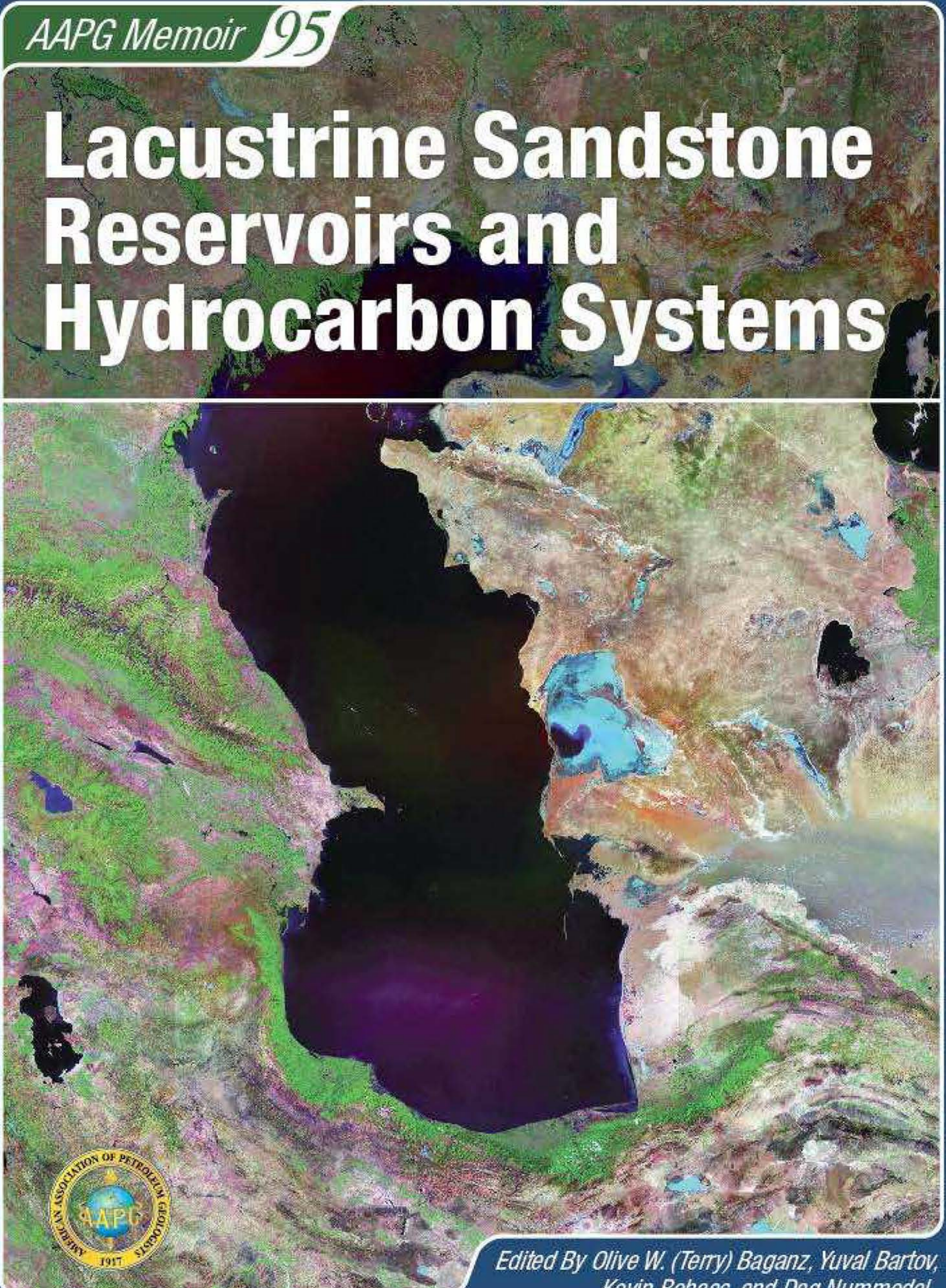
AAPG Memoir 95

Lacustrine Sandstone Reservoirs and Hydrocarbon Systems



Edited By Olive W. (Terry) Baganz, Yuval Bartov, Kevin Bohacs, and Dag Nummedal

Lacustrine Sandstone Reservoirs and Hydrocarbon Systems

Edited by
Olive W. (Terry) Baganz, Yuval Bartov, Kevin M. Bohacs,
and Dag Nummedal

AAPG Memoir 95

Published by

The American Association of Petroleum Geologists

Tulsa, Oklahoma

ISBN13: 978-0-89181-377-4

AAPG Editor: Stephen E. Laubach
AAPG Geoscience Director: James B. Blankenship

COVER: The cover of this book features an areal image of the Caspian Sea. The Caspian has multiple field developments in all countries that share the lake. It is likely to be the largest worldwide lake in terms of current daily production volumes, number of platforms and pipelines, reserve volumes, and remaining exploration potential. The Caspian also resides in a physically and politically challenging environment.

This publication is available from:

The AAPG Bookstore
P.O. Box 979
Tulsa, OK U.S.A. 74101-0979
Phone: 1-918-584-2555 or 1-800-364-AAPG (U.S.A. only)
E-mail: bookstore@aapg.org
www.aapg.org

Canadian Society of Petroleum Geologists
600, 640 – 8th Avenue S.W.
Calgary, Alberta T2P 1G7
Canada
Phone: 1-403-264-5610
Fax: 1-403-264-5898
E-mail: reception@cspg.org
www.cspg.org

Geological Society Publishing House
Unit 7, Brassmill Enterprise Centre
Brassmill Lane, Bath BA13JN
United Kingdom
Phone: +44-1225-445046
Fax: +44-1225-442836
E-mail: sales@geolsoc.org.uk
www.geolsoc.org.uk

Affiliated East-West Press Private Ltd.
G-1/16 Ansari Road, Darya Gaaj
New Delhi 110-002
India
Phone: +91-11-23279113
Fax: +91-11-23260538
E-mail: affiliate@vsnl.com

The American Association of Petroleum Geologists

The American Association of Petroleum Geologists Books Refereeing Procedures

The Association makes every effort to ensure that the scientific and production quality of its books matches that of its journals. Since 1937, all book proposals have been refereed by specialist reviewers as well as by the Association's Publications Committee. If the referees identify weaknesses in the proposal, these must be addressed before the proposal is accepted.

Once the book is accepted, the Association Book Editors ensure that the volume editors follow strict guidelines on refereeing and quality control. We insist that individual papers can only be accepted after satisfactory review by two independent referees. The questions on the review forms are similar to those for the AAPG Bulletin. The referees' forms and comments must be available to the Association's Book Editors on request.

Although many of the books result from meetings, the editors are expected to commission papers that were not presented at the meeting to ensure that the book provides a balanced coverage of the subject. Being accepted for presentation at the meeting does not guarantee inclusion in the book.

More information about submitting a proposal and producing a book for The American Association of Petroleum Geologists can be found on its web site: www.aapg.org.

Acknowledgements

AAPG MEMOIR

Lacustrine Sandstone Reservoir and Hydrocarbon Systems

A Hedberg Conference is a mighty undertaking and requires the hard work, cooperation, and support of many people; they would not be possible without the active participation of the hosts, researchers, AAPG staff, and organizers. This conference was particularly challenging, as it included a core workshop, field trip, and many opportunities to experience the rich and varied culture of Azerbajian. We gratefully acknowledge and thank our hosts in Baku, the Azerbaijan Society of Petroleum Geologists, our core workshop and field trip leaders, Anthony Reynolds and Greg Riley, Dag Nummedal, our session chairs, Imre Magyar, Mark Allen, Akif Narimanov, Gabor Vakarcs, Kevin Bohacs, Simon Lang, Michael Kuykendall, Ibrahim Guliev, and, of course, all the participants. The support of our sponsors, BP, ConocoPhillips, and ExxonMobil was essential to the success of the conference. The memoir editors thank their organizations, BHPBilliton Petroleum, Colorado School of Mines, and ExxonMobil Upstream Research Company for their support, and the AAPG Publications Committee for their patience. We want to extend a very special thanks to the authors for having stayed with us, while the editors fell so very far behind their anticipated completion schedule.

We would also like to acknowledge the following colleagues, who kindly took time from their busy schedules and helped with the reviewing of the papers submitted for this volume.

John Armentrout
Yuval Ben-Guy
Jerry Boak
Marie-Francoise Brunet
Mary Carr
Alan Carroll
Ed Clifton
Rex Cole
Frank Ethridge
David Houseknecht
Eric Huton
Ron Johnson
Barry Katz
Lindsay Kaye
David Keighly
Simon Lang
Amisha Maharaja
Penny Patterson
Matthew Pranter
Meridith Rhodes-Carson
Greg Riley
Amir Sagy
Juergen Schieber
Mike Simmons
Joe Smoot
Mike Soreghan
Mike Steckler
Art Trevena
Roger Witmer
Xiangyang Xie

About the Editors

Olive W. (Terry) Baganz received a B.Sc. in geology and B.A. in Russian Studies from the University of Southern California and a M.Sc. in geology from University of California, Santa Cruz. She began her career working for the USGS on Alaska, Chukchi and Beaufort Seas. She joined Conoco (now ConocoPhillips) in Houston, Texas, where she worked exploration new ventures in Alaska, onshore Lower 48, Gulf of Mexico, and Australia, before embarking on evaluating exploration and field development new ventures opportunities in Europe and Central Asia region, which includes Russia and the Caspian Sea.

She was one of the key organizers of the Hedberg Conference that led to this volume. In 2008 she joined BHP Petroleum based in Houston, Texas, where she continues to evaluate opportunities in the Russia and Caspian Sea region.

Yuval Bartov is currently the CEO of Israel Energy Initiatives (IEI), which is an oil company that is working towards extracting oil from the Israeli oil shale. Prior to joining IEI in 2008, Bartov served as a research professor in the Colorado Energy Research Institute at the Colorado School of Mines.

Kevin M. Bohacs 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. He joined Exxon Production Research Company in Houston, Texas, in 1981, where he is currently a sedimentologist and stratigrapher with the Hydrocarbon Systems Division.

At ExxonMobil Upstream Research Company, Bohacs leads the application of sequence stratigraphy and sedimentology to fine-grained rocks from deep sea to swamps and lakes, in basins around the world, integrating field work, subsurface investigation, and laboratory analyses. As Senior Hydrocarbon Systems Consultant, he works closely with exploration affiliates in evaluating their hydrocarbon systems, teaches field schools in sequence stratigraphy, sedimentology, and field safety, and conducts field work for research and exploration.

Bohacs has written more than 89 scientific contributions on the stratigraphy and sedimentology of mudstones 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 for his work on lacustrine systems.

He has served as AAPG Distinguished Lecturer (1999–2000), Petroleum Exploration Society of Australia Distinguished Lecturer (2001), URC Outstanding Instructor (1994–1998, 2003–2009), and AAPG Distinguished Instructor (2007–2009). He has been elected a Fellow of the Geological Society of America, as well as Fellow of the Geological Society (London), The Explorers Club, and the Royal Geographical Society.

Dag Nummedal is currently the Director of the Colorado Energy Research Institute, an institute at the Colorado School of Mines focused on broad multi-disciplinary research programs in both fossil and renewable energy. He is also the director of the Colorado Carbon Management Center, a multi-disciplinary and multi-institutional center engaged in research on geological and terrestrial carbon sequestration, as well as economic and policy analysis of different approaches to reductions in carbon emissions from global energy systems.

Prior to joining the Colorado School of Mines in 2004, Nummedal served as professor of geology and geophysics at Louisiana State University and the University of Wyoming. He also served for five years as manager of exploration and production technology at the Unocal Corporation.

Dag Nummedal has served as president of SEPM and as an AAPG Distinguished Lecturer (2001–2002).

Table of Contents

Baganz, Olive W. (Terry), Yuval Bartov, Kevin Bohacs, and Dag Nummedal, 2012, Lacustrine sandstone reservoirs and hydrocarbon systems, *in* O. W. Baganz, Y. Bartov, K. Bohacs, and D. Nummedal, eds., Lacustrine sandstone reservoirs and hydrocarbon systems: AAPG Memoir 95, p. 1–11.

Introduction

Lacustrine Sandstone Reservoirs and Hydrocarbon Systems

Olive W. (Terry) Baganz[1]
ConocoPhillips, Houston, Texas, U.S.A.

Yuval Bartov
IEI Ltd., Jerusalem, Israel

Kevin Bohacs
ExxonMobil Upstream Research Company, Houston, Texas, U.S.A.

Dag Nummedal
Colorado Energy Research Institute, Colorado School of Mines, Golden, Colorado, U.S.A.

This AAPG volume is the first to concentrate on the occurrence, distribution, and character of lacustrine sandstone reservoirs and to put those reservoirs into a hydrocarbon system and depositional process context. Although much research has been conducted on lacustrine systems, most of that work concentrated on reconstructing paleoenvironments, deciphering paleoclimate, or estimating hydrocarbon source potential.

As of 2008, about 2.2% (16×10^9 bbl; 2.5×10^9 m^3) of the world's discovered oil has hydrocarbon sources associated with lacustrine or coal-bearing strata, whereas lacustrine reservoirs appear to account for only about 7% of daily oil production ($\sim 5 \times 10^6$ bbl of oil/0.8×10^6 m^3). Lacustrine reservoirs appear to hold only about 3% of proven oil reserves (based on U.S. Geological Survey and BP published information; see chapter by Bohacs in this volume for more details). Does this small proportion discovered in lacustrine reservoirs reflect a fundamental problem with lacustrine reservoirs or a great opportunity for exploration? This is a major question addressed in this volume. The answer may be that lacustrine reservoirs pose both great opportunities and great challenges.

Lakes are complex 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. At the hydrocarbon-reservoir scale, these challenges affect every aspect of prediction.

To address these challenges, more than 60 researchers from 17 countries who are actively working on lacustrine sandstones and hydrocarbon systems convened in Baku, Azerbaijan, for a Hedberg Conference in May 2004. This was the first conference to our knowledge that has focused on sandstone deposition and stratigraphy in lacustrine basins. Of course, much active paleolimnological research exists, but most paleolimnologists and climate researchers consciously avoid sandy intervals or areas and tend to focus on the muds and mudstone intervals to study

---

[1] *Present address*: BHP Billiton Petroleum, Houston, Texas, U.S.A.

DOI:10.1306/13291382M953444

carbon cycling, paleoclimate, and hydrocarbon source potential. Like any good research conference, the Baku meeting raised as many questions as it answered, but all participants thought that they acquired a greater appreciation of the complexity of lake systems, of what the general state of the art is, and what some potentially important and fruitful avenues for further work are. This volume attempts to capture the key messages and research opportunities highlighted in discussions at the conference. Although a few years have passed since the conference, many of the chapters contain more recent findings, and the work presented herein is still quite germane to current exploration and development issues and provides a useful starting point for further investigation. Moreover, several of the chapters included in this volume extend beyond, and postdate, the Hedberg Conference. Most of the research captured in this volume has not been presented before, and this format allows quite a bit of depth in each chapter.

The conference included three days of presentations, structured and informal discussions, one day on the outcrops in Kirmaky Valley (field guidebook included in Appendix 1), and a day examining core from equivalent units in the Azeri-Chirag-Guneshli megastructure field. Twenty-one talks and 22 posters presented examples ranging from the Mesozoic of north Texas and China to the Cenozoic of Azerbaijan and Wyoming to modern lake systems of Lake Eyre, Lake Michigan, and the Caspian Sea or Volga River delta (see Appendix 2 for a list of the abstracts available on the AAPG Search and Discovery Web site). The presentations covered a broad spectrum— from basin-forming tectonics through lake stratigraphy, physical, chemical, and biological sedimentary processes, interaction of climate and tectonics, modern analogs, to petrography and detailed reservoir modeling.

We captured key issues raised during the presentations and focused the structured discussions around five big questions (elaborated in Table 1):

a) What exactly about reservoirs are we trying to predict?
b) Lake classifications for prediction— Are there other or better parameters to use for reservoir prediction?
c) How can updip character be used to predict downdip reservoirs?
d) What exactly do we need to know about tectonics and climate to make reservoir predictions?
e) What are the key tools for integrated sequence-stratigraphic analyses?

The attendees self-organized into various groups during the discussion periods and reported back to all at the end of the conference. The main points are summarized in the Key Lessons and Issues section. If these are the answers, then Table 2 captures the attendant questions raised and ideas for further research.

Table 1. Big questions.

A. What exactly about reservoirs are we trying to predict?
  - 3D architecture: In high net::gross systems— Shales, Vertical trends in Sandstones; In low net::gross systems— Geobody shapes, sand distribution
    - Lateral extent of mudstones
    - Parameters by which to select appropriate analogs
    - Shoreline reservoirs: river vs. wave dominated?
    - Relative development by lake type, highstand?
    - Ultimate preservation potential of each?
    - Fluid interactions with reservoir properties?

B. Lake classifications for prediction— Are there other or better parameters to use for reservoir prediction?
  - Consider proximate vs. ultimate causes (Potential Accommodation/sediment + water supply vs. tectonics or climate)
  - Geomorphology vs. stacking/aggradation

C. How to use updip character to predict downdip reservoirs?
  - Three-dimensional sequence stratigraphic models: How many do we need?
    - Relative development of systems tracts by lake type
    - Do fluvial systems that debouch into oceans differ from lakes?
    - How far upstream does base level have influence?

D. What exactly do we need to know about tectonics and climate to make reservoir predictions?
  - Spatial, temporal scales
    - Inherent time scales of lake systems (quasi periodicity)
    - Link of structural evolution to reservoir prediction— Chad, Caspian
    - Hard vs. soft response to tectonics (onlap vs. thinning)
    - Rift dynamics (plume locations, crust strength, etc.)
    - History of uplift relative to provenance
    - Rate of forcing mechanisms vs. rate, mode of response (nonlinear, threshold effects)

E. Key tools for integrated sequence stratigraphic analyses: Hints and traps
  - Seismic
    - Sedimentology
    - Paleontology
    - Palynology/organic petrography
    - Paleoichnology
    - Geochemistry: Inorganic, organic— composition, isotopes
    - Paleopedology
    - Forward modeling

KEY LESSONS AND ISSUES

Lake-basin type (Carroll and Bohacs, 1995) shows a strong influence not only on the source potential of the mudrocks and hydrocarbon quality, but also on the type, distribution, and ultimate reservoir quality of the sandstones. Overfilled lake basins have the highest porosity and permeability and the largest overall reserves, mostly associated with fluvial channels on the lake plain; their challenges include the lowest vertical drainage or connectivity (Kv) and the lowest average net-to-gross ratio. Balanced-filled lake basins have good Kv and lateral drainage or connectivity (Kh) in highstand and transgressive systems tracts and the best Kv overall; on the downside, they have the smallest lateral extents and lowest average recovery factor (because of both reservoir and fluid properties). Underfilled lake-basin reservoirs tend to have the best Kh and the thickest net pay (as they tend to occur at high rates of potential accommodation); their drawbacks include the common occurrence of early cements (carbonates, evaporites) and a typically wide lateral displacement of highstand from lowstand systems tracts that diminishes resource density.

The key to unraveling much of a lake's depositional history is to study the mudstones interbedded with the sandstones. Mudstones are much more continuous and sensitive recorders of depositional conditions, especially in systems where lake levels varied over hundreds of meters in thousands of years.

The character of depositional sequences in lakes is controlled not only by accommodation and sediment supply, but also by preexisting topography or bathymetry and the timing of peak clastic influx relative to lake level.

The tectonic setting of a basin is important not only in affecting the temporal but also the lateral distribution of accommodation. The tectonic setting of a basin also influences the development of drainage networks in the hinterland as well as the climate in the drainage basin (through rain shadows or traps). Tectonic factors also have far-field effects on fluvial systems and sediment supply through large-scale drainage evolution (different provenances, across different climate zones) and through climatic effects of tectonics in far upstream watersheds (rain shadows or traps).

In upstream reaches of fluvial systems, erosion on sequence boundaries is interpreted to record increased water discharge. How does this tie to expression of sequence boundaries downstream and in the lake (where lake level might be rising because of increased water discharge)? A strong need exists to define sequence stratigraphy by geometric recognition criteria and to keep them separate from inferred changes of lake or base level.

Not only can lake level and the flux of sediment and water be out of phase, but water discharge and sediment flux can be variously linked (there can be a lag between increasing water discharge and increased sediment delivery to the basin). The ExxonMobil work in Chad by Penny Patterson, Dave Reynolds, and Clive Jones provided an excellent example of this and its effects on reservoir distribution.

Eolian reworking can have a significant impact on reservoir quality (by winnowing the fines, armoring surfaces with coarse lags); there could be potential for developing significant eolian dune sandstones such as illustrated in this volume in Lake Chad, Lake Michigan, and Caspian Sea examples.

What is the potential importance of lake density underflows (long lived = flood hydrograph) versus episodic turbidity currents? How are they identified and differentiated in vertical sections? Do the differences significantly impact reservoir potential?

Several examples (mostly Pleistocene to Holocene) highlighted the potential importance of downstepping parasequences and ravinement in open-hydrology (overfilled) lake systems. Much discussion exists on the preservation potential of such downstepping parasequences. How about in closed hydrology lakes (underfilled lake basins)?

How characteristic is the modern Volga River delta with its poorly developed stream mouth bars and well-developed subaqueous levees? Is the lack of stream mouth bars because of the strong influence of preexisting bathymetry in the present-day delta (where preexisting subaqueous channels continue to confine river discharge well beyond the river mouth)?

Evolution of lakes and rivers with respect to tectonics: if most drainage nets evolve from isolated to integrated in divergent settings, do they evolve from integrated to isolated in convergent settings (or, more probably, from integrated to isolated to integrated)?

Does dominance of terminal splays downdip mean that a lot of sandstones are trapped updip along highstand shorelines (underfilled lake-basin-type model would predict this)? How do we differentiate sandstone deposition into relatively permanent standing water versus floodwaters (subaqueous vs. subaerial)? These differences may have a significant impact on reservoir distribution and connectivity, bedding style, and stacking patterns.

VOLUME HIGHLIGHTS

This memoir is organized into four sections based on tectonic setting instead of lacustrine-facies associations: Global Overview, Compressional Regimes, Extensional

Table 2. Key issues and research ideas.

Importance of spillpoint/threshold as ultimate limit on accommodation— How important is it to identify location and elevation of the spillpoint?
Contingent nonunique responses of lake to climate and tectonic forcing factors
Importance of shoreline progradation vs. shoreline withdrawal by desiccation
Variable strength and phase relation of ties among lake level, water supply, and sediment supply
Faster rates of process change and response
Updip surfaces: Relations to downdip strata?
Scale of influence of climate and tectonics (variety of temporal and spatial scales)?
Influence of tectonic basin type/formation on lake systems, relative development, and distribution of sandstones?
Influence of preexisting/inherited topography and bathymetry?
Key processes and influences on lake-floor fan sandstone accumulation?
Influence on ultimate sandstone composition of interaction of various rivers and provenances mixing in the lake basin?
Far-field effects of tectonics on fluvial sytems and sediment supply: large-scale drainage evolution (different provenances, across climate zones), climatic effects of tectonics in watershed (rain shadows/traps)
Influence of structural development on sediment entry points and sediment dispersal in the lake basin?
Chain of lakes effects on sediment supply (fill and spill processes)
Superimposed grabens of different orientations: How common, how difficult to recognize, influence of reactivated tectonic elements?
Impact of evolution of vegetation types and organisms on sediment supply, development of soils, relation of clastic yield to climate changes?
In upstream reaches of fluvial systems, erosion on sequence boundary interpreted to record increased water discharge— How does this tie to expression of sequence boundary downstream and in lake (where lake level might be rising because of increased water discharge)? Need to define sequence stratigraphy by geometric recognition criteria and keep separate from inferred changes of lake or base level.
Impact of eolian reworking on reservoir quality; potential development of significant eolian dune sandstones (preservation potential)? Lake Chad, Michigan, Caspian examples
Syndepositional effects of tectonics on process and sandstone distribution: Changes in fluvial style, capture or diversion of rivers, downdip attractor of fluvial systems?
Relation of lake-level changes to eustacy: Timing, latitudinal distribution, mechanisms?
What elements or attributes to keep during scale up for reservoir modeling: Insights from lake type, key processes?
Relation of shapes (lithosomes) to facies: Not necessarily 1:1, need to explicitly integrate
Importance of mudstones as baffles in reservoirs (permeability extremes)
How to account for hiatuses or erosion in cyclicity analyses? ''You can't measure time with a ruler,'' (Sadler, 1981). Relations of forcing functions, sedimentary response, rock record— how closely tied, importance in understanding sandstone distribution?
Importance of lake density underflows (long lived = flood hydrograph) vs. episodic turbidity currents? How to identify or differentiate in vertical section?
Variety of sandstone settings in overfilled/open-hydrology lakes: Estuary/Bayhead delta, strand plain, eolian dunes, longshore migrating strand plain lithosome detached from sediment supply, lake floor fan
Importance of downstepping parasequences and ravinement in open lake systems? Preservation potential of downstepping parasequences? How about in closed hydrology lakes (underfilled)?
How characteristic is the modern Volga River delta with its poorly developed stream mouth bars and well-developed subaqueous levees? Influence of preexisting bathymetry?
Existence and depth of shelf break influence on response of river-delta system to lake-level fall (above break = rapid progradation, below break = bypass and erosion)
What parameters should be used for choosing appropriate analogues: climate, base-level change, basin geometry, tectonic history; major issues of scales and types of observations: proximal vs. distal rates, short vs. long time intervals, outcrop vs. core (Volga River delta, Pannonian Basin examples).
Persistence of influence of basin-forming structuring (subtle thickening, location of depositional environments)? Caspian, Turkey, Mongolian examples

Evolution of lakes and rivers with respect to tectonics: If most drainage nets evolve from isolated to integrated in divergent settings, do they evolve from integrated to isolated in convergent settings (or, more probably, from integrated to isolated to integrated)?
Influence of sudden increase in sediment supply on rivers and lake style (influence on Ss location, distribution; reservoir quality [composition, cements])
Need perspective from updip to downdip end of profile (do sheet sandstones on AGC megastructure represent an alluvial braid plain or overlapping delta fronts?)
Does dominance of terminal splays downdip mean lots of sandstone trapped updip at highstand shorelines (underfilled lake-basin-type model would predict this)?
How to differentiate sandstone deposition into relatively permanent standing water vs. floodwaters (ephemeral flood-plain ponds vs. perennial lakes; subaqueous vs. subaerial deposition [has significant impact on reservoir distribution and connectivity, bedding style, stacking patterns])?
What is the fill of meandering channels seen on seismic data on sub-lacustrine slopes (mostly sandstone or mudstone)?
Time-scale effects on ultimate nature of deposit: 3-D distribution of lithofacies
Extra basinal storage of sediments and varying yield and timing
Sediment yield relation to water influx (in time and space)
Does reservoir quality increase with eolian reworking at lowstands of lake level?

Regimes, and Modern Analogs. Detailed examples range in age from Carboniferous to the Holocene of Lake Michigan and Dead Sea and cover the following nine countries: Azerbaijan, Brazil, Chad, Germany, Hungary, Israel, People's Republic of China, Uganda, and the United States.

Global Overview

We start the memoir with a global overview by Bohacs of lacustrine hydrocarbon reservoirs. He compares and contrasts them to marine reservoirs and places them into a context of lake-basin type, tectonic setting, depositional conditions, and hydrocarbon systems. He presents detailed rock and fluid data on 83 producing intervals from 54 hydrocarbon fields, as well as data gleaned from more than 211 ancient and 253 modern lake systems spanning Cambrian to Pleistocene in age (with an extensive listing of primary sources).

Each lake-basin type can host commercially significant reservoirs, but each type has different challenges to economic viability. The genetic framework of the lake-basin-type approach can provide useful guidance for prediction. This approach also highlights the necessity of considering a variety of possible causes for changing lake character. These causes arise from various interactions among rates of sediment supply, water supply, basin floor subsidence, and sill uplift— the proximate controls through which tectonics and climate act. One common theme seen in many chapters in this volume is that the clastic components in lake systems at the reservoir scale appear to record climatic changes and cycles through time: dry versus wet and cold versus warm.

Compressional Regimes

This volume begins with a series of chapters on the Neogene Azerbaijani South Caspian and the Paleogene Green River Formation of Wyoming. The volume concludes with a chapter on Lake Pannon of Hungary, a long-lived Neogene brackish lake. The South Caspian chapters concentrate on describing regional facies associations to better understand the history of deposition of the main reservoir intervals, whereas the studies of the Green River Formation mainly concentrate on reservoir characterization and modeling. Note that all of the lake systems in this section are associated with significant river systems with large drainage areas, high-discharge streams, and large clastic loads, and that the main focus is on the evolution of depositional facies relations and on relating them to interpreted changes of lake level.

The chapter by Baganz et al. is the first chapter on the South Caspian in offshore Azerbaijan and describes the history of exploration in the region and the petroleum system. Azerbaijan has a long history of exploration that begins in the early 19th century. Hydrocarbon generation started about 4 m.y., with peak expulsion at about 2 m.y., concurrent with the formation of the many large compression-derived buckle folds. Source rocks are Oligocene to Miocene marine shales, and the reservoirs were deposited in the Pliocene, a time when the region was experiencing rapid subsidence, isolation from a marine setting, and a large river system termination. High fluid pressure gradients can inhibit the development of effective seals associated with the large buckle folds.

Nummedal et al. delve into the outcrops and well data along the Azerbaijan margin of the South Caspian. The exposed section is a great laboratory for collection of data for the Pliocene Productive Series. Data collected on facies associations in the Pliocene allow an interpretation that incorporates orbital changes influencing climate, which subsequently controlled the deposition of clastics. The Productive Series consists of an interval of genetically related fluvial to lake-center deposits that they relate to climate change and consequent lake-level signals. The section records arid and humid intervals, which are postulated to be associated with orbitally induced climate and lake-level changes. The end result is a series of nested sequences with the farthest extension of the shoreline interpreted to be at the top of the lowstand systems tract. These sequences are the fundamental building blocks of the offshore Pereryva reservoirs, the stacking of which controls reservoir architecture.

Abdullayev et al. present a comprehensive regional study of the entire Productive Series across the South Caspian Basin of Azerbaijan, built around a total of 16 paleogeographic maps derived from BP's very extensive regional subsurface database. They cover the entire interval from the Messinian (major lowstand) to the present-day Caspian Sea, a period of approximately 6 m.y., out of which the Productive Series accounts for about 2.6 m.y. The chapter concentrates on describing the key basin-scale variable of the stratigraphy, which begins with inherited basin morphology and evolution of this morphology through time. Climatic fluctuations control changes in water discharge and sediment input. These variations were then superimposed on the long-term changes in basin morphology, which began as a deep basin or hole, then became a low-gradient ramp that evolved into a gentler ramp with clastics trapped updip and evaporites deposited in the center of the lake.

Salamov focuses on the northern margin of the South Caspian Basin, which is commonly called the North Apsheron Ridge, an area that offers great insights into the stratigraphic development of the oil reservoirs that are produced on the ridge farther south, the Apsheron Ridge. The use of three-dimensional (3-D) seismic data allowed the use of amplitudes and spectral decomposition to reveal a set of integrated valleys and channels that may represent a feeder system of the paleo-Volga that trends from the northwest to southeast before structural deformation occurred in the basin. His work illustrates the spatial patterns of reservoir distribution and their key controls.

The chapter by Sylvester et al. on reservoir modeling of this complex system is the last of the series of articles on the depositional system of the South Caspian Basin. The chapter focuses on modeling one of the reservoir units from the large Azeri-Chirag-Guneshli producing field. Reservoir modeling revealed that channel width was the key to accurate estimation of stock tank barrels of oil initially in place (STOIIP). Equally important is the vertical communication between layers derived from hand-contoured maps and referred to as interface transmissibility. These deterministic channel maps were essential for accurate modeling of reserves recovery, optimization of the pattern for water flooding, and to target sweet spots for development where channel sands stack vertically across stratigraphy. To achieve a material balance match, the hand-contoured map-based model had to be reduced by a factor of 2 to achieve material balance; models based on computer-contoured maps must be reduced by a factor of 4 to achieve material balance.

Moore et al. document lithofacies, facies assemblages, and the dimensions and stacking patterns of architectural elements in the Eocene Sunnyside delta interval of the Green River Formation in Nine Mile Canyon, Utah. Their careful description discriminated a variety of depositional settings for potential reservoir lithosomes, from fluvial to sublittoral, each with inherently different spatial distributions. They constructed a digital outcrop model from detailed measurements of vertical outcrop sections, paleocurrent directions, lithologic descriptions, and facies mapping of photopanoramas and digital light detection and ranging (LIDAR) data. This model significantly aided characterization of the lateral and vertical connectivity of potential reservoir units. Their analyses provide a predictive guide for modeling and developing analogous marginal lacustrine reservoirs.

Archer et al. present three groups of reservoir simulation models based on companion field-based geologic investigations by Moore et al. (this volume). The models address fluid flow in reservoirs deposited by deltaic systems in lacustrine basins. The basis for the simulations range from fairly simple two-dimensional (2-D) frameworks to quite complete 3-D characterization based on LIDAR and detailed geologic measurements. The results of even the first relatively simple simulation models indicate the importance of channels to flow in such lacustrine deltaic systems. More detailed simulations demonstrate that the dominant characteristics that control production efficiency are the abundance, geometry, distribution, and internal characteristics of different lithofacies elements. Specifically, channel units exert significant control on linking reservoir elements through lateral and vertical amalgamation in delta plain and fluvial facies. Any reduction of permeability inside the channel or on channel margins reduces the performance of the reservoir in its entirety and requires greater energy to achieve similar recovery efficiency as would be obtained for homogeneous channel deposits.

Mason uses data on the mineralogy and organic contents from 10 core holes in the Green River Formation to define its stratigraphy and major genetic influences. Thirty mineral relations were used to define distinct correlatable stratigraphic intervals. The distribution of evaluated minerals and organic matter illustrates the strong coupling of lake-water chemistry to the stratigraphic changes in the lake system. The four principal influences upon mineralogical variations were interpreted to be (1) deposition and preservation of organic matter, (2) volcaniclastics, (3) periods of evaporation and concentration, and (4) influxes of fresh water accompanied by increased transported detrital material.

Magyar et al. present the only biostratigraphic chapter in this volume and illustrate how, in the past, many stratigraphers were misled in their correlations in late Miocene to early Pliocene Lake Pannon because of the fossil record being endemic. Anagenetically (linear descent without branching or splitting) evolving mollusks and dinoflagellate algae correlations in the past did not consider the seismically documented progradational lake-basin style when they correlated the biostratigraphic record. Work is ongoing on the evolution of the mollusks and the dinoflagellates, as well as radiometric dating, so that the detailed biochronostratigraphy is advancing and reflecting the fact that younger sediment packages were deposited horizontally next to each other instead of forming perfectly vertical successions in the context of what is now a well-documented stratal architecture.

Extensional Regimes

Rift basins with lacustrine settings in depositional systems have been a major focus of past research. The volume begins with two chapters on the East African rift basins of Lake Doba in Chad and Lake Albert in Uganda. Beyond East Africa, chapters on China, Brazil, and southwest Germany add to our understanding of lake systems in extensional settings. Although all of the examples are from rift basins, the accumulation of potential reservoir sandstones varies for each basin— it is dependent not only on local climate, but also the regional gradient and the extent of the drainage basin, as well as its lake-basin phase.

Patterson et al. illustrate how continental reservoir and seal facies develop along a low-gradient basin margin using Cretaceous strata from Lake Doba in Chad. Their model of alluvial and lacustrine fill invokes high-frequency climatic fluctuations superimposed on longer term climatic cycles interacting with variable accommodation produced by extensional tectonic processes. Alluvial deposits dominate the coarser clastics in the section, whereas lacustrine facies are mainly composed of thin terminal splay strata. Humid periods correspond to times of erosion, transport, and deposition of coarse clastics. Arid periods are times of low sediment input and low amounts of coarse clastics being supplied to the lake (or basin). The lacustrine environment is dominated by widespread deposition of mud-rich strata. Understanding the complex interplay of long-term structural evolution and with climatic fluctuations is essential to make accurate predictions of reservoir and seal distribution and continuity. These insights have proven critical in developing an effective depletion strategy for the three field areas of southern Chad.

Karp et al. discuss the regional structure and stratigraphy of Lake Albert, part of the western branch of the East African rift valley. Extensive seismic and gravity data, with stratigraphic control from a well on the Ugandan margin, reveal this lake basin to be a full nearly symmetrical graben— this contrasts with the more common half-graben geometry of the other East African rift basins. The lake evolved from a continuously open-hydrology (overfilled), possibly deep, lake in the Miocene to an alternating shallow lacustrine and fluvial system in the middle and late Pleistocene. Modern Lake Albert is overfilled and alternated between a fluvial and lacustrine depositional system during the Quaternary. An overall coarsening-upward pattern in lake strata is interpreted to reflect increasing aridification in East Africa during the past approximately 7 m.y.

The lake developed a robust hydrocarbon system, as recently proven by new Ugandan oil discovery, and this makes the chapter particularly relevant. The key elements of this petroleum system include the potential source rocks in the overfilled deep lake conditions in the middle–upper Kisegi interval. The clastic reservoirs include sandstone and conglomerate intervals in the basal Kisegi, sandstone in the basal Kaiso, and sandstone and conglomerate in the upper Kaiso.

Sneider et al. document their work on the Cretaceous reservoirs of the Daan field in the Songliao Basin in China— a field that was considered marginally commercial until they defined a cost-effective and technologically strong field development program. The main geologic risk factor was reservoir sandstone distribution. They constructed a new model to predict distribution of the primary reservoir objective. This model was based on structural control of fluvial and marginal lacustrine environments associated with small- to medium-size lake systems that developed in fault-controlled trending depocenters. The main reservoir facies comprised Cretaceous lake-delta-mouth-bar and fluvial channel-bar deposits.

Outside the structurally controlled sweet spot areas, well productivity was lower because of reduced reservoir sandstone development. Although the development plan called for a consistent grid pattern of wells, the order of drilling had a significant impact on the commerciality of the project and the reservoir distribution model was key to defining the drilling order. Appraisal and development wells were drilled simultaneously, focused first on the sweet spot areas. This systematic drilling approach lowered reservoir risk and improved early well productivity by as much as 40% to 50%, thereby significantly enhancing the project's profitability. Understanding of the reservoir distribution has also contributed to a large increase in the estimate of oil in place for the Daan field.

Picarelli and Abreu present a detailed sequence-stratigraphic interpretation of the Neocomian section of the central compartment of the Recôncavo Basin. This interval illustrates rift-basin evolution from deep lakes to deltaic and fluvial systems and records complete changes in drainage patterns and stratigraphic signature. Their framework is based on 190 wells, including core, cuttings and well-log data, biostratigraphic and sedimentologic data integration, and structural maps based on 2-D seismic and well-log data. The Recôncavo Basin contains more than 7000 m (22,966 ft) of continental strata deposited in eolian, fluvial, deltaic, and deep lacustrine environments.

Their work suggests that the key controls on stratal character, distribution, and stacking patterns in divergent settings include location, rate, and history of fault movement, lateral differences in fault activity, and climatic processes (similar to the findings of Sneider et al.). These controls affect the evolution of basin physiography, catchment area, and drainage systems through their influence on the rates and distribution of sediment supply as well as of accommodation change. The interaction of these controls produces a distinctive stratigraphic record and strongly influences the nature and distribution of potential hydrocarbon reservoirs.

Schäfer addresses the controls on the accumulation and distribution of sandstone and algal carbonate in the fluvial-lacustrine system of the Carboniferous–Permian Saar-Nahe Basin, Germany. Deltaic sandstone, algal limestone (biostromes and bioherms), and lacustrine organic matter-rich mudstone (paper shales) accumulated in lakes, ponds, and flood basins under a tropical climate.

These strata demonstrate that hydrocarbon reservoir and source-prone lithofacies can accumulate in relatively close proximity. Seasonality of clastic input resulted in variable thicknesses of delicate light-dark laminite couplets that he attributes to storm or flood events (''weather-bedded''). Algal bioherms and biostromes are also influenced by the same set of processes and sometimes formed in the same lake or pond. Interbedded organic matter–lean siltstones are the distal equivalents of lacustrine deltas, resulting from the same floods that carried coarse clastics from rivers into flood-plain ponds and lakes.

His work illustrates the critical insights into paleoclimate and sediment supply provided by fine-grained rocks, even in continental depositional systems. These rocks not only contain a record that is not only the most complete, but also one that is integrated across the entire alluvial landscape, recording the myriad physical, biological, and chemical processes that influenced sediment accumulation.

Modern Regimes

The volume concludes with four examples in three chapters from modern settings. Lake Michigan in the United States is a large overfilled lake system that has many features that are typical of ocean coasts, but with significant differences. The Dead Sea in Israel is an underfilled lake system that evolved from Pleistocene Lake Lisan, which is well studied and dated. These chapters provide key insights that tie depositional processes to the occurrence, distribution, and character of potential hydrocarbon reservoirs. The last chapter in this volume is on modern traces from Lake Tanganyika (balanced-filled lake) in Tanzania and Lake Eyre (underfilled lake) in Central Australia. These two different climatic settings (humid and arid) and lake types show that ichnocoenoses are better suited than ichnofacies to subdivide lacustrine, alluvial, and eolian deposits. Ichnocoenoses provide greater environmental uniqueness so that trace fossils, combined with sedimentary and pedogenic facies, can be used more effectively to differentiate continental from marine deposits, as well as aquatic from terrestrial environments.

Fraser et al. summarize a lifetime (and a community) of work on Lake Michigan, the world's sixth largest-area freshwater lake (overfilled lake basin). They illustrate how hydrodynamic processes, cyclic and acyclic lake-level changes, and sediment supply pathways interacted with inherited basin configuration to shape the architecture of coastal and deep-basinal strata. This work provides useful insights for both the areal extent of potential reservoir lithosomes and the processes that deposited them.

The modern lake shares many features with oceanic settings, albeit at a smaller scale: barrier spits and islands, strand plains, deltas, eolian dune fields, fluvial flood-plain systems, and estuaries, as well as a shelf-slope system with coastwise rectification of currents, coastal downwelling jets, Coriolis veering of lake currents, a benthic nepheloid layer, and density currents. The lake does, however, differ from the ocean in several significant ways: predominantly mild wave climate, very small lunar tide, and a spillpoint that is the ultimate upper limit on accommodation. In addition, its coast experienced multiple noncyclic transgressive and regressive events during the last deglaciation, with lake-level changes of up to tens of meters, commonly at rates several magnitudes greater than the most rapid eustatic changes.

Seismic surveys indicate that depositional architectures formed during the fluctuating retreat of the Laurentide ice sheet are similar to those found in marine systems developed during sea level oscillations of comparable magnitude but longer duration. Erosional sequence boundaries with overlying lowstand fans form the base of sequences, overlain by transgressive and highstand systems tracts. Rises and falls of shorter duration and smaller magnitude were superimposed on major lake-level changes and are interpreted to have formed parasequences. Lake-level events that formed these units were probably the product of climatic cycles that continue to influence sedimentation to the present day.

Bartov et al. used computer forward simulation to reconstruct stratigraphic sequences observed in the late Pleistocene Lake Lisan (Dead Sea Basin), integrating multiple data sets. Extensive and detailed fieldwork constrained the model through reconstruction of high-resolution lake-level curve, subsidence history, and depositional rates in the offshore sections. They then tested the sensitivity of the model to changes in individual forcing parameters and evaluated the contribution of each of them to the resulting cross section. By establishing and quantifying the controlling factors that govern the basin fill, the computer simulations can help predict stratigraphic architecture within unexplored parts on the basin. Their work also indicates a productive path for those seeking to quantify the various relations among processes and depositional controls posited by many of the other authors in this volume.

Hasiotis et al. review the biota and the traces produced in two modern lake settings, Lake Tanganyika (balanced-filled lake in a tropical setting) in Tanzania and Lake Eyre (underfilled lake in an arid setting) in Central Australia. The purpose of this approach is to develop an understanding of the physicochemical factors that control the occurrence, diversity, abundance, and tiering of organism behavior that parallels what is known for benthic and other trace-making organisms in marine environments. The diversity and distribution of modern traces in Lake Tanganyika and Lake Eyre are compared with those of the *Mermia*, *Coprinisphaera*, *Skolithos*, and *Scoyenia* ichnofacies models that have been proposed for continental environments.

The actualistic lake studies show that all the models are inappropriate for the fluvial-lacustrine settings of Lake Tanganyika and Lake Eyre because the models do not support the environmental uniqueness or distinctive collection of traces across these environments, nor do they provide sufficient interpretive power. Multiple ichnocoenoses for each subenvironment observed in each lacustrine system more accurately record the environmental uniqueness and distinctive collection of traces found in each environment. Ichnocoenoses are better suited for continental depositional systems and their environments because they reflect the nature of processes and distribution of life in the continental settings that are inherently heterogeneous spatially and temporally.

Trace fossil evaluation is another data set that should be used when the lacustrine, fluvial, and eolian environments need to be identified. Ichnocoenoses for the examples of balanced-filled and underfilled lakes provide sufficient interpretive power for trace fossil associations formed under different physicochemical conditions for each type of environmental setting. General trends in trace fossil diversity, abundance, distribution, and tiering are proposed for alluvial (fluvial), lacustrine, and eolian environments so that new models based on the distribution of ichnocoenoses and their sedimentary and pedogenic characteristics from outcrop and core can be constructed.

In conclusion, this set of chapters, although not a complete description of every lacustrine system in the world, does illustrate the complexities and commonalities associated with the deposition of lacustrine reservoirs. Table 3 summarizes the key elements of the lake systems described in this memoir to direct you to all the work that might be of assistance to you. We hope you will find this volume useful to you in your explorations.

Table 3. Summary of key elements in lake systems.*

Lake Name	South Caspian	Green River	Lake Pannon	Lake Chad	Lake Albert	Lake Tanganyika
Tectonic setting	Compressional	Compressional	Compressional	Extensional	Extensional	Extensional
Location	Azerbaijan	U.S.A.	Hungary	Chad	Uganda	Tanzania
Age	Late Miocene–early Pliocene	Eocene	Late miocene–early Pliocene	Upper Cretaceous	Miocene	Miocene–Holocene
Paleolatitude of lake	Mid (40–60°)	Mid (40–60°)	Mid (40–60°)	Equatorial (0–20°)	Equatorial (0–20°)	Equatorial (0–20°)
Reported climate class	Semiarid to steppe	Humid to semiarid	Warm temperate	Humid to semiarid	Tropical to arid	Tropical
Drainage basin gradient	Low	Moderate	Low to moderate	Low to moderate	High	High
Relative area of drainage basin	Large	Large	Large	Large	Small	Small
Discharge rate	High	High	High	Variable	Low	Variable
Relative coarse clastic load	Large	Large	Large	Variable	Moderate	Variable
Lake-basin type and evolution**	UF	OF-BF-UF-BF-OF	OF	BF	OF	BF
Depositional environment for reservoirs	Fluvial	Fluvial to shoreline	Fluvial to shoreline	Fluvial, alluvial, terminal splays at shoreline	Alluvial to shoreline	Lacustrine, fluvial and alluvial
Dominant control on reservoir distribution	Lake level; filled with gently to local steeply dipping clinoforms from river mouth to basin center	Lake level; meandering fluvial system, prograding delta	Lake level and prograding clinoforms (not recognized in early studies because of lithofacies– and biofacies–based approach in stratigraphy)	High-frequency climate fluctuations of 200–500 k.y. duration superimposed on longer term climate cycles of 1–3 m.y. Climate fluctuations, evident as cyclic variations of discharge, sediment flux	Fault control, rift valley dominated by a flat valley floor	High-frequency climate fluctuations of 200–500 k.y. duration superimposed on longer term climate cycles of 1–3 m.y. Climate fluctuations, evident as cyclic variations of discharge, sediment flux
Other key controls on reservoir deposition	Delta backstepping as basin gradient decreases through time	Reservoir quality dependent on facies: Distributary mouth bars and channels contain best reservoirs	Basement morphology, synsediment tectonics	Sediment accumulation during sag phase of an extensional rift system	Symmetrical graben with continuous subsidence	Interconnected, asymmetrical half-graben northern and southern basins, separated by a complex block-faulted structure, coupled with climate control on lake level
Memoir location	Chapters 2–6	Chapters 7–9	Chapter 10	Chapter 11	Chapter 12	Chapter 18

*sensu Carroll and Bohacs (1999).

**Lake-basin types listed in stratigraphic order to specify basin-fill evolution. UF = Underfilled; OF = Overfilled; BF = Balanced-filled.

Songliao	Recôncavo	Saar-Nahe	Lake Michigan	Lake Lisan (Dead Sea)	Lake Eyre
Extensional	Extensional	Extensional	Extensional	Extensional	Flexural
China	Brazil	Germany	U.S.A.	Israel	Australia
Early Cretaceous	Early Cretaceous	Carboniferous–Permian	Pleistocene–Holocene	Late Pleistocene–Holocene	Late Paleocene–Holocene
Mid (40–60°)	Equatorial (0–20°)	Equatorial (5–20°)	Mid (40–60°)	Low (30–35°)	Mid (-60 to -30°)
Humid	Humid seasonal	Humid, tropical	Glacial to humid seasonal	Arid	Humid to arid
Moderate	High	Low	Low	High	Low
Small to medium	Small	Medium	Large	Small	Large
Low	Low	Low	Moderate	Low	Variable (moderate to low)
Large	Large	Large	Low	Variable	Variable (moderate to low)
BF-OF	UF-BF-OF	OF	OF	UF	OF-BF-UF
Fluvial to shoreline	Fluviodeltaic, lake floor fan	Lacustrine, fluvial and alluvial	Lacustrine and estuarine	Fluvial	Fluvial, eolian, shoreline (each ridges and terminal splays)
Structurally controlled depocenters	Asymetric, half-graben basin geometry with fault-controlled slope near depocenter, ramp geometry along basin axis	Structure-related coarse-grained facies transported by braided rivers along basin axis; alluvial fans along the active strike-slip boundary fault; strike-slip causes shifts of depocenters	Lake level; clastics predominantly occur in a coastal prism (nearshore to onshore), making some of the largest inland dunes in the world and in drowned river mouths (estuaries)	Lake level	Lake level, climate, drainage basin gradient
Deposition during postrift thermal subsidence above an asymetrical graben	Climate control on high-frequency changes of lake level	Climate; lowland meandering river system with frequent crevasse-splay deltas into fluvial flood basins and lakes (dominated by black shales)	Large-scale fluctuations of lake level in response to glacial advances and retreats; isostatic rebound caused outlets to open and close	Sediment supply and basin subsidence associated with extension within strike-slip system	Subsidence rates (thermal control), increasing aridity through the Cenozoic, lake level fluctuations resulting in large changes in lake area because of low gradients
Chapter 13	Chapter 14	Chapter 15	Chapter 16	Chapter 17	Chapter 18

REFERENCES CITED

Carroll, A. R., and K. M. Bohacs, 1995, A stratigraphic classification of lake types and hydrocarbon source potential: Balancing climatic and tectonic controls, Abstract Volume, First International Limno-Geological Congress, Copenhagen, Denmark, p. 18–19.

Carroll, A. R., and K. M. Bohacs, 1999, Stratigraphic classification of ancient lakes: Balancing tectonic and climatic controls: Geology, v. 27, no. 2, p. 99–102.

Sadler, P., 1981, Sediment accumulation rates and the completeness of stratigraphic sections: Journal of Geology, v. 89, no. 5, p. 569–584. doi:10.1086/628623.