Lacustrine Petroleum Source Rocks

Geological Society Special Publications

Series Editor K. COE

GEOLOGICAL SOCIETY SPECIAL PUBLICATION NO 40

Lacustrine Petroleum Source Rocks

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1988

Published for
The Geological Society by
Blackwell Scientific Publications
OXFORD LONDON EDINBURGH
BOSTON PALO ALTO MELBOURNE

Published for
The Geological Society by
Blackwell Scientific Publications
Osney Mead, Oxford OX2 0EL
(*Orders:* Tel. 0865 240201)
8 John Street, London WC1 2ES
23 Ainslie Place, Edinburgh EH3 6AJ
3 Cambridge Center, Suite 208, Cambridge,
Massachusetts 02142, USA
667 Lytton Avenue, Palo Alto,
California 94301, USA
107 Barry Street, Carlton, Victoria 3053,
Australia

First published 1988

0305-8719/88 $03.00

Typeset, printed and bound in Great Britain by
William Clowes Limited, Beccles and London

DISTRIBUTORS

USA
Blackwell Scientific Publications Inc.
PO Box 50009, Palo Alto
California 94303
(*Orders:* Tel. (415) 965–4081)

Canada
Oxford University Press
70 Wynford Drive
Don Mills
Ontario M3C 1J9
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Australia
Blackwell Scientific Publications
(Australia) Pty Ltd.
107 Barry Street, Carlton,
Victoria 3053
(*Orders:* Tel. (03) 347 0300)

British Library
Cataloguing in Publication Data

Lacustrine petroleum source rocks.—
(Geological Society special publication
ISSN 0305–8719).
1. Lacustrine sediments. Petroleum deposits
I. Fleet, A. J. (Andy J) II. Kelts, K.
III. Talbot, M. R. IV. Series
553.2'82

ISBN 0–632–01803–8

Library of Congress Cataloguing-in-Publication Data

Lacustrine petroleum source rocks.
(Geological Society special publication,
ISSN 0305–8719; no. 40).
Includes index.
1. Petroleum—Geology. 2. Paleolimnology.
I. Fleet, A. J. II. Kelts, K. R. III. Talbot,
M. R. IV. Geological Society of London. V.
Series.
TN870.5.L22 1988 553.2'82 88–2870

ISBN 0–632–01803–8

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Introduction

Lacustrine Petroleum Source Rocks is a collection of papers arising from a meeting held at the Geology Society, London, in September 1985. The meeting was organized by the IGCP Project 219, 'Comparative lacustrine sedimentology in space and time', and the Petroleum Group of the Geological Society.

Organic-rich lacustrine sediments, potential sources of oil and/or gas, represent a group of lacustrine sediments whose interpretation is not only intellectually challenging but whose subsurface prediction, in terms of location, nature and lateral variation, is economically important. The papers in this volume represent an attempt to bring together synthesized concepts, techniques and real examples in order to provide ideas for both interpretation and prediction.

Petroleum source rocks deposited in lakes have come more into focus over recent years as petroleum exploration has shifted to new areas and as more detailed analysis of known petroleum provinces has become an exploration necessity. New areas include the multifarious basins of onshore China, for instance as described in this volume by Fu Jiamo *et al.*, Brassell *et al.*, Wang Tieguan *et al.* and Luo Binjie *et al.*, and the rift basins of Africa (e.g. Sudan: Schull 1984; Frostick *et al.* 1986). Lacustrine sources of petroleum must also be accounted for in some established petroleum provinces ranging from passive margin sequences, such as offshore Gabon (e.g. Brice *et al.* 1980), to the North Sea (e.g. Duncan & Hamilton, this volume). Lacustrine source rocks are often unsampled, being among the first deposits of a syn-rift sequence, in which case evidence for them is indirect, provided by oils themselves (e.g. McKirdy *et al.*, this volume).

Lacustrine petroleum source rocks represent one suite of the very varied lithologies which can accumulate in lakes. This variety reflects the broad range of dissolved and detrital inputs to lakes and the large spectrum of environmental conditions which can occur in lakes. Rapidly fluctuating conditions in individual lakes and, in some cases, the ephemeral nature of lakes often complicates particular sequences further. The variety of lacustrine sediments in general, and the complexity of individual deposits, has meant that lacustrine sediments have, with notable exceptions (e.g. the Green River basins, western USA), frequently received scant attention. IGCP Project 219 has set out to rectify this by gathering data and interpreting the distribution and variability of lacustrine sediments in space and time.

The volume is divided into three parts. The papers of the first part provide the overall framework and background against which to consider the more specific studies presented in Parts II and III. No attempt has been made here to give a precis of the nature of petroleum source rocks: the reader should refer to standard texts such as Tissot & Welte (1984) for such fundamentals. Part II of the volume details a range of techniques and approaches which can be used when interpreting the palaeoenvironments of lakes. Part III provides various case studies from around the world arranged in stratigraphic sequence.

Frameworks

The first six papers of the volume provide an overview of lacustrine sedimentation, in particular the factors which control organic matter deposition and preservation. These factors are founded on fundamental tectonic and hydrologic controls which cause a lake to exist and allow it to persist. Organic matter supply is both autochthonous and allochthonous. Autochthonous supply depends on nutrient availability and resulting biological productivity in the surface waters of the lake. Allochthonous input reflects bordering vegetation and transport mechanisms into the lake. Organic preservation is governed by various factors. For labile, potentially oil-prone aquatic detritus it depends most significantly on oxygen-deficient or -depleted bottom-water conditions and thus on lake hydrodynamics. However, rapid sedimentation may also lead to preservation, while sulphate reducing organisms may cause significant destruction even after deposition under anaerobic–anoxic conditions. The interrelated factors of geography, tectonics, hydrology, lake circulation, inorganic and organic sediment supply and preservational conditions, therefore, all need consideration when assessing the presence, nature and variability of lacustrine source rocks.

The scene is set by Kelts, who spans from the essential conditions for a lake (a topographic depression and a hydrological balance adequate to support surface water) to an outline of currently perceived problems relating to lacustrine kerogens, the sources of petroleum. Modern and ancient lakes and their tectonic settings are put in context and the variable chemistry of lakes is outlined. The stratigraphic distribution of lacus-

trine source rocks and published models of their formation are briefly reviewed. This leads to a survey of how carbon cycles and deposition vary between lakes with differing chemistries.

Recent African lakes provide natural laboratories. Talling's brief contribution focuses on a first step in the formation of lacustrine source rocks: biological productivity. Talbot follows the process further by considering the nature and accumulation of Pleistocene organic-rich sediments in six tropical African lakes. The preserved organic matter is a mixture of aquatic and terrigenous higher-plant detritus. The richest potential oil-prone source rocks accumulated in both stratified (meromictic) and annually mixed (monomictic) lakes when the climate was humid and winds slack. The humid climate ensured two things: firstly, dense land vegetation and thus minimal clastic input to the lakes which would have diluted accumulating organic matter; secondly, intense chemical weathering and thus a supply of nutrients. Stable stratification in the lakes allowed organic matter preservation under oxygen-deficient or -depleted bottom-water conditions; occasional mixing may have occurred in those lakes where organic accumulation rates were high. Overall Talbot finds no evidence from his studies to support the idea that shallow saline lakes are especially favourable as sites for the deposition of potential oil-prone source rocks.

Organic matter preservation in various types of lake is discussed by De Deckker. He considers three types of large Neogene lake from Australia: deep lakes, lakes with ephemeral (and shallow) water and 'dry' lakes. He thus extends discussion to more saline conditions. His work suggests that petroleum source rocks are principally limited to deep lakes in which organic matter is preserved under anaerobic bottom-water conditions. In ephemeral lakes significant algal mat bioherms can develop under hypersaline conditions but these are subject to attack during early diagenesis by sulphate-reducing organisms which destroy their organic content. Some ephemeral and 'dry' Australian lakes therefore tend to be sites of metalliferous deposits rather than petroleum source rocks.

Saline conditions are considered further in the next paper. This illustrates the kind of detailed study necessary to understand organic productivity and deposition in just one such lake. It discusses the ongoing work of Oremland *et al.* who are investigating microbial and biogeochemical processes in Big Soda Lake, Nevada, which is stratified, 65 m deep and alkaline (pH 9.7).

A final aspect of understanding the framework of lacustrine deposits is outlined by Summerhayes who discusses recent work on predicting palaeoclimates which can be used to assess the regional environments of lake basins.

Palaeoenvironmental indicators

Organic, inorganic, mineralogical and isotopic indicators of organic matter input and environmental conditions are all considered in Part II of the volume. (Information on the range and ecological significance of many limnic biota in the geologic record is generally lacking.) Organic geochemistry is dealt with first. The first two papers are concerned with bulk characterization of the organic matter of organic-rich lacustrine sediments and the second two with molecular parameters. Katz compares clastic lacustrine sediments from three modern African lakes with lacustrine carbonates represented by the ancient, but thermally immature, Green River Formation of Utah and Colorado. The former contain more inert material than the latter but both types of sediments are capable of generating oils, indicating that hydrogen-rich, oil-prone material can be preserved in both types of lacustrine environment. Katz's pyrolysis–gas chromatography results indicate that the oils derived from either type of potential source rock on maturation would have high wax contents. Vandenbroucke and Behar also discuss a pyrolysis technique. This involves fractionation of the pyrolysate into groups of organic compounds and analysis of the compounds by gas chromatography and gas chromatography–mass spectrometry. Their results tentatively suggest that lacustrine kerogens can be distinguished from other kerogens and are indeed characterized by Type I kerogen.

In contrast to bulk analyses, molecular or biological markers are very specific indicators of either organic matter inputs (types of organisms or even specific genera) or depositional environment. They can be derived from either sediments or oils. The first paper on this topic, by Volkman, is a comprehensive state-of-the-art review. It highlights the pitfalls associated with blindly using some published biological markers and suggests future directions for relevant research. In contrast, the second biological marker paper, by ten Haven *et al.*, is specific in scope dealing with the molecular characterization of sediments or oils from hypersaline environments.

Inorganic chemical or mineralogical indicators of palaeoenvironment are the subject of the next three papers. Because of the lack of dissolved sulphate in freshwater lakes relative to seawater, carbon–sulphur ratios and the partitioning of sulphur between pyrite and organic matter have

been used to distinguish lacustrine and marine environments. Davison reviews this approach and, while accepting that it is soundly based, urges cautious use because of our limited understanding, particularly of pyrite formation in freshwater environments. Yuretich also suggests that there are gaps in our knowledge of lacustrine systems. He argues that the inherently heterogeneous nature of lacustrine clays and the extremes of porewater chemistries likely to occur beneath lakes probably mean that lacustrine clays behave very differently from their marine counterparts during diagenesis. He suggests this may affect the catalytic influence of clays during kerogen breakdown to petroleum and thus explain the localized migration in lacustrine oilfields and their small size. Bahrig's contribution on siderite illustrates how isotopic evidence can be used to interpret the origin of mineral phases and so help build up the depositional and diagenetic histories of lacustrine sediments.

Finally in this Part of the volume, Jiang De-xin presents a novel technique for studying the origin and migration history of oils. This involves using spore and pollen recovered from oils as indicators of both the source rock of the oils and the carrier beds through which the oils have migrated. From an investigation of the spores and pollen of Chinese oils, Jiang De-xin concludes that wet, hot climatic conditions are conducive for the deposition of lacustrine oil-prone source rocks.

Case studies

The final part of the volume is devoted to fifteen examples of actual or potential lacustrine source rocks. The ordering of these case studies is stratigraphic. The first three deal with the Devonian Orcadian basin of Scotland. Duncan and Hamilton extend a depositional model for organic-rich lacustrine laminites, based on outcrop data, to the ill-defined subsurface of the offshore Moray Firth basin. They illustrate the strengths of molecular marker geochemistry by using the approach to argue for a component of Orcadian lacustrine-derived oil in the Beatrice field. Hillier and Marshall briefly summarize points concerning the distribution and maturity of source rocks in the Orcadian Basin. Parnell interprets cherts from the Orcadian Basin as evidence of saline, alkaline conditions of source-rock deposition.

The lacustrine Carboniferous Oil Shales of the Scottish Midland Valley, the foundations of the ancestral UK petroleum industry, are the subject of the next two papers. Loftus and Greensmith identify a series of freshwater stratified lakes in a wet tropical climate. These underwent cyclic changes and some connection to the open sea. Oil-shale deposition occurred at intervals. Parnell reviews the petroleum potential and composition of the oil-shales and the associated sediments.

The Newark Rift System of eastern North America provides analogues of lacustrine sediments for some passive margin and intracontinental rift sequences. Gore provides a detailed review and interpretation of one of the basins of the Rift System: the Culpeper Basin. Late Triassic to Early Jurassic lacustrine sediments occur in the Culpeper Basin, which is a half-graben, along with fluvial and alluvial fan deposits. Gore recognizes freshwater, saline and hypersaline lakes as both lateral equivalents and successive water bodies. Organic-rich laminated shales were deposited where the lakes were stratified and bottom waters 'anoxic'. Gore suggests that climatic variations, controlled by Milankovitch-type cyclicity, influenced chemical sedimentation in the basin and thus the hydrology of the area including lake formation.

The next four papers deal with petroleum-bearing Chinese continental basins. These basins constitute the most significant area of lacustrine-sourced petroleum production in the world. They vary in age from the Late Palaeozoic to Cenozoic and cover the full range of possible lacustrine environments. This wide spectrum is illustrated by Fu Jiamo *et al.* and Luo Binjie *et al.* The former authors emphasize the relationship between tectonic setting and lacustrine sedimentation, while the latter group suggests that humid or semi-humid climatic conditions and deep to intermediate lakes most favoured oil-prone source-rock deposition. Both discuss the natures of the source rocks and their oils. Brassell *et al.* and Wang Tieguan *et al.* expand on these themes with detailed geochemical studies.

Two Australian studies are considered next. McKirdy *et al.* use the indirect evidence provided by the chemical compositions of surface bitumens to argue for Early Cretaceous lacustrine source rocks in the rift-valley sequence of the Otway basin, offshore of southeastern Australia. The nature of Australian Tertiary oil shales as freshwater lacustrine deposits is then illustrated by Hutton who describes the Condor Oil Shale of Queensland as an example.

Finally, three sets of Cenozoic lacustrine basins are considered. Gibling describes and interprets oil shales and associated coals and sediments which accumulated in various sized strike-slip basins of Thailand during Oligocene and Miocene times. In general, the oil shales represent early

episodes of aquatic productivity during the history of the lakes, but in one case deposition occurred in a deep, persistent, 'perennially stagnant' lake. The existence of lacustrine carbonates and siliciclastic sediments in adjacent basins points to the strong influence of localized sediment supply and water compositions. Local and temporally-variable controls on lacustrine deposition are further emphasized by Anadon *et al.*'s study of anoxic–oxic lacustrine cycles in the Miocene Rubielos de Mora basin of Spain. Lastly, Crossley and Owen return the volume to Africa with a detailed study of cores from Lake Malawi which illustrates the interplay of mass flow sedimentation and productivity events in lakes.

Our understanding of the formation of lacustrine petroleum source rocks is more diffuse than that of their marine counterparts (e.g. Brooks and Fleet 1987). This volume should provide stimulation on directions to follow in attempting to improve this understanding. We believe that future prospects are exciting. There is a new challenge for geologists to formulate sophisticated models for lake deposits, integrating results from diverse modern lake environments with those from ancient lake deposits.

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Acknowledgements

The meeting on 'Lacustrine Petroleum Source Rocks', and hence this volume, would not have been possible without the financial support of the International Geological Correlation Programme (IGCP) and the organization and help of the Geological Society. We are particularly grateful to Caroline Symonds and her colleagues in the Society Office and Mr and Mrs Ewens and their helpers for the smooth running of the meeting.

The volume itself reflects not only the efforts of the authors but also the contributions of the questioning and constructive reviewers and the patience of Mary-Clare Swatman of Blackwell Scientific Publications who pulled the book together.