Journal of African Earth Sciences 71–72 (2012) 43–79

Contents lists available at SciVerse ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Stratigraphy, sedimentology and diagenetic evolution of the Lapur Sandstone in northern Kenya: Implications for oil exploration of the Meso-Cenozoic Turkana depression

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A R T I C L E   I N F O

Article history:
Received 30 July 2010
Received in revised form 20 June 2012
Accepted 22 June 2012
Available online 1 July 2012

Keywords:
Lapur Sandstone
Cretaceous
Late Eocene
East African Rift System
Anza and south Sudan Rifts
Turkana depression

A B S T R A C T

The northern Turkana region of northwestern Kenya forms the intersection between two major rift systems in Africa, the Cretaceous–Paleogene Central African Rift System (CARS), and the eastern arm of the Paleogene–Present East African Rift System (EARS). The southern Sudanese oil-rich rift basins form part of the CARS, and their extension into the Anza Rift in northeastern Kenya makes the area of northern Turkana an important target for oil exploration. Limited past exploration activity in the area leaves the study of surface outcrops as the main avenue for understanding the reservoir potential of the fluvial deposits of these rift systems. The outcrops of these potential reservoirs, collectively referred to as "Turkana Grits" in the past, are represented on the western side of Lake Turkana by the Lapur Sandstone in the north, and by other grit formations in the central and southern parts of the basin. Isotopic age determinations on the basal parts of the "Turkana Volcanics" that overlie the Lapur Sandstone have enabled the precise dating of the upper parts of the LS at between 35 and 37 Ma, while the lower part of the formation near the contact with the underlying Precambrian basement is estimated as Upper Cretaceous (Turonian–early Campanian), based on the discovery of dinosaur and other reptilian fauna. Detailed lithological logging, coupled with subsequent petrographic and sedimentological studies, have enabled the determination of the depositional environments and the diagenetic evolution of the Lapur Sandstone. The basal and uppermost parts of the formation are interpreted as distal alluvial fan environments possibly connected to the last stages of rifting characterizing the Central African Rift System. The middle part of the Lapur Sandstone corresponds to a wide braided fluvial system that can be compared to fluvial episodes of Late Cretaceous age in the Sudan region, associated to major palaeogeographical changes in northern Africa. The nearly abrupt disappearance of the Lapur upper fan system relates to the deposition of the "Turkana Volcanics" from Late Eocene, possibly as a consequence of the emplacement of the Afar Plume at 45–35 Ma. In terms of diagenesis, the main cement material at the base of the Lapur Sandstone is calcite, whereas at the middle of the formation, hematite becomes the dominant cement, and at the topmost section, kaolin cement dominates. The diagenetic evolution of the sandstones has been favourable to the retention of adequate primary intergranular porosity and the creation of secondary intragranular dissolution porosity, mainly through feldspar dissolution, and thus preserving the reservoir potential of the Lapur Sandstone. The reservoir characteristics, such as the porosity and cementation style, of the Lapur Sandstone are comparable to those of the fluvial sandstone reservoirs of the southern Sudan oil fields and this should positively contribute to the overall petroleum potential of the northern Turkana region. Though the northern Turkana area has remained largely unexplored, it is

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1464-343X/$ - see front matter
http://dx.doi.org/10.1016/j.jafrearsci.2012.06.007

hoped that the demonstration of the presence of reasonably good reservoir quality sandstones in the Lapur Sandstone will serve to encourage further interest in hydrocarbon exploration in the Turkana area.

1. Introduction

Thick piles of siliciclastic rocks characterize the northern, central and eastern parts of the African continent and relate to successions of eustatically and tectonically controlled depositional cycles that took place during Paleozoic and Mesozoic (Beauchamp, 1988; Wycisk et al., 1990; Khalifa and Catuneanu, 2008; Wolela, 2008, 2010), as well as early Cenozoic (Tiercelin and Lezzar, 2002). Among these periods, the Cretaceous is considered a crucial period for the geological evolution of northern and central Africa, with numerous active rifts linked to the break-up of western Gondwana and the opening of the south and equatorial Atlantic oceans (Guiraud et al., 2005). Thick series of continental deposits, associated with basins belonging to the Central African Rift System (CARS), covered a large part of northern and central Africa during this period (Whiteman, 1970; Prasad, 1971; Vail, 1974; Mateer et al., 1992; Bosworth and Morley, 1994; Morley et al., 1999a) (Fig. 1a). In Sudan, the main continental sedimentary formation of Mesozoic age (Late Jurassic to Late Cretaceous) is known as the "Nubian Sandstone" (Whiteman, 1970; Vail, 1974, 1982; Schull, 1988; Bussert, 1993) or as the "Nubian Cycles" (Klitzsch and Squiyres, 1990) (Fig. 1b). This formation was interpreted as having accumulated in a large sag basin that evolved from isolated half-graben geometries belonging to the rift segments of northern, central and southern Sudan (Jorgensen and Bosworth, 1989; Bosworth, 1992) (Fig. 1b).

In northeastern Kenya, fluvial sandstones, lacustrine carbonates and shales, as well as deepwater marine sediments, were investigated by seismic reflection surveys and several exploration wells drilled in the late 1980s (Bosworth, 1992; Bosworth and Morley, 1994). These deposits relate to the Anza Rift, a large multi-phase rift basin that was active from Late Jurassic–Cretaceous to Paleogene time (Winn et al., 1993; Morley et al., 1999c) (Fig. 1b and c). At different places in the Turkana depression as well as in the central Kenya Rift, immature siliciclastic strata (10s–100s meters thick) resting on basement rocks were originally named "Turkana Grits" in the pioneering works of Arambourg (1933a,b), Murray-Hughes (1933) and Fuchs (1939) (Figs. 2 and 3).

These "Turkana Grits" were at the time interpreted as having been deposited in lacustrine basins as shown by the presence of features such as current bedding, layers of well-rounded pebbles and calcareous mudstones, grits and shales (Walsh and Dodson, 1969). Arambourg (1935, 1943) designated the grits occurring at the northwest end of Lake Turkana as the "Lubur Series" based on their impressive exposure in the Lubur Range (also known as the Lapur Range) (Figs. 3–5). Palaeontological evidence, both from vertebrate fossils (dinosaurs) and fossil wood of the genus *Dryoxylon*, suggested an Eocene to early Miocene or even Mesozoic (Cretaceous) age for all these strata (Murray-Hughes, 1933; Fuchs, 1939; Arambourg, 1943; Shackleton, 1946; Arambourg and Wolf, 1969). During the 1960s, the "Lubur Series" were briefly described in reports by the Geological Survey of Kenya (Joubert, 1966; Walsh and Dodson, 1969; Dodson, 1971), but this work has been largely ignored in more recent detailed studies, though mentioned in several papers (Beauchamp, 1977; Zanettin et al., 1983; Savage and Williamson, 1978; Handford, 1987; Morley et al., 1999e; Wescott et al., 1999; Tiercelin et al., 2004).

In the 1980s, following the discovery of large hydrocarbon accumulations in the Cretaceous–Paleogene rifts of southern Sudan (Schull, 1984, 1988; Peterson, 1986; Genik, 1993; Mohammed et al., 1999; Mohamed et al., 2002; Obaje et al., 2004), a phase of aggressive exploration was developed by Amoco Kenya Petroleum Company (AKPC), and later by Shell Exploration & Production Kenya B.V. (SEPK) in the western part of the Turkana depression. An initial seismic acquisition campaign was conducted in 1984 under the auspices of the Project PROBE ("Proto-Rifts and Ocean Basin Evolution") (Rosendahl et al., 1986, 1992; Rosendahl, 1987) covering the offshore areas of Lake Turkana (Dunkelman et al., 1988, 1989). Then, an intense onshore seismic reflection survey by AKPC (1985–1986) and the drilling of two exploration wells (Loperot-1 and Eliye Springs-1) by SEPK in 1990–1991 (Figs. 1c and 2) contributed to the imaging of the geometry and stratigraphy of a suite of Cretaceous?–Paleogene to Upper Miocene half-graben basins to the immediate west and southwest of Lake Turkana. Sub-surface data indicated the existence to the northwest of two deep half-grabens, the Lotikipi and Gatome Basins (Fig. 1c), partly filled by thick piles of volcanics (up to 3.5 km) and sub-volcanic sedimentary formations of possible Cretaceous or early Cenozoic age. These sediments were interpreted as possibly correlative with the "Lubur Series" outcropping to the east of these basins (Morley et al., 1999e; Wescott et al., 1999), or with the Muruanachok Sandstone that outcrops to the south-southwest (Wescott et al., 1999; Thuo, 2009; Tiercelin et al., 2011) (Figs. 2 and 3). The hydrocarbon potential in these basins (Morley, 1999) was confirmed by the Loperot-1 exploration well that encountered high TOC potential source rocks and significant oil shows (Wescott et al., 1999; Talbot et al., 2004). A second exploration well, named Ngamia-1, operated by African Oil Corp. and Tullow Oil in the Lokichar Basin closeby the Loperot-1 well, encountered in March and May 2012 several good quality oil-bearing reservoir zones at depths between 1041 and 1515 m. These facts, together with the proximity of these basins to the southern Sudanese oil-producing fields, and the similarity in the structural trends of the two regions (Schull, 1988) (Fig. 1), makes the "Lubur Series" an important target for oil exploration, particularly in terms of its reservoir potential. It is indeed very surprising that a formation of such importance has until now received no more than a casual mention by oil exploration geologists.

In this paper, we present the results of the first detailed chronostratigraphic, sedimentologic, petrologic and diagenetic study of a complete section of the "Lubur Series", which was recently renamed the Lapur Sandstone (LS) by Thuo (2009). The measured section presented here is proposed as the "type-section" for this formation. This study provides the necessary basic data set for any potential oil explorers in the Turkana region. It evaluates the depositional setting and structural background of the LS, its diagenetic evolution and reservoir potential, as well as the implications for the overall hydrocarbon prospectivity of the Turkana depression.

2. Regional geological setting

The Turkana depression is a vast lowland lying at a mean elevation of ~400 m above sea level between the Kenya and Ethiopia domes. The main geographical feature in this region is Lake Turkana, which is essentially fed at its northern end by the Omo River flowing from the Ethiopian Plateaus (Fig. 2). This region has been described as the most important area in eastern Africa for studying a long-lived segment of the East African Rift System and how it interacted with the Cretaceous–Paleogene southern Sudan and