by Kevin M. Bohacs,
ExxonMobil Upstream Research Company,
Houston, Texas

Keys to exploration: lake-basin type, source potential, and hydrocarbon character within an integrated sequence-stratigraphic/geochemical framework

Rocks associated with lakes probably account for more than 20% of current worldwide petroleum production (Kulke, 1995; Britannica Yearbook, 1999), and lacustrine organic-rich rocks are significant sources of the petroleum. Lacustrine sources and reservoirs are important in many areas of current and future exploration opportunities including Africa, South America, southeast Asia, and China (Hedberg, 1968; Powell, 1986; Smith, 1990; Katz, 1990).

We have developed the concept of lake-basin type, which is useful for sorting out the complexities of lacustrine deposition to derive a predictive framework (Carroll and Bohacs, 1995, 1999). Three lake-basin types are recognized from recurring lithofacies associations and stratal stacking patterns at scales of meters to decameters, based on numerous observations of lake strata from Cambrian to Recent age.

Lacustrine strata record the integrated history of lake hydrology arising from the interaction of potential accommodation and the supply of sediment+water. Both factors together govern the major stratigraphic features of ancient lake deposits. In conjunction with lake ecology, geologic age, basin shape, and drainage-basin lithology, they exert a strong influence on source character, reservoir-rock distribution, and petroleum potential.

The named lake-basin types, overfilled, balanced-fill, and underfilled, are based on the interpreted relation of potential accommodation and sediment+water supply (Figure 1). Expression of parasequences and sequences ranges from very similar to shallow-marine sequences in some overfilled lake basins to very different in underfilled lake basins (Table 1). Balanced-fill lake systems contain the most prolific lacustrine source rocks and beneficent facies juxtapositions for hydrocarbon accumulation,

Figure 1: Lake-Basin Type Phase Diagram

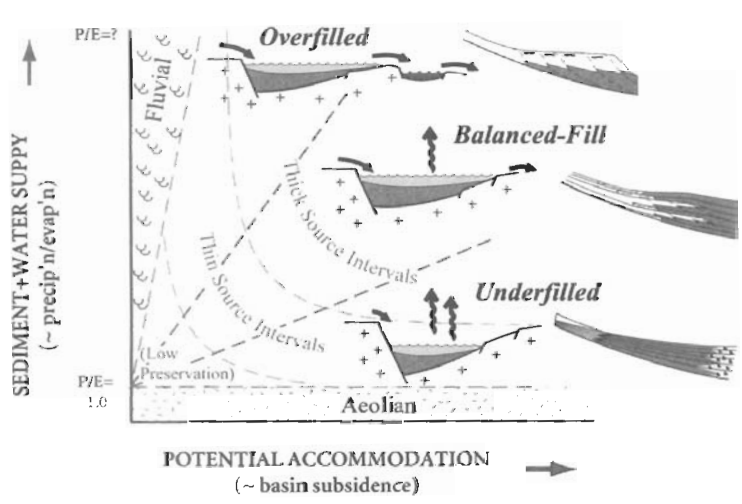

Figure 1: *Lake-basin-type phase diagram showing existence and character of non-marine strata in general and lacustrine strata in particular as a function of both sediment+water supply and potential accommodation. Interaction of the two controls is reflected in the lithology, stratal stacking, biota, and geochemistry of lake deposits. Potential accommodation is the space available for sediment accumulation below the basin's outlet or spillpoint (a key difference from marine systems; Carroll and Bohacs, 1995). It is mainly influenced by basin tectonics, along with uplift and erosion of a sill and inherited topography. Sediment+water supply is primarily a function of climatic humidity, along with seasonality, local relief, and bedrock geology. (Clastic sediment yield is a non-linear, non-monotonic function of climatic factors, generally peaking in semi-arid, distinctly seasonal climates— Einsele, 1992.)*

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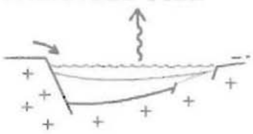
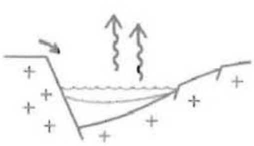
Table 2: *Characteristics of Lake-Basin Types: Strata, Source Facies, and Hydrocarbons*

Lake Type & Lacustrine Facies Association	*Stratigraphy*	*Source Potential*	*Hydrocarbon Characteristics*
OVERFILLED  *Fluvial-Lacustrine Facies Association*	Maximum progradation:  • Parasequences related to lateral progradation (relatively subtle) • Maximum fluvial input	• Low to moderate TOC • Mixed Type I-III kerogen • Marked organic facies contrasts • Distinct lateral changes in organic facies	• Generate both oil and gas • Very waxy, low-sulfur oils • Terrigenous biomarker assemblage dominant
BALANCED-FILL  *Fluctuating-Profundal Facies Association*	Mixed progradation and desiccation:  • Distinct shoaling cycles common • Fluvial input variable	• Moderate to high TOC • Predominantly Type I kerogen, with Type I-III mixtures near flooding surfaces • Relatively homogenous and laterally consistent organic facies	• Mostly oil generative • Paraffinic but relatively non-waxy oils; low sulfur • Algal biomarker assemblage dominant
UNDERFILLED  *Evaporative Facies Association*	Maximum desiccation:  • High-frequency wet-dry cycles • Minimum fluvial input	• Low overall TOC (w/ some high TOC intervals) • Type I kerogen • Minimum organic facies contrasts • Laterally consistent organic facies	• Mostly oil generative • Paraffinic oils; moderate to high sulfur • Distinctive "hypersaline" biomarker assemblage

based on observations of lacustrine strata of many different ages and basins (e.g.: East Africa Quaternary; U.S.A. Tertiary; Africa, Brazil, and China Cretaceous).

Lake-basin type commonly evolves among the three end members, often within a single formation, on a variety of time scales as a result of changes in climate or tectonic subsidence. Different lake types can also coexist in adjacent basins. Lake water depth and overall thickness of lacustrine strata are functions of both total subsidence and sediment+water supply and are not necessarily related to lake-basin type.

Lake-basin type offers significant advantages over previous models that were based on paleoclimate alone, and allows lacustrine source rocks to be genetically linked with reservoir and seal lithofacies through sequence stratigraphy. However, sequence-stratigraphic models specific to each type of lake basin are necessary because, unlike most marine systems, the supply of sediment in lake basins commonly can be closely linked to the supply of water and lake level. The integrated framework provides an approach to predicting hydrocarbon character from stratigraphic information or lake-strata character from geochemical data and suggests strategies for successful exploration and exploitation. The framework also enables one to appreciate and begin to comprehend small-scale variations and complexities of lake strata within a bigger picture.

Biographical Sketch

Kevin M. Bohacs is a sedimentologist and stratigrapher with the Petroleum Geochemistry section of Exxon Production Research Company in Houston, Texas. He received his B.Sc.(Honors) in geology from the University of Connecticut in 1976 and his Sc.D. in experimental sedimentology from M.I.T. in 1981. At EPR, he leads the application of sequence stratigraphy and sedimentology to organic-rich rocks from deep sea to swamps and lakes, in basins around the world. As a Research Associate, his primary focus is to keep the geo- in geochemistry, integrating field work, subsurface investigation, and laboratory analyses. He has written numerous papers on the stratigraphy and sedimentology of mudrocks and hydrocarbon source rocks. He was co-recipient of the AAPG Jules Braunstein Memorial Award for best poster session paper in 1995 for work on coal sequence stratigraphy and the AAPG award for best international paper in 1998.

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