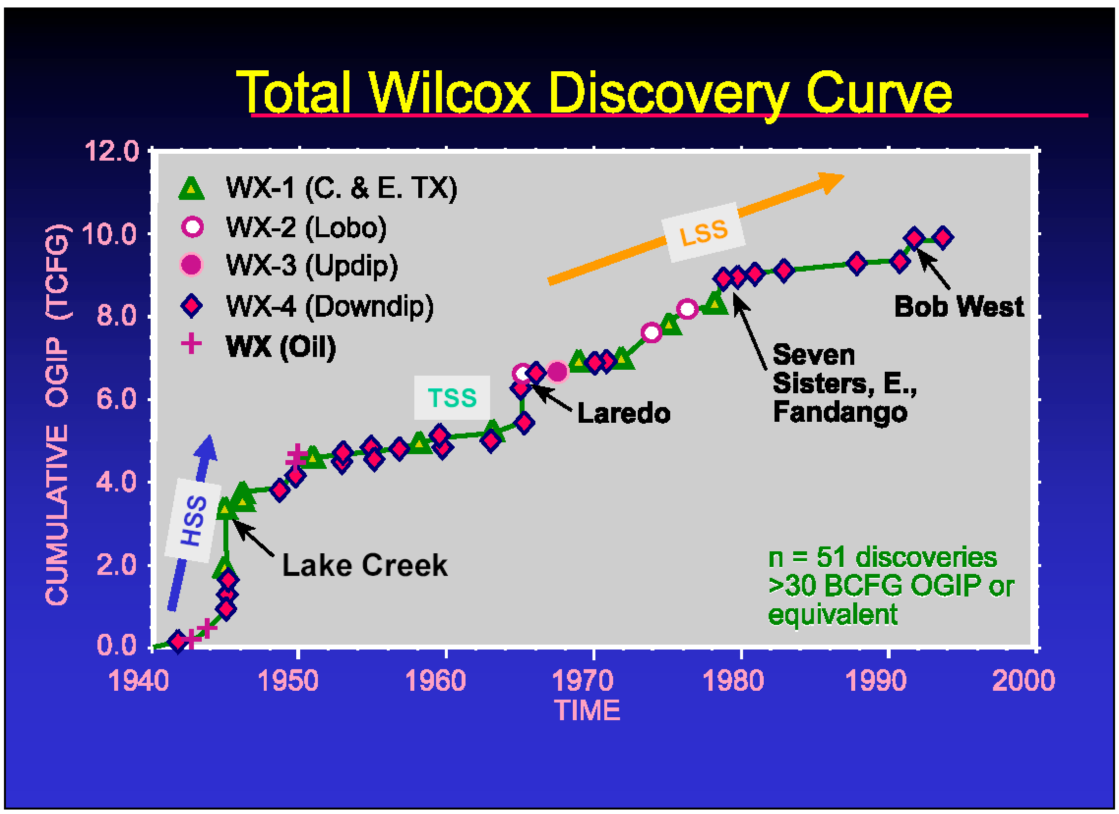

Figure 9. Creaming curve, Wilcox Play, Texas. OGIP=original gas in place, Trillion cubic feet. Data from Seni *et al.* (1994), with recent updates. HSS= highstand sequence set; TSS=transgressive sequence set; LSS=lowstand sequence set.

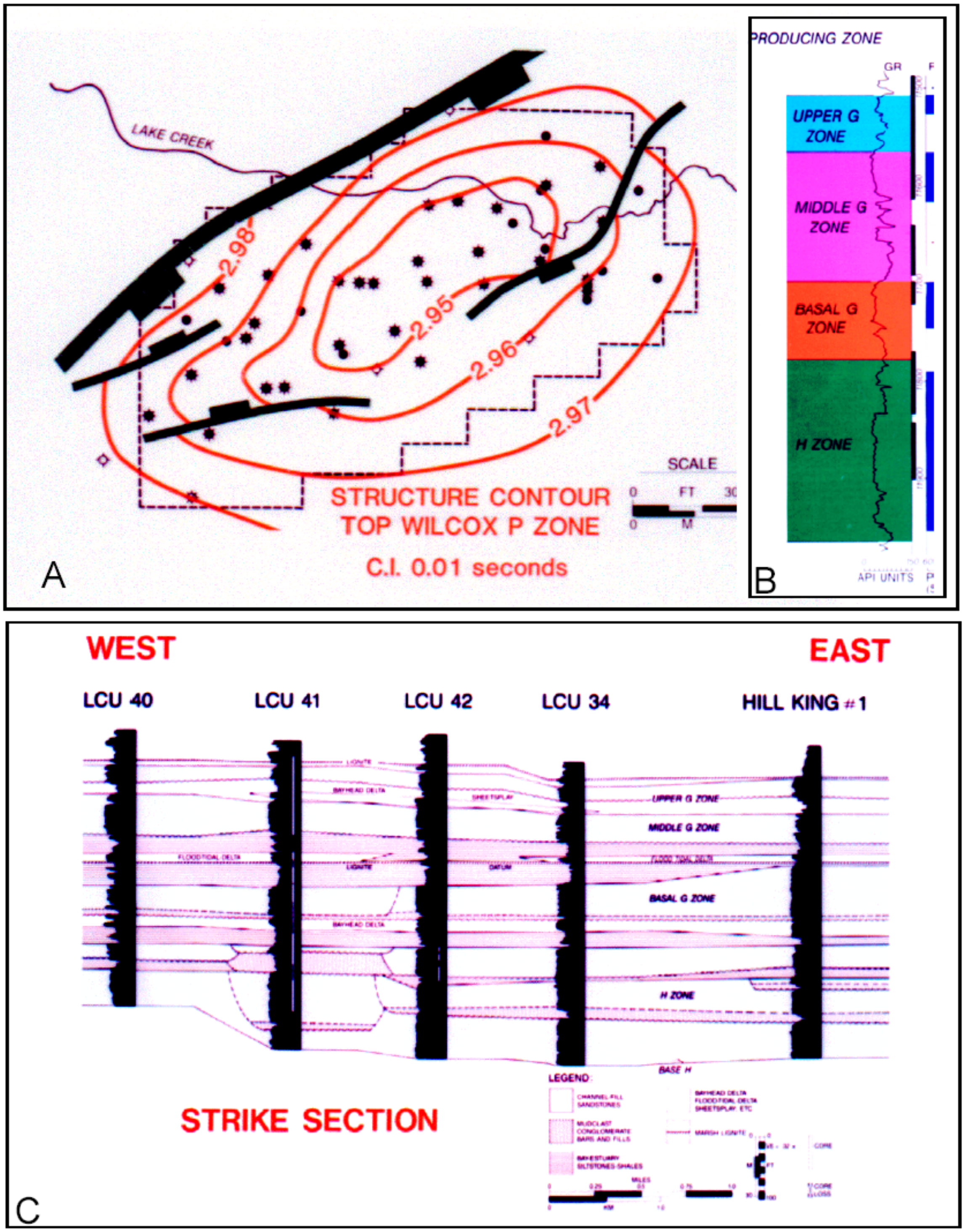

Figure 10. A) Lake Creek structure map, top of Wilcox P zone; B) Well-log showing thick sandstones of the overlying G and H zones; C) Lateral continuity of braided fluvial channels and incised valley-fills in the G and H zones. Modified from Snedden *et al.* (1996b) and Bebout *et al.* (1982).

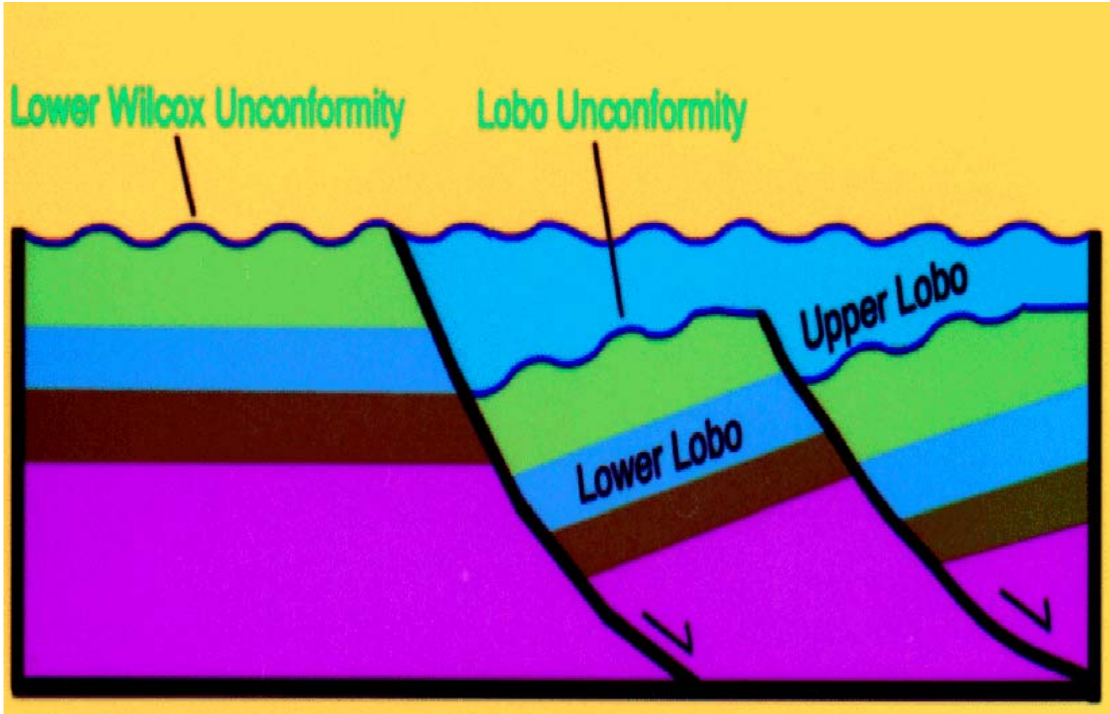

Figure 11. Idealized Wilcox Lobo transgressive combination structural-stratigraphic trap type. Shallow marine sandstones are sealed by both faults and high frequency sequence bounding unconformities.

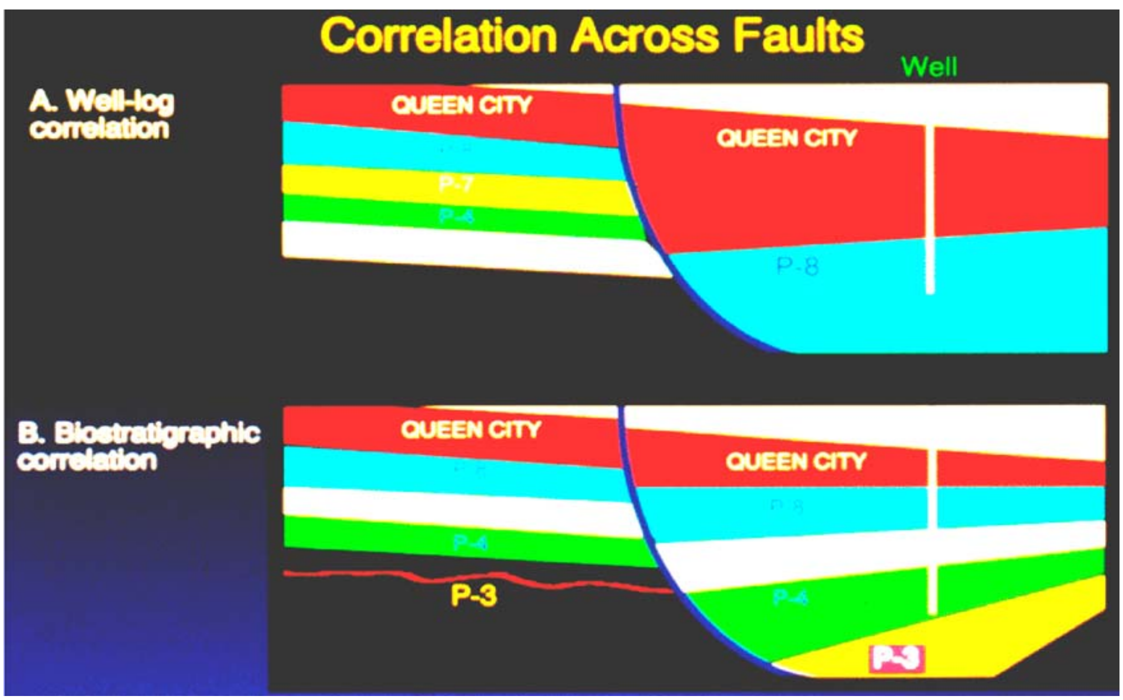

Figure 12. Alternative models for Wilcox growth wedges. A. Conventional, well log (lithostratigraphic) correlation holds that expansion across major growth faults is limited to Upper Wilcox Group and overlying Queen City Formations. B. Queen City and Upper Wilcox growth is more limited. Model provides for inclusion of an older Wilcox wedge on the downdip side of fault and a coeval updip unconformity. Modified from Snedden *et al.* (1996b).

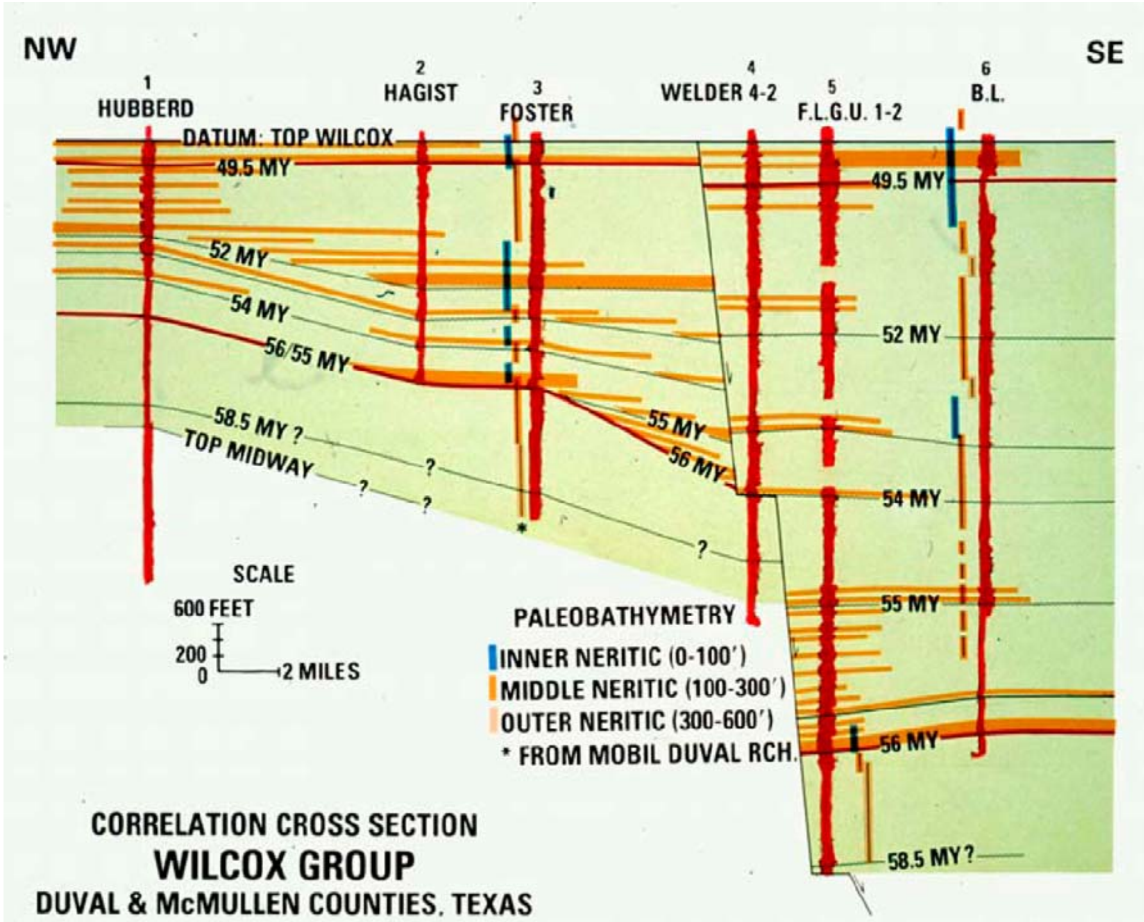

Figure 13. Sequence stratigraphic correlation of Wilcox sandstones in the East Seven Sisters area of Duval and McMullen counties, Texas. The thick package of neritic (deltaic) sandstones of Paleocene-age in Well 5 terminates updip at the sequence boundary (55 to 56 my). Modified from Snedden *et al.* (1996b).

Plio-Miocene Play, Kutei Basin, Indonesia

A final example of an exploration play with a history following the sequence stratigraphic paradigm is the Plio-Miocene Play of the Kutei Basin offshore region of Indonesia (Figure 3). This is a case where predictions made from creaming curve analysis supported exploration decision-making about whether to participate in this play or exit. Predictions (Snedden *et al*., 1996a) preceded actual discoveries, confirming the validity of this approach.

Exploration on the Kutei Basin onshore began nearly 100 years ago (Figure 3). Significant large discoveries in this area occurred in the 1960's and 1970's in simple anticlinal closures within HSS fluvial and deltaic reservoirs of the paleo-Mahakam (Duval *et al*., 1992). Fields like Badak, Tunu and the Handil-Tambora-Nilam trend are all large structural traps, which are required in order to hold hydrocarbon columns in this very sand-prone Miocene section delta (Huffington and Helmig, 1980).

However, exploration success diminished after the identification of Tunu field in 1977. Nearly ten years passed before Total found hydrocarbons in the TSS sandstones at the Sisi-Nubi Field area in 1986 (Duval *et al*., 1992). However, established local operators were reluctant to drill farther basinward because of several dry holes and concerns about distance from established coastal-plain coaly source rocks of this Type III petroleum system. However, an alternative view suggested that the "rim" of dryholes on the outer shelf simply defined the basinward shale-out of the HSS and TSS and were not representative of the LSS present (Snedden *et al*., 1996a). In fact, it was argued that an incompletely explored lowstand component was present, one that had a high chance of success if the adequate source rocks were present.

With limited well data and a detailed geochemical and stratigraphic model as support, the authors postulated a pre-drill model that these LSS reservoirs would be: 1) present in economic thickness; and 2) sourced by a series of "lowstand kitchens" (Snedden *et al*., 1996a). Lowstand kitchens were described as areas where terrestrial organic matter had been transported by lowstand bypass, collected, matured, and expelled oil and gas into the LSS reservoirs (Figure 14; Peters *et al*., 2000).

Following completion of detailed studies and recommendations to drill, and in partnership with a new operator (Unocal), a series of wells were drilled in deepwater regime of the Kutei Basin and adjacent Makassar straits. Recent successes in the Merah-Besar, Seno, and West Seno in the Makassar PSC have proven the presence of both adequate transported terrestrial organics (Dunham *et al*., 2000) and reservoir in the lowstand component of the Plio-Miocene play (Saller *et al*., 2000).

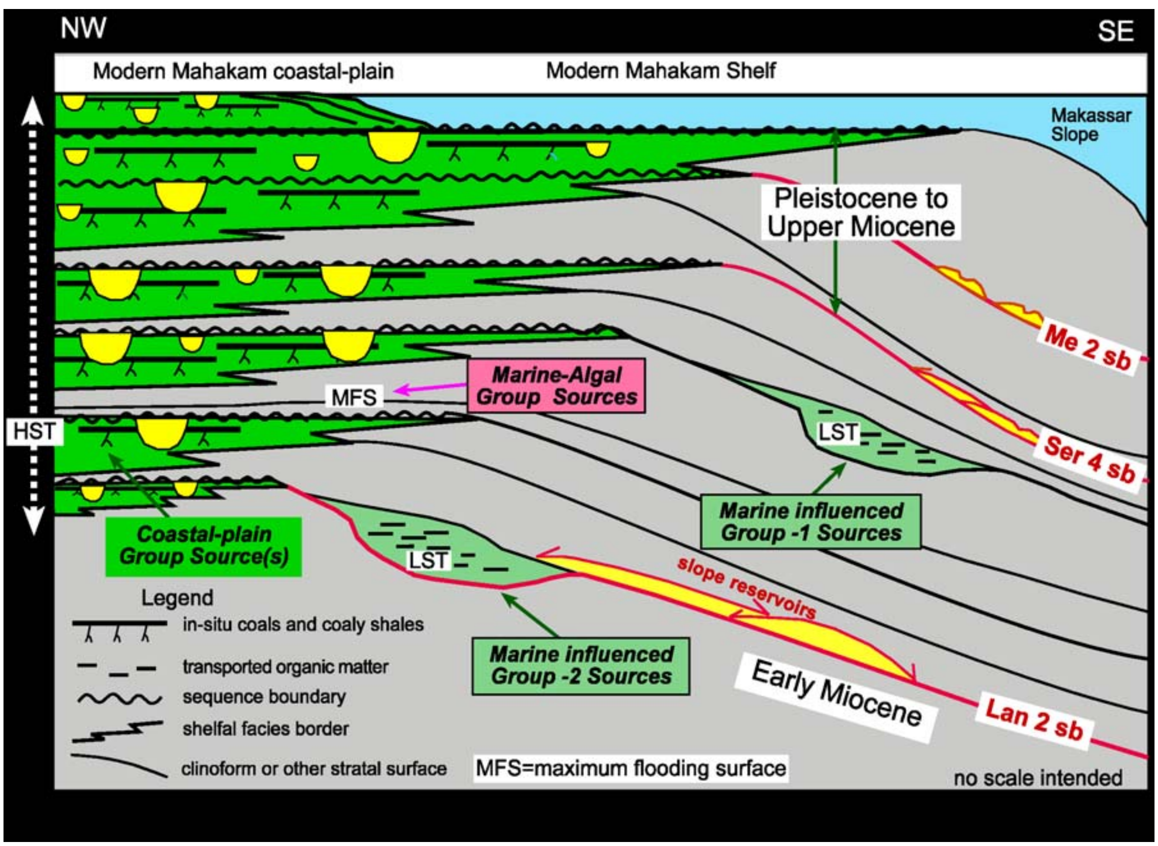

Figure 14. Stratigraphic model for the Plio-Miocene play of the Kutei basin, Indonesia. Modified from Peters *et al.* (1998).

Using the Creaming Curve as a Predictive Tool

As the Kutei Basin example superbly demonstrates, there is some utility to recognizing the potential for a second or third "tier" to a given exploration play. In fact, this approach follows the philosophy of Magoon and Sanchez (1995): a complementary play can be inferred from mapping the total petroleum system and subtracting the discovered fields and non-commercial accumulations. If the difference is large or whole elements (e.g., systems tracts or sequence sets) are under- or unexplored, this exploration play should be pursued, at least to understand why such a disparity exists.

One way to identify an under- or unexplored play is to compile field statistics by systems tracts or sequence set-type. For example, analysis of the Texas lower coastal province (onshore) reveals that the HST (HSS) components contains the bulk of gas reserves discovered to date in 32 onshore plays (inset, Figure 15). This predominance of fields developed in structural traps in thick, laterally continuous shallow water sandstones of the HST or HSS accounts for such a disparity (Kosters *et al*., 1989).

Examination of the same 32 onshore plays indicates that in less than a third of these produce from more than two systems tracts or sequence sets, with an additional 30% limited to one systems tract or sequence set (Figure 16). While there may be good reasons for such differences (e.g., burial diagenesis in deeper, more basinward components, stratigraphic trap failure, low sand content in the TST-TSS), the trend in all 32 onshore plays is suspicious, suggesting underexplored plays.

In fact, Kosters *et al*. (1989) has estimated that 20 TCFG of undiscovered, recoverable gas reserves remains in the Lower coastal province of Texas. A rough estimate of the partitioning of reserves suggests that most of the future potential lies in the lowstand systems tracts or sequence sets of these 32 existing plays (Figure 15).

Understanding the natural progression of an exploration play can facilitate decision-making on company resource (manpower and skill set) allocation. Critical risk elements shift in tandem with the progressive exploration of the highstand to lowstand components (Figure 4). Highstand plays often require thorough understanding of the critical risk associated with trap, transgressive plays tend to require a stratigraphic component of sealing, while lowstand plays typically have significant reservoir risk. For example, the stepwise shift to lowstand, deepwater plays worldwide (George, 1996) has led to a focus on imaging of reservoir and fluid occurrence, continuity, and architecture (Imbert *et al*., 1996). This contrasts with earlier days when trap identification was the paramount focus of exploration (e.g., Halbouty *et al*., 1970).

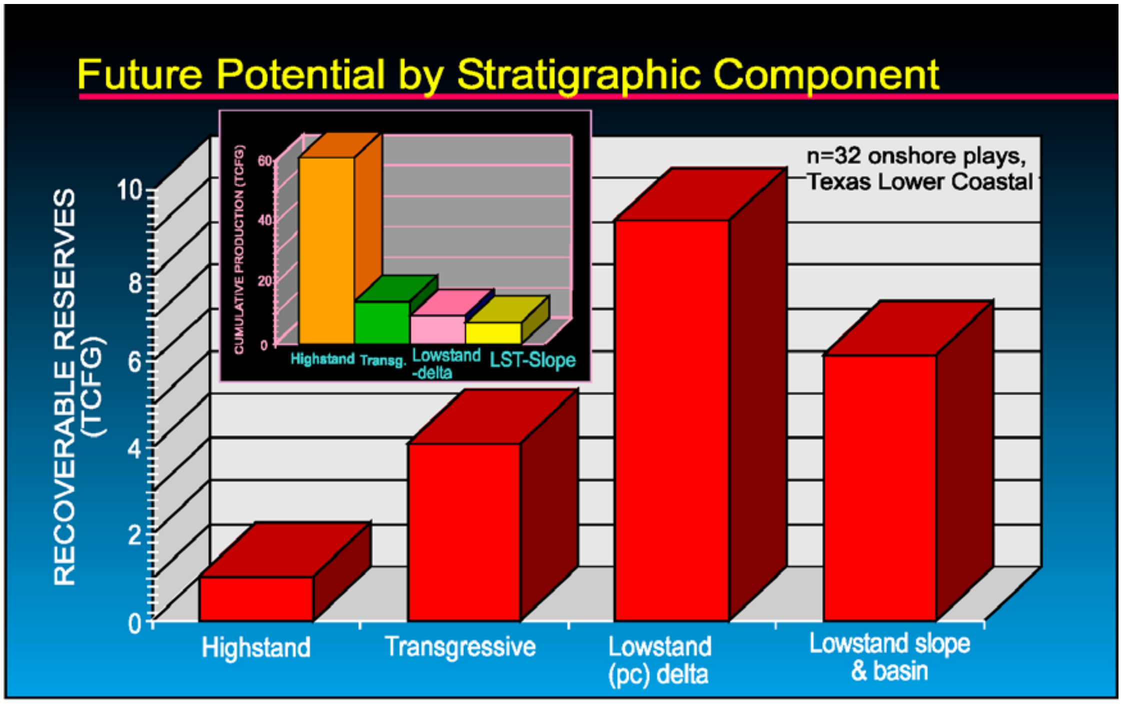

Figure 15. Future potential by sequence stratigraphic package, onshore Gulf of Mexico, Lower coastal province, Texas (n=32 plays). Inset shows cumulative production by sequence set or systems tract type. Data from Kosters *et al.* (1989) and Seni *et al.* (1994) but interpretation by the authors as to systems tract/sequence set . Modified from Snedden *et al.* (1996b). TCFG=Trillion cubic feet of gas.

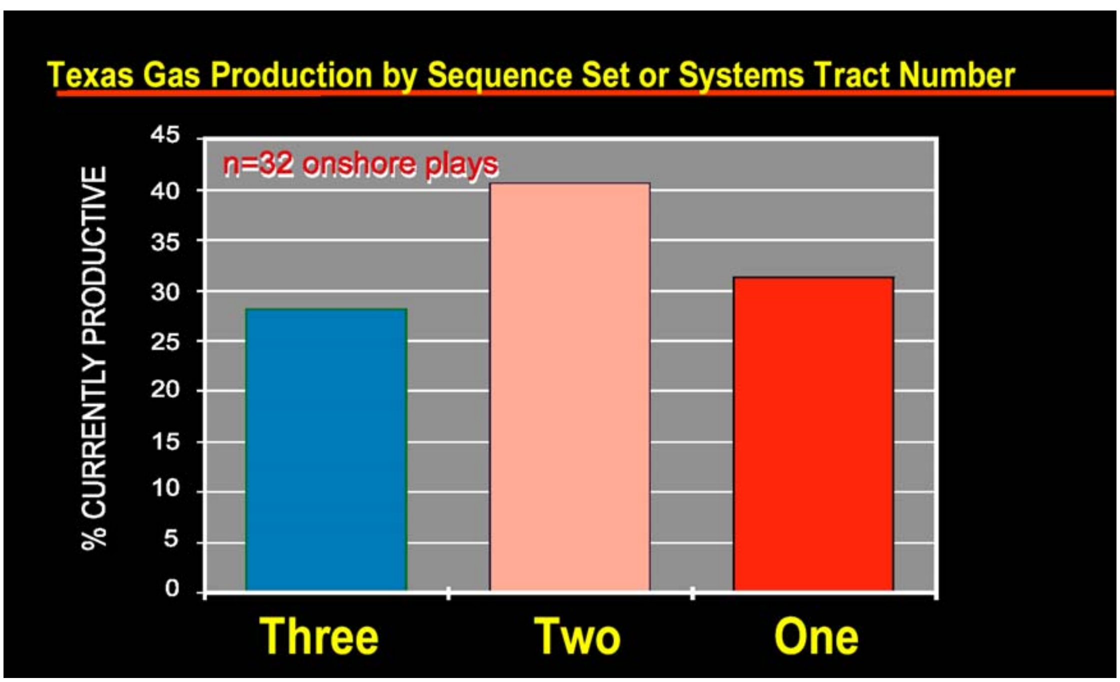

Figure 16. Systems tract/sequence sets with significant hydrocarbon content in 32 onshore plays, Lower Coastal of Texas. Data from Seni *et al.* (1994) but interpretation of the authors as to systems tract/sequence set number. Modified from Snedden *et al.* (1996b).

Summary and Conclusions

The creaming curve method has proven to be a useful tool in exploration play prediction worldwide, particularly in relatively simple, traditional plays. However, complex patterns seen in some exploration histories suggest that more sophisticated approaches are warranted. Viewing play development from a sequence stratigraphic perspective is one means of re-evaluating these plays and ascertaining if: 1) a play is truly “mature”; or 2) contains un-or underexplored components like lowstand systems tracts or sequence sets. New plays often stem from reconsideration of old plays, sometimes through better technology (e.g., seismic imaging around and under salt) or just simple conceptual breakthroughs (e.g., sequence stratigraphy).

Of course, caveats should be offered in any case. Some plays do not develop the full range of sequence stratigraphic components, simply because natural conditions do not allow it. The Wilcox play of South Texas has failed to exhibit a significant paleo-deepwater reservoir play because of the high accommodation of shelf margin deltaics and limitations on bypass and deep burial diagenesis of the relatively finer grained, isolated slope channels. Some plays fail completely because critical elements are never de-risked to a sufficient level to warrant additional drilling (e.g., Barents Shelf Jurassic play due to seal failure; Berge, 1997).

Exploration decision-making requires consideration of all the elements of risk. Our approach, historical in nature, appeals to the explorationist’s intuition: the past is the key to the present and perhaps the future.

Acknowledgements

The authors would like to acknowledge technical input and discussions with Jeff Brown, Pete Rose, Stephen Setterdahl, Kenneth Petersen, John Armentrout, John Suter, Jeff Faber, and Art Saller. Reviews by Jory Pacht, Hongliu. Zeng, Jeanne Phelps, and John Armentrout are greatly appreciated.

References

Ahlbrandt, T.S., 2000, U.S. Geological Survey World Petroleum Assessment 2000: Multi-Volume CD-ROM set, United States Geological Survey Digital Data Series, DDS-60.

Antosh, N., 2001, Deeper than the ocean/Gulf canyons hide strange creatures and topography, plus huge supply of oil, gas: Houston Chronicle Archives, 8/12/01, http://www.chron.com/content/archiv.

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

Bartek, L R., P.R. Vail, J.B. Anderson, P.A. Emmet, and S. Wu, 1991, Effect of Cenozoic ice sheet fluctuations in Antarctica on the stratigraphic signature of the Neogene: Journal of Geophysical Research, v. 96, no. B4, p. 6753-6778.

Bebout, D.G., B.R. Weise, A.R. Gregory, and M.B. Edwards, 1982, Wilcox sandstone reservoirs in the deep subsurface along the Texas Gulf Coast, their potential for production of geopressured geothermal energy: The Univ. of Texas at Austin, Bureau of Economic Geology Report of Investigations, no. 117, 125 pp.

Berge, G. 1997, Discoveries on the Norwegian continental shelf: Norwegian Petroleum Directorate, 32 p.

Bourgeois, T.M., D.G. Godfrey, M.J. Bailey, 1998, Race on for deepwater acreage, 3,500 meter depth capability: Offshore, October, 1998, p. 40-41.

Brown, P.J., and P.R. Rose, 2002, Plays and concessions—a straightforward method for assessing volumes, values, and chance: Search and Discovery website, http://searchanddiscovery.com/documents/brown/index.htm., 10 p.

Diegel, E.A., D.C. Schuster, J.F. Karlo, R.C.Shoup, and P.R. Tauvers, 2001, Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin: Search and Discovery website, http://searchanddiscovery.com/documents/97021/index.htm., 34 p.

Dunham, J.B., T.J. Brown, R. Lin, R.B. Redhead, H.F. Schwing, and S.H. Shirley, 2000, Transport and concentration of gas- and oil-prone kerogens into deepwater sediments of the Kutei Basin, East Kalimantan., Indonesia: AAPG International Meeting, Oct. 15-18, 2000 (abstract).

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.

Edwards, M.B., 1981, Upper Wilcox Rosita delta system of south Texas: growth-faulted shelf-edge deltas: AAPG Bulletin, v. 65, p. 54-73.

Edwards, M.B., 2001, Origin and significance of retrograde failed shelf margins; Tertiary northern Gulf Coast Basin: Search and Discovery website, http://searchanddiscovery.com/documents/edwards/index.htm., 15 p.

George, D., 1996, Remote and deepwater frontier areas seeing more exploration: Offshore, April, 1996, p. 40-44.

Gibbons, K., T. Hellam, A. Kjemperud, S. Nio, and K. Vebenstad, 1993, Sequence architecture, facies development, and carbonate-cemented horizons in the Troll Field reservoir. Offshore Norway, *in*, A. Hurst. ed., Advances in Reservoir Geology: Geological Society of London Special Publication, no. 69, p. 1-31.

de Graciansky, P.C. , J. Hardenbol, T. Jacquin, P.R. Vail, 1998, Mesozoic and Cenozoic Sequence Stratigraphy of European Basins: SEPM Special Publication no. 60, 783 pp.

Gray, D.I., 1987, Troll, *in*, A.M. Spencer,., ed., Geology of the Norwegian Oil and Gas Fields: Graham and Trotman, London, p. 389-401.

Greenlee, S.P., W.J. Devlin, K.G. Miller,G.S. Mountain, and P.B. Flemings,., 1992, Integrated sequence stratigraphy of Neogene deposits, New Jersey continental shelf and slope: comparison with Exxon model: Geological Society of America Bulletin, v. 104, p. 1403-1411.

Halbouty, M.T., A.A. Meyerhoff, R.E. King, R.H. Dott, Sr., H. Douglas Y. Klemme, and T. Shabad, 1970, World's giant oil and gas fields, geologic factors affecting their formation, and basin classification [Part 1], *in*, M.T. Halbouty, ed., Geology of Giant Petroleum Fields: AAPG Memoir 14, p. 502-528.

Hentz, T.F., H. Zeng, L.J. Wood,., 2002, Sequence stratigraphy and hydrocarbon distribution of Miocene plays: a case study from Starfak and Tiger Shoal Fields, Offshore Louisiana: AAPG Annual Meeting, Houston, Texas, March 10-13, 2002 (abstract).

Huffington, R.M., and H.M. Helmig, 1980, Discovery and development of the Badak Field, east Kalimantan, Indonesia: AAPG Giant Fields, p. 441-458.

Imbert, P., J.L. Pittion, and A.K. Yeats, 1996, Heavier hydrocarbons, cooler environment found in deepwater: Offshore, April, 1996, p. 47-55.

Johannessen, E.P., R. Mjos, D. Renshaw, A. Dalland, and T. Jacobsen, 1995, Northern limit of the "Brent Delta" at the Tampen Spur—A sequence stratigraphic approach for sandstone prediction, *in*, Steel, R.J., V.L. Felt, E.P. Johannessen, and C. Mathieu, eds., Sequence Stratigraphy on the Northwest European Margin: Elsevier, Amsterdam, p. 213-256.

Jones, W.E., 1994, Bob West Field-Zapata and Starr Counties, a developing giant: South Texas Geological Society Bulletin, v. 34, no. 5, p. 13-33.

Kosters, E.C. *et al*., 1989, Atlas of Major Texas Gas Reservoirs: Gas Research Institute, University of Texas at Austin, Bureau of Economic Geology, 161 p.

Lawrence, D.T., 1997, Gulf of Mexico shelf, exploration in a mature province, in, Shanley, K.W., and B.F. Perkins, eds, Shallow marine and nonmarine reservoirs: sequence stratigraphy, reservoir architecture, and production characteristics: GCS-SEPM Research Conference, v. 18, p. 149-153.

Magoon, L.B., and W.G. Dow, 1994, The petroleum system, *in*, Magoon, L.B., and W.G. Dow, eds, The Petroleum System-from Source to Trap: AAPG Memoir 60, p. 3-24.

Magoon, L.B., and R.M.O. Sanchez, 1995, Beyond the petroleum system: AAPG Bulletin, v. 79, no. 12, p. 1731-1736.

Meisner, J. and F. Demirmen, 1981, The creaming method: a bayesian procedure to forecast future oil and gas discoveries in mature exploration provinces: Journal of the Royal Statistical Society, v. 144, part A, p. 1-31.

Mitchum, R.M., J.B. Sangree, P.R. Vail, and W.W. Wornardt, 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.

Peel, F.J., C.J. Travis, and J.R. Hossack, 1995, Genetic structural provinces and salt tectonics of the Cenozoic offshore, US Gulf of Mexico, a preliminary analysis, *in*, Jackson, M.P.A., D.G. Roberts, and S. Snelson, eds., Salt Tectonics: A Global Perspective: AAPG Memoir 65, p. 153-175.

Peters, K.E., J.W. Snedden, A. Sulaeman, J.F. Sarg, and R.J. Enrico, 2000, A new geochemical-sequence stratigraphic model for the Mahakam delta and Makassar slope, Kalimantan, Indonesia: American Association Petroleum Geologists, v. 84, p. 12-44.

Petroconsultants, 1998, Oil future less bright than gas: EAGE, First Break, v. 16, no.7, p.241-242.

Posamentier, H.W., G.P. Allen, D.P. James,., and M. Tesson, 1993, Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance: Amer. Assoc. Petrol. Geol. Bulletin, v. 76, no. 11, p. 1687-1709.

Provan, D.M.J., 1993, Draugen oil field, Haltenbanken Province, Offshore Norway: in. M.T. Halbouty, ed., Giant Oil and Gas Fields of the Decade 1978-1988, AAPG Memoir 54, p. 371-382.

Saller, A., T. Brown, R. Redhead, H. Schwing, and J. Inaray, 2000, Deepwater depositional facies and their reservoir characteristics, West Seno Field, Offshore East Kalimantan, Indonesia: AAPG International Meeting, Oct. 15-18, 2000 (abstract).

Seni, S.J., Tremblay, T.T., and D.A. Salazar, 1994, Atlas of Northern Gulf of Mexico Gas and Oil reservoirs: GIS Files and Tabular data: Bureau of Economic Geology and Minerals Management Service CD-ROM.

Seni, S., J. Brooke, D. Marin, and E. Kazanis, 1995, Chronostratigraphic hydrocarbon plays and depositional styles in the northern Gulf of Mexico: GCAGS Transactions, v. 45, p. 519-528.

Snedden, J.W., J.C. Cooke, R.K. Johnson, and K.T. Conrad, 1991, Sequence stratigraphy and sedimentology of a shelf-margin lowstand wedge in the deep Wilcox Flexure Trend of South Texas: American Association of Petroleum Geologists, Bulletin, v. 75, p. 673 (abstract).

Snedden, J.W., J.F. (Rick) Sarg, M.J. Clutson, M. Maas, T.E. Okon, M.H. Carter, B.S Smith, T.H. Kolich, and Md. Y. Mansor, 1996a, 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., Sarg, J.F., Faber, J.A., and J. Brown, 1996b, Downdip plays: highstand versus lowstand exploration: Luncheon keynote address, Gulf Coast Association of Geological Societies 1996 Annual Meeting, San Antonio, Texas (expanded abstract).

Steinshouser, D.W., J. Qiang, P.J. McCabe, and R.T. Ryer, 1999, Maps showing geology, oil and gas fields, and geologic provinces of the Asia Pacific Region: United States Geological Survey, Open File report 97-470F, CD-ROM.

Stricklin, F.L., 1994, Genetic variations in a growth-fault system: downdip Wilcox trend of south Texas: Transactions Gulf Coast Association Geological Societies, v. 44, p. 717-723.

Van der Zwan, C.J., 1989, Palynostratigraphic principles as applied in the Jurassic of the Troll and Draugen Field areas, offshore Norway: in, Collinson, J., ed., Correlation in Hydrocarbon Provinces: Graham and Trotman, London, p. 357-365.

Wilgus. C.K., *et al*., 1988, Sea-level Changes, An Integrated Approach: SEPM Special Publication No. 42, 400 p.

About the Authors

John W. Snedden

John W. Snedden is currently Stratigraphy skill area advisor with ExxonMobil Exploration Company in Houston, Texas. He received his geology degrees from Trinity University (B.A.) Texas A&M (M.S.), and Louisiana State University (Ph.D.). John has worked in U.S. production and exploration, global exploration, exploration research, and E&P technical service with Mobil and ExxonMobil over the last twenty-three years. He has published and made presentations on ancient reservoirs of Texas, the North Sea, Norway, Nigeria, Papua-New Guinea, Malaysia, Indonesia, Germany, and Azerbaijan as well as general sedimentological interpretation of the SP log. He also written papers on modern storm deposits of the Texas shelf and Atlantic shelves, winning the SEPM Excellence in Oral Presentation award at the 1995 AAPG/SEPM Meeting in Houston. In 1995, he convened an SEPM research conference on shallow marine sands in Wyoming and was later SEPM technical program chair for the 1997 AAPG/SEPM Meeting in Dallas. Recent work has focused upon sequence stratigraphy and shallow water depositional systems.

J.F. 'Rick' Sarg

Rick Sarg is Stratigraphy Coordinator, ExxonMobil Exploration Company. He received his Ph.D. in Geology, at the University of Wisconsin, Madison in 1976, his MS (1971) and BS (1969) in Geology at the University of Pittsburgh, Pittsburgh, PA. His twenty-six years petroleum exploration and production experience include assignments in research, supervision and operations with Mobil (1976), Exxon (1976-90), Independent Consultant (1990-92), Mobil Technology Company (1992-99), and now ExxonMobil Exploration (2000-present). He was a member of the exploration research group at Exxon that developed sequence stratigraphy, with an emphasis on carbonate sequence concepts. He has worldwide experience in integrated seismic-well-outcrop interpretation of siliciclastic and carbonate sequences. Rick has authored or co-authored 27 papers on carbonate sedimentology and stratigraphy. He recently was elected President-Elect of SEPM.

Don X. Ying

Don Ying is a senior research geologist in ExxonMobil Upstream Research Company. He joined Mobil Exploration and Production Technology Company after receiving a Ph.D. in geology from Stanford University in 1998. During his career with Mobil and ExxonMobil, Don worked on a variety of research and research application projects on deep-water reservoirs in offshore Nigeria, Angola and Gulf of Mexico as well as shallow marine sediments in Ahnet Basin, Algeria.

His petroleum career started with Research Institute of Petroleum Exploration and Development (RIPED) of PetroChina after receiving a B.S. in geology from Beijing University in 1984. His assignments in RIPED and his graduate research included sequence stratigraphy, basin analysis, source rock studies, and reservoir characterization for a number of Cenozoic rifted basin in Eastern China and South China Sea.

His current research interests are developing processes and workflows that enable geoscienсts to build realistic geologic models during different business stages of petroleum exploration and production.