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Reservoir Prediction in Lake Systems: Complex, Contingent, and Challenging

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Lakes are complex non-linear dynamical systems whose behavior can differ distinctly from marine systems. Predictions of reservoir presence, distribution, and character similarly pose distinct challenges. These challenges arise from the fundamental nature of lacustrine systems: non-unique 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.

At the reservoir scale, these challenges affect every aspect of prediction: Lake shoreline shapes encompass a wider and more complex diversity than typically seen in marine settings: 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 highstands and lowstands may obviate the application of Walther's Law for predicting lateral distributions, especially in underfilled lake basins. Even the well-log expression of lacustrine strata varies widely among lake-basin types and can differ greatly from that of marine siliciclastic strata.

Despite all 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 inter-related ways: Table 1 lists typical attributes of hydrocarbon play elements in each lake basin type.

Table 1: Inter-relation of Hydrocarbon Play Elements by Lake Basin Type

Lake Basin Type	Source	Reservoir	Seal
Overfilled	▪ Gas & Oil ▪ Mixed algal & land plant material	• Progradational shoreline clastics • Point-bar Ss	– Highstand profundal mudstone, claystone – Lake-plain mudstone, claystone
Balanced Fill	▪ Paraffinic oil ▪ Mostly algal material	• Carbonates and clastics in fluvial, shoreline, & lake-floor settings	– Highstand systems tract profundal micrites & marls
Underfilled	▪ Mostly oil ▪ Exclusively algal material	• Sheetflood sandstones to • Shoreline grainstones	– Lowstand evaporites – Highstand profundal mudstones, marls, micrites – Lake plain mudstones, marls, micrites

The strong genetic relation between lake-basin type and reservoir development aids predictions at the scale of depositional sequences and systems tracts in several significant ways: 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 (see Table 2). 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 platform of shoreline systems. In overfilled lake basins, reservoirs generally are best developed in aggradationally stacked highstand clastic shoreline strata, and occasionally in skeletal carbonate or charophytic algal lithosomes and in lowstand incised valley fills and lake-floor “fans” (basinally restricted turbidite and mass-flow deposits). In balanced-fill lake basin intervals, reservoir facies can include lake-floor “fans,” incised-valley fills, and shoreline clastics or carbonates deposited during transgressions and highstands. In underfilled lake basin strata, reservoir facies are best developed in transgressive sheetflood clastics, early highstand fluvial channels, and late highstand shoreline carbonate grainstones-- commonly widely displaced laterally.

Table 2: Relative Development of Sequence Boundaries & Systems Tracts within Lake Basin Types

Lake Basin Type		Sequence Boundary	Lowstand	Transgressive	Highstand
Overfilled	*Permanently*	Not developed	Not developed	Relatively thin	Oblique progradation
	Dominantly	Maximal erosion	Aggradational wedge		
Balanced Fill		▪ Minimal erosion ▪ Maximal basinward shift	Highly variable	Relatively thick	Sigmoidal to oblique progradation
Underfilled		Widespread exposure	▪ Soils ▪ Evaporites	Relatively thin	Relatively thick

Associated fluvial styles among the lake basin types appear to vary systematically, as a function of sediment+water supply relative to potential accommodation rates: perennial, high sinuosity streams in overfilled, intermittent to perennial low-sinuosity streams in balanced fill, and a wide range from ephemeral sheetflood/braided streams to perennial high sinuosity streams 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. 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, vertisols and multi-tier, moderate depth insect burrows in balanced fill, and aridisols and entisols with multi-tier, multiple generation, relatively deep burrows in underfilled lake basins.

The strong genetic association of play elements in lacustrine systems requires an integrated approach to prediction, which is facilitated by expanding the lake basin type diagram (Carroll and Bohacs, 1995, 1999) to a comprehensive continental-environment phase-stability framework. This framework places fluvial, floodplain, coal, aeolian, and the three main lake basin strata into relative stability fields, based on the rate of potential accommodation relative to supply rates of sediment and of water. The phase trajectory of basin evolution determines the proportion of each lake basin type in the resultant basin fill. This approach also helps explain why all lake basins do not contain the full suite of lake basin types and how the fill of a chain of ancient lakes may be genetically related, contingent on upstream conditions. One can predict the phase trajectory for a basin in a forward sense from estimates of basin subsidence, paleoclimate, and sediment yield or one can reconstruct the phase trajectory from relative thicknesses and areal extents of each continental environment stratal package: thick underfilled lake packages point to dominant control of potential accommodation rates whereas thin underfilled lake packages indicate dominant control of supply rates of sediment+water.

This approach indicates how contingent and non-unique the causes of major changes in lake character can be: small structural movements at the sill can cause large changes in lake behavior, whereas even relatively large structural movements on the lake floor can have little effect.

Our observations indicate that these associations of hydrocarbon play elements occur in a wide variety of tectonic settings and ages, from continental rift to convergent foreland basins of Cambrian to Recent age. 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.