Stratigraphic classification of ancient lakes: Balancing tectonic and climatic controls

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ABSTRACT

Lakes and lake deposits present two fundamental paradoxes: (1) Modern lakes are vastly complicated, but the rock records of lakes are relatively simple; extensive observations reveal three distinct facies associations of common and widespread occurrence. These are referred to here as fluvial-lacustrine, fluctuating profundal, and evaporative facies associations. (2) Most explanations of modern and ancient lakes attribute their nature to climate, but neither modern lake parameters (lake size, depth, and salinity) nor the character of ancient-lake strata (thickness, extent, lithology) correlate with measured or inferred climatic humidity. We propose that it is the relative balance of rates of potential accommodation (mostly tectonic) with sediment + water fill (mostly a function of climate) that controls lake occurrence, distribution, and character. Lake basins may be termed overfilled, balanced fill, or underfilled, depending on the balance between these rates. We conclude that climate and tectonics exert coequal influence on lake deposits at both mesoscales (1 m to hundreds of meters) and macroscales (hundreds to thousands of meters).

INTRODUCTION

Lakes and lake deposits are important to understand and predict because they host significant economic resources, are used to address climate change and paleoclimate questions, and are significant sources of biodiversity. The application of modern studies to gaining this understanding, so successful in shallow-marine environments, has not yielded widely applicable general models due to the many complexities of modern lakes. Rather, an ad hoc approach to interpreting ancient successions is often adopted, whereby each occurrence is treated as unique. The many good studies of modern lakes reveal an almost bewildering array of processes, interactions, and feedbacks that would indicate a corresponding large complexity in ancient lake deposits. This complexity, however, is not observed in ancient lake records from many ages and basins. We, along with several others (e.g., Bradley, 1925; Olsen, 1990), see three end-member facies associations that characterize most lake strata, and we observe a characteristic stacking of these associations as a basin fills.

The genesis of these facies associations has remained elusive. Previous models emphasized the importance of climate in controlling lacustrine deposition, and focused on the differences between open versus closed lakes (e.g., Eugster and Kelts, 1983) and on cyclic records of climatic forcing (cf. Glenn and Kelts, 1991). Paleoclimate-based models have met with little success, however, in predicting the occurrence and character of ancient lake facies. For example, several studies have suggested that organic-rich facies are most likely to occur in humid, low-latitude settings (e.g., Talbot, 1988), but some of the richest and thickest lacustrine petroleum source rocks occur at mid-paleolatitudes (e.g., Carroll et al., 1992; Carroll, 1998; Roehler, 1992), and no clear correlation between humid paleoclimates and source facies deposition has been demonstrated.

MODERN COMPLEXITY, ANCIENT SIMPLICITY

We were struck by the common recurrence of three characteristic associations of physical, chemical, and biological attributes as we examined and compiled published data on numerous lake deposits of Devonian to Holocene age from around the world (Carroll and Bohacs, 1995). The successions varied widely in accidental attributes such as thickness, color, absolute area, or paleolatitude, but the associations of lithologies, geochemical indicators, and biofacies, as well as successions of sedimentary structures and stratal stacking patterns, were remarkably similar. The same associations were also recognized by Olsen (1990), who divided the widespread and diverse lacustrine deposits of the Newark Supergroup into Richmond-type, Newark-type, and Fundy-type facies complexes. We introduce the names fluvial-lacustrine, fluctuating profundal, and evaporative facies associations for more general application. We illustrate their identifying characteristics using several members of the well-studied and relatively familiar Green River Formation in Wyoming as illustrative examples (Fig. 1). The same associations are present in many other basins, however, and may be recognized using objective criteria (cf. Olsen, 1990, and references therein; Table 1).

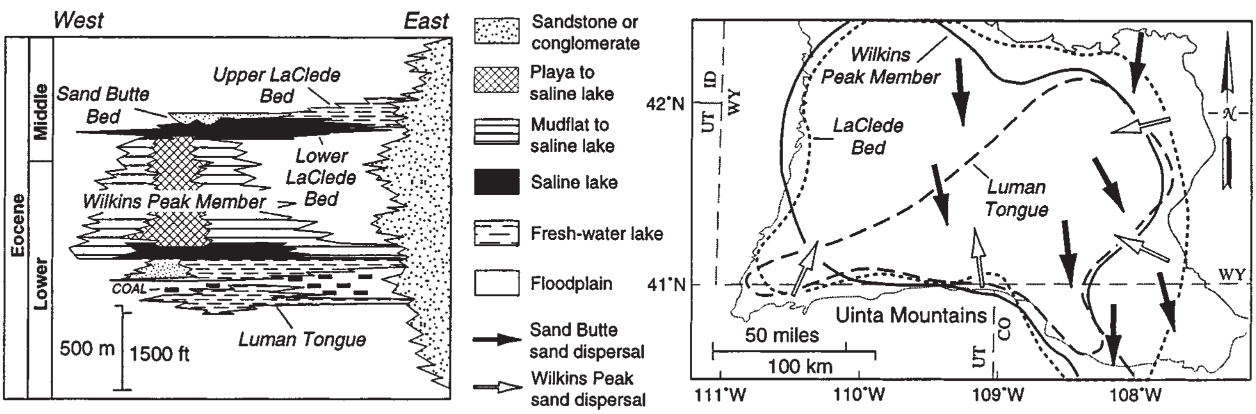

Figure 1. East-west cross section of Green River Formation in Wyoming (WY) (left) and maximum extent of three lacustrine members (right; modified from Roehler, 1992). UT, Utah; ID, Idaho; CO, Colorado.

Data Repository item 9916 contains additional material related to this article.

TABLE 1. TYPICAL ATTRIBUTES AND EXAMPLES OF THREE MAJOR LACUSTRINE FACIES ASSOCIATIONS

Facies Association	Stratal patterns	Lithologies	Structures (biota)	Organic matter	Examples	Reference
Fluvial - lacustrine	Indistinct progradational parasequences	Mudstone	Root casts	Low to moderate TOC	Richmond-type facies	Olsen, 1990
	Maximum fluvial (deltaic) input	Sandstone	Coarse lamination	Type I-III kerogen	Fort Union Formation	Liro and Pardus, 1990
		Coal	Fluvial channels	Terrestrial + aquatic biomarkers	QYN Formations	Xue and Galloway, 1993
		Coquina	(Fresh water)		Hongyanchi Formation	Carroll, 1998
Fluctuating profundal	Distinct shoaling cycles	Mudstone	Fine lamination	Moderate to high TOC	Newark-type facies	Olsen, 1990
	Aggradational + progradational	Kerogenite	Stromatolites	Type I kerogen	Buccomazi Formation	Burwood et al., 1995
	Fluvial input possible	Siltstone	Mudcracks	Aquatic biomarkers	Lago Feia Formation	Trinidade et al., 1995
		Sandstone	(Fresh to saline)		Lucaogou Formation	Carroll, 1998
Evaporative	High-frequency wet-dry cycles	Evaporite	Mudcracks	Low to high TOC	Fundy-type facies	Olsen, 1990
	Dominantly aggradational	Mudstone	Displacive fabrics	Type I kerogen	Blanca Lila Formation	Vandervoort, 1997
	Minimum fluvial input	Siltstone	Fine lamination	Hypersaline (aquatic) biomarkers	Jianghan basin	Fu et al., 1986
		Eolianite	(Salinity tolerant)		Jingjingzigou Formation	Carroll, 1998

Fluvial-Lacustrine Facies Association

Lacustrine facies of the Luman Tongue of the Green River Formation (Fig. 1) are predominantly marlstone and argillaceous coquina containing abundant freshwater fauna (Roehler, 1992). The organic matter content is relatively low (0.5%–7% total organic carbon [TOC]), and its composition indicates mixed aquatic and terrestrial input to freshwater lakes (Horsfield et al., 1994). Typical parasequences are about 10 m thick and grade upward from calcareous mudstone or siltstone into shelly coquinas, small sandy deltas, and scattered thin coals (Horsfield et al., 1994). Flood-plain and fluvial facies are also common. Luman parasequences are indistinctly expressed, but record repeated shoreline progradation into a hydrologically open lake. These features are typical of the deposits of many other hydrologically open lakes, which often are fossiliferous and contain abundant siliciclastic lithologies (Table 1).

Fluctuating Profundal Facies Association

The lower LaClede Bed (Fig. 1) consists of a heterogeneous mix of various carbonate, siliciclastic, kerogenite, and siliceous mudstone facies (Roehler, 1992). Well-defined parasequences distinctively record major lake flooding, progradation, and desiccation (Surdam and Stanley, 1979; Horsfield et al., 1994). Algal stromatolites and oolite beds were typically deposited soon after flooding, followed by deposition of microlaminated, organic-rich calcareous mudstone facies as the lake deepened. Dolomitic mud-cracked grainstones and mudstones accumulated as the lake desiccated. Low-relief deltas prograded intermittently. Other sequences contain lake-plain dolomites deposited on subaerially exposed lake-center kerogenites (Surdam and Stanley, 1979). Organic enrichments in excess of 20% TOC are common in the laminated mudstone facies (Horsfield et al., 1994). Similar facies elsewhere represent deposition by lakes of widely fluctuating depth and salinity that commonly covered wide areas at their maxima; these facies may be either carbonate rich or siliciclastic (Table 1).

Evaporative Facies Association

The Wilkins Peak Member (Fig. 1) encompasses a wide variety of facies, ranging from alluvial-fan and sheetflood sandstones to laminated oil shale and thickly bedded trona and halite (Smoot, 1983). Basin-center deposits record dominantly aggradational stacking of carbonate and evaporite facies during lake flooding and desiccation, whereas stratigraphic relationships in shoreline and lake-plain facies record complex interactions between alluvial sheetfloods and rising lake levels (Smoot, 1983). Oil shales in the Wilkins Peak are thinner, but only slightly less areally extensive than those in the LaClede Bed (Smoot, 1983); they may be equal in organic enrichment (up to 20% TOC; Grabowski and Bohacs, 1996). Paleontology and biomarkers indicate an extremely low diversity flora and fauna owing to elevated salinities (Grabowski and Bohacs, 1996). Although the chemistry of the Wilkins Peak evaporites is unusual, otherwise similar evaporative facies occur in other lacustrine basins (Table 1).

CLIMATIC CONTROLS—NOT THE WHOLE STORY

Given the dependence of lakes on a positive hydrologic balance, it seems intuitive to expect a lake's size or water chemistry to correlate with measures of climatic humidity. This correlation is not observed, however, for the largest modern lakes. No correlation exists between precipitation/evaporation ratio (P/E) and any measure of lake size (e.g., depth, surface area, volume), based either on visual inspection or on appropriate statistical tests (Fig. 2; Table 2;[1] Herdendorf, 1984). Other measures, such as P – E + runoff, show a similar lack of correlation with lake size or depth. Predictions based on climate alone also fail to explain the complexity of modern lakes. Within one climatic zone, lakes may range from freshwater to hypersaline, carbonate precipitating to purely siliciclastic, and barren to eutrophic (Herdendorf, 1984). Modern Utah Lake, for example, contains fresh water, but drains into the adjacent, hypersaline Great Salt Lake, only 70 km away (Stansbury, 1852). Short-term climatic fluctuations influence lake levels and salinities in hydrologically closed basins, and freshwater tectonic lakes average more than twice the surface area and ten times the depth of saline or hypersaline lakes (Table 2). Note, however, that the scatter in these data is

[1]GSA Data Repository item 9916, Modern lake data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

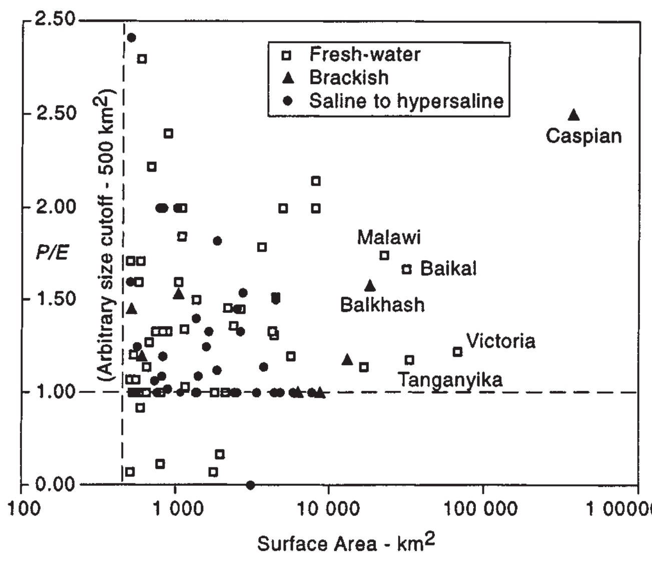

Figure 2. Surface area vs. P/E (precipitation/evaporation) ratio for 90 largest modern tectonic lakes (data of Herdendorf, 1984). Correlation coefficient $r^2 = 0.11$.

larger than the differences among lake types (Fig. 2). Collectively, these observations demonstrate no general correspondence between specific absolute climatic conditions and lake size or type.

An additional paradox arises when attempting to apply these observations to ancient deposits. For basins containing both freshwater and saline lacustrine facies, we have observed that stratal units deposited by saline lakes commonly span larger areas than those deposited by freshwater lakes. For example, the freshwater Luman Tongue is actually thinner and less extensive than the more saline LaClede Bed or Wilkins Peak Member (Fig. 1). Similar observations have been reported from the Newark Supergroup, where freshwater units are relatively discontinuous, but saline units can apparently be correlated between different basins (Olsen, 1990).

TECTONIC INFLUENCE ON LACUSTRINE FACIES ASSOCIATIONS

It is generally accepted that geologically significant lake deposits record impoundment of drainages due to tectonic basin subsidence, uplift of drainage barriers, or both (e.g., Kelts, 1988). These processes both accommodate the lake and its sediments and preserve its deposits from erosion. Differential subsidence can also substantially alter sedimentation patterns through time and space in rift basins, according to a growing body of evidence from east Africa (e.g., Lambiase, 1990; Soreghan and Cohen, 1996). Despite the obvious importance of tectonic accommodation in creating and preserving lake deposits, very little attention has been given to its influence on the character of ancient lacustrine basin fill, especially at mesoscales.

Basin tectonics appear to have affected lacustrine facies of the Green River Formation in Wyoming (Surdam and Stanley, 1980). Paleocurrent and sandstone provenance data attest to major structural changes in the configuration of its depositional basin coincident with changes in dominant lacustrine facies associations. During deposition of the evaporative facies of the Wilkins Peak Member, clastic sediments were derived principally from Laramide-style uplifts bounding the greater Green River basin (Surdam and Stanley, 1979), especially the Uinta uplift to the south (Sullivan, 1985; Fig. 1). In contrast, volcanic source areas to the north of the basin dominated sand compositions during the gradual lake freshening recorded by the LaClede and Sand Butte Beds (Surdam and Stanley, 1980). Surdam and Stanley (1980) argued that this shift toward freshwater facies resulted not from a climate change, but from decreased regional tectonic activity. Decreased basin subsidence and reduction of tectonic drainage divides led to infill of the Wind River basin to the north, and allowed the development of throughgoing river systems. These rivers carried volcanic lithic sands southward into Wyoming, and ultimately into the northern Piceance Creek basin in Colorado. Paleobotantical studies reinforce this interpretation, indicating either little change in climatic conditions (Y. Y. Chen, 1990, personal commun.), or a slight unidirectional shift toward cooler, drier conditions (Roehler, 1992).

TABLE 2. MEAN CLIMATIC AND MORPHOMETRIC STATISTICS FOR 91 LARGEST MODERN TECTONIC LAKES

Salinity and total dissolved solids (*TDS*)	*P/E* ratio	Area (A; km^2)	Mean depth (m) $\bar{Z}$= volume/area
Fresh-water (n = 48) *TDS* < 1 000 ppm	1.4 *(0.6-2.8)*	5 256 *(500-68 460)*	69 *(1-730)*
Brackish (n = 8) *TDS* < 20 000 ppm	1.4 *(1.0-2.5)*	52 783* *(510-374 000)*	77 *(2-277)*
Saline to hypersaline (n = 35) *TDS* > 20 000 ppm	1.3 *(0.5-2.9)*	2 229 *(500-7 690)*	14 *(1-184)*

Note: calculated by using the data of Herdendorf (1984). Ranges of values are shown in parentheses.

* Data skewed by one occurrence (Caspian Sea).

DISCUSSION AND CONCLUSIONS

We propose that it is the relative balance of rates of potential accommodation (mostly tectonic) with sediment + water supply (mostly climatic) that controls lake occurrence, distribution, character, and stratigraphic architecture. Potential accommodation, defined herein as the difference in elevation between the lowest point in the basin and its drainage spillover point (sill), defines the maximum space available for sediments to accumulate. The sill limits the ultimate height of lake highstands, a key contrast with marine systems. Sill height is commonly controlled by uplift, modified by erosion and stream piracy. Sediment + water supply is strongly tied to climate (e.g., Schumm, 1977), as are lake levels. Our genetic classification subdivides ancient lake basins into three lake types: overfilled, balanced fill, and underfilled (Fig. 3). These lake-basin types correspond to the three lacustrine facies associations discussed herein; their identification therefore is based on the attributes detailed in Table 1.

In overfilled lake basins the influx rate of water + sediment fill generally exceeds potential accommodation. Climatically driven lake-level fluctuations are minimal because water inflows nearly always equal outflows. These freshwater lakes are closely related to fluvial systems and mires. Lakes may be either deep or shallow, depending on structurally controlled basin geometries. Fluvial-lacustrine facies dominate basin fill.

In balanced-fill lake basins potential accommodation approximately equals water + sediment fill over the depositional time span of a unit. Water + sediment inflows are sufficient periodically to fill the lake to sill level and even create surface outflows, but significant lake-level drops below sill level may occur. Fluctuating profundal facies dominate basin fill, and record shoreline movement by both progradation and desiccation. Note that over any geologically significant time period, such basins are neither always hydrologically open nor hydrologically closed. For example, Lake Malawi in the East African rift system is currently filled approximately to its spill point, and water levels fluctuate only 1 to 2 m/yr. However, high-resolution seismic surveys document fluctuations as high as 100 m in past centuries and drops of as much as 300 m during the late Pleistocene to early Holocene (Scholz, 1995). These findings imply that both hydrologically open and closed conditions may be recorded even at the scale of individual parasequences.

In underfilled lake basins, rates of potential accommodation continuously exceed water + sediment fill. Lake levels never or rarely reach sill level. Evaporative facies typify basin fill, which may be interbedded with eolian and alluvial-fan strata. Various Quaternary playa-lake systems provide good examples of underfilled lake basins, which alternate rapidly

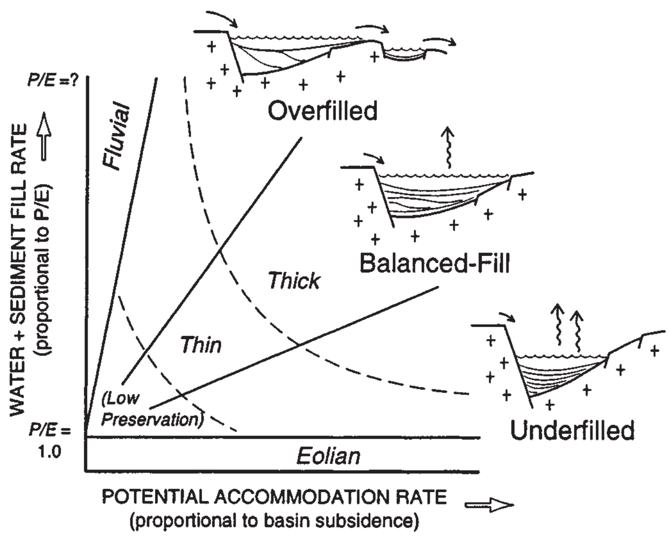

Figure 3. Schematic lake-type model (see text for explanation). P/E = precipitation/evaporation.

between desiccation and flooding, but normally do not spill over into adjacent basins (e.g., Vandervoort, 1997).

Most basin fills contain a predictable evolution between different lacustrine facies associations (Neal et al., 1997), which may be interpreted in terms of major controls on lake basin type. For example, the Green River Formation in the Wyoming records a complete gradational cycle of lake basin types (Fig. 1), from overfilled (freshwater lake), through balanced fill (saline lake) and underfilled (playa to saline lake), then back through balanced fill and overfilled (Fig. 1). The early part of this evolution could have resulted either from increasing potential accommodation or from decreasing climatic humidity, but as discussed here the latter part probably resulted principally from changing basin tectonics (Surdam and Stanley, 1980). An important goal for future research will be to better quantify the relative impact of tectonic subsidence and uplift versus climate change on the character of lacustrine basin fill.

Lacustrine basin fills often grade from one facies association into another, without recognized major unconformities (e.g., Fig. 1). Dissimilar assemblages of depositional environments may therefore be recorded within apparently conformable depositional stratal successions. In balanced-fill and underfilled lake basins, rapidly fluctuating lake levels may result in a changing mix of depositional subenvironments even at the parasequence scale. Note that direct comparison of ancient-lake types to modern analogues therefore may only be valid for overfilled lake basins, where continuously open hydrology permits reasonably stable depositional environments. This limitation to Walther's law has created considerable confusion: lacustrine facies models frequently attempt to reconcile a more diverse assemblage of depositional environments than actually existed at one time (cf. Sullivan, 1985).

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