Relation of Hydrocarbon Reservoir Potential to Lake-Basin Type: An Integrated Approach to Unraveling Complex Genetic Relations Among Fluvial, Lake-Plain, Lake Margin, and Lake Center Strata

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ABSTRACT

A relatively small range of lacustrine-facies associations record the complexly contingent interactions of a wide range of physical, chemical, and biological processes (climate, tectonics, sediment supply, vegetation, landscape evolution). Each lacustrine-facies association contains fluvial, lake-plain, lake margin, and lake center strata with characteristic hydrocarbon reservoir potential. The accumulation of these lacustrine-facies associations and their potential hydrocarbon reservoirs arise from interactions of typical ranges of rates of potential accommodation and sediment plus water supply and can be interpreted genetically as overfilled, balanced-filled, and underfilled lake-basin types.

Fluvial-lacustrine lacustrine-facies associations (interpreted as forming in overfilled lake basins) generally contain reservoirs that are best developed in aggradationally stacked highstand clastic shoreline strata and occasionally in skeletal carbonate or charophytic algal lithosomes or in lowstand incised valley fills and lake floor fans (basically restricted turbidite and mass flow deposits). These reservoirs tend to have low vertical permeability (Kv) because flooding surfaces are generally marked by decreased input of coarse sediment and increased subsidence. They have the lowest average net reservoir: gross interval of the three lacustrine-facies associations. They do, however, have the highest average porosity and permeability and contain the largest overall reserves, mainly in lake-plain fluvial strata.

Fluctuating profundal lacustrine-facies association (balanced-filled lake basins) have reservoir facies that include lake floor fans, incised valley fills, and shoreline clastics or carbonates deposited during transgressions and highstands. These reservoirs tend to have the smallest lateral extent and lowest average recovery factor of the three lacustrine-facies associations; (based on reservoir and fluid properties), but do have good vertical and horizontal permeability (Kh) in highstand and transgressive systems tracts and the best Kv of all the lake-basin types.
Evaporative lacustrine-facies associations (underfilled lake basins) contain reservoir facies that are best developed in transgressive sheetflood clastics, early highstand fluvial channels, and late highstand shoreline carbonate grainstones. Early carbonate and evaporite cements are common in these reservoirs, and there tends to be a wide lateral displacement of highstand from lowstand systems tracts. They do, however, have the best Kh (because of common erosion that enhances lateral connectivity) as well as the thickest net pay of all the lake-basin-type reservoirs (as they tend to occur at relatively large potential accommodation rates).

Associated fluvial styles among the lacustrine-facies associations (lake-basin types) appear to vary systematically, as a function of sediment plus water supply relative to potential accommodation rates: perennial, high sinuosity streams are most common in overfilled lake basins, intermittent to perennial low-sinuosity streams in balanced fill, and a wide range from ephemeral sheetflood or multithread braided streams to perennial high-sinuosity streams in underfilled lake basins.

Observations indicate that these associations of hydrocarbon reservoir and seal play elements occur in a wide variety of tectonic settings and ages, from continental rift to convergent foreland basins of the Cambrian to Holocene. Continued success in economic discovery and efficient recovery depend upon continued testing and elaboration of these concepts and a deeper understanding of the essential processes controlling deposition of lacustrine strata.

INTRODUCTION

Lakes are complex nonlinear dynamic systems whose behavior can differ significantly from marine systems. Predictions of hydrocarbon-reservoir presence, distribution, and character in lake systems similarly pose distinct challenges. These challenges arise from the fundamental nature of lacustrine systems: nonunique relations of lake character to climate or tectonics, contingent responses of lakes to climate change, and variable ties among lake level, sediment supply, and water supply (e.g., Bohacs et al., 2003b).

At the hydrocarbon-reservoir scale, these challenges affect every aspect of prediction. Lake shoreline shapes vary widely at relatively short temporal and spatial scales: shorelines tend to be straighter and better developed under dominantly open hydrologic conditions and more highly constructive and dispersive at times of more persistently closed hydrology. Fundamental changes in shoreline type and lake character between highstand and lowstand systems tracts can make the application of Walther Law for predicting lateral distributions quite difficult, especially in strata dominated by evaporative lacustrine-facies associations (underfilled lake basins). Even the well-log expression of lacustrine strata varies widely among lacustrine-facies associations and can differ greatly from that commonly observed in marine siliciclastic strata (Bohacs and Miskell-Gerhardt, 1998).

Despite these challenges, it is possible to make significant predictions because each lake-basin type has different characteristic associations and distributions of hydrocarbon-reservoir strata. These characteristics arise mainly from distinct histories of lake hydrology, which control the evolution of lake-water chemistry, the nature and stability of food webs, and the relation of clastic sediment supply rates to lake level. Reservoir-prone strata are linked to these controls through the timing of clastic sediment supply relative to lake level and the influence of water chemistry on the dominant lithology (e.g., clastic, carbonate, evaporite). Other play elements also respond to these controls in interrelated ways.

The data presented herein come from a large number of articles in the published literature and on the World Wide Web. Information on ancient lacustrine strata spans 211 examples from the Cambrian to Pleistocene (e.g., Gierlowski-Kordesch and Kelts, 1994; Carroll and Bohacs, 1999; Bohacs et al., 2000), with detailed data on 83 producing intervals in 54 hydrocarbon fields (primary sources of data are listed separately in the References). Most of our information on modern lakes comes from 253 examples that are more than 500 km² (193 mi²) in surface area compiled by Herdendorf (1984; digital data in GSA Data Repository 9916). Hydrocarbon reserve and production data are from the published literature as well as compilations by the U.S. Geological Survey (United States Geological Survey, 2006) and British Petroleum (British Petroleum, 2006).

CHARACTERISTICS OF LAKE-BASIN RESERVOIRS

More than 120 × 10⁶ barrels of oil equivalent (BOE) (19 × 10⁶ m³) have been reported in the literature or on the
World Wide Web as discovered in hydrocarbon systems associated with lake-basin strata, with an approximate split of $48.3 \times 10^9$ bbl $(7.7 \times 10^8 \text{m}^3)$ of oil, $49.3 \times 10^{12}$ cf $(1.4 \times 10^{12} \text{m}^3)$ of gas, and $85.7 \times 10^6$ bbl $(13.6 \times 10^6 \text{m}^3)$ of condensate, with an estimated ultimate recovery of about $57 \times 10^9 \text{BOE}$ $(9 \times 10^9 \text{m}^3)$ according to U.S. Geological Survey estimates and the references cited in this chapter. These systems occur in more than 16 countries, with the largest reserves in China, Brazil, and Indonesia. The hydrocarbons occur in a variety of settings and systems, with about two-thirds of the fields having a lacustrine source and reservoir, the other third having lacustrine source and marine reservoir strata (e.g., offshore Brazil; Mello et al., 1988). A few systems (~5% of the fields) have marine-sourced oil in lacustrine reservoirs (e.g., Pliocene Productive Series in Bahar, Cheleken, and other fields, South Caspian Basin; Pliocene Tulare Formation in Cymric, Lost Hills, and Belridge South fields, California).

No one reservoir type dominates large oil accumulations in lake basins, where the largest 20 fields occur in a range of depositional environments from fluvial, through submarine fan, paralic marine, lacustrine clastic shoreline, to lacustrine carbonate shoreline (Figure 1A). This chapter concentrates on genetically related lacustrine reservoirs, where significant hydrocarbon reserves occur in the full range of depositional environments from alluvial fan through fan delta, braided river, meandering river, lake margin/shoreline, and carbonate bank to lake floor fan (Figure 1B).

Within a global context, about 2.2% of discovered oil ($16 \times 10^8 \text{BOE}; 2.5 \times 10^8 \text{m}^3$) has hydrocarbon sources associated with lacustrine or coal-bearing strata, whereas lacustrine reservoirs account for only about 7% of daily oil production in 2002 ($-5 \times 10^6 \text{BOE}/0.8 \times 10^6 \text{m}^3$) (Figure 2). Lacustrine reservoirs appear to hold only about 3% of proven oil reserves (based on U.S. Geological Survey and British Petroleum published information). Does this small proportion reflect a fundamental problem with lacustrine systems or a great opportunity for exploration? This is a major question addressed in this chapter, starting in the next section with a comparison of lacustrine with other reservoirs.

**LACUSTRINE RESERVOIRS COMPARED WITH MARINE AND OTHER CONTINENTAL SYSTEMS**

A widespread perception that lacustrine reservoirs are inherently of lower quality than marine reservoirs exists. The perception does not hold up under detailed examination of published data (Figure 3). The ranges of reservoir and fluid properties in producing fields, as well as oil recovery factors, are not significantly different between lacustrine reservoirs and marine reservoirs; reported average porosities range from 5 to 35% (lacustrine) versus 1.1 to 58% (marine), and average permeabilities range from 0.1 to 3000 md versus 0.004 to 10,000 md. Hydrocarbon fluids within lacustrine reservoirs have average viscosities that range from 0.38 to 79 cp versus 0.016 to 878 cp (marine) and average densities that range from 14 to 46° API versus 10.2 to 64° API. Oil recovery factors for lacustrine reservoirs average about 36%, spanning 17 to 58% versus a 39% average (5–85%) for marine systems.

In detail, lacustrine reservoirs do have a wide range of properties: net pay (as reported by the operator) ranges from 28 to 80 ft (8.5–24.4 m) and average net/gross ratio
from 3 to more than 85% (Figure 4). Average porosity by field ranges from 4 to 38%, and permeability ranges from less than 0.1 md to greater than 4 darcys. Field size distribution of our 53 examples ranges from less than $32 \times 10^6$ BOE ($5 \times 10^8$ m$^3$) to greater than $18 \times 10^9$ BOE ($2.9 \times 10^9$ m$^3$). A similar wide range of hydrocarbon fluid properties exist, with densities from 11 to 48° API and viscosities from less than 0.3 to greater than 5000 cp. The chemical nature of the oils also varies, with sulfur content up to 1.8% and wax content from 5 to 46%. The wide span of single oil production rates and field well spacings indicate a wide range of producibility and flow-unit complexity.

One significant contrast with marine systems is that the well-log expression of lacustrine strata ranges widely and can differ greatly from common marine siliciclastics, including completely opposite responses to the same rock types (Bohacs and Miskell-Gerhardt, 1998). For example, fluctuating-profundal lacustrine-facies association strata with abundant volcanioclastic sandstones can have a reversed gamma-ray log signature, with organic matter-enriched mudstones that have low gamma-ray activity caused by very low amounts of chelated uranium and high gamma-ray-activity sandstones caused by abundant $^{40}$K (Figure 5). These variations appear to be mainly influenced by lacustrine-facies association and provenance of clastics.

These considerations indicate that reservoirs in lacustrine strata are challenging, although worthy, targets for exploration because of the wide range of properties. There do appear, however, to be characteristic features of hydrocarbon reservoir potential of specific associations of lacustrine facies that can be understood in the context of the lake-basin-type framework (Carroll and Bohacs, 1995, 1999, 2001; Bohacs et al., 2000; Bohacs et al., 2003a, b). These observations are presented in the following section.

**LACUSTRINE SEDIMENTARY FACIES ASSOCIATIONS AND THEIR RESERVOIR PROPERTIES**

Despite the complex nonlinear nature of modern lake systems, the rock record of these systems tends to be relatively straightforward, even at the scale of stratigraphic member to tongue (Carroll and Bohacs, 1999; Bohacs et al., 2003b). Examination of lake strata of Cambrian to Holocene from around the world reveals three main facies associations based on their physical, chemical, and biological attributes (Carroll and Bohacs, 1999, 2001; Bohacs et al., 2000; as well as many other workers, e.g., Lyell, 1830; Bradley, 1931; Olsen, 1990). The three lacustrine-facies associations are summarized in Figure 6.
and Table 1. The fluvial-lacustrine lacustrine-facies association is dominated by clastic strata (including biogenic clastics) associated with coaly shales and contains mostly physical transport sedimentary structures. The fluctuating-profundal facies association is marked by carbonate strata, along with clastic rock types and kerogenite, and physical and biogenic structures. The evaporative lacustrine-facies association is distinguished by evaporites interbedded with carbonate and clastic beds containing a wide variety of physical, biogenic, and chemical sedimentary structures. Stratal stacking also varies systematically, with progradation dominant in the fluvial-lacustrine lacustrine-facies association, aggradation dominant in the evaporative lacustrine-facies association, and a mixture of progradation and aggradation in the fluctuating-profundal lacustrine-facies association. In addition, each lacustrine-facies association has characteristic hydrocarbon reservoir potential in fluvial, lake-plain, lake margin, and lake center strata elaborated in the following sections (Table 1).

**Fluvial-Lacustrine Lacustrine-Facies Association**

Hydrocarbon reservoir lithologies in the fluvial-lacustrine lacustrine-facies association comprise mainly sandstone, with some conglomerate and bioclastic limestone. They are best developed in strata interpreted as forming in perennial rivers (commonly high-sinuosity streams) and in deltas with river and mixed wave-river dominance. Stratal stacking of many deltaic reservoirs is dominated by oblique progradation (Figure 7). At the depositional-sequence scale, reservoirs have a characteristic distribution: aggradational wedges over sequence boundaries with maximal erosion in basin margin positions in lowstand systems tracts, relatively thin wave-dominated shoreline strata in transgressive systems tracts, and obliquely progradational shoreline strata and relatively thick fluvial channel strata in highstand systems tracts.

Channel-belt reservoir lithosomes in this lacustrine-facies association tend to have stratal patterns dominated by lateral accretion, commonly interpreted as point-bar deposits of relatively high-sinuosity perennial streams of fairly constant discharge.

Reservoir properties have characteristic ranges of averages at the field scale, with net pay thicknesses from 33 to 700 ft (10–213 m), net pay:gross interval values from 10 to 70%, porosity from 4 to 38%, and permeability from 1 to 4000 md (Table 1).

Figure 8 illustrates a representative example from the Shanshan field, Turpan Basin, China, where well-based mapping shows progradation of a wave-dominated meandering river delta. The five main reservoir intervals have an average net pay of 20 m (range, 6–95 m) and net/gross ratio of about 33% (Wang and Leng, 1994). Significant variations in reservoir character at the bed, bedset, and parasequence scale exist, especially among delta-front and distributary channel facies. In this field, reservoir properties are strongly related to depositional subenvironments; distributary channel sandstone intervals have the best porosity and permeability, with average porosity of 25% (range, 15–35%) and average permeability of 200 md (range, 0.01–5000 md). At a larger scale, all the deltaic depositional subenvironments are well connected over several kilometers laterally, but very poorly connected vertically (Figure 8B). This distribution of connectivity is characteristic of fluvial-lacustrine lacustrine-facies associations and is a consequence of its typical oblique progradational pattern. This geometry can have significant influence on the distribution of hydrocarbons within these types of reservoirs and result in inefficient sweep and bypass of considerable amounts of oil if not recognized (Figure 9). Ainsworth and others (1999) quantified this effect with detailed reservoir modeling and increased reserve estimates by 43% using this more accurate and appropriate correlation strategy.

In summary, reservoir intervals in fluvial-lacustrine lake facies-association strata tend to have low Kv because flooding surfaces are generally marked by decreased input of coarse sediments and increased subidence and they have the lowest average net/gross ratio. They do, however, have the highest porosity and permeability and contain the largest overall reserves, mainly in lake-plain fluvial facies. Examples of fluvial-lacustrine lacustrine-facies association strata from Turkey, Chad, Hungary, Utah, Indonesia, Texas, China, Mongolia, and Michigan are discussed in other chapters in this volume (Archer et al., Fraser et al., Karp, Magyar, Mason, Patterson et al., Picarelli et al., and Schäfer).

**Fluctuating-Profundal Lacustrine-Facies Association**

Hydrocarbon reservoirs in the fluctuating-profundal lacustrine-facies association comprise conglomerate, sandstone, and muddy sandstone, as well as bioclastic microbial, and oolitic limestone and dolomitic grainstone. They are well developed in strata interpreted as forming in a broad range of environments: lake floor fan, river-dominated delta, wave-dominated delta, coquina-grainstone shoals, and intermittent rivers (commonly low-sinuosity to braided streams; Figure 10). Stratal stacking of shoreline reservoirs is commonly a mixture of progradation and aggradation. At the depositional sequence scale, reservoirs have a characteristic distribution: lake floor fans over sequence boundaries with minimal erosion but significant basinward shifts, variably
developed reservoirs in lowstand systems tracts, relatively thick river-dominated shoreline and fluvial strata in transgressive systems tracts, and sigmoidally to obliquely progradational shoreline strata in highstand systems tracts (see Mitchum, 1977, for definition of progradation style).

Channel-belt reservoir lithosomes in this lacustrine facies association tend to be dominated by strata with significant downstream accretion, probably deposited in relatively shallow broad low-sinuosity streams, commonly interpreted as braided rivers.

Reservoir properties have characteristic ranges of field averages, with thicknesses from 38 to 678 ft (11.6–207 m), net pay: gross interval values from 10 to 84%, porosity from 5 to 27.6%, and permeability from 1 to 4000 md (Table 2).

Figure 11 illustrates a lake-floor fan example with significant oil production from the Recôncavo Basin, Brazil, with net pay of about 20 m (66 ft) and net/gross ratio of about 42% in a characteristic distributary pattern. Although these strata are dominantly clean sublitharenite and subarkose, early quartz cement from

Figure 3. Ranges of reservoir and fluid properties in producing fields, as well as oil recovery factors, are not significantly different between lacustrine and marine reservoirs. (A) Reservoir interval average porosity versus average permeability by environment of deposition. Each point represents a producing field. (B) Fluid properties of density and viscosity by reservoir environment of deposition. Each point represents a producing field. (C) Comparison of oil recovery factor calculated for estimated ultimate recovery (EUR) among continental (fluvial and eolian), marine, and lacustrine reservoir environments of deposition.
genetically related encasing mudstone strata occludes most porosity (de Figueiredo et al., 1994). This appears to be a common problem with lake floor fan sandstone reservoirs. In this field, porosity ranges from 9 to 18% (average, 14%) and permeability from 1.2 to 2000 md (average, 200 md). These properties vary systematically and correlate strongly with net reservoir thickness, which in turn correlates well with depositional environment (Sousa et al., 1992; Figure 11A, B, C). Individual lake-floor-fan reservoir units are connected laterally over a kilometer or two, but have abrupt lateral pinch-outs and are very poorly connected vertically (Figure 11D, E). These characteristics, along with their stacking architecture, require production wells spaced only 220 to 300 m (722–984 ft) apart in this field.

The other important reservoir facies in fluctuating-profundal lacustrine-facies association strata is the braided river delta, illustrated by the Sha-2 member of the Shahejie Formation, Bohai Basin, China (Figure 12). These deltaic intervals have thicker net pay and higher net/gross ratio than the meandering river delta examples in fluvial-lacustrine lacustrine-facies associations. Similar to fluvial-lacustrine lake facies, however, are the significant variation in reservoir quality at the bed and bedset scale, with slightly higher porosity, but a similar range of four orders of magnitude of permeability (Qiu, 1984; Yang, 1988). At the parasequence scale,
porosity and permeability vary by subenvironment, being best developed in updip distributary-channel sandstone intervals and decreasing distally (Figure 12B, D). These units are well connected laterally and vertically with extended lateral pinch-outs—significantly better than the lake floor fan or fluvial-lacustrine lake-facies association delta units (Figure 12C, D).

In summary, reservoirs in fluctuating-profundal lake-facies association strata tend to have the smallest lateral extent and the lowest average recovery factor (based on reservoir and fluid properties), but do have good Kv and Kh in highstand and transgressive systems and the best Kv of all the lake types. Examples of fluctuating-profundal lacustrine-facies association strata from Turkey, Chad, Hungary, and China are discussed in other chapters in this volume (Ali-Adeeb et al., Archer et al., Karp, Mason, Patterson et al., and Picarelli et al.).

Evaporative Lacustrine-Facies Association

Hydrocarbon reservoir rock types in the evaporative lacustrine-facies association comprise a broad variety of

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**Figure 4.** Distribution of reservoir properties of lacustrine reservoirs. The wide span of attributes indicate a wide range of producibility and flow-unit complexity. (A) Distribution of field average net pay and field average net/gross ratio. (B) Distribution of field average porosity and field average permeability. (C) Distribution of stratigraphic compartments per field, field maximum single well oil production rates, and well spacing.
lithology, from sandstone, conglomerate, and muddy sandstone to dolomitic grainstone. They are developed in strata interpreted as forming in a wide range of environments: terminal splay, river-dominated delta, wave-dominated delta, grainstone shoreline, eolian dune, and ephemeral to perennial rivers (commonly multithreaded braided streams with some meandering streams; Figure 13A, B). Stratal stacking of shoreline and fluvial reservoirs is dominantly aggradational. At the depositional sequence scale, reservoirs have characteristics and distributions that vary widely and systematically: sequence boundaries have widespread exposure and minimal erosion, with minimally developed overlying thin reservoirs if the lake system receives most of its water input from local catchments; relatively thin poorly organized terminal splay and sheetflood units of the transgressive systems tracts directly overlie the sequence boundary across wide expanses, and relatively thick progradational shoreline strata whose stacking pattern evolves from sigmoidal to oblique to degradational (downstepping) in highstand systems tracts. Significant clastic reservoirs do occur in evaporative lacustrine-facies associations in lake basins with significant fluvial influx from distal catchments with different climatic conditions (e.g., the Pliocene Productive series of the South Caspian Sea; Adbullaev et al., 1998, 2012; Reynolds et al., 1998; Red Series, Turkmenistan, Tebaldi et al., 2002; Buryakovsky et al., 2001; Riley et al., 2006).

Channel-belt reservoir lithosomes in this lacustrine-facies association are dominated by vertical and downstream accretion and are closely associated with terminal splay or very shallow-water braided river delta strata. The rivers are interpreted to range from moderate-sinuosity streams to low-sinuosity multithreaded rivers with highly and rapidly variable discharge.

Reservoir properties have characteristic ranges, with thicknesses from 28 to 800 ft (8.5–244 m), net pay: gross interval values from 3 to 65%, porosity from 17 to 23%, and permeability from 22 to 386 md (Table 1).
Figure 14 illustrates a representative example from the Paleocene in the Zhongshi field, Jianghan Basin, China. Maps of total sandstone thickness show a complex pattern with net pay that ranges from 3.9 to 71 m (12.8–233 ft) average, 13 m (43 ft) at the kilometer scale (Figure 14A; net to gross averages 30%; Qiu and Gong, 1999). Detailed mapping shows two distinctive planform patterns associated with two types of reservoir units recognized in the field (Figure 14B). We interpret the relatively thin and elongated dip-oriented sandstone

Figure 5. The well-log expression of lacustrine strata ranges widely and can differ greatly from common marine siliciclastics, including completely opposite responses to the same rock types. (A) Well-log expression of two members of the Green River Formation (Eocene, Wyoming) deposited in the same lake basin with common provenance, but different lake-basin type. (B) Well-log response of the Laney Member, Green River Formation (Eocene, Wyoming) calibrated to a nearby outcrop section. In contrast to normal marine siliciclastic response, the organic matter–rich oil shales have low total gamma-ray activity because of low concentrations of uranium in the lake waters at time of accumulation, whereas the sandstones have a high total gamma-ray activity because they are volcaniclastic and rich in $^{40}$K.
Table 1. Representative attributes of three major lacustrine facies associations.

<table>
<thead>
<tr>
<th>Lacustrine Facies Association; Lake Basin Type</th>
<th>Stratigraphy</th>
<th>Stratal stacking patterns Peak Clastic Influx</th>
<th>Sedimentary structures</th>
<th>Lithologies</th>
<th>Organic matter</th>
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</thead>
<tbody>
<tr>
<td>Fluvial-Lacustrine; Overfilled Lake Basin</td>
<td>Maximum progradation:</td>
<td>Dominantly progradation</td>
<td>Physical transport: ripples, dunes, flat bed</td>
<td>Mudstone, marl</td>
<td>Freshwater biota</td>
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<td></td>
<td></td>
<td>Indistinctly expressed parasequences</td>
<td>Root casts</td>
<td>Sandstone</td>
<td>Land-plant, charophytic and aquatic algal OM</td>
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<td></td>
<td></td>
<td>Lowstand Systems Tract</td>
<td>Burrows (in- &amp; epi-faunal)</td>
<td>Coquina</td>
<td>Low to moderate TOC</td>
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<tr>
<td></td>
<td></td>
<td>* Parasequences related to lateral progradation</td>
<td></td>
<td>Coal, coaly shale</td>
<td>Terrigenous &amp; algal biomarkers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* Maximum fluvial input</td>
<td></td>
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<tr>
<td>Fluctuating Profundal; Balanced-fill Lake Basin</td>
<td>Mixed progradation and desiccation:</td>
<td>Mixed progradation and aggradation</td>
<td>Physical and Biogenic: flat bed, current, wave, &amp; wind ripples; stromatolites, pisoliths, oncinites</td>
<td>Marl, mudstone</td>
<td>Salinity tolerant biota</td>
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<td></td>
<td></td>
<td>Distinctly expressed parasequences</td>
<td>Muddcracks</td>
<td>Siltstone, sandstone</td>
<td>Aquatic algal OM</td>
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<td></td>
<td></td>
<td>Transgressive Systems Tract</td>
<td>Burrows (epifaunal)</td>
<td>Carbonate grainstone, wackestone, micrite</td>
<td>Minimal land plant</td>
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<td></td>
<td></td>
<td>* Distinct shoaling cycles common</td>
<td></td>
<td>Kerogenite</td>
<td>Moderate to high TOC</td>
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<tr>
<td></td>
<td></td>
<td>* Fluvial input variable</td>
<td></td>
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<td>Algal biomarkers</td>
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<tr>
<td>Evaporative; Underfilled Lake Basin</td>
<td>Maximum desiccation:</td>
<td>Dominantly aggradation</td>
<td>Physical, Biogenic and Chemical: climbing current ripples, flat bed, stromatolites, displace fabrics, cumulative textures</td>
<td>Mudstone, Kerogenite</td>
<td>Low-diversity, halophytic biota</td>
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<tr>
<td></td>
<td></td>
<td>Distinctly to indistinctly expressed parasequences</td>
<td></td>
<td>Evaporite</td>
<td>Algal-bacterial OM</td>
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<tr>
<td></td>
<td></td>
<td>Highstand Systems Tract</td>
<td></td>
<td>Siltstone, sandstone</td>
<td>Low to high TOC</td>
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<td></td>
<td></td>
<td>* Closely spaced packages of wet-dry lithologies</td>
<td></td>
<td>Grainstone, boundstone, flat-pebble cgl</td>
<td>Hypersaline biomarkers</td>
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<tr>
<td></td>
<td></td>
<td>* Minimum fluvial input</td>
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Notes: OM = organic matter; TOC = total organic carbon content. Table adapted from Bohacs et al., 2002a.
units as fluvially dominated lowstand systems tracts and the relatively thick, wide, strike-oriented sandstone units as wave-dominated highstand systems tracts. The complex pattern of the total sandstone thickness map thus results from the variable depositional environments and offset lateral stacking of these two types of units basinward of a bounding fault that influences local accommodation. The two types of reservoir units also have different distributions of porosity and permeability, with high permeability at the top of the highstand systems tract units and near the base of the lowstand systems tract units (Figure 14C). Accounting for these distinctive permeability distributions in perforation and injection strategies has greatly improved sweep efficiencies and water cuts (Wang and Wang, 1998). Both types of units are well connected laterally, and the highstand systems tract units are better connected vertically than lowstand systems tract units, which are typically interbedded with profundal mudstone or evaporite (Figure 14D). The close association with evaporites, although providing an excellent vertical seal, also indicates the main challenge with reservoir quality in this lacustrine-facies association: These systems are prone to early cementation by either carbonate or evaporite minerals (Figure 15). Ultimate reservoir potential in many fields of this lacustrine-facies association depends on development of secondary porosity at depth.

In summary, reservoirs in evaporative lake-facies association strata tend to be widely displaced laterally between highstand and lowstand systems tracts and commonly have extensive early carbonate and evaporite cements. They do, however, have the best Kh (because of common erosion that enhances lateral connectivity) as well as the thickest net pay (as a function of potential accommodation) of all the lake-basin-type reservoirs. Examples of evaporative lacustrine-facies association strata from the South Caspian Sea region, Australia, Wyoming, and the Dead Sea are discussed in other chapters in this volume (Abdullayev et al., Baganz et al., Bartov et al., Mason, Nummedal et al., Salamov, and Sylvester et al.).

KEY CONTROLLING FACTORS AND LAKE-BASIN TYPES

The widespread occurrence of the three major lake-facies associations and their distinctly different stratigraphic records makes it necessary to construct three distinct models to summarize their various expressions of depositional sequences, reservoir character, and modes of system behavior and also to understand controls on their formation (Carroll and Bohacs, 1999; Bohacs et al., 2002b, 2007c). It appears useful to cast the three models in terms of the interaction of the rates of potential
Figure 8. Representative subsurface example of producing reservoirs in the fluvial-lacustrine lacustrine-facies association from the Turpan Basin, China. (A) Well-based mapping shows progradation of a wave-dominated meandering river delta. (B) The five main reservoir intervals have an average net pay of 20 m (66 ft) and net/gross ratio of about 33%. Reservoir properties are strongly related to depositional subenvironment. Distributary channel sandstone intervals have the best porosity and permeabilities, with average porosity of 25% and average permeability of 200 md. (modified from Bohacs et al., 2002a).
accommodation and the supply of sediment plus water. This allows the construction of a phase diagram that portrays the boundary conditions among continental depositional systems and lake-basin types and their interrelations (Figure 16) (Carroll and Bohacs, 1995; 1999). The three lake-facies associations translate directly into three lake-basin types: overfilled, balanced fill, and underfilled. The overfilled lake-basin type accumulates fluvial-lacustrine lake-facies association, under mostly open hydrology, stable lake level, and consequent freshwater conditions, hence, its fill is dominated by progradation of mostly clastic sediments. The open hydrologic conditions are commonly recorded on the lower lake plain in shallow burrow assemblages and in histosols, coaly mudstones, and coals. Associated fluvial systems are dominated by relatively steady discharge rivers whose channels tend to be highly sinuous. The balanced-filled lake-basin type accumulates fluctuating-profundal lacustrine facies under hydrology that varies between open and closed, yielding lake waters of alkaline-saline to fresh character; its fill is a mixture of progradational and aggradational stacks of clastic and carbonate lithologies. The intermittently open hydrologic conditions are commonly recorded on the lower lake plain in moderate depth, multiltier burrow assemblages, and in vertisols and entisols (Bohacs et al., 2007c). Associated fluvial systems are dominated by variable unsteady discharge rivers (intermittent to perennial) that are prone to have low-sinuosity to braided channel patterns. The underfilled lake-basin type accumulates evaporative lacustrine-facies association strata under mostly closed hydrology and consequent saline to hypersaline waters; its fill is dominated by aggradational stratal stacking with a significant component of evaporites or other chemical rock types. The persistently closed hydrologic conditions are commonly recorded on the lower lake plain in multiltier, multigeneration burrow assemblages (some relatively deep) and in aridisols and entisols (Bohacs et al., 2007c). Associated fluvial systems are dominated by ephemeral to intermittent rivers with channel patterns that tend to be multithreaded to braided.

Lake-basin types are distinct from each other because similar changes in boundary conditions result in different system responses, depending largely on antecedent conditions. This characteristic, as well as the common occurrence of three main lacustrine-facies associations, indicates that lake-basin types represent intransitive self-organized criticalities (Bak et al., 1987, 1988; Bohacs et al., 2003b). This behavior translates directly into their distinctive stratigraphic expressions (Table 2). One can thus recognize each lake-basin type by the characteristic development of each component of its depositional sequences (Table 1). Many of the criteria in Table 1 are applicable at the scale of reflection seismic data: degree of erosion and amount of basinward shift of facies associated with the basal sequence boundary and the internal character and stacking patterns of progradation. It is the relative development of component systems tracts that is most diagnostic of lake-basin type (Table 2); the overfilled lake-basin type shows either no lowstand systems tract or a very distinctively developed lowstand systems tract, with characteristic oblique progradation in the highstand systems tract. The balanced-filled lake-basin type has the best-developed and thickest transgressive systems tracts and widely variable lowstand systems tracts, and the underfilled lake-basin type has minimal erosion on sequence boundaries and a well-developed highstand systems tract dominated by sigmoidal progradation.

The characteristic associations of stratal stacking patterns, seismic geometries, lithologies, and organic geochemical attributes commonly allow one to classify lacustrine depositional sequences and sequence sets
Figure 8. (cont.). (D) At the field scale, all deltaic depositional subenvironments are well connected laterally over several kilometers but very poorly connected vertically. This distribution of connectivity is characteristic of fluvial-lacustrine lacustrine-facies associations and is a consequence of its typical oblique progradational pattern. (modified from Wang and Leng, 1994). 200 m (656 ft).
according to lake-basin type, despite the relatively wide range of stratal expression and noise of real-world data. The close interrelations of stratal packaging and rock attributes enable one to make meaningful interpretations and predictions of play-element adequacy and distribution with sparse sample data (Bohacs et al., 2000).

**COMPARISON OF RESERVOIR PROPERTIES AMONG LAKE-BASIN TYPES**

One might ask: Do the observed differences among lake types actually make a difference in the way one correlates, maps, or explores in lake systems? These differences do make a significant difference, as each lake-basin type has distinctive character, distribution, and stacking of stratal units (Bohacs et al., 2000). Depositional sequences are significantly different in each lake-basin type, as shown in Table 2; some are dominated by lowstand systems tracts, others by well-developed transgressive systems tracts, and still others by highstand systems tracts. This approach has been shown to be quite effective for estimating and predicting the type, richness, and distribution of potential source rocks (e.g., Carroll and Bohacs, 1999, 2001; Bohacs et al., 2000). Different lake-basin types also exhibit critical differences in reservoir type and distribution (Figures 17–21). These differences arise mainly from the tendency of each lake-basin type to have its peak clastic influx at a different phase in relation to lake level: overfilled lake basins tend to peak in lowstand systems tracts, balanced-filled lake basins in transgressive systems tracts, and underfilled in highstand systems tracts (Table 2) (Neal et al., 1997; Bohacs et al., 2002).

The following paragraphs discuss the differences in reservoir properties among the lake-basin types and possible underlying controls. For example, both average net pay and average net/gross ratio reservoir proportion are largest in underfilled lake basins, which also have the largest range in these properties (Figure 17A). This relation is probably related to the tendency of underfilled lake basin phases to occur at higher rates of potential accommodation. Looking at the distribution of the ranges of these two parameters, a slight tendency exists for each lake-basin type to have a different relation of net pay:gross stratigraphic interval (Figure 17B). The low slope of the relation for underfilled lake basins may record the tendency for their high potential

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**Figure 9.** Distribution of connectivity in the Lan Krabu Formation (Miocene), Sirikit Field, Thailand. Delta-front and stream–mouth bar facies are well connected obliquely across the field but poorly connected vertically in any one well bore. Recognition of this characteristic pattern and reservoir modeling using a more accurate and appropriate correlation strategy increased reserve estimates by 43%. (modified from Ainsworth et al., 1999).
accommodation rates to trap both fine and coarse sediments as well as the dissolved load of inflowing rivers (detailed studies of the underfilled lake-basin strata of the Wilkins Peak Member, Green River Formation indicate that this lake-basin type has sediment accumulation rates two to four times greater than the surrounding balanced-filled and overfilled lake-basin strata; Smith et al., 2003). Porosity and permeability also show systematic differences: overall highest in overfilled lake-basin types and lowest in underfilled ones (Figure 17). This appears to be related to the prevalence of early cements and associated evaporites in underfilled lake basins.

Ultimate reservoir quality may be related to lake-basin type and its evolution through the diagenetic effects of fluctuating groundwater tables and lake-water chemistry. Each lake-basin type has a characteristic history of groundwater level changes, recorded in recurring associations of paleosol types and ichnofossil assemblages: histosols and shallow single-tier burrows, tracks, and trails in overfilled lake basins, and vertisols and multitier moderate-depth insect burrows in underfilled lake basins (Bohacs et al., 2002, 2007c; Hasiotis et al., 2003). Thus, the development of highly saline lake waters and extensive evaporative pumping are probably the causes of the extensive early cements found in underfilled lake-basin strata.

Measures related to reservoir connectivity are not commonly reported nor readily comparable. Possible indicators of reservoir connectivity that are widely available, such as the number of reservoir intervals per field and well spacing, indicate a slight tendency for balanced-filled lake-basin reservoirs to be better connected on average (Figure 18). The other aspects of producibility and hydrocarbon fluid properties (density, pour point) show significant variation (Figure 19A): overfilled lake-basin reservoirs contain the lowest average and widest range of densities and pour points. This is probably because of the mix of land plant and algal organic matter that is most common in this lake-basin type (Carroll and Bohacs, 2001).

Oil quality, in terms of sulfur and wax content, shows very distinct trends among lake-basin types. Sulfur content is lowest in overfilled lake-basin reservoirs because of their commonly open hydrology freshwater conditions (Figure 19B). In contrast, average sulfur content is highest on average in underfilled lake-basin reservoirs as well as having the broadest range related to hydrologic conditions that are characteristically closed, but with intermittent overflow and flushing, along with the influence of various provenance lithotypes (e.g., Great Salt Lake to Lake Bonneville conditions, Utah; see also Bohacs et al., 2000; Carroll and Bohacs, 2001). Wax content is also largest in overfilled lake-basin reservoirs probably because of their abundant content of land plant material (Figure 19B). These oil quality relations are exactly what we expect from our work on

Figure 10. Examples from the Lower Cretaceous, Sergipe-Alagoas and Recôncavo basins, Brazil, of the variety of lithofacies that form hydrocarbon reservoirs in the fluctuating-profundal lacustrine facies association. (A) Wave-dominated deltaic strata with abundant bioclastic fragments (coquinas), Coquiere Seco formation; (B) River-dominated deltaic strata, Taquipe Formation; (C) Lake-floor fan strata, Candeias Formation.
Table 2. Lacustrine-facies association and lake-basin type V reservoir properties: lacustrine-facies association, porosity, permeability, net/gross ratio, net pay.

<table>
<thead>
<tr>
<th>Lacustrine Facies Association; Lake-Basin Type</th>
<th>Porosity</th>
<th>Permeability</th>
<th>Net Pay</th>
<th>Net/Gross Reservoir</th>
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<td><img src="image" alt="Permeability" /></td>
<td><img src="image" alt="Net Pay" /></td>
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<tr>
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<td><img src="image" alt="Net Pay" /></td>
<td><img src="image" alt="Net/Gross Reservoir" /></td>
</tr>
<tr>
<td>Evaporative; Underfilled Lake Basin</td>
<td><img src="image" alt="Porosity" /></td>
<td><img src="image" alt="Permeability" /></td>
<td><img src="image" alt="Net Pay" /></td>
<td><img src="image" alt="Net/Gross Reservoir" /></td>
</tr>
</tbody>
</table>

Mean = 19.2; SD = 2.4; Median = 18.3; n = 7
Mean = 137; SD = 141; Median = 100; n = 7
Mean = 270; SD = 283; Median = 190; n = 7
Mean = 0.33; SD = 0.26; Median = 0.32; n = 4

Notes: All values are field averages; n = number of examples used.
lacustrine source rocks—the fine-grained part of the basin fill. That these relations also hold for reservoir intervals strongly indicates that most lacustrine reservoirs and sources are closely and genetically related (see also discussion in Bohacs et al., 2000).

Interestingly, even the associated nonhydrocarbon gases vary systematically, with overfilled lake-basin-type reservoirs having the largest carbon dioxide and nitrogen contents (Figure 20). This may be related to the close genetic association of overfilled lake-basin strata with coaly strata and land plant debris.

Lastly, the estimated ultimate recovery factor, the practical combination of all these important parameters, also appears related to lake-basin type: overfilled lake-basin reservoirs have slightly higher averages than underfilled ones; both have significantly greater recovery factors than balanced-filled lake-basin reservoirs (Figure 21A).

In summary, these data indicate that practically all reservoir parameters vary systematically with lake-basin type. Their overall relative ranking based on all parameters examined suggests that all lake-basin types have promise for commercially viable reservoirs (Table 3).

Figure 11. Example of a lake floor fan reservoir from the Reconcavo Basin, Brazil, Taquipe Formation with net pay of about 20 m (66 ft) and net/gross ratio of about 42% in a characteristic distributary pattern. Porosity ranges from 9 to 18% (average, 14%) and permeability from 1.2 to 2000 md (average, 200 md). These properties vary systematically and correlate strongly with net reservoir thickness, which in turn correlates well with depositional environment (Sousa et al., 1992). Lake floor fan reservoir units are well connected laterally over a kilometer or two but have abrupt lateral pinch-outs and are very poorly connected vertically. This architecture requires production wells spaced only 220 to 300 m (722–984 ft) apart in this field. (modified from de Figueiredo et al., 1994; Sousa et al., 1992).
Figure 11. (cont.)

Relation of Hydrocarbon Reservoir Potential to Lake-Basin Type

**B** Porosity

Contour interval: 3%

- Porosity trend

**C** Permeability

Contour unit in md

- Permeability trend

**D** SW

Subsea depth (m)

- Datum: 800 m subsea

- Gamma member of Candace Formation

- Surface 53

- Surface 64

- Sandstone (permeable)

- Regional Fault

- 100 m
These same data also indicate that each lake-basin type has different challenges to economic viability. Published estimates of original hydrocarbon volumes in place support this conclusion: oil-in-place reserves are, on average, similar among the three lake-basin types, although overfilled lake-basin reservoirs have the widest range (Figure 21B). Gas reserves similarly have about equal averages, but again range most widely in overfilled lake-basin reservoirs.

**DISCUSSION**

The strong genetic relation between lake-basin type and reservoir development aids prediction across a wide range of vertical and lateral scales in several significant ways. At the largest-supersequence scale (group or formation scale, as seen on reflection seismic data), just as lake-basin type evolves along a predictable pathway through lake-phase space as a basin forms and fills, so do the reservoir and seal properties. This scale of evolution is well portrayed on a lake-phase diagram that portrays the commonly observed evolution of lake-basin fill from fluvial strata through a variety of lake-type strata back to fluvial strata (e.g., Lambiase, 1990).

Figure 22 illustrates how lake-basin evolution can be portrayed as phase-trajectory curves under increasing then decreasing subsidence (potential accommodation) under different climatic conditions (as a proxy for sediment plus water supply). This approach indicates that potential accommodation rate is the primary control on the development of lake conditions in a basin, with the deepest lake occurring at maximum rate of potential accommodation (Bohacs et al., 2003b). Climate, however, as the main control on sediment plus water supply, controls what type of lake occurs at maximum rate of potential accommodation increase. Thus, one expects the full range of lake-basin types under low sediment plus water supply rates (relatively dry climates) and only overfilled to balanced-filled lakes under high sediment plus water supply rates (relatively wet climates; Bohacs et al., 2003b).

These ranges of lake-basin type development have been observed in many continental basins:

- **Paleocene, Wind River Basin, Wyoming**: fluvial $\Rightarrow$ overfilled $\Rightarrow$ fluvial (Bohacs, 2004)
- **Cretaceous, Erlian Basin, China**: fluvial $\Rightarrow$ overfilled $\Rightarrow$ balanced fill $\Rightarrow$ overfilled $\Rightarrow$ fluvial (Lin et al., 2001; Bohacs et al., 2003a, 2007b)

(see also examples in Bohacs et al., 2003b). These relations can be interpreted from seismic and well-log data integrated with regional paleoclimatic and paleogeographic information (e.g., Figures 23, 24).

Unfortunately, no simple relations exist between the two proximate controls (sediment plus water supply, potential accommodation) and the larger scale controls of climate and tectonics. Sediment plus water supply is certainly strongly influenced by climate (both over the lake and in its catchment area); it also is affected by other factors. Uplift can increase sediment supply by increasing gradient or decrease it by diverting river input; volcanism can also increase sediment supply by direct input or decrease it by blocking or diverting river input; and landscape evolution can capture or divert river input by stream piracy or change sediment supply by changing the rock types exposed in the catchment area (e.g., Chetel et al., 2005; Carroll et al., 2006). Even the apparently straightforward potential accommodation has two significant components: lake floor subsidence (a function of tectonics and sediment plus water load) and sill elevation (a function of tectonics and landscape evolution). For an example of how convoluted these relations can be, consider the various pathways that can change a lake from saline to fresh water: (1) increase precipitation/evaporation by having more rain or lower temperatures (less evaporation); (2) decrease potential accommodation (which leads to more flushing and fresher waters) by decreased lake floor subsidence or lowered sill elevation by erosion; or (3) increase freshwater influx by stream capture (caused by landscape evolution or tectonics or both). This example points out that a major change in the stratal record of a lake is not necessarily caused by a major change in climate or tectonics or any other single factor but is probably caused by the integrated effects of the forcing factors and their contingent interactions. Thus, although the lake phase diagram provides good general direction at the supersequence scale, the exact timing of changes in lake-basin type reflects when the integrated effects of the forcing functions cross critical thresholds and result in a shift in system behavior (Bohacs et al., 2003b). A system may shift from one lake-basin type to another by crossing a threshold after a gradual approach (e.g., slowly increasing potential accommodation rate or climate change, Figure 22) or after a sudden event under relatively constant climatic conditions (e.g., river capture by geomorphic evolution, diversion of river inputs by tectonic uplift, increased sediment supply by volcanism, decreased sediment supply by changing provenance, etc.). This system behavior has been documented in detail for the Eocene Green River Formation in Wyoming (Rhodes, 2002; Pietras, 2003; Carroll et al., 2005, 2006; Chetel et al., 2005).

At depositional sequence set (formation to member) scales, recognizing the appropriate lake-basin type provides good initial guidance for the occurrence, character, and distribution of lacustrine reservoirs. Predicting lacustrine reservoirs is, however, somewhat more challenging than predicting lacustrine source character for several reasons. Reservoirs show more overlap in properties among lake-basin types because reservoir properties are much more sensitive to boundary conditions (provenance, transportation distance and mechanisms, distribution of clastic entry points, etc.), and their settings tend to be more segmented and less integrative than lake center settings that accumulate fine-grained strata that more accurately record the state of the entire lake ecosystem.

At the scale of depositional sequences and systems tracts (member to tongue scale), the interaction of lake-basin phase and local depositional gradient controls the existence and relative development of depositional systems tracts, sequence boundaries, and flooding surfaces. These interactions also influence the vertical stacking and lateral displacement of systems tracts, the genetic association of reservoir and seal, and the type, development, and planform of shoreline systems. For example, underfilled lake-basin systems tend to develop river-dominated shorelines in upper lowstand and transgressive systems tracts and wave-dominated shoreline systems in highstand systems tracts (Figure 14 in the Zhongshi field). In addition, lowstand and highstand systems tract shorelines tend to be widely separated laterally in underfilled lake basins because of characteristically large basinward shifts during lowstands of lake level. The actual amount of displacement between highstand and lowstand shorelines is also a strong function of basin morphology and position in the basin: for example, larger shifts typify the low relief or flexural margin of half-graben rift basins. The lake-basin type approach also highlights the necessity to consider a variety of possible causes for changing lake character based on the four main state variables: sediment supply, water supply, basin floor subsidence, and sill uplift.

CONCLUSIONS

Observations in this study indicate that lacustrine reservoirs are complex because of the nonlinear and contingent influence of a variety of factors that control
Figure 12. Example of the braided-river delta reservoir facies of the fluctuating-profundal-lacustrine facies association, Sha-2 member, Shahejie Formation, Bohai Basin, China. The data are from Yang (1988) and Qiu (1984). (A) Overall stratigraphic section and paleogeographic map showing major structural elements, depositional environments, and clastic input areas. (B) Representative sections and well-log character of two main reservoir facies, along with porosity and permeability measured on core samples. Significant variations in reservoir quality at the bed and bedset scale exist, with a range of four orders of magnitude of permeability. At the parasequence scale, porosity and permeability are best developed in updip distributary-channel sandstone intervals and decrease distally. (C) Map of reservoir thickness in various depositional environments in braided-river delta unit, with the location of cross section shown in (D) indicated. Note significant changes in reservoir thickness at lateral scales of hundreds of meters. (D) Cross section of braided-river delta reservoir units oriented along depositional dip. These units are well connected laterally and vertically with extended lateral pinch-outs—significantly better than the lake-floor fan or fluvial-lacustrine lake-facies-association delta units. 323 m (1060 ft).
Figure 12. (cont.)
Figure 12. (cont.).
Figure 13. Hydrocarbon reservoir lithologies in the evaporative lacustrine-facies association develop in a wide range of environments: terminal splay, river-dominated delta, wave-dominated delta, grainstone shoreline, eolian dune, and ephemeral to perennial rivers (commonly multi-threaded braided streams with some meandering streams). These are illustrated here in modern-day Bosten Hu, western China (A) and in the Eocene Wilkins Peak Member, Green River Formation, Wyoming (B).
Figure 14. Example of evaporative lacustrine-facies-association reservoirs, Qiangjiang Formation (Eocene–Oligocene), Zhongshi field, Jianghan Basin, China. (A) Maps of total sandstone thickness show a complex pattern with net pay that ranges from 3.9 to 71 m (12.8–233 ft) (average, 13 m [43 ft]) at the kilometer scale. (B) Detailed mapping shows two distinctive platform patterns associated with two types of reservoir units recognized in the field. We interpret the relatively thin and elongated dip-oriented sandstone units as fluvially dominated lowstand systems tracts and the relatively thick, wide, strike-oriented sandstone units as wave-dominated highstand systems tracts. The complex pattern of the total sandstone thickness map thus results from the variable depositional environments and offset lateral stacking of these two types of units basinward of a bounding fault that influences local accommodation. (C) Illustration of the differences in rock properties and well-log response between lowstand and highstand systems tract intervals. (D) Cross sections indicate the differences in reservoir distribution between these two systems tracts: the lowstand system tract has thicker sandstone intervals, but is closely associated with thick evaporite intervals, whereas the highstand systems tract has thinner but better connected reservoir intervals (modified from Wang and Wang, 1998; Qiu and Gong, 1999).
Figure 14. (cont.)
lake-basin type and stratal accumulation: antecedent basin conditions, sediment supply, water supply, basin floor subsidence, and sill uplift. Contingency is what generates a major part of their complexity—how a lake system responds to a change in external forcing factors depends sensitively on the state of the system when the change occurs (Bohacs et al., 2003b).

Predicting economic viability is challenging because of the wide range of stratigraphic, reservoir, and fluid properties. Lacustrine reservoirs are worthy of this effort, as they are closely associated with the lacustrine mudstone and coaly strata that are the source of about 20% of current oil production worldwide. Although lacustrine reservoir properties are not a simple function of climate or tectonics or any other single factor, the characteristic lacustrine-facies associations indicate that linked and predictable controls exist. These relations allow meaningful predictions based on widely observed lake-facies associations with typical reservoir character through an understanding of the underlying dynamics that give rise to these recurring facies associations.

The strong genetic relation between lake-basin type and reservoir character aids predictions across a wide range of vertical and lateral scales in several significant ways: at the largest, supersequence scale (group or formation scale, as seen on reflection seismic data), just as lake-basin type evolves along a predictable pathway through lake-phase space as a basin forms and fills, so do reservoir and seal properties. This scale of evolution is well portrayed on a lake-phase diagram. At depositional sequence set (formation to member) scales, recognizing the appropriate lake-basin type provides good initial guidance for correlation and evaluation. At the scale of depositional sequences and systems tracts (member-scale), the interaction of lake-basin phase and local depositional gradient controls the existence and relative development of depositional systems tracts, sequence boundaries, and flooding surfaces. These interactions also influence the vertical stacking and lateral displacement of systems tracts, the genetic association of reservoir and seal, and the type, development, and planform of shoreline systems. The lake-basin type approach also highlights the necessity to consider a variety of possible causes for changing lake character based on the four main state variables: sediment supply, water supply, basin floor subsidence, and sill uplift.

Each lake-basin type can host commercially significant reservoirs, but each lake-basin type has different challenges to economic viability. The genetic framework of the lake-basin type approach can provide significant guidance for prediction. Continued success in economic discovery and efficient environmentally sound recovery depends upon continued testing and elaboration of these concepts and a deeper understanding of the essential processes controlling deposition of lacustrine strata.
Figure 17. (A) Comparison among lake-basin types of the distributions of the means of average net pay and average net/gross ratio. Both average net pay and average net/gross ratio reservoir proportion are largest in underfilled (UF) lake basins, which also has the largest range in these properties. This is probably related to the tendency of UF lake basin phases to occur at higher rates of potential accommodation. (B) The distribution of the ranges of these two parameters indicates that each lake-basin type tends to have a different relation of net pay to gross stratigraphic interval. (C) Comparison among lake-basin types of the distributions of the means of average porosity and permeability. BF = balanced-filled; OF = overfilled.

Figure 18. Comparison among lake-basin types of the distributions of the means of number of reservoir intervals per field and of well spacing in each field. There appear to be no significant or systematic differences among lake-basin types in these parameters.
Figure 19. (A) Comparison among lake-basin type reservoirs of the distributions of the means of oil density (API gravity) and of pour points. Oils in underfilled lake-basin-type reservoirs tend to have higher gravities but also higher pour points. (B) Comparison among lake-basin-type reservoirs of the distributions of the means of sulfur and of wax contents. Oils in overfilled lake-basin-type reservoirs tend to have lower sulfur, but higher wax contents.

Figure 20. Comparison among lake-basin-type reservoirs of the distributions of the means of nonhydrocarbon gases carbon dioxide and nitrogen. The associated nonhydrocarbon gases vary systematically, with overfilled lake-basin-type reservoirs having the largest carbon dioxide and nitrogen contents. This may be related to the close genetic association of overfilled lake-basin strata with coaly strata and land plant debris.
Figure 21. (A) Comparison among lake-basin-type reservoirs of the distributions of the means of recovery factors. Overfilled lake-basin reservoirs have slightly higher averages than underfilled ones; both have significantly greater recovery factors than balanced-filled lake-basin reservoirs. (B) Oil-in-place reserves are, on average, similar among the three lake-basin types, although overfilled lake-basin reservoirs have the widest range. Gas reserves similarly have about equal averages but again range most widely in overfilled lake-basin reservoirs.
Table 3. Lake-basin type relative ranking.*

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<th>Parameter</th>
<th>OF**</th>
<th>BF†</th>
<th>UF††</th>
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<tbody>
<tr>
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<td>1</td>
<td>2</td>
<td>3</td>
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<tr>
<td>Net/gross ratio</td>
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<td>1</td>
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<td>Porosity</td>
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<td></td>
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</table>

*Scale: 3 = higher, 1 = lower.
**OF = overfilled.
†BF = balanced-filled.
††UF = underfilled.
OIP = oil-in-place.

Figure 22. Lake basin evolution portrayed as phase trajectory curves under increasing then decreasing subsidence (potential accommodation) under different climatic conditions (as a proxy for sediment plus water supply). This approach indicates that potential accommodation rate is the primary control on the development of lake conditions in a basin, with the deepest lake occurring at maximum rate of potential accommodation. Climate, however, as the main control on sediment plus water supply, controls what type of lake occurs at maximum rate of potential accommodation increase. Thus, one expects the full range of lake-basin types under low sediment plus water supply rates (relatively dry climates) and only overfilled to balanced filled lakes under high sediment plus water supply rates (relatively wet climates). (based on an original figure by Jack E. Neal, ExxonMobil).
Figure 23. Example of lake-basin type evolution in the Paleocene Fort Union and Waltman Shale formations, Wind River Basin, Wyoming, of fluvial ⇒ overfilled ⇒ fluvial. This set of depositional environments is interpreted to have formed under very high rates of sediment plus water supply during an episode of basin evolution (increasing then decreasing potential accommodation). Although potential accommodation rate is the primary control on the development of lake conditions in a basin, sediment plus water supply controls what type of lake occurs at maximum rate of potential accommodation increase. Thus, one expects the full range of lake-basin types under low sediment plus water supply rates (relatively dry climates), overfilled to balanced-filled lakes under moderate sediment plus water supply rates (moderately wet climates), and only overfilled lakes under very high sediment plus water supply rates (relatively wet climates; Bohacs et al., 2003b).
Figure 24. Example of lake-basin type evolution in the Jurassic-Cretaceous units of the Erlian Basin, China, of fluvial $\Rightarrow$ overfilled $\Rightarrow$ balanced fill $\Rightarrow$ overfilled $\Rightarrow$ fluvial. This set of depositional environments is interpreted to have formed under relatively high rates of sediment plus water supply during an episode of basin evolution (increasing then decreasing Potential Accommodation). Seismic data from Lin et al., 2001.
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