LACUSTRINE FACIES ANALYSIS
Lacustrine Facies Analysis

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Preface

Lake basins are fascinating systems that define palaeoenvironments on a regional scale. The interactions between biospheric, geospheric, hydrospheric and atmospheric elements produce unique fingerprints. Large and small lakes have response rates greater than the oceans and two further degrees of freedom with varied chemistries and salinities. Long-lived lakes are common in tectonic basins and thus record overprints of tectonic and climatic change. How can these be separated? What are the criteria for recognition of subfacies? Lake basins also present difficult problems of correlation, without global index fossils and with a plethora of endemic species.

It has been 13 years since the publication of International Association of Sedimentology (IAS) Special Publication Number 2 Modern and Ancient Lake Sediments (Matter and Tucker, eds, 1978). Much has happened since. Lacustrine sedimentology has developed from a marginal curiosity into a frontier area of geology. Many lake-basin sequences contain hydrocarbon source rocks; others contain pristine archives of environmental dynamics. The field has become increasingly diversified. In 1984 the International Geological Correlation Program (IGCP) established IGCP project Number 219 on Comparative Lacustrine Sedimentology in Space and Time. This volume presents selected papers derived from two meetings co-sponsored by the IAS and IGCP 219. One was a field symposium in Rubielos, Spain (3–6 October 1988) on Lacustrine facies models in rift systems and related natural resources. The other was in the context of an IAS Symposium in Beijing, China (30 July–4 August, 1988) on Sedimentology related to mineral deposits. The reader is also referred to related presentations on lacustrine basins given at the large Beijing meeting which appear in two 1991 issues of the Journal of China Earth Sciences.

The first group of papers in this volume focus on natural resources in lacustrine basins, and underline the economic potential of lacustrine sequences. Tiercelin summarizes the diversity of lacustrine environments found in the great East African rift system, and reviews their known links to mineral deposits. Ordoñez, Calvo, García del Cura, Alonso-Zarza and Hoyos synthesize data on the occurrence of sodium sulphate and unusual clay minerals in lacustrine evaporite sequences from the Tertiary Madrid Basin, an intra-plate, compressional depression. Platt and Wright propose a general framework of diverse lacustrine facies in the context of source rocks and reservoirs and hydrocarbon exploration. This theme is further developed by Lin, Yang and Li with a perspective on a Tertiary strike-slip, deep-lake basin in southeast China. Kasinska shows the importance and environment of coal deposition in Cenozoic rift basins of central and eastern Europe. His emphasis is on links with the timing of tectonic events. Coal deposition is also a theme for Gierlowski-Kordesch, Gómez Fernández and Meléndez but in the context of the interplay of carbonate and alluvial sediments from Cretaceous lake basins in central Spain. They caution on the impact of diageneesis for the interpretation of lacustrine carbonates.

Modern processes in lakes of the East African rift are at the focus of a second theme with three papers. Scott, Ng’ang’a, Johnson and Rosendahl interpret new high-resolution seismic profiles and cores from deep Lake Malawi, showing the interplay of active faulting, hiatus, and sedimentation patterns. Seismic studies of the East African lakes are providing new insights into the mechanisms of rifting. Balthzer demonstrates the impact of muddy turbidity currents on the basin facies of Lake Tanganyika. In contrast, Renaut and Owen dissect nearshore sediments from shallow, brackish alkaline Lake Bogoria, Kenya with a model for the dynamics of beach development.

A third set of four papers examines sequence stratigraphy and rhythmicity in lacustrine deposits. These show the problems of separating signatures of orbital forcing from tectonic movements. Rogers and Astin propose a reinterpretation of cyclic lacustrine sequences from the extensive Middle Devonian, Orcadian deposits of northern Britain with playa features. These are considered in terms of orbital forcing of palaeoclimate. Martel and Gibling stress the tectonic component in Early Car-
boniferous lacustrine rhythms from Nova Scotia, Canada. Gómez Fernández and Meléndez discuss a mixture of high-frequency climate variability and lower frequency tectonic pulsing illustrated by carbonate rhythms in Lower Cretaceous lacustrine sequences of northeast Spain. Anadón, Cabrera, Julià and Marzo describe well-developed, multiple lacustrine rhythms comprising deeper-water laminated carbonates, oil shales and shallow-water clastics from the middle Miocene Rubielos Basin, northeast Spain. They also emphasize tectonics overprinted on climatic fingerprints for the interpretation of sequence characteristics.

A fourth set of papers link lacustrine sedimentology and other palaeoenvironmental approaches. Szulc, Roger, Mouline and Lenguin include new isotopic data on the origin of sediments in the late Oligocene Narbonne Basin, southwest France. Robbins, Zhou and Zhou apply organic facies analyses and petrography toward palaeoenvironmental interpretations of calcareous lacustrine deposits from one of the Tertiary strike-slip basins of eastern China.

The papers of this volume thus represent a mixture of syntheses and case studies. They expand our knowledge of the regional distribution of diverse lacustrine deposits and further document the tendency for occurrences linked to preferred geological periods and zones of active tectonics. Many of the lacustrine sequences display the typical threshold behaviour of lacustrine systems. The central theme illustrates the interplay of climate changes modulated within megasequences controlled by regional tectonics. We need better, integrated tools which can provide sufficient time-resolution to identify unequivocally orbital-scale forcing. As our knowledge of sequence stratigraphy and palaeoenvironments in ancient lacustrine basins expands, the results can be applied to improve modelling of deposition in continental basins. Better exploration models for the diverse lacustrine resources will result. The papers of this volume also illustrate how the interest in lacustrine systems has expanded to a larger, more international, sedimentology community.

We are very appreciative of the efforts of reviewers. Each paper was examined by at least two. In particular we wish to acknowledge the following: P.A. Allen, B. Alonso, J.P. Calvo, C. Dabrio, M. Esteban, R. Flores, E. Gierlowski-Kordesch, T. Kreuser, M.R. Leeder, N. Platt, C. Pumot, E.I. Robbins, M.R. Talbot, J.-J. Tiercelin, N.H. Trewin, M.E. Tucker, and others remaining anonymous. We benefited greatly from the technical assistance of E. Clavero, C. Docherty, R. Ramis, and Béatrice Schwertfeger.

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Natural Resources in
Lacustrine Basins
Natural resources in the lacustrine facies of the Cenozoic rift basins of East Africa

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ABSTRACT

Ancient lacustrine sediments deposited in continental rift systems contain large quantities of economic resources. The world’s largest active continental rift system, the East African rift system, is characterized by a combination of troughs of various tectonic styles occupied by small modern to large ancient ‘teutonic’ lakes, up to late Cenozoic or older. Large lakes are generally fresh water, fed by permanent streams; others are saline, fed by groundwater or hot springs, with ephemeral surface water inflow. At least eight primary lacustrine deposits and associated minerals are considered in terms of natural resources. Several are mined. These are organic-rich oozes, diatomites, zeolites and sodium silicates, metallic proto-ores, clays, phosphates, and coals. Other facies, such as stromatolites and lake-deposited pyroclastics, have primary economic significance or later importance, such as hydrocarbon reservoirs. Occurrences of such natural resources within the East African rift system are described in terms of processes of formation, industrial uses, and mining operations.

INTRODUCTION

Hydrocarbons, metallic minerals, and non-metallic resources commonly occur in large quantities in the sediments of modern and ancient continental rifts. Robbins (1983) noted that such resources accumulate in rift systems as a result of interactions between rift forming and sedimentation processes. These controls include tectonic, magmatic, climatic, hydrological, chemical, biological, and sedimentological factors. The world’s largest active continental rift, the East African rift system, illustrates well examples of rift deposition and natural resources.

THE EAST AFRICAN RIFT SYSTEM ARCHITECTURE

The architecture of the East African rift system comprises a series of troughs and faults. Spanning the Equator, the system is 4000 km long. From north to south, there are two extensional branches, the eastern and western, three major NW–SE transcurrent fault zones, Aswa, Tanganyika–Rukwa–Malawi (TRM), and Zambezi–Mwanza, several hundred kilometres long; and a ‘southern complex’ of NE–SW troughs related to the western branch, extending from the Luangwa Trough of Zimbabwe to the Okavango Basin of South Africa (Chorowitz & Mukonki, 1980; Kazmin, 1980; Chorowitz et al., 1983; Rosendahl, 1987; Tiercelin et al., 1988a; Daly et al., 1989; Ebinger, 1989b; Mondeguer et al., 1989) (Fig. 1). Depressions or rift basins along the eastern and western branches form by links between smaller basins (mean size 50 × 30 km). These are generally asymmetric half-grabens, organized in line or ‘en échelon’. These half-grabens are linked together by various structures, which generally follow the fabric of the pre-rift rocks (McConnell, 1967, 1972; Daly et al., 1989; Versfelt & Rosendahl, 1989). Transfer faults (Gibbs, 1984) occur between half-grabens, whereas the major Aswa, TRM, and Zambezi–Mwanza fault zones are areas of strike-slip (transform) motion between rift segments. These zones are considered as large sutures in the pre-rift rocks that have been reactivated during successive African orogenies and rifting episodes (Tiercelin et al., 1988a; Daly et al., 1989).
Fig. 1. Sketch showing the fundamental architecture of the East African rift system, eastern branch, western branch and seaward extensions, and southern complex (after Mougenot et al., 1986; Mondeguer et al., 1989).
The eastern branch

The eastern branch is divided into three rift segments from north to south: the Afar Depression, the Ethiopian rift, and the Gregory rift. The Gregory rift intersects the NW–SE Aswa transform fault zone near the Equator, and extends to the south along the North Tanzanian Divergence. On the continental margin of northern Mozambique, the N–S trending Kerimbas and Lacerda grabens form a seaward extension of the North Tanzanian Divergence (Mougenot et al., 1986, 1989) (Fig. 1). One major characteristic of the eastern branch is the voluminous syntectonic alkaline volcanism, which filled depressions nearly as fast as they subsided (Fig. 2).

Estimated volumes of the eastern branch flood volcanics range up to 470,000 km³ (Baker et al., 1972). The major volcanic episodes in the Ethiopian and Somali plateaus were Eocene–Oligocene Trap Series fissure basalts. In the northern Gregory rift, volcanism was early Miocene. In the Ethiopian and Gregory rifts, volcanic episodes range from late Miocene to early Pliocene flood phonolites to Pliocene to early Pleistocene fissure and central eruptions (Baker et al., 1971). Middle Pleistocene and later volcanism formed an axial chain of central volcanoes along the floor of the rift from northern Tanzania to Afar. These divide the eastern branch into separate valleys.

The western branch

The western branch is divisible into two main segments oriented NNE–SSW to N–S. From north to south, these are the Lake Albert and Lake Edward troughs, the Kivu and northern Tanganyika troughs, and the northern Malawi Trough down to the Urema and Dombe Troughs (Fig. 1). Its northern and southern terminations correspond to intersections with the NW–SE Aswa and Zambezi–Mwanza fault zones. Two main segments are connected through the major structure of the TRM dextral transform fault zone. The extreme difference in the quantity of volcanics in the two branches is characteristic. There are only four main centres of Eocene to Recent volcanism: the Rungwe massif in the northern Malawi Trough, the south and north (Virunga) Kivu volcanic fields, and the Toro–Ankole volcanic field east of Lake Edward (Fig. 2). The western branch is considered as volcanically 'dry' compared with the 'wetter' eastern branch (Mohr, 1982).

The transverse fault zones

From north to south the transverse fault zones are (Fig. 1):
1. The Aswa lineament is an important fault zone 1200 km long by 60 km wide, underlined by mylonites of Pan-African age (Cahen, 1970). It links the western branch of the rift (Lake Albert Trough) with the eastern branch (central Gregory rift). Transcurrent movements varied during its period of activity (Vidal, 1985).
2. The 1000 km long by 200 km wide TRM fault zone intersects the western branch of the rift. This mobile belt has the imprint of the Ubendian Orogeny.
(Dodson et al., 1975), and has acted during the Cenozoic as a dextral strike-slip system (Tiercelin et al., 1988a).

The Zambezi-Mwanza Fault ends the rift system to the south. It defines a regional transfer zone that links displacement to the Urema and Dombe grabens (Daly et al., 1989).

The sedimentary basins of the East African rift system

The geological history of rift basins and lakes in the East African rift system is complex. It is remarkably different depending on location in the eastern or western branches. The large quantity of volcanic rocks results in the eastern branch being characterized by shallow and ephemeral sedimentary basins; the western branch has had little volcanism, leading to deep, long-lived basins and thick sedimentary fill (Tiercelin, 1981, 1990).

The major sedimentary basins within the eastern branch today have small (maximum 30 × 20 km), shallow (maximum 10 m) tectonic lakes (Hutchinson, 1957). The exception is Lake Turkana at the northern end of the Gregory rift, which is 250 km long, 15–30 km wide, and has a maximum water depth of 125 m. Some of the lakes are fresh water or weakly saline, fed by permanent streams, such as Lakes Abbe and Langano in the Afar Depression and the Ethiopian rift, and Lakes Turkana, Baringo, and Naivasha in the Gregory rift. Others are saline, fed by groundwater or hot springs having temporary inflows from ephemeral streams. These are Lake Asal in the Afar Depression, Lakes Ziway, Abiyata, and Shala in the Ethiopian rift, Lakes Bogoria, Nakuru, Elmenteita, Magadi, and Little Magadi in the Gregory rift, and Lakes Natron, Eyasi, and Manyara in the North Tanzanian Divergence. All these present-day water-bodies are remnants of larger and fresher Pliocene or Pleistocene–Holocene precursors (Grove & Goudie, 1971; Grove et al., 1975). The total thickness of sediment packages within each basin is generally unknown, as there have been few deep drilling or seismic surveys. In Lake Turkana, 24-fold reflection data indicated a maximum sediment thickness of about 4 km (Dunkelman et al., 1988). A magnetotelluric study in the Baringo–Bogoria half-graben of the Gregory rift indicated a sediment thickness of 500–1000 m (Rooney & Hutton, 1977). Ancient Miocene or Pliocene lake sediments are present in the eastern branch as outcrops of sedimentary packages of varying thickness, situated in grabens beyond the limits of present-day tectonic and magmatic activity. Sediments of lacustrine origin, several tens to a hundred metres thick, occur in the Tugen (Kamasia) Hills sequence within the northern Gregory rift. These bury a large part of the tectonic fabric of this part of the rift from older than 14 Ma to younger than 4 Ma (Hill et al., 1986). Mio-Pliocene lacustrine series, several tens or a hundred metres thick, occur in the southern and central Afar Depression, such as at Ch’orora, Bodo, and Hadar (Tiercelin et al., 1979; Tiercelin, 1986; Williams et al., 1986) (Fig. 3).

In contrast to these short-lived (0.5–3 Ma) lacustrine episodes, the major basins of the western branch contain long-lived, large and deep lakes, including 1470-m-deep Lake Tanganyika and 770-m-deep Lake Malawi (Fig. 3). Recent seismic investigations indicate a sedimentary sequence 6 km thick beneath Lake Tanganyika (Rosendahl et al., 1986).

Fig. 3. Lacustrine basins and Cenozoic sedimentary formations of the East African rift system cited in the text.
and a maximum of 4.5 km beneath Lake Malawi (Livingstone Basin) (Johnson & Ng’ang’a, 1990). Lake Kivu is 485 m deep, with approximately 0.5 km of infill (Degens et al., 1973). Extrapolating modern sedimentation rates and correcting for compaction implies that Lake Tanganyika would date to the Miocene epoch, Lake Malawi to late Miocene, and Lake Kivu to mid-Pleistocene. Further north, Lakes Edward and Albert are less well known. In contrast to the Tanganyika, Malawi and Kivu Basins, where very little sediment crops out along the basin margins, the Edward and Albert basins contain sediment packages several hundreds of metres thick, which crop out along faulted basin margins and are dated as lower Miocene to lower Pliocene (Pickford et al., 1988, 1989). Boreholes drilled in the north-eastern Albert Basin penetrated 1200 m of sediment overlying crystalline basement; geophysical evidence suggests a total thickness of at least 2400 m of sediments may fill the depression (Harris et al., 1956).

In the structural context of basins in the western branch, the Lake Rukwa Basin (Fig. 3) is the only one strictly controlled on its southwest and northeast borders by NW–SE trending faults belonging to the TRM transform fault zone, which follow a Precambrian basement and later the Karoo structural trend (Peirce & Lipkow, 1988; Tiercelin et al., 1988a; Morley et al., 1989). Present Lake Rukwa is large (120 × 16 km) and very shallow (3 m maximum). Extensive gravity and seismic reflection surveys and two wells drilled by the Amoco Production Company provide much new information (Morley et al., 1989). The sedimentary package is divided into Karoo sedimentary rocks, late Miocene fluvial red beds, and late Miocene–Recent lacustrine sediments (Haberyan, 1987). The thickness of the Tertiary–Recent sediments is 6–7 km, and the base of the section is only 7–5 Ma old.

LACUSTRINE FACIES OF THE EAST AFRICAN RIFT VALLEY IN TERMS OF NATURAL RESOURCES

Among the sedimentary facies and mineralizations associated with rift lakes, at least eight may be considered as important in terms of natural resources. These are primary deposits, such as organic-rich (or hydrocarbon-rich) oozes, diatomites, evaporites, zeolites and sodium silicates, metallic proto-ores, clays, phosphates, and coals. Other sediments, such as stromatolites and lake-deposited pyroclastics, may have immediate industrial uses or hydrocarbon reservoir properties (Fig. 4A, B).

Hydrocarbon-rich oozes

Organic-rich lacustrine sediments are good source rocks for hydrocarbons. Oilfields occur in lacustrine rocks in Mesozoic continental rift basins along the Atlantic margins of Africa and South America, and other fields in China, Europe or North America (e.g. Talbot, 1988).

Oil seeps and gas emanations have long been known from the Lake Albert Trough. Oil shales of presumed Miocene age were drilled in the Lake Albert depression by the Anglo-Persian Oil Company in 1940, and asphaltic oil was recovered from some wells (Harris et al., 1956). No significant oil has yet been discovered in the East African rift system. Chevron made discoveries in troughs from a Cretaceous rift system in Sudan (Schull, 1984). Explorations, including seismic surveys and onshore drilling, have been carried out by the Amoco Production Company in northern Tanganyika Trough, where sublacustrine asphalt seeps are known at Cape Kalamba on the Zaire side of the lake (Le Mut, 1983; Tiercelin et al., 1989a), and in the Rukwa Trough (Morley et al., 1989). Sediments with a rich hydrocarbon potential have been identified in several East African rift lakes (Talbot, 1988). Three provide models for lake basins: Lake Bogoria in the eastern branch, and Lakes Tanganyika and Kivu in the western branch.

Lake Bogoria (formerly Hannington): a shallow, hypersaline, meromictic, organic-rich lake (Figs 3, 5)

This small (17 × 3.5 km), shallow (10–12 m), meromictic, hypersaline, sodium carbonate lake is located in the Gregory rift (Kenya) immediately north of the Equator (Fig. 5). It sits in a marked asymmetrical, N–S trending half-graben bounded by abrupt fault escarpments (Bogoria and Emsos Faults) to the east, and to the west by a zone of N–S ribbon-like structures cutting Pleistocene trachyphonolitic lavas (Griffiths, 1977; Tiercelin et al., 1980). This half-graben was formed during the major volcano-tectonic phase that affected the northern Gregory rift in the middle Pleistocene. Strong seismic activity is still felt in the vicinity of Lake Bogoria (Loupekeine, 1971) and there are almost 200 hydrothermal springs (Tiercelin et al., 1980,1987). Modern
Fig. 4. Block diagrams showing distribution of potential facies along lakes in hypothetical segments of a continental rift.
(A) Young, shallow half-graben occupied by a small ephemeral lake. The sedimentary fill, a few hundred metres thick, is mainly formed by cycles of organic-rich oozes and evaporites. (B) Ancient, deep half-graben occupied by a large, permanent lake, often stratified. The sedimentary fill is thick (several thousands of metres) and mainly formed by organic-rich oozes and diatomites, sometimes interbedded with metallic proto-ores or lake-deposited pyroclastics (modified from Frostick & Reid, 1987).
Fig. 5. Lake Bogoria, northern Gregory rift. (1) Location of Lake Bogoria within the northern Gregory rift. (2) Regional distribution of the total organic carbon (TOC) in its modern sediments (after Herbin, 1979): A, the cyanobacteria Oscillatoria (= Spirulina = Arthrospira) platensis (Gomont) Bourrelly, main contributor to modern organic matter in Lake Bogoria (length 100 μm); B, specimen with very unrolled spiral (length 80 μm). (3) Vertical distribution of the TOC in the organic-rich oozes — evaporite sequence in Bogoria II drill core: C and D, Botryococcus algae, contributor to organic matter in upper Pleistocene to Holocene sediments of Lake Bogoria (from Tiereelin et al., 1987).
organic-rich oozes have been collected from the deeper parts (6–12 m) of Lake Bogoria. They are generally homogeneous, but some are laminated, black or dark-green, very fine-grained muds. Total organic carbon (TOC; wt. % of dry sediment) contents vary from 1.5 to 3%. Hydrogen index (HI) values vary between 150 and 400 (Herbin, 1979). The horizontal distribution of organic carbon reveals a very strong relationship to the topography of the lake floor, in that a significant increase of organic carbon content is seen towards the deeper parts of the lake (Fig. 5). Amorphous organic matter is dominant in most samples (Palacios et al., 1987a). Contributing to this organic matter is mainly phytoplankton, which in Lake Bogoria consists predominantly of cyanobacteria (Type I kerogen) (Talbot, 1988), the prevailing species being Oscillatoria platensis (Gomont) Bourrelly (Fig. 5A,B). Cyanobacteria are now recognized as forming the kerogen of some oil shales, such as the Green River Shale, the Belt Series (USA), or the Fig Tree Series (South Africa) (Pénaud et al., 1989). Their production has been studied by various authors (Milbrink, 1977; Vareschi, 1978; Melack, 1979). Organic production can reach the exceptional level of 100 g of Oscillatoria per square metre per day, or 3500 tons of fresh weight of cyanobacteria per day for the lake (Tiercelin et al., 1987).

Organic-rich oozes have been encountered also in the form of metre-thick, homogeneous or finely laminated, black or black-green muds interbedded with evaporites dominated by sodium carbonate in the 18.5 m long Bogoria II drill core (Tiercelin et al., 1982; Renaut et al., 1986; Tiercelin et al., 1987). The TOC values in these upper Pleistocene to Holocene sediments are moderate, 1–3 or 2–6% (Fig. 5). Amorphous organic matter is dominant. Botryococcus is abundant among identifiable phytoplankton remains (Fig. 5C,D). Locally, cyanobacteria and some higher plant debris are also seen (Palacios et al., 1987b). This suite characterizes sediments that accumulated during the dilute phases of Lake Bogoria. In terms of an oil source rock, the Bogoria organic oozes show a good petroleum potential, ranging up to 10 kg of hydrocarbons per ton of sediment (Herbin, 1979), in basin filling sediments tens of metres thick. Accumulation and preservation of high TOC, high HI sediments are mainly controlled by environmental conditions, essentially nutrients, lake levels, and winds. Frequent turnover in shallow water-bodies favours higher bottom water oxygenation and more persistent oxidizing conditions, thereby greatly reducing the preservation potential of the more labile organic components (Talbot, 1988). Lake Bogoria appears to have been characterized by a stable stratification regime during several late Pleistocene to Holocene intervals. Stratification was independent of low or high lake levels (Tiercelin et al., 1987), thus enhancing the preservation potential. Maturation of petroleum-precursor organisms requires temperatures in the range of 66–132°C, at burial depths greater than 1200 m, and some minimal amount of time, usually cited as 10000 years for petroleum generation (Tissot & Welte, 1978; Robbins, 1983). Some of these requirements are satisfied in the Bogoria half-graben, where surface sediment temperatures are greater than 60°C as a consequence of hydrothermal activity (Naylor, 1972). Up to 20 m of organic-rich sediments have accumulated in the Bogoria depression in the last 30000 years. The estimated thickness of the Bogoria sedimentary fill is only 250 m (Tiercelin, 1981; Renaut, 1982), but greater temperatures at depth might compensate a shallow burial depth.

Lake Tanganyika: a deep fresh water, anoxic, and organic-rich lake (Figs 3, 6)

Lake Tanganyika is a stratified lake 1470 m deep (Coulter, 1968), the second largest tectonic lake in the world after Lake Baikal (Hutchinson, 1957). Demaison and Moore (1980) used it as the type basin for a deep anoxic lake model of lacustrine source rock accumulation. It lies between 3°30′ and 9°S. At 5°S, it intersects the NW–SE Tanganyika–Rukwa–Malawi dextral transform fault zone (Tiercelin et al., 1988a), which delineates a 250 km long, N–S trending North Tanganyika Basin, and a 400 km long, NW–SSE trending South Tanganyika Basin (Mondeguer et al., 1989). These basins are subdivided into a mosaic of seven asymmetric, rectangular-shaped sub-basins separated by ridges of basement rocks (Rosendahl et al., 1986; Tiercelin & Mondeguer, 1991) (Fig. 6A). Recent organic-rich oozes dredged in northern and southern Tanganyika Basin during the Georift Project of the Elf-Aquitaine oil company comprise black or black-green, homogeneous or finely laminated muds. The TOC contents are from 6 to 9.7%, and the HI is as much as 600 (mean value 387) (Huc et al., 1987, 1990). The main source for this organic matter is diatoms. Primary productivity is high (800 mg C/m²/day) (De Bont, 1972; Hecky & Kling, 1981). In contrast to Lake Bogoria, the lateral distribution of organic matter is
Fig. 6. Lake Tanganyika, western branch of the East African rift system. (A) Structural sketch map: 1. major normal faults; 2. sublacustrine fault escarpments; 3. transverse shoals; 4. TRM transcurrent fault zone. (B) Regional distribution of TOC in modern sediments from the northern end of the lake (Bujumbura and Rumonge sub-basins) (simplified from Huc et al., 1986).

d-characterized by considerable heterogeneity. The TOC content increases significantly below water depths of about 100 m, which corresponds to the thermocline (Coulter, 1968). The highest TOC values occur on top of sublacustrine shoals (structural blocks), such as the sublacustrine extension of the Ubwari Peninsula in the northern basin (Fig. 6B). Organic matter accumulates because it is located below the thermocline and protected from disturbance by waves and currents and clastic dilution. Cores from these raised areas have uniform pelagic sequences. Winnowing processes sweep low-density organic matter from the shallow waters (above the thermocline) towards the deeper parts of the basin. Gravity transport mechanisms are generally related to major pulses of river-fed suspensions. Turbidity currents fill deeper depocentres. Cores of green to black clays and diatom-rich laminated muds pen-
etrate up to 40,000 years (Tiercelin et al., 1989b). They are characterized by TOC contents as much as 10% and HI as high as 632 (Huc et al., 1986). Downcore parameters vary in relation to shifting environmental conditions, such as lake levels and wind regimes. Meromixis probably persisted during middle–late Pleistocene, when levels were as low as the 300–600 m depth contour (Tiercelin et al., 1989b).

Thus, in terms of source rock, the Tanganyika sediments appear extremely heterogeneous, with sediments having petroleum potential and yielding as much as 35 kg of hydrocarbons per ton of rock only a few metres from sediments having low petroleum potential and yielding as little as 3 kg of hydrocarbons per ton of rock (Huc et al., 1987). In terms of preservation potential, Lake Tanganyika offers optimal conditions in the form of a thick, almost permanently anoxic hypolimnion. Maturation prerequisites are satisfied with sediment thickness as much as 6000 m, ranging in age to the Miocene (Rosendahl et al., 1986). Sufficient temperature and heat flow values probably relate to sublacustrine hydrothermal activity (Le Douaran, 1986; Tiercelin et al., 1989a). Asphalt occurs in the form of floating fragments along the eastern shore of the Ubwari Peninsula as far as the delta of the Rusizi River. A geochemical analysis of this asphalt yielded 56% resins + asphaltanes and 44% hydrocarbons (Le Mut, 1983). Local fisherman use it as caulking. Asphalt appears to be related to sublacustrine hydrothermal activity located at Cape Kalambo on the Ubwari Peninsula (Fig. 7). Similar occurrences of hydrothermally generated petroleum have been noted in the Guaymas Basin, Gulf of California (Simoneit, 1985). Gaseous hydrocarbons (methane and heavier hydrocarbons) also have been discovered in hydrothermal fluids at the Pemba and Cape Banza sites north of Cape Kalambo (Fig. 7). The Pemba site is located along the major, N–S trending normal Uvira Fault, which forms the western boundary of the 250-m-deep Bujumbura sub-basin and is a zone of strong seismic activity (Wohlenberg, 1969). The Cape Banza site is located along the N–S trending fault escarpment of the Ubwari Peninsula, which bounds the 1200-m-deep Rumonge sub-basin (Figs 6, 7). At Pemba, abundant gas and hydrothermal fluids having a measured temperature of 65°C escape through sandy bottom-sediments or basement fractures (Fig. 7A). At Cape Banza, fluids having temperatures of 70–80°C flow through orificial chimneys constructed of aragonite in various sizes and morphologies (Fig. 7D, E, F) (Tiercelin et al., 1989a). Methane and heavier hydrocarbons are present in the Pemba and Cape Banza hydrothermal fluids. Maximum values have been measured at Cape Banza, 842 μl/l CH₄, which are equivalent to those found at the latitude 21°N hydrothermal sites of the East Pacific Rise (Welhan & Lupton, 1987). Tiercelin et al. (1989a) suggest a thermocatalytic origin for the North Tanganyika hydrocarbons or a mixture of gases having both thermocatalytic and biogenic origins.

Methane added to the oxic zone, such as at the Pemba and Cape Banza sites is rapidly oxidized. At 360 m depth, methane concentrations reach 70–80 μmol/l (Rudd, 1980), and increase downward through the hypolimnion (Craig & Craig, 1981). Craig (1973) and Hecky (1978) suggest that Lake Tanganyika’s hypolimnion may be a relict water mass from a cooler, drier period, and some of the methane would therefore derive from old carbon deposited during previous intervals of the lake’s history. Craig et al. (1974) suggest emissions from geothermal sources at depth, because the gas helium is highly supersaturated below the metalimnion. High heat-flow values measured during the Géorift Project in the northern basin (Le Douaran, 1986) may be linked to these sources, which supply heat and thermocatalytic methane to the hypolimnion.

Fig. 7. The Pemba, Cape Banza, and Cape Kalambo sublacustrine hydrothermal sites of the northern Tanganyika Trough. (A) Gas (H₂S, CH₄) bubbling from sandy bottom-sediment and basement fractures at Pemba site, 10 m water depth. (B) Sulphide block at a depth of 10 m at Pemba site. (C) Section of block fragment showing an assemblage of corrogated flakes formed by layered massive and porous sulphides (pyrite and marcasite) (a); enclosed translucent patches formed by quartz, kaolinite and acicular crystals of barite (b); and encrusted detrital grains (c). (D), (E) Hydrothermal aragonite chimneys having hot fluid plumes, Cape Banza site, 6 m water depth. (F) “Big Chimney”: multiple orifice hydrothermal vent, Cape Banza site, 4 m water depth. Photograph (G) and sketch (H) of circulation pipes of hydrothermal fluids after removal of an aragonite chimney: (S) rock substratum, (OC) old chimneys, (Ac) aragonite coating, (P) circulation pipes. The walls of these pipes and entrapped detrital grains (I), mainly quartz, show thin coatings of pyrite (J): SEM photographs — scale bar is 100 μm for (I), 10 μm for (J).
Lake Kivu: a deep meromictic, methane-rich lake (Figs 3, 8)

Situated between 1°40' and 2°30'S, Lake Kivu has a depth of 485 m and an area of 2060 km². It lies in a NE-SW trending graben (Fig. 8A) that formed in the late Miocene to early Pliocene, following two major stages of volcanic activity at 10-6 Ma and 8-4 Ma (Ebinger, 1989a). Lacustrine sedimentation began approximately 3 Ma ago, and has accumulated 0.5 km (Degens et al., 1971, 1973; Wong & Von Herzen, 1974). Hydrologically, Lake Kivu is meromictic with an unusual thermohaline structure showing increasing temperature and salinity with depth. Its hypolimnion is anoxic (Degens et al., 1973). Large quantities of economic hydrocarbons (methane and higher gaseous hydrocarbons) and other gases (hydrogen sulphide, carbon dioxide) are stored in the hypolimnion (Damas, 1937; Tietze et al., 1980). The total amount of methane is about $63 \times 10^9$ m³ at standard temperature and pressure (0°C, 1 atm). No comparable methane accumulation occurs in any other lake. These large quantities are the result of stable density layering over a long period.

Models for the origin of Kivu methane have for long been controversial (Deuser et al., 1973; Jannasch, 1975). Recent work by Tietze et al. (1980) confirms that most of the Kivu methane is bacterially generated from the organic matter in the sediment (Fig. 8B). As much as 200 ppm of gaseous hydrocarbons with higher carbon numbers suggests small amounts of thermocatalytic methane in addition to bacterial methane. According to Wong and Von Herzen (1974), a sedimentary package 0.5 km thick and active volcanoes provide heat sources. Hydrothermal inputs, mainly characterized by metallic deposits, also have been identified in Lake Kivu for the late Pleistocene to Holocene period (Degens & Kulbecki, 1973). Such sources, similar to northern

Fig. 8. Lake Kivu, western branch of the East African rift system. (A) Structural sketch map and bathymetry. (B) Model of methane genesis: 1, water gradient boundaries; 2, main gradient boundary; 3, water containing gas; 4, sediment (after Tietze et al., 1980).
Lake Tanganyika (Tiercelin et al., 1989a), may inject significant quantities of methan in the deep waters of Lake Kivu.

The practicability of extracting economic methane from Lake Kivu has been studied recently at the request of the Communauté Économique des Pays des Grands Lacs (CEPGL) by the French group Technip and associates (Sogreah, Sedes, and Bureau de Recherches Géologiques et Minières — BRGM). The rate of replenishment of the methane has been estimated to be about 400 years (Jannasch, 1975). An environmental impact statement remains to be completed before exploitation of methane begins. The fear of oxygenation of the bottom leading to lake overturn in the manner of Lake Nyos in Cameroon (Kling et al., 1987) must also be addressed.

Other organic-rich lake deposits in the East African rift system

Other lakes in the rift have deposits with high to very high TOC values. Lake Edward has an 11.6% mean TOC in premodern sediments. Lake Albert, which has intermittent stratification, and Lake Malawi, which is permanently stratified in the north, are accumulating sediments with TOCs of 1.4–4.0% and 3–6%, respectively (Talbot, 1988; Johnson & Ng’ang’a, 1990). In sharp contrast, Lakes Turkana and Baringo (northern Gregory rift) have less than 1% TOC preserved in the modern sediments (Yuretich, 1979; Tiercelin & le Fournier, 1980). High sedimentation rates may, in part, be responsible for the low TOC, which would then be dominated by autochthonous material, in the case of Lake Turkana (Kelts, 1988). The permanently well-mixed waters of shallow Lake Baringo are the principal limitation on organic matter preservation. Despite low TOC, Lake Turkana sediments are methane-rich (Johnson & Davis, 1989).

Meromictic conditions appear favourable but not essential for the accumulation of organic-rich sediments. Rift valley lacustrine sediments are characterized by Type II kerogens, which result from a mixture of alginite and exinite (Talbot, 1988). The hydrocarbon potential of the East African rift system lakes also relates to quality and extent of reservoir beds. Multifold seismic investigations of thick sedimentary fills in Lakes Albert, Kivu, Tanganyika, and Malawi should define the geometry of such bodies. Deep drilling will be required to ascertain the quality of potential reservoir beds. Recent exploration using extensive gravity and seismic reflection surveys and wells by the Amoco Production Company in the North Tanganyika and Lake Rukwa portions of the East African rift show the complexity of the regional tectonics and stratigraphy (Morley et al., 1989), and suggest occurrences of hydrocarbon source rocks within pre-Cenozoic rift series, mainly of Karoo age.

Diatomites

Diatomite is derived from marine or lacustrine diatom frustules. Chemically it consists mainly of silica. Several hundred diatomite products are used commercially, including filter aids, thermal and sound insulation, absorbents, insecticide carriers and diluents, fertilizer conditioners, abrasives, ceramics, and drilling mud thickener (Kirk-Othmer, 1985).

Pure diatomites of great thickness are rare in geological sequences. Controls include: a diatom-dominated phytoplanktonic ecosystem, a high and consistent rate of surface productivity, a regular source of nutrients, and a lack of detrital sediment in the area of diatom deposition.

East African rift water-bodies span an enormous range of ecological and sedimentological conditions, and their diatom flora is often abundant and highly diversified. Large, deep, freshwater rift lakes, having regular hydrodynamic regimes, such as Lakes Tanganyika and Malawi, are characterized by high biological productivity rates. In such environments, diatom productivity is largely controlled by competition with other algal species (Hecky & Kling, 1981). Wide, open water areas in these environments are generally protected from the influence of detrital inputs associated with permanent streams feeding the lake. Very fine-grained sedimentation, mainly dominated by diatom frustules (up to 10⁶ frustules per gram of sediment), results. Small, shallow, often saline, rift lakes are affected by drastic changes in lake levels as a consequence of seasonal climatic variations (or major climatic changes throughout the Quaternary). Diatom communities vary strongly according to changes in water volume and salinity. High pH values, which characterize most of the saline lakes of the East African rift system, greatly reduce the preservation potential of opaline diatom frustules.

High diatom productivity is stimulated by high dissolved-silica content in lake waters, provided by weathering of volcanic ashfalls, or directly through
hydrothermal springs, which are abundant in rift systems (Kilham et al., 1986). An ashfall-produced *Nitzschia* bloom was suggested for an 11,000 yr BP layer in a southern Tanganyika Basin core (Haberyan & Hecky, 1987; Tiercelin et al., 1988b; Mondeguer et al., 1989).

**Diatomite occurrences in the East African rift system**

Pure diatomites of Pliocene to lower Pleistocene and Holocene age were formerly extensive in the Abbe Basin, northern Afar Depression (Republic of Djibouti) (Fig. 9). Present or past erosion has removed most of the diatomites, leaving very small residual hills along the palaeoshorelines (Fig. 9A). Pliocene to lower Pleistocene diatomites generally underlie basaltic lavas (Fig. 9B). Because of the small size of these outcrops, no economic exploitation can be foreseen for the Abbe diatomites. Other occurrences of diatomite exist as decimetres to metres thick beds interbedded with pumice, ash, and clays in the Miocene Ch’orora Formation (Tiercelin et al., 1979) (Fig. 9C, D) and in the Pliocene diatomite beds at Bo (Williams et al., 1986) of the southern Afar Depression (Ethiopia). The bed thickness and transport problems limit exploitation at present.

**Diatomite occurrences of the Gregory rift**

Among the numerous sedimentary basins of the East African rift system, only a few contain thick (several metres to tens of metres) pure diatomites. The only occurrences of pure diatomite of a workable thickness are at Kariandusi (reserves estimated at over 1,500,000 tons) and at Kockum and Brown’s working on the Soysambu estate (reserves estimated at nearly 4,000,000 tons), both middle Pleistocene, near Lakes Nakuru and Elmenteita (McCall, 1967) (Figs 3, 9). Kariandusi diatomites are now quarried by the E.A. Diatomite Syndicate. Production first began around 1940 to supply the local soap and sugar industries and the Indian market. The best diatomite outcrops as a layer over 30 m thick. Difficulty of quarrying is increased by thick overburden, and the presence of interbedded pumice and clay layers (Fig. 9E). Other diatomite beds of Pleistocene age exist in the Gregory rift as discontinuous horizons in the Lake Naivasha Basin (Thompson & Dodson, 1963), or as widespread beds in the Olorgesailie Formation (Magadi Basin), where diatomite was mined by the Magadi Soda Company for filtration in its sodium bicarbonate plant (Baker, 1958).

**Evaporites**

Continental evaporites are generally associated with desert regions having internal drainage basins. Economic evaporitic lacustrine minerals include gypsum, halite, trona, and associated minerals (fluorite and villiaumite, gaylussite, sodium silicate). Trona is the most important form of sodium carbonate. Its primary economic use is in the glass industry. In particular, sodium silicate and sodium phosphates are used in the production of chemicals for the pulp and paper industries, detergents and cleaners, and water treatment. Calcium fluoride or fluorspar is the principal source of fluorspar and its compounds, and is mainly used in ceramics, electric arc welders, certain cements, dentifrices, paint pigments, and as a catalyst in wood preservatives. Sodium fluoride or villiaumite is used for fluoridation of municipal water, wood preservative, insecticide, and glass manufacture. Gypsum is used for numerous purposes, including Portland cement retarder, as a source of sulphur and sulphuric acid, for paints and paper, and for metallurgy. Halite or sodium chloride is used by the chemical industry, for metallurgy, in mineral waters and soap manufacture, and for road deicing (Hawley, 1981).

Rift systems favour the formation of partitioned basins, as the result of interval faulting. Structures act as morphological barriers, which lead to basin isolation by controlling the course of potential tributary rivers. Volcanic activity produces large volcanic cones or lava flows, which alter drainage patterns and contribute to basin isolation. Such isolation enhances evaporation of rift lakes in areas where

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**Fig. 9.** Main diatomite occurrences in the East African rift system. (1) Lake Abbe Basin, northern Afar, Republic of Djibouti: (A) residual hills of diatomite of Holocene age; (B) Pliocene to lower Pleistocene diatomite overlain by basaltic lavas. (2) The Ch’orora Formation, southern Afar, Ethiopia: (C) faulted contact between basalts of the Lower Afar Series and Miocene diatomites, Aria River; (D) 10.5 Ma diatomite beds interbedded with pumice beds at the Ch’orora type locality. (3) The Kariandusi quarry, central Gregory rift, Nakuru area, Kenya: (E) the Pleistocene diatomites of Kariandusi, interbedded with pumice beds and faulted.
Resources of rift basins, East Africa
geographical position and rift structure contribute to increasing aridity. Hydrothermal circulation favoured by earthquake rupturing (Sibson, 1981, 1987) contributes to the input of solutes.

Only a few East African basins contain evaporites. All are in the eastern branch, mainly as a consequence of its more arid conditions and of its 'wet' volcanic character (Mohr, 1982; Yuretich, 1982; Tiercelin, 1990). These evaporite basins include, from north to south, the Asal Basin (11°40′N) and the Abbe Basin (11°10′N) in the Afar Depression, the Bogoria (0°15′N), Nakuru (0°20′S), Elmenteita (0°25′S), Magadi, and Little Magadi (1°50′S) Basins in the Gregory rift, and the Natron (2°30′S) and Manyara (3°35′S) Basins in the North Tanzanian Divergence (Fig. 3). Among these basins, Asal can be distinguished by the chemistry of its brines, which are of chloride–calcium sulphate type, and by its associated deposits of halite and gypsum. All the others have sodium carbonate type brines and associated salts and silicates (Jones et al., 1977). Only two sites, Nakuru and Magadi, have been worked for industrial purposes.

Lake Magadi: an evaporitic basin with sodium carbonate brines and salts (Figs 3, 10)

The Lake Magadi sodium carbonate deposits were first surveyed in 1904, and later in 1908 (Anonymous, 1923). The first concession was to a private prospector; in 1911 the Magadi Soda Co. Ltd was created (Baker, 1958). Today the Magadi Soda Company is part of the Imperial Chemical Industries PLC group of the UK.

Lake Magadi occupies a narrow (164 km²) graben defined by a complex system of small N—S, NNW—SSE, and NNE—SSW faults in the axial part of the Gregory rift floor (Figs 10, 11A). Volcanism in this

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**Fig. 10.** Lake Magadi, southern Gregory rift, Kenya. Structural and sedimentological sketch map and schematic cross-section through the Magadi graben: 1, trona; 2, chert and evaporites; 3, volcanic tuffs and silts; 4, bedrock (trachytes); bold star, thermal springs. Schematic diagram showing stream inflow to closed brine system (courtesy of Magadi Soda Company Limited).
part of the rift floor ceased by 0.8 Ma, after which many small faults created the Magadi and Natron Basins (Baker, 1963, 1986). Deposits from two Pleistocene precursors of Lake Magadi can be recognized, dated to > 780 000 yr BP for Lake Oloronga and 10 000 yr BP for High Magadi Lake phases (Eugster, 1986). Both lakes had alkaline brines throughout their existence, without ever reaching the stage of extensive trona precipitation of the early Holocene to modern Lake Magadi. As much as 40 m of the Holocene evaporite series has been drilled in the Magadi Basin (Eugster, 1980). The chief mineral is trona, which occurs as a very porous, sparry framework of large blades; the interstices are filled by saturated brines (Fig. 11B). The lake covers about 80 km² (Fig. 10) and contains enough raw material to extract 100 million tons of soda ash. At the present time, during the dry season, the level of the interstitial brine falls several metres below the trona surface, whereas during the rainy season, flooding occurs, dissolving the surface trona crust. After a few months, this flood layer evaporates, precipitating and recrystallizing the surface layer at an estimated accumulation rate of 2–3 mm/year (Eugster, 1980) (Fig. 11C). Additional solutes are contributed to the interstitial brines by ephemeral storm runoff dissolving the evaporitic crusts (trona—monothermonite—halite) that coat the Pleistocene lake deposits, and by perennial saline springs, which issue through the sediments and trachyte lava flows surrounding the lake (Eugster, 1970; Jones et al., 1977) (Fig. 10).

Today, the Magadi Soda Company exploits raw trona with two dredges. Because the brine level is never far below the trona surface, the dredges remain more or less at ground-level and are designed to cut to 8 ft. below the trona surface (Fig. 11D,E,F). Crushed trona is mixed with brine, thus forming a slurry that is pumped through a pipeline to the factory. After dehydration and washing, the trona mush is passed to calciners and transformed into soda ash or anhydrous sodium carbonate (Na₂CO₃), which is bagged and loaded into railway trucks for the port at Mombasa. Magadi Soda is planning to increase its production to 550 000 tons/year.

Soda ash has always been the company’s main product. It also manufactures sodium chloride by pumping a liquor rich in sodium chloride from a depth of 8–10 ft. in a series of wells, and concentrating it into ‘salt-making ponds’ (Fig. 11G). Magadi Soda produces as much as 40 000 tons of salt a year, enough to meet Kenya’s demands for industrial and edible salt. Sodium fluoride (villiaumite) was also extracted from the trona slurry, particularly during World War II for use by air forces in Africa and India (Baker, 1958).

Among the three other soda lakes in the Gregory rift, Elmenteita, Nakuru, and Bogoria (Fig. 3), only Lake Nakuru has been worked for the extraction of soda. Nakuru Lake Syndicate was granted a licence in 1952 to remove and process soda goods upon the lake shore. Solar ponds were constructed for this purpose. Limited production of soda ash was carried out for the fertilizer industry. From 1955, a rapid rise of the lake in a series of wet years prevented the formation of a trona crust. By 1959, the buildings and installations had been removed and the lake water almost covered the site of the original establishment. Lake Elmenteita and Lake Bogoria, which is known to contain metre-thick trona beds interbedded with organic oozes (Tiercelin et al., 1982), have never been worked. It seems doubtful if such operations could compete economically with Lake Magadi.

Other evaporite deposits, while unlikely to prove commercially exploitable, play an important part in the life of the Kenya tribes. In the Suguta valley (northern Gregory rift), evaporite deposits consist of variable-sized layers of fine acicular crystals contained in a clay about 0.15 m thick. Although the composition of this salt is unlike the trona from Lake Magadi, it is used for the same purposes as unprocessed trona, namely, as an addition to finely ground tobacco to produce snuff, which is extensively used by most tribes in Kenya, and particularly by Turkana tribesmen who travel for considerable distances to collect supplies of the salt (Dodson, 1963).

Gaylussite, a hydrated double carbonate of sodium and calcium, occurs in large quantities in a black or dark green host clays in the Amboseli Lake Beds of upper Pleistocene age in southern Kenya (Williams, 1972). Proved resources of 15 000 000 tons of gaylussite were found in an area of 15 square miles. An increase to 16 500 000 tons is possible if particles of –30 mesh size are recovered during working of the ore. Despite this amount of reserves, preliminary investigations were proved disappointing. Gaylussite deposits also have been recorded from drill core SII from the northern basin of Lake Bogoria (Tiercelin et al., 1982; Renaut et al., 1986). There, crystals (2–10 mm) occur at several levels in grey to brown clays in beds a few decimetres to a metre thick; the beds have been dated between 14 000 and 8000 yr BP (Tiercelin et al., 1987). Small gaylussite euhedra were also observed on the margins of the lake near
freshwater springs (Cerling, 1979), and as surficial efflorescent crusts on the Sandai delta-plain north of Lake Bogoria. The small proportion of gaylussite in the sediment and the remoteness of the outcrops mean that these occurrences have no commercial interest.

Lake Asal: an evaporitic basin having chloride and calcium-sulphate brines and salts (Figs 3, 12)

The Asal Basin (Republic of Djibouti) is within the NW-SE tectonic system of the Asal-Ghoubbat al Kharab rift, which extends to the northeast via the oceanic structure of the Gulf of Aden (Fig. 12A). This system is considered to be the type spreading segment in the world rift system and is characterized by an extension rate of 30–60 mm/yr (McKenzie et al., 1970; Ruegg & Kasser, 1987). Lake Asal is shallow (maximum depth 30 m; mean depth 7.4 m), having an area of 55 km², and is located at an altitude of -155 m below sea-level (Langguth & Pouchan, 1975). Its waters reach salinities of 350 g/l and are rich in Cl, Na, K, SO₄, and Mg ions (Lopoukhine, 1973). Local rainfall is insignificant. Several springs, hot and cold, of continental and marine origin, located along the southeastern, northern, eastern, and southwestern shores compensate for this rainfall deficit (Valette, 1975); these springs supply an estimated 45 × 10⁶ m³/year of water (Lopoukhine, in Demange et al., 1971). The age of the spring waters are of the order of tens of years, or, at most, one or two centuries (Fontes et al., 1980). Modern sedimentation in Lake Asal is essentially evaporitic; gypsum precipitates in the southeastern part of the lake because of the mixing of lake brines with sea water rising up from fractures through the lake bottom (Fig. 12B, C). In the northeastern part of the lake, halite is precipitating and forming a wide (60 km²) and thick (20–80 m) salt plain rising 0.30–0.80 m above the lake level. Bedded gypsum crops out around the lake as high as 55 m above the present lake level (Stieltjes, 1973) (Fig. 12D, F, G). The salt plain was dry until volcano-tectonic activity in 1978, which gave rise to fractures and fault openings. The resulting increase of sea water inflow from the Ghoubbat al Kharab partially submerged the salt plain (Ruegg et al., 1979) (Fig. 12E, H). Lake Asal has not been worked for the extraction of gypsum or halite except for local salt use by the Afar tribesmen. This indifference to such a substantial evaporite accumulation can be explained by the difficult access to the area, which should only be undertaken by 4-wheel drive vehicles, and also by the wide abundance of halite and gypsum resources throughout the world.

Another evaporite sequence is known to the north-northwest of the Asal Basin in the Danakil area of Tigre and Eritrea provinces of Ethiopia (northern Afar Depression). There, 960 m of bedded halite, including two potash-bearing horizons and a sylvite-rich member, a kainite-rich member (MgSO₄·KCl·3H₂O), and gypsum, anhydrite, and shale interbeds, were drilled in the area of Dallol (Holwerda & Hutchinson, 1968). This sylvestbearing sequence, which has been known for at least 80 years, was further explored by the Ralph M. Parsons Company of Los Angeles in 1954. Preproduction and development working of the sylvite and kainite, used as a source of potassium compounds for fertilizers, were completed in 1965.

In contrast to the Asal evaporite sequence, the Danakil strata are of exclusively marine origin. They were laid down during a Pleistocene high stand in a NNW-SSE trending, asymmetric basin that formed during late Miocene to Pleistocene rifting and subsidence related to the opening of the southern Red Sea (Hutchinson & Engels, 1970). These data serve to explain that continental rift basins may also evolve into marine environments.

Zoelites and sodium silicates

Large-scale precipitation of authigenic minerals is produced by the interaction of alkaline carbonate

Fig. 11. (A) General view of the Magadi salt pan. (B) Block of trona crystals (blades up to 10 cm long) interbedded with organic ooze. (C) Trona crust at the surface of salt pan at the end of the dry season, showing 'tepee structures' — which are the consequence of water pumping mechanisms. (D), (E), (F) Distant view and details of the Magadi Soda Company dredges. From the dredge buckets (E) or mill (F), the raw trona passes down to breakers that crush it to two-inch fragments, thence to vibrating screen and crushing rolls for oversize material. Next the crushed trona is mixed with lake liquor and pumped through a pipeline to the factory. (G) General view of the 'salt-making ponds' used for sodium chloride production.
brines with the volcanogenic sediment that fills evaporitic rift basins. These minerals include zeolites, such as erionite or analcime and their precursors the Na—Al—Si gels, and sodium silicates, such as magadiite, kenyaita or kanemite, all described in the lacustrine sediments of the Bogoria and Magadi—Natron Basins (Gregory rift) (Eugster & Jones, 1968; Pénet et al., 1982; Renault et al., 1986), or of the Manyara Basin (North Tanzanian Divergence) (Eugster, 1967; Swardan & Eugster, 1976). Zeolites are used industrially for water softening and as detergent builders, but they are not economically workable in the Bogoria, Magadi or Manyara Basins. Sodium silicate is industrially known as the simplest form of glass. The magadiite and kenyaita forms, which often transform into chert (Eugster, 1967, 1969), have never been worked for industrial uses.

Metalliferous sediments and metallic ores

Metalliferous sedimentation has become linked to spreading on oceanic ridges. Such deposits are the metalliferous sediments and encrustations and massive sulphide bodies that share a common origin as precipitates from hydrothermal solutions in regions of volcanism and high heat flux at ocean spreading centres (Rona, 1984). However, the occurrence of systems capable of concentrating hydrothermal mineral deposits is not limited to sea-floor spreading centres, but may occur wherever the components are present: volcanogenic heat source, parent fluid, and permeable rocks or sediments. As an extension of oceanic structures of the Red Sea and the Gulf of Aden, the East African rift system would appear to be an environment quite propitious to the formation of metalliferous sediments. Differences might exist because of changes in the spreading rates, the petrological composition of the underlying magma and surrounding rocks, and the geochemistry of parent fluids. Wide geothermal fields exist all along the rift and are characterized by various mineral deposits (Fig. 13). Several fields have been explored recently for geothermal energy, Asal in the Afar Depression, Gallha Lakes in the Ethiopian rift, Bogoria—Loburu and Okaria in the Gregory rift (Fig. 14A,B). Among the wide variety of hydrothermal metallic minerals in East African rift lakes, pyrite and marcasite, limonite, siderite, nontronite (Fe silicate), and vivianite (Fe phosphate) are the most abundant and occur as single crystals concentrated in the sediment or as metallic ores, and are of great economic interest. Large amounts of other elements are also concentrated in lake sediments, including Ni, Al, Mn, Pb, Ti, Ba, Cr, Cu, Zn, V; all of these present an increasing interest because of modern alloy metallurgy. Pyrite (and marcasite) is used for manufacture of sulphur, sulphuric acid and sulphur dioxide, cheap jewelry, and recovery of other metals. Limonite and siderite are major ores of iron. Sphalerite, a natural zinc sulphide, is the most important ore of zinc, which is used for alloys, galvanizing iron and other metals, and electroplating. Lead is used for storage batteries, gasoline additive, radiation shielding, and cable covering. Barite is used for weighting mud in oil-drilling, paper coatings, paints, plastics, and X-ray photography.

Among the deepest lakes of the East African rift system, Lakes Kivu and Malawi have been described as containing metalliferous sediments and encrustations, the origin of which would be bound to hydrothermal activity developing along fractures within the lakes. Concerning Lake Tanganyika, mineralization of the massive sulphide type occurs in areas having sublacustrine hydrothermal activity. Although no economic extraction has been undertaken on these metallic ores and metalliferous sediments, wide attention has been devoted recently to Lakes Kivu and Malawi. The recent discovery of sublacustrine hydrothermal activity and associated massive sulphides in Lake Tanganyika will undoubtedly increase the interest of at least geologists and geochemists.

Fig. 12. Lake Asal, northern Afar Depression, Republic of Djibouti. (A) Location of the lake at the ‘triple junction’ of the Red Sea, Gulf of Aden, and East African rift. (B) Simplified geological map of the Asal Basin: 1, stratified basalts and rhyolites (4–1 Ma); 2, late Pleistocene to present basaltic flows of the Asal rift; 3, lacustrine carbonates, early and mid-Holocene; 4, halite, late Holocene to present (after Stieljes, 1973). (C) Structural connection between Lake Asal and the Ghoubbat al-Kharab—Gulf of Aden through the intensively fissured and active Asal rift. (D) Aerial view of Lake Asal and the salt plain in the direction of the Asal—Ghoubbat al-Kharab rift structure. (E) ‘Le Petit Riff’, junction of the Asal rift and Ghoubbat al-Kharab oceanic structures. (F) Halite crystals on the salt plain surface. (G) Aerial view of the salt plain at the northwest end of the lake. (H) Open cracks in the Asal rift floor formed during the November 1978 seismo-tectonic crisis allowing intense water circulation between the Ghoubbat al-Kharab and Lake Asal, which is –155 m below sea-level.