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PETROLEUM GEOLOGY OF THE NOGAL BASIN AND SURROUNDING AREA, NORTHERN SOMALIA: PART 1, STRATIGRAPHY AND TECTONIC EVOLUTION

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In this study, 92 closely-spaced reflection seismic profiles (~4000 line-km) were tied to biostratigraphic and lithological data from six deep exploration wells in the poorly-known Nogal rift basin, northern Somalia, and were integrated with outcrop and aeromagnetic data to investigate the basin stratigraphy and tectonic evolution. Aeromagnetic data show NW-SE trending magnetic anomalies which are interpreted as plutonic bodies intruded during the Early Cretaceous, probably contemporaneously with a pre-Cenomanian uplift phase. The aeromagnetic data also suggest a change of basement type from Inda Ad Series metasediments in the SE of the study area to igneous and high-grade metamorphic basement in the NW. Biostratigraphic data and seismic reflection profiles define the Nogal Basin as a WNW–ESE striking half-graben, approximately 250 km long and 40 km wide, which formed as a result of mainly Cenomanian–Maastrichtian and Oligocene–Miocene intracontinental rifting. The depocentre contains at least 7000 m of Mesozoic and Cenozoic sediments and is located in the centre of the basin (east of well Nogal-1), to the south of the Shileh Madu Range. To the north, the basin is bounded by a major border fault along which significant variations in the thickness of sedimentary units are observed, suggesting that the fault controlled basin architecture and patterns of sedimentation. Oligocene–Miocene normal faults which resulted in north-tilted fault blocks are widespread within the main basin; smaller-scale sub-basins oriented NW-SE to WNW-ESE are observed to the NW of the basin and probably developed contemporaneously.

The Late Jurassic rift phase which has been documented elsewhere in northern Somalia is either missing in the Nogal Basin or is preserved only in localised grabens in the western and central parts of the basin. This is probably due to the pre-Cenomanian uplift and erosion which removed almost the entire Jurassic and Lower Cretaceous successions over a wide area referred to as the Nogal-Erigavo Arch. A more pronounced rifting episode followed this erosional event in the Cenomanian–Maastrichtian and resulted in the deposition of well-sorted fluvio-deltaic sandstones (Gumburo and Jesomma Formations), more than 2000 m thick. In wells in the Nogal Basin, these formations are between two and three times thicker than in wells drilled in footwall locations, and include excellent reservoir rocks sealed by transgressive mudstones and carbonates. A final rifting event in the Oligocene–Miocene was related to the opening of the Gulf of Aden. A rift sag phase which accommodated the Early Oligocene continental sediments of the Nogal Group initially developed at the centre of the basin. This was followed by a period of strong rotational faulting and tilting, which reactivated the Cenomanian–Maastrichtian structures.

Key words: Nogal Basin, Somalia, Somaliland, stratigraphy, tectonic evolution, rift basins.

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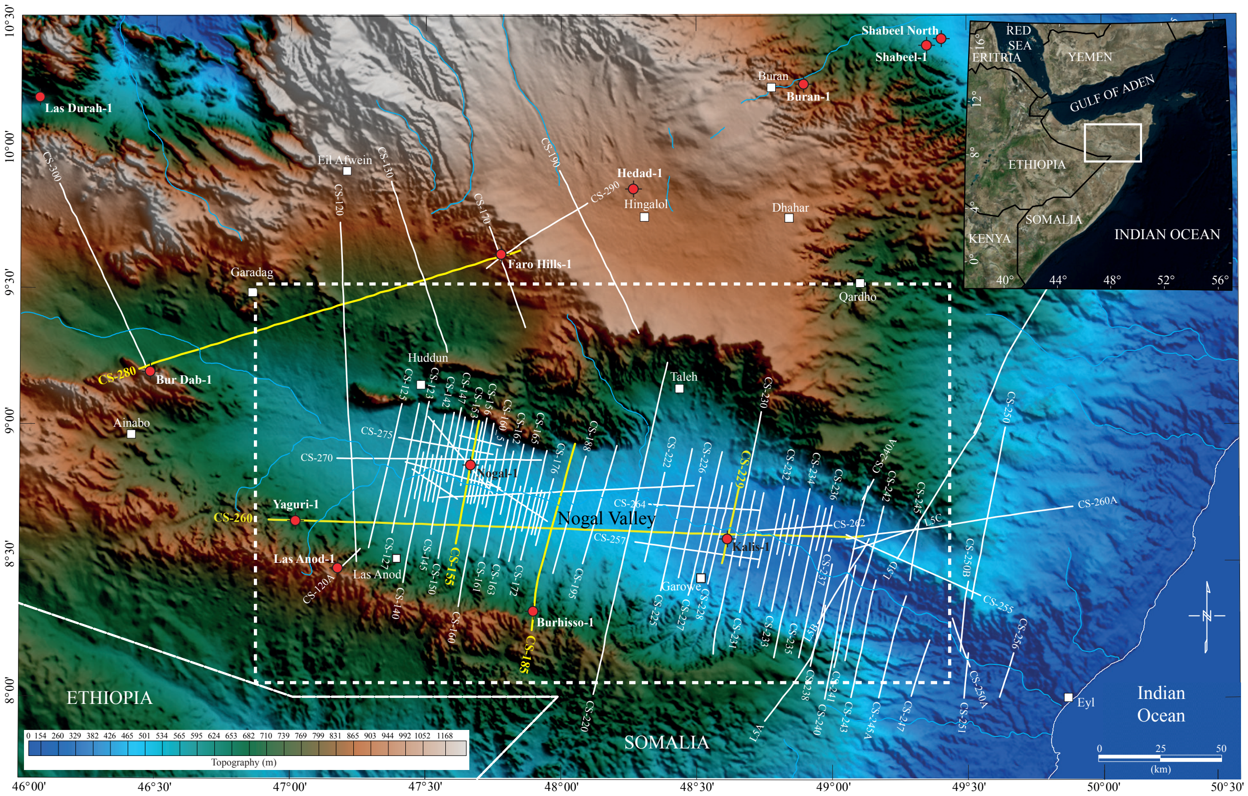

Fig. 1. Topographic map of the Nogal region based on Shuttle Radar Topography (SRTM) 1 arc-second global (data available from the US Geological Survey). The white lines show seismic profiles used in this study; thick yellow lines show seismic profiles presented in Figs 8–12. Also shown are locations of well data used in this study; and major towns (white-filled squares). Dashed white rectangular box shows the location of the Nogal Basin (Figs 13–6). Inset (top right) is a Landsat map of Somalia and the surrounding region showing the study area (white rectangle).

INTRODUCTION

The geology of northern Somalia is dominated by uplifted and exhumed basement blocks which are exposed along the Gulf of Aden, and rift basins containing thick Mesozoic and Cenozoic sedimentary successions (Ali and Watts, 2016; Mackay *et al.*, 1954). Although there have been a number of stratigraphic and structural studies of the Mesozoic and Cenozoic sequences in northern Somalia (e.g. Abbate *et al.*, 1974; Abbate *et al.*, 1993a; Boeckelmann and Schreiber, 1990; Hunt *et al.,* 1956; Luger *et al.*, 1990), few studies have delineated the subsurface basin architecture as they were heavily reliant on outcrop geology. However, investigating the subsurface structure of the basins is of relevance for hydrocarbon exploration as recent wells have indicated a regional hydrocarbon potential.

Ali and Watts (2016) used two regional-scale seismic reflection profiles tied to lithological and biostratigraphic data to investigate the stratigraphy of northern Somalia. They showed that basin fills in general can be divided into five stratigraphic sequences that range in age from Late Jurassic to Neogene. In addition, Ali (2015) investigated the petroleum geology and hydrocarbon potential of the Mesozoic–Neogene Guban rift basin, which is located along the southern coast of the Gulf of Aden and NW of the Nogal Basin. The basin contains both Upper Jurassic source rocks and a variety of reservoir rocks. Furthermore, by backstripping biostratigraphic data from exploration wells Ali and Watts (2013) and Ali and Watts (2016) showed that basins in northern Somalia have undergone three main rift phases with intervening periods of uplift and erosion. Initial phases of rifting occurred in the Late Jurassic and Late Cretaceous as a result of the late-stage break-up of Gondwana and a rapid increase in the spreading rate on the ridges separating the African and Indian plates respectively (Ali and Watts, 2016). The final rift phase in the Oligocene–Miocene was related to the opening of the Gulf of Aden (Ali and Watts, 2016).

The Nogal Basin, the subject of this paper, is a WNW-ESE striking half-graben which extends from north of Garowe to north of Las Anod below the Nogal Valley (Figs 1 and 2), and which formed as a result of Late Cretaceous and Oligocene–Miocene rifting (Ali and Watts, 2016). The basin has been explored by Amerada Oil and Conoco Somalia Ltd with rather discouraging results. However, petroleum systems modelling which is presented in Part 2 of this paper (Ali and Lee, *in press)* suggests that the western and central parts of the basin may be prospective, with hydrocarbons possibly trapped in the Adigrat and Gumburo Formation sandstones.

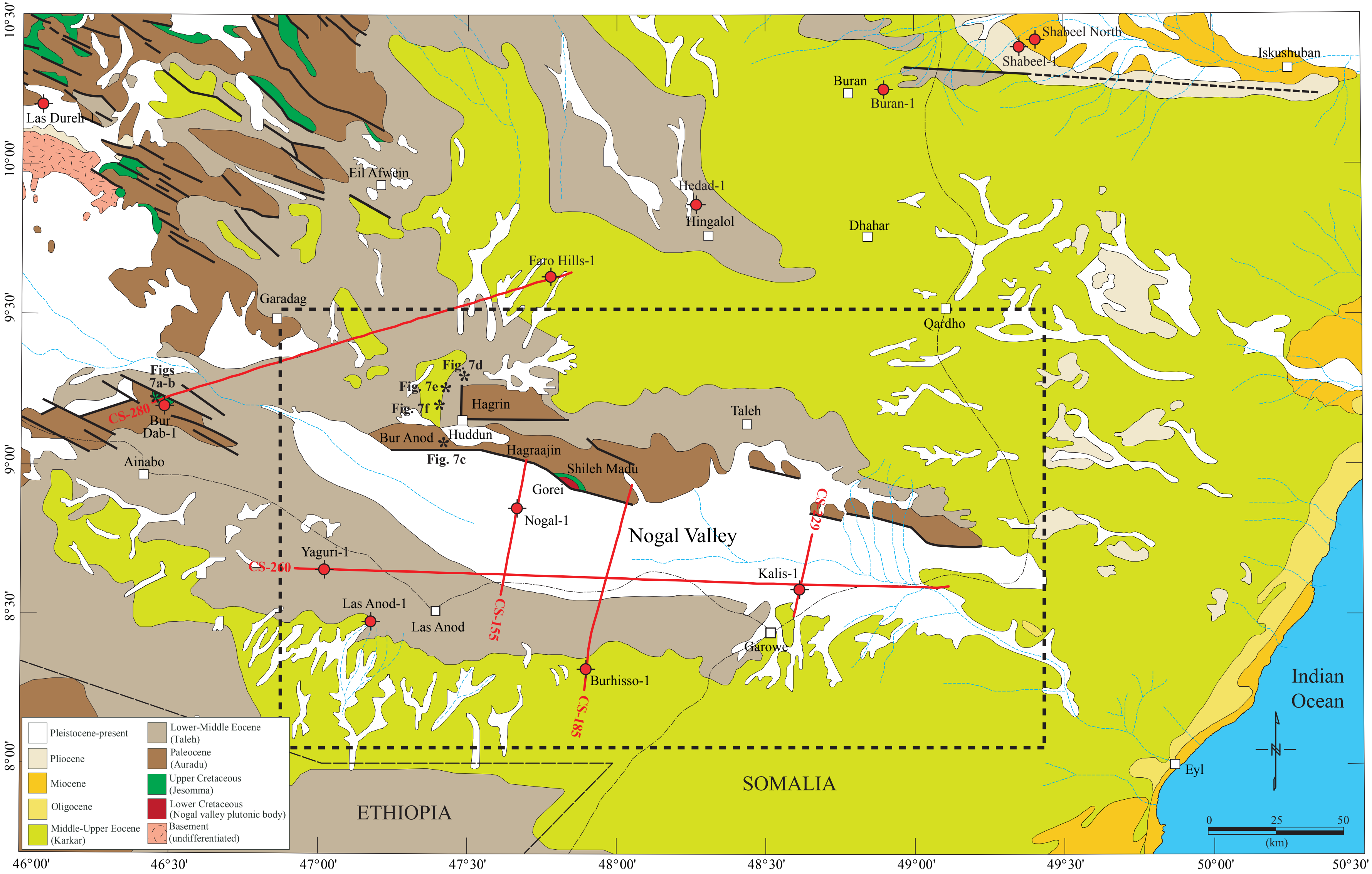

Fig. 2. Simplified geological map of the Nogal Basin and surrounding area (modified from Abbate *et al.*, 1993b). Black asterisks illustrate locations of field photographs shown in Fig. 7. Thick red lines show seismic profiles presented in Figs 8–12. Also shown are locations of well data used in this study; and major towns (white-filled squares). Dashed black rectangular box shows the location of the Nogal Basin (Figs 13–16).

Table 1. Available well data in the Nogal region.

Wells	Coordinates (degrees)		Ground Elevation (m)	Operator	Spud Date	Completion Date	TD (m)	Available well logs	Comments
	Longitude	Latitude							
Burhisso-1	47.896667	8.3175	664	Amerada	29-Apr-58	26-Jun-58	1551	GR, Electric, Microlog	Dead oil stain in Tertiary
Hedad-1	48.266667	9.866667	939	Amerada	1958	1958	312	No logs available	Shallow stratigraphic test
Bur Dab-1	46.476721	9.197264	672	Amerada	1958	1958	256	No logs available	Shallow stratigraphic test
Faro Hills-1	47.777778	9.626389	880	Amerada	07-Aug-57	07-Nov-57	1637	GR, Electric, Microlog, checkshot	Dead oil stain in Taleh, DST recovered no fluids
Las Anod-1	47.175	8.475	792	Amerada	09-May-57	19-Jul-57	1664	GR, Electric, Laterolog, Microlog	No shows, DST in Adigrat recovered water
Yaguri-1	47.018889	8.648333	724	Amerada	12-Jul-58	26-Aug-58	1440	GR, Electric, Microlog	No shows, TOC of 0.5-3.5 in Adigrat, DST in Adigrat recovered water
Buran-1	48.896667	10.249444	853	Amerada	27-Nov-1957	16-Mar-1958	2437	No logs available	Dead oil stains in Taleh, Cretaceous and Jurassic, TOC = 0.43 avg. in Cretaceous, DST recovered no fluids
Nogal-1	47.665111	8.853639	500	Conoco	16-Nov-89	12-Apr-90	3272	GR, CALI, RHOB, NPHI, ILD, ILM, SFLU, DT, SP, VSP	Jesomma flashed by water. Oil shows in Gumburo. Over-pressured section within Gumburo
Kalis-1	48.6125	8.583056	417	Conoco	02-May-90	26-Jul-90	2978	GR, CALI, RHOB, NPHI, ILD, ILM, SFLU, DT, SP, VSP	16 brl of heavy oil recovered in Jesomma. Gumburo recovered 60 brl of mud filtrate.

In this paper, we report the results of a detailed study of stratigraphy, structure and regional tectonic history of the Nogal Basin and the surrounding area based upon outcrop observations integrated with closely-spaced 2D seismic profiles, exploration wells and aeromagnetic data. The study shows that the basin is infilled by a thick Upper Cretaceous and Cenozoic succession, which record periods of extension and subsidence alternating with uplift and erosion. These results have led to a revised stratigraphy of northern Somalia, and provide a framework within which the regional-scale basin development and hydrocarbon potential can be reassessed.

DATASET AND METHODOLOGY

Aeromagnetic Data

In 1986, Conoco Somalia Ltd acquired Total Magnetic Intensity (TMI) data in the Nogal region. The TMI field measurements were made along NW-SE flight lines with a line spacing of 2 km and perpendicular control lines at 10 km intervals. Processing of the TMI data included removal of the International Geomagnetic Reference Field and line intersection adjustments to remove diurnal changes in the field strength. As part of this study, we transformed the TMI map to Reduction-to-the-Pole (RTP) and Reduction-to-the-Equator (RTE) maps to minimize the inclination effect of the TMI field. These transformations reduced the magnetic anomalies to the magnetic pole/equator and corrected for variations in inclination and declination over the study area, assuming that all magnetization is induced (Baranov and Naudy, 1964; Leu, 1981). However, The RTP and RTE transformations were not successful since positive anomalies still had negative anomalies after the RTE operation (Fig. 3a). This was probably due to the magnetic remanence of the crustal rocks and the low latitude of the study area which is close to the geomagnetic equator (average inclination and declination of 1.927° and 0.195° respectively). The dipole nature of magnetic anomalies makes it difficult to infer the position of magnetic sources from an RTE map, as anomaly peaks may not coincide with their corresponding magnetic sources. Thus, to analyse the distribution of centres of magnetic sources, we constructed the Analytic Signal (AS) of the RTE map (Fig. 3b). The AS repositioned magnetic anomalies over related sources to facilitate geological interpretation (Roest *et al.*, 1992).

Fieldwork

Fieldwork by the authors was conducted in two seasons (August 2014 and July–August 2018) and covered most of the western Nogal Basin and surrounding area. The objectives were to conduct geological traverses along the Nogal Valley and surrounding area, to record structural measurements and stratigraphy, and to collect rock samples from the oldest parts of the stratigraphy.

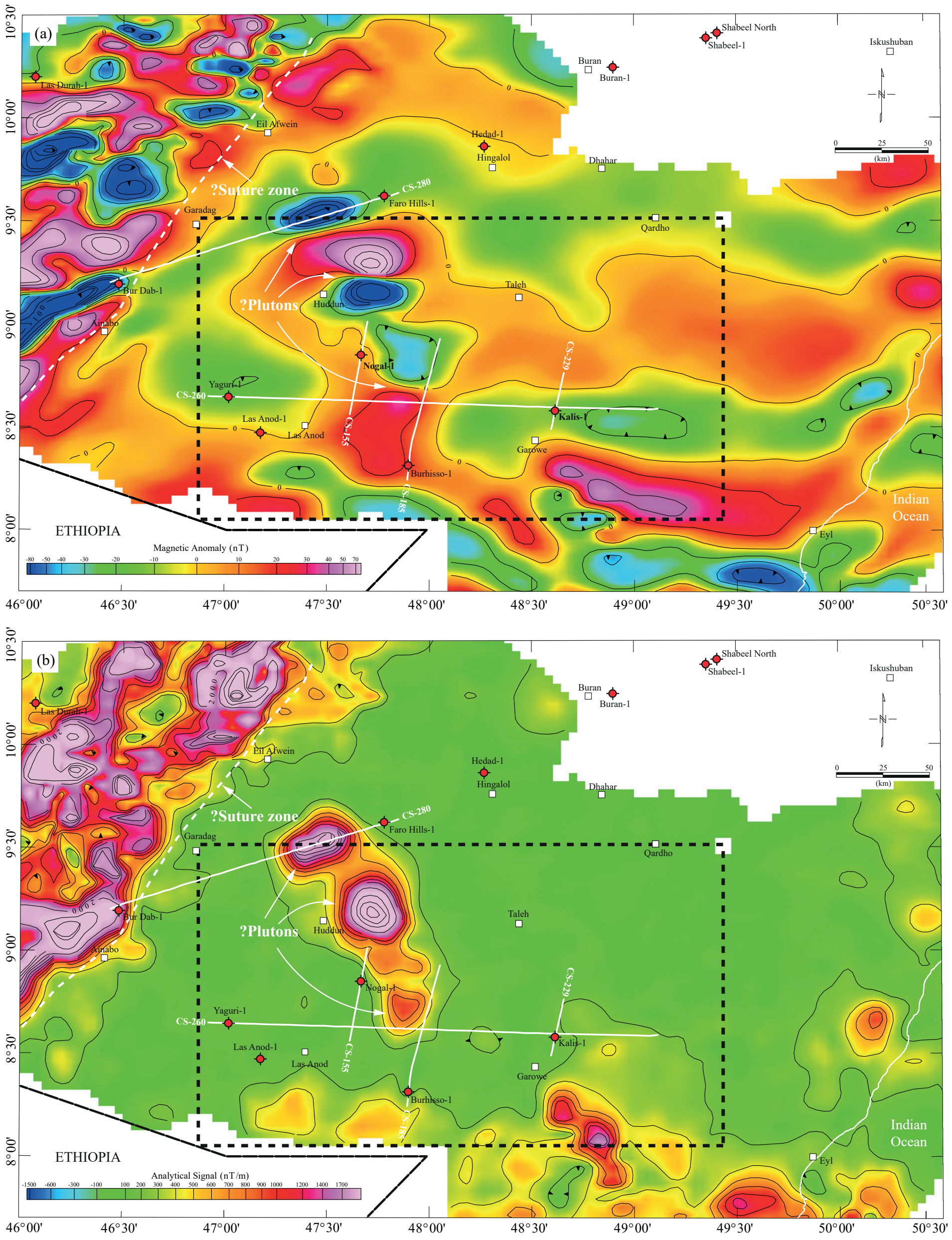

Fig. 3. (a) Magnetic anomaly map of the Nogal Basin and surrounding area acquired by Conoco Somalia Ltd in 1986. (b) Analytical Signal (AS) of the Reduced-to-the-Equator (RTE) processed data. The probable plutonic bodies and interpreted suture zone are labelled. Thick white lines show seismic profiles presented in Figs 8–12. Dashed black rectangular box shows the location of the Nogal Basin (Figs 13–16).

Well Data

Nine wells have been drilled in the Nogal region (Table 1, Fig. 2). Wells Hedad-1 and Bur Dab-1 were shallow stratigraphic wells, and Buran-1 was drilled close to the Daroor Basin in the northeast. The remaining six wells provided useful data for this study (Table 2). However, four of them (Burhisso-1, Las Anod-1, Yaguri-1 and Faro Hills-1) were drilled on regional highs, and only wells Nogal-1 and Kalis-1 were drilled in basin centre locations (Fig. 2). All of the wells (except Nogal-1) bottomed in Proterozoic granitic basement or metasediments of the Inda Ad Series. Geophysical logs (Table 1) and biostratigraphic and lithological information from these six wells (Nogal-1, Kalis-1, Las Anod-1, Yaguri-1, Burhisso-1, and Faro Hills-1) were used to determine physical properties of the formations. However, only wells Faro Hills-1, Nogal-1 and Kalis-1 had check-shot, Vertical Seismic Profile (VSP) and/or sonic data (Table 1). The velocity profiles of other wells (Burhisso-1, Las Anod-1 and Yaguri-1) were estimated from lithologies encountered by the wells. The corrected velocities of all six wells and synthetic seismograms of wells Nogal-1 and Kalis-1 were used to tie the seismic and well data. In addition, core descriptions from Kalis-1 were used to evaluate lithologies and reservoir properties. The cored intervals covered the basement of the Inda Ad Series and the overlying Gumburo, Jesomma and Taleh Formations.

Table 2. Ages and thicknesses of the formations penetrated by wells in the Nogal region. The depths are Measured Depth (MD) below rig floor, which are roughly equal to True Vertical Depth (TVD) since the wells are vertical.

Period	Epoch		Formation Tops	Faro Hills-1		Nogal-1		Kalis-1		Yaguri-1		Las Anod-1		Burhisso-1	
				Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)
NEOGENE	Recent-Pliocene		Nogal Group			Surface	200								
NEOGENE PALEOGENE	Mio. Olig.					200	677								
	Eocene	L.	Karkar	Surface	104	-	0	Surface	306						
		M.	Taleh	104	338	877	104	306	205			Surface	177	Surface	258
	Paleocene	E.	Auradu	442	430	981	544	511	571	Surface	471	177	421	258	422
CRET.	Early		Jesomma	872	263	1525	1001	1082	585	471	326	598	277	680	172
			Gumburo	1135	399	2526	746+	1667	1061	797	368	875	375	852	558
JURASSIC	Late		Gawan (Gabredarre)	-	0	?	?	-	0	-	0	-	0	-	0
			Daghani, Wanderer, Gahodleh (Uarandab)	-	0			-	0	-	0	-	0	-	0
	Middle		Bihen U. Hamanlei	-	0			-	0	1165	230	1250	270	1410	76
	Early		Adigrat	1534	103			2728	103	1395	32	1520	64	1486	54
PROTEROZOIC			Basement	1637	1+			2831	116+	1427	14+	1584	81+	1540	11+

Seismic Data

From 1987 to 1990, Conoco Somalia Ltd acquired 4596 line-km of closely-spaced 2D seismic reflection data in the Nogal Basin and surrounding area, and 92 profiles (~4000 line-km) were interpreted in this study (Fig. 1). The spacing between 2D seismic lines varies from 2 to 10 km, and the maximum depth of profiles is 4.8 sec TWT (Two-Way-Travel Time). Five vibrator sources with 12 sweeps of 6-56 Hz and split spread geometry were used to acquire the data. Shot point and recording group intervals were 120 m and 60 m respectively. The near and far offsets were 150 m and 3690 m respectively. In addition, up-hole surveys were acquired at approximately 2 km intervals along the seismic lines. The maximum CMP (Common Mid-Point) coverage was 30-fold.

Conoco Somalia Ltd applied a standard processing sequence to the seismic data. The noise content of the data was primarily reduced by the application of three processes: deconvolution, CMP stacking and migration. In addition, secondary processes were applied which included corrections for weathering-related statics that were derived from the up-hole surveys, an F-K filter, and a bandpass filter that varied from 6-56 Hz in the shallower section to 8-40 Hz in the deeper sections.

For the purposes of this study, the 2D seismic profiles were converted from high-quality image files in TIF format to SEGY format. This procedure included scanning and rasterising of the TIF files. Seismic data quality is generally fair to good in the upper 2 sec TWT. In the central area of the basin, interference of multiple reflections distorts the data quality in the deeper part of the sections. Regardless of this, seismic data allowed us to perform an acceptable analysis of the basin infill and geometry.

A mis-tie correction was applied to all the seismic lines. All the lines were calibrated with line CS-260, which passed through the basin in east-west direction (Fig. 1). The maximum vertical shift between seismic lines was less than 10 msec.

In addition, zero-offset VSP surveys were acquired from wells Nogal-1 and Kalis-1 to generate time-depth relationships for the seismic horizons, distinguish primary from multiple reflections and identifying the top-basement reflector. For well Nogal-1, 87 levels were recorded in an open hole from 2914 m to 2599 m, and in a cased hole from 2599 m to 305 m (Poppendeck and Cowen, 1990). Recordings were taken at 15 m, 23 m and 76 m intervals from 2914 m to 2438 m, 2438 m to 1524 m and 1524 m to 305 m respectively. A vibrator energy source with sweep parameters of 12 sweeps per level and 8 seconds per sweep with a 6-56 Hz filter was employed. For well Kalis-1, the VSP was recorded in two stages. The initial VSP recorded 113 levels in an uncased hole from 2104 m to 378 m at 15 m intervals (Overmyer and Cowen, 1990). Check-shots at every 76 m were recorded from 305 m to 152 m inside casing. The final VSP recorded 60 levels in an uncased hole from 2941 m to 1920 m at 15 m intervals. A vibrator energy source located at 37 m and 15° north of the borehole was used. Sweep parameters included 12 sweeps per level and 8 seconds per sweep with a 6-56 Hz bandpass filter. Table 3 lists key formation tops encountered in the Kalis-1 well and their corresponding seismic times.

Table 3. Time-depth pairs obtained from the VSP data of the Kalis-1 well (Overmyer and Cowen, 1990). TVD = True Vertical Depth; TWT = Two-Way-Travel Time.

Tops	Depth, TVD (m)	TWT (sec)
Karkar	152	0.238
Faulted Taleh	235	0.296
Top Auradu	512	0.410
Top Jesomma	1173	0.762
Lower Jesomma	1456	0.960
Top Gumburo	1667	1.041
Top Cenomanian	2588	1.500
Adigrat	2728	1.550
Basement	2831	1.598
TD	2947	1.640

Horizon and Fault Interpretation

The interpretation of stratigraphic horizons was based on well-to-seismic ties, the lateral continuity of seismic horizons and seismic facies. The interpretation started from the seismic lines that pass through wells Nogal-1, Kalis-1, Las Anod-1, Yaguri-1, Burhisso-1 and Faro Hills-1. Biostratigraphic data from these wells were used to constrain relative horizon ages. Seven key stratigraphic tops were identified and mapped across the Nogal Basin: top-Basement, top-Adigrat, top-Bihendula, top-Gumburo, top-Jesomma, top-Auradu and top-Taleh. Faults were interpreted by the termination of reflectors and from observable offsets in interpreted horizons. All seismic horizons and faults were manually interpreted.

The VSP and sonic data from wells Nogal-1 and Kalis-1 and check-shot velocity of well Faro Hills-1 together with velocity profiles estimated for other three wells (Burhisso-1, Las Anod-1 and Yaguri-1) and interval velocities from seismic processing were used to obtain time-depth pairs. These allowed the derivation of time-depth functions that were used to convert the interpreted time horizons into the depth domain. The depth converted maps were constrained by actual formation top depths in all wells within map area.

Structure contour maps of each horizon top were generated by combining horizon and fault interpretations of all the seismic lines. A convergent interpolation method was used to make the surface maps, and individual faults were connected to create fault polygons which were then incorporated.

STRATIGRAPHY AND DEPOSITIONAL SETTING

A tectonostratigraphic chart for northern Somalia was published by Ali and Watts (2016). However, in this study a new stratigraphic chart for the Nogal Basin and surrounding area is adopted as a result of integrating new information obtained by the authors from the Nogal-1 and Kalis-1 wells located in the west and east of the basin, respectively (Figs 1 and 2). In addition, radiometric dates acquired by Conoco Somalia Ltd as well as seismic and aeromagnetic data have allowed a better understanding of the regional tectonic evolution.

A tectonostratigraphic summary of the Nogal Basin and surrounding area is illustrated in Fig. 4 and is supported by the regional well correlation section in Fig. 5. The figures show that a basal transgressive sequence (Adigrat Formation) of ?Early–Middle Jurassic age rests on basement, and is overlain by Upper Jurassic carbonates and shales, Upper Cretaceous sandstones and carbonates, and carbonates and evaporites of Paleogene age. Major unconformities below the Cenomanian and at the top of the Eocene mark periods of regional uplift and erosion which are tied to documented deformation phases in northern Somalia and Yemen. The following section summarises the stratigraphy of the Nogal Basin area.

Crystalline Basement and Inda Ad Series

All the wells drilled in the Nogal region (Fig. 5) which reached the basement bottomed in metasediments or granites. Wells Kalis-1, Yaguri-1, Burhisso-1 and Las Anod-1 bottomed in metasediments (schists, quartzites, sandstones and phyllites) assigned to the Inda Ad Series which outcrops in the Mait area, north of the Nogal Valley (Amerada, 1958; Mackay *et al.*, 1954; Overmyer and Cowen, 1990). A core of basement from well Yaguri-1 is described as consisting of dark grey to black phyllite and quartz-muscovite paragneiss (Amerada, 1958). However, Faro Hills-1 bottomed in a granite containing coarse, pink feldspars, clear quartz and white and lavender mica (Amerada, 1957). The granite could be part of a Lower Palaeozoic intrusion into the Inda Ad Series as reported in the northern Somalia Plateau (Greenwood, 1960; Greenwood, 1961; Mackay *et al.*, 1954; Mason and Warden, 1956); alternatively, the granite may be related to the Lower Cretaceous quartz-syenite intrusion at Gorei, south of the Shileh Madu Range (Fig. 2).

The Inda Ad Series is usually considered to form part of the basement of northern Somalia. However, the unit consists of slates, greyish and greenish quartzites, slaty sandstones and beds of limestones, and therefore

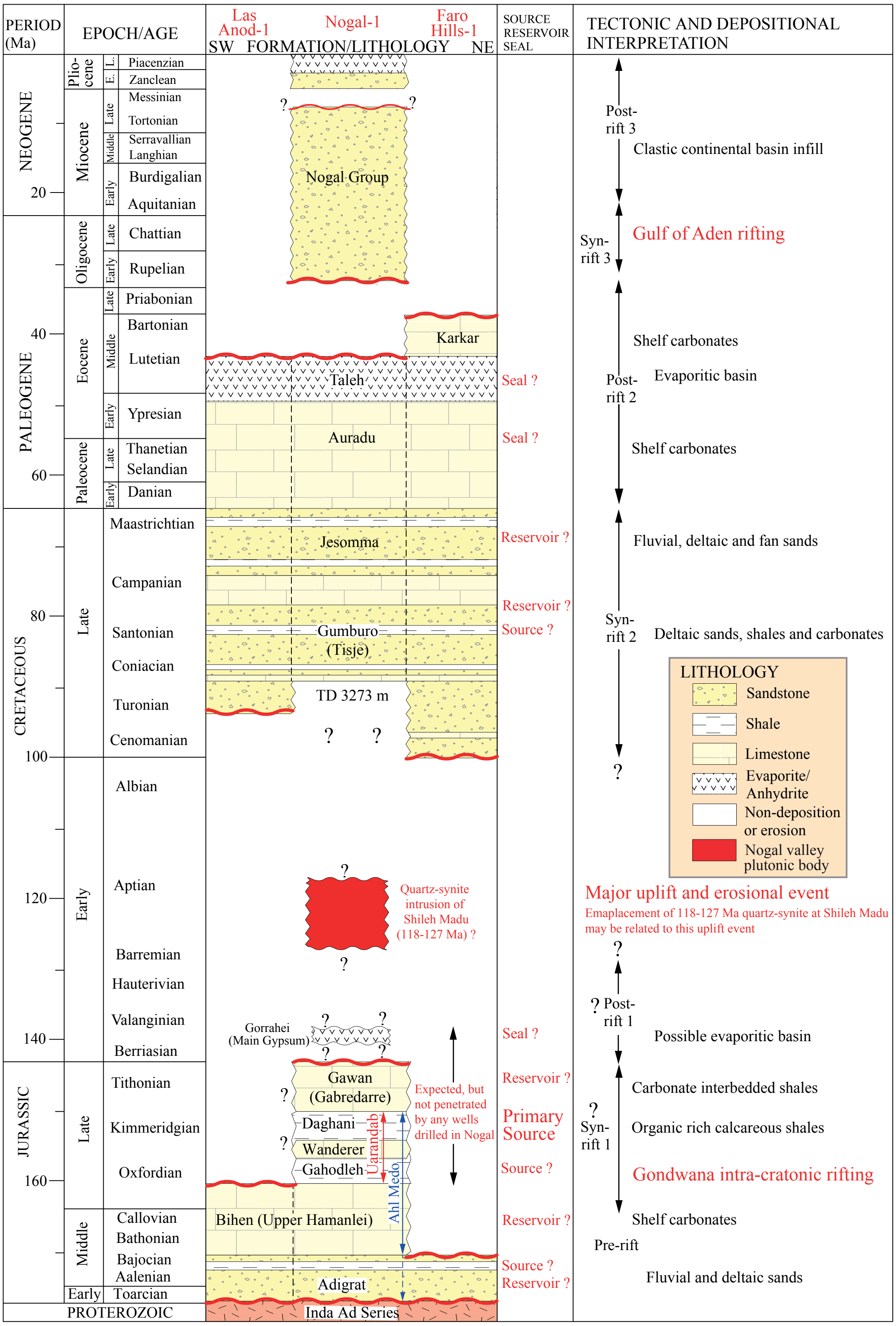

Fig. 4. Summary stratigraphic elements of the Nogal region obtained from wells Las Anod-1, Nogal-1 and Faro Hills-1 showing major tectonic events, lithologies of the basin succession and proposed petroleum system elements.

often displays the effects of low grade metamorphism; it can thus be clearly differentiated from the underlying highly-metamorphosed basement complex (Hunt *et al.,* 1956; Kröner and Sassi, 1996; Utke *et al.*, 1990; Warden and Horkel, 1984). Mackay *et al.* (1954) suggested that the unit could be several thousands of metres thick. The Inda Ad Series is considered to be Proterozoic in age (Merla *et al.*, 1979) and it is cut by younger granites and porphyritic dykes that are dated at 515-500 Ma (Snelling, 1967).

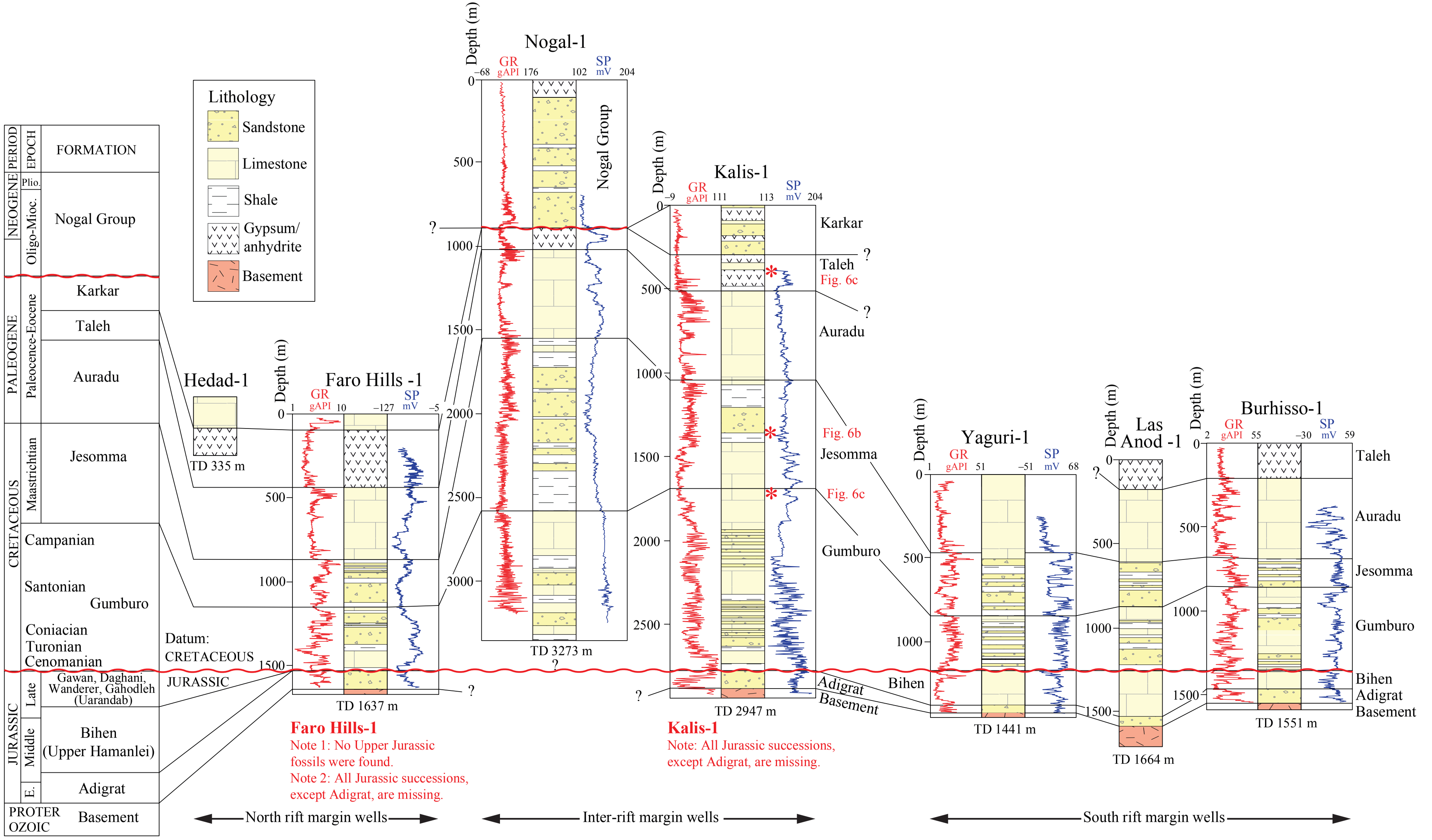

Fig. 5. Well correlation in the Nogal Basin. For location of the wells, see Fig. 1. GR: Gamma Ray; SP: Spontaneous Potential. Red asterisks beside Kalis-1 show the depths of the core photographs shown in Fig. 6.

The Jurassic succession

In the Nogal region, the oldest sediments overlying the Inda Ad Series are ?Lower–Middle Jurassic continental sandstones and conglomerates of the Adigrat Formation. The formation is conformably overlain by transgressive marine carbonates with minor interbedded marlstones of the Bihendula Group.

? Pliensbachian–Toarcian: Adigrat Formation

In the Nogal region, the Adigrat Formation was penetrated by wells Faro Hills-1, Yaguri-1, Burhisso-1, Las Anod-1 and Kalis-1 (Fig. 5). The formation is composed of pre-rift sandstones which were deposited in fluvial and marginal-marine environments (Abbate *et al.*, 1974; Bosellini, 1989; Bruni and Fazzuoli, 1977; Luger *et al.*, 1990; Merla *et al.*, 1979). At its base, the Adigrat sandstones rest abruptly against the underlying Inda Ad Series; above, they pass gradationally into the overlying Jurassic carbonates (Harms *et al.*, 1989). The thickness of the formation ranges from 32 m in Yaguri-1 to 103 m in Faro Hills-1 and Kalis-1 (Table 2). This variation in thickness may be related to post-Jurassic erosion or a pre-Adigrat high onto which the formation onlapped (Harms *et al.*, 1989).

In the Nogal region, the Adigrat Formation consists of conglomeratic sandstones at the base grading upwards into interbedded, dark grey to variegated shales and sandy carbonates. Black carbonaceous matter and lignitic streaks are common (Harms *et al.*, 1989). Lithological descriptions of cuttings from the Kalis-1 well describe the sandstones as unconsolidated and containing quartz and mica grains that are fine to coarse grained and poorly sorted with angular to sub-angular clasts, and of generally low porosity (Overmyer and Cowen, 1990).

The Adigrat sandstones are poorly dated and their age may be variable regionally. In northern Somalia, it is regarded as being entirely Middle–Late Jurassic, possibly Bathonian–Kimmeridgian (Abbate *et al.*, 1974; Merla *et al.*, 1979). However in eastern and central Somalia, shales and carbonates above the sandstones apparently range from Pliensbachian to Callovian (Harms *et al.*, 1989). In addition, Luger *et al.* (1990) suggested the occurrence of early Toarcian ammonites at the base of overlying Alh Medo sequence, NE of Erigavo, which may indicate a late Pliensbachian to early Toarcian age for the Adigrat sandstone succession.

Callovian–Tithonian: Bihendula Group

The Bihendula Group consists of a limestone succession with marl and shale intervals and establishes a transition to a marine environment (Bosellini, 1992; Hunt *et al*., 1956; MacFadyen, 1933). In the Bihendula area SE of Berbera, MacFadyen (1933) divided the Group into five lithologic units, from bottom to top: the Bihen limestone, Gahodleh shale, Wanderer limestone, Daghani shale and Gawan limestone (Fig. 4). In central Somalia and eastern Ethiopia, the Bihen, Gahodleh-Wanderer-Daghani and Gawan Formations are equivalent to the upper Hamanlei, Uarandab and Gabredarre Formations respectively (Fig. 4) (Barnes, 1976). However, in northern Somalia including the Nogal Basin, the formation names of the Bihendula Group should be retained as proposed by MacFadyen (1933). In central Somalia, the Gabredarre Formation is conformably overlain by the Main Gypsum/Gorrahei Formation (Barnes, 1976; Merla *et al.*, 1979). In SW Somalia, the Gorrahei is represented by the more distal equivalent of the Garba Harre Formation, which consists of alternating dolomitic limestones, sandstones and siltstones with gypsum lenses (Barnes, 1976).

Fossils in the Bihendula area suggest that the Bihen limestone is Callovian–Oxfordian to possibly Kimmeridgian in age (Mackay *et al.*, 1954). However, wells drilled in central Somalia that penetrated the Hamanlei Formation recorded Pliensbachian foraminifera (e.g. *Vidalina mertana, Lingulina teneras* and *Orbitopsella precursor*) (Harms *et al.*, 1989) and it is therefore possible that the Bihen limestone in the Nogal region is significantly older than at the type section in the Bihendula area. Alternatively, the wells in central Somalia sampled the lower Hamanlei Formation of Pliensbachian–Aalenian age, and the Bihen Formation in the Nogal and Bihendula areas is equivalent to the bioclastic limestones of the Callovian upper Hamanlei Formation mapped in the Ogaden Basin, SE Ethiopia (Hunegnaw *et al.*, 1998). In this case, the lower Hamanlei (Toarcian–Aalenian) and middle Hamanlei (Aalenian – early Bathonian) that are observed in the Ogaden Basin are absent in the Nogal area.

All the drilled wells in the Nogal region (except Nogal-1, which bottomed in the Coniacian) show that the Bihendula Group is either absent or very thin (Fig. 5); only wells Yaguri-1, Las Anod-1 and Burhisso-1 penetrated a thin section of Bihen limestone. In these wells, the Bihen limestone consists of shoal-water packstones and grainstones with interbedded dolomites, anhydrites and marls. The thickness of the Bihen limestone ranges from 76 m in well Burhisso-1 to 270 m in Las Anod-1 (Table 2). The Gahodle shale, Wanderer limestone, Dhagani shale and Gawan limestone are absent at these well locations.

Neocomian–Albian uplift

A major pre-Cenomanian deformation event is documented over northern Somalia and the Neocomian–Albian interval is absent (Fig. 4). Ali and Watts (2016) suggested that pre-Cenomanian uplift gave rise to the Nogal-Erigavo Arch, and resulted in the erosion of up to 1500 m of the Upper Jurassic Bihendula Group

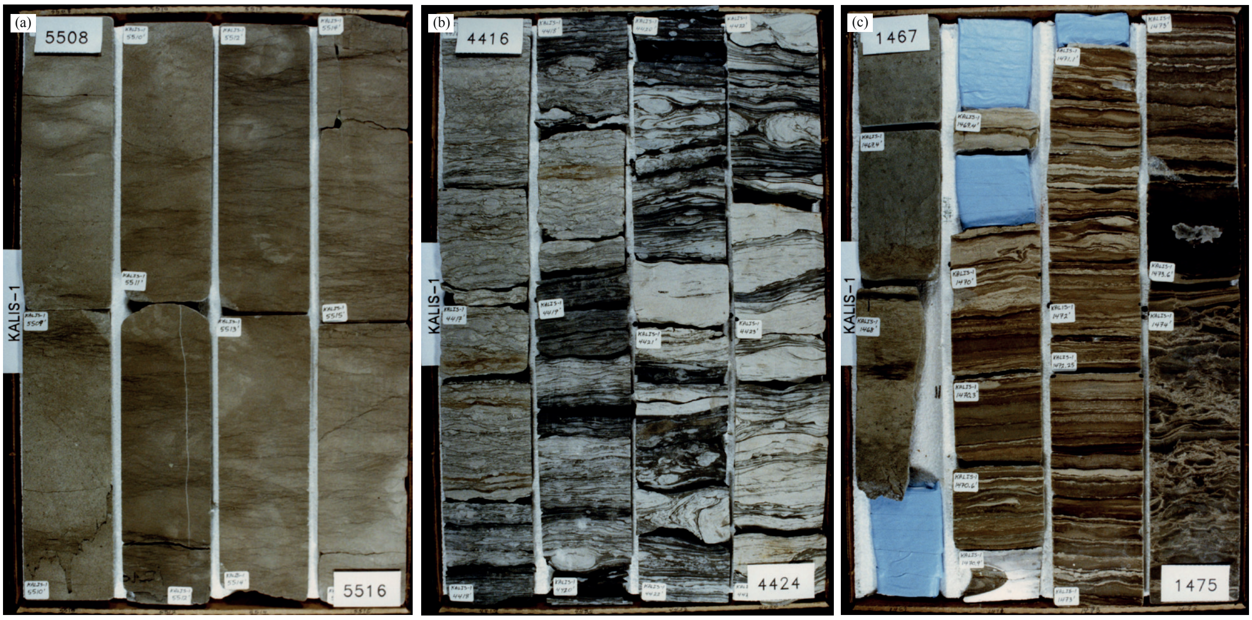

Fig. 6. Core photographs from the Kalis-1 well. (a) Core photograph of the Gumburo Formation from depth interval 1678–1681 m; the core shows brown, finely crystalline argillaceous limestone with vertical fracture porosity partly filled with calcite. (b) Core photograph of the Jesomma Formation from depth interval 1346–1348 m; the core shows fine-grained, sub-angular, well-sorted sandstones with good to fair porosity. Abundant carbonaceous material, mostly woody plant fragments, are contained in laminated black shales. (c) Core photograph of the Taleh Formation from depth interval 447–450 m; the core shows brown argillaceous dolomite with patchy oil staining at the top. Dark brown, microcrystalline massive anhydrite is seen at 448–450 m. For the depths of the core intervals, see Fig. 5.

succession over a wide area. This uplift probably resulted from regional thermal doming related to the intrusion of plutonic bodies. Consequently, the entire Upper Jurassic and Lower Cretaceous succession was removed from the platforms but may be preserved in localised grabens if the Nogal rift-bounding faults had already become active in the Late Jurassic.

The pre-Cenomanian unconformity is well documented both in the Nogal wells (Fig. 5) and in outcrop sections in the Erigavo region, north of the Nogal Basin. In the Nogal region, the Cenomanian to Campanian Gumburo Formation rests directly the Adigrat sandstone or Bihen limestone, as recorded in wells Faro Hills-1, Las Anod-1, Yaguri-1, Burhiso-1 and Kalis-1 (Figs 4 and 5). In the Erigavo area, the entire Jurassic and Lower Cretaceous are absent (Bott *et al.*, 1992) and the Upper Cretaceous Tisje Formation rests unconformably on the Inda Ad Series basement (Beydoun, 1970; Luger *et al.*, 1990). To the west of Erigavo in the Bihendula region, up to 1200 m of Jurassic sediments have been preserved (Beydoun, 1970; Bruni and Fazzuoli, 1977; MacFadyen, 1933); to the NE, the Adigrat and Middle–Upper Jurassic Ahl Medo Formations are exposed in the Ahl Medo sub-basin.

In southern and central parts of Somalia, the Neocomian–Barremian interval is represented by a variety of sediments including a thick evaporite succession known as the Main Gypsum or Gorahei Formation (Barnes, 1976). In the Ogaden Basin, the Lower Cretaceous includes gypsum with calcareous and marly shale intercalations (Hunegnaw *et al.*, 1998). However, there is no evidence of pre-Cenomanian deposits contemporaneous with the evaporites of the Main Gypsum/Gorrahei Formation and associated basinal deposits in the Nogal region. Harms *et al.* (1989) suggested that a low-lying land area, which was exposed during a lowstand of the Neocomian ocean, could have served as part of the barrier which resulted in the restricted conditions in which the Main Gypsum evaporites were deposited. It is also possible that a Lower Cretaceous sequence equivalent to the Main Gypsum may have been deposited over part or all of the Nogal area but was removed by the pre-Cenomanian erosion (Harms *et al.*, 1989).

Quartz-syenites in the Shileh Madu Range

The small quartz-syenite outcrop near Gorei (about 50 km SE of Huddun) on the northern flank of the Nogal Valley and the southern footwall of the Shileh Madu Range (Fig. 2) has commonly been interpreted as a small erosional window of Proterozoic crystalline basement (Barnes, 1976; Mackay *et al.*, 1954; Mason, 1957). However, Rb-Sr and K-Ar radiometric dating by Conoco Somalia Ltd puts the age of the quartz-syenite complex in the range 118 to 127 Ma which suggests that it is intrusive (Granath, 2001; Harms *et al.*, 1989). The complex is composed of several separate intrusions

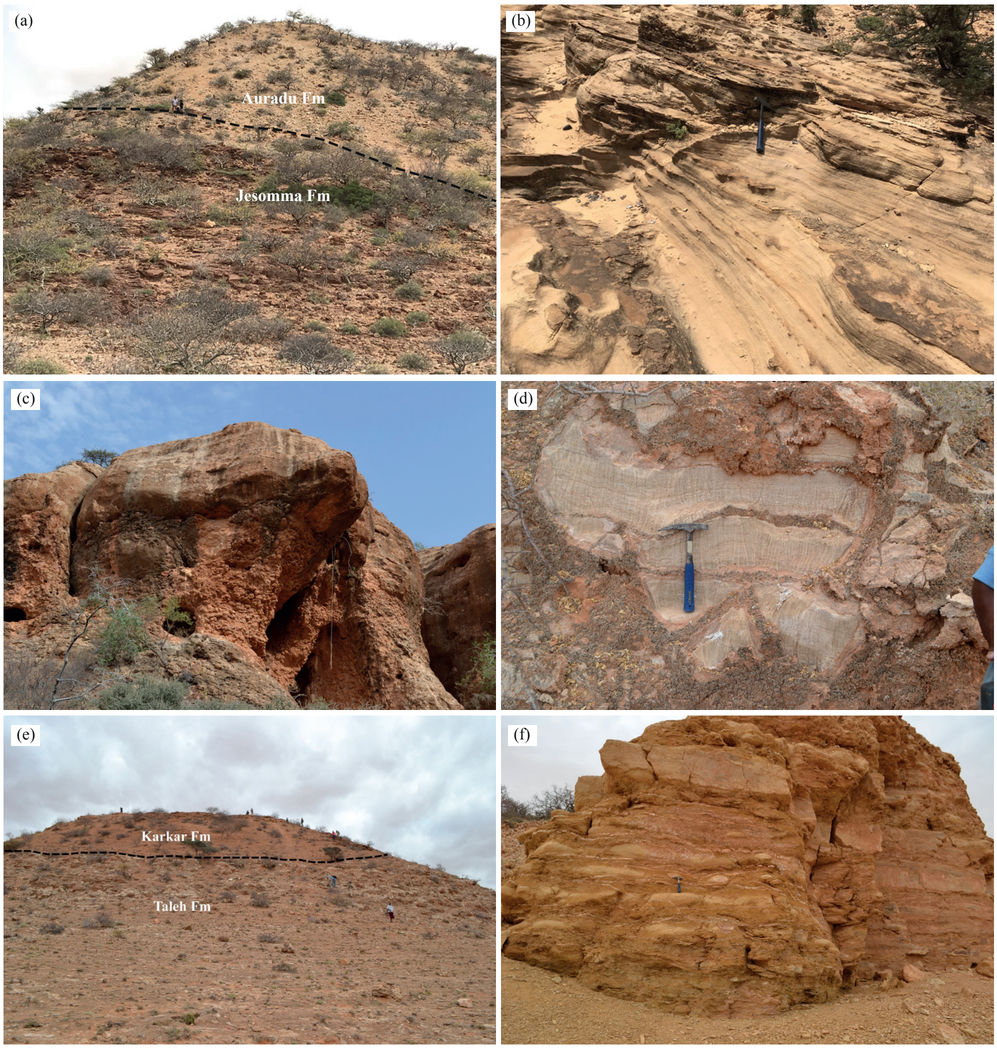

Fig. 7. Field photographs showing (a-b) the Upper Cretaceous sedimentary succession in the Bur Dab area. The Paleocene Auradu limestone conformably overlies the Jesomma sandstone. The photos are taken facing north. (c) Nodular limestones of the Auradu Formation underlying massive finely crystalline limestone, Bur Anod Range, south of Huddun. (d) Laminated gypsum of the Taleh Formation, north of Huddun. (e) Contact between the Taleh and Karkar Formations at Saed Bahane hills, NW of Huddun. The weathered gypsum at the base of the outcrop forms the Taleh Formation and is overlain by well-bedded and nodular limestones and marls of the Karkar Formation. (f) Lower Karkar Formation, NW of Huddun, showing marly limestones and grey, thin-bedded, fine-grained limestones with cm-scale gypsum bands. For location of photographs, see Fig. 2.

composed of coarse, feldspar-dominated lithologies and fine-grained porphyritic dikes.

The quartz-syenite body was deeply weathered and eroded prior to deposition of the overlying Jesomma Formation during a hiatus that lasted around 40 Ma, based on radiometric age dates and chronostratigraphic analysis of the Nogal-1 well (Granath, 2001; Poppendeck and Cowen, 1990). The Jesomma Formation consists of fine-grained fluvial sandstones showing no evidence of thermal overprint, and unconformably overlies both the breccia and the quartz-syenite complex. Furthermore, none of the dikes intrude either the breccia or the Jesomma sandstones, nor is there any evidence of recrystallization of the breccia matrix (Granath, 2001). In addition, the lowest sandstone strata of Jesomma Formation contain boulders, cobbles, and pebbles derived from the quartz-syenite complex (Granath, 2001; Mason, 1957). Hence, the age of the quartz-syenite complex coincides with the phase of uplift and erosion which removed the Upper Jurassic Bihendula Group.

The Cenomanian–Campanian Gumburo Formation which is well developed in the Nogal Basin is absent from the Gorei area. Therefore, it appears that the area was part of an exposed footwall block that underwent erosional denudation throughout most of the Late Cretaceous. The area was transgressed by the end of the Maastrichtian with deposition of the upper Jesomma Formation (Granath, 2001).

The Upper Cretaceous succession

The wells drilled in the Nogal region record a major unconformity which separates the Upper Cretaceous succession either from the Adigrat sandstone (as at wells Faro Hills-1 and Kalis-1) or the Bihen (upper Hamanlei) Formation as at wells Yaguri-1, Las Anod-1 and Burhisso-1 (Fig. 5). The well and seismic data suggest a major rift phase during the Cenomanian to Maastrichtian with coeval deposition of the thick, predominantly shallow-water clastics of the Gumburo and Jesomma Formations. These formations are at least 2000 m thick e.g. at well Nogal-1, and are between two and three times thicker in basin-centre locations than in the uplifted footwall (e.g. at wells Yaguri-1, Burhisso-1, Las Anod-1 and Faro Hills-1). However, there is little variation in the lithological composition of Upper Cretaceous strata between wells drilled in the centre of the basin or in platform locations.

The Late Cretaceous rift phase correlates with a rapid increase in spreading rate on the ridges separating the African and Indian and African and Antarctica plates, and a contemporaneous slowing-down of the African plate's motion (Ali and Watts, 2016).

Cenomanian-Campanian: Gumburo Formation

In the Nogal Basin, the Gumburo Formation directly overlies the Adigrat sandstone or the Bihen (upper Hamanlei) limestone, as recorded in wells Faro Hills-1, Las Anod-1, Yaguri-1, Burhiso-1 and Kalis-1 (Fig. 5). The Gumburo Formation is dated as Cenomanian–Campanian in wells Burhisso-1, Faro Hills-1 and Kalis-1 (Amerada, 1957; Overmyer and Cowen, 1990). Harms *et al.* (1989) suggested the lower Gumburo is of early Cenomanian age (92-96 Ma) in well Burhisso-1. The Nogal-1 and Kalis-1 wells show that the formation consists of fine- to coarse-grained, poorly-sorted fluvio-deltaic sandstones with marginal-marine limestones and shales deposited in the rift axis. Core data from the Kalis-1 well over the interval 1678 m to 1681 m show that it consists of shallow-water, finely crystalline, argillaceous limestones with a vertical fracture porosity partly filled with calcite (Fig. 6a). The Nogal-1 well encountered a major overpressured shale section from 2134 m to 2520 m within the Gumburo Formation with a pressure gradient of 2.03 psi/m (Poppendeck and Cowen, 1990). The contact with the overlying Jesomma Formation is transitional and reflects a shallowing of water depths accompanied by an influx of siliciclastic material. The Gumburo Formation ranges in thickness from 1061 m (Kalis-1) in grabenal locations to 368 m (Yaguri-1) on the platform (Table 2).

Maastrichtian: Jesomma Formation

In the Nogal Basin area, the Jesomma Formation crops out at Gorie (SE of Huddun) in the southern footwall of the Shileh Madu Range and the NE corner of the Bur Dab Range, north of Ainabo (Fig. 2). The Jesomma Formation consists of sandstones, siltstones and carbonaceous shales whose age is poorly documented but which are believed to be entirely Maastrichtian. The uppermost part of the Jesomma is exposed at Bur Dab area along a NW–SE trending fault (Fig. 2). Here it consists of a 180 m sequence of fine to coarse grained quartz sandstones with siltstones, shales, calcareous sandstones and limestones (Figs 7a and 7b), overlain conformably by the Auradu Formation (Fig. 7b). At Gorei, the Jesomma Formation consists of a ~40 m sequence of medium- to coarse-grained, fossiliferous (plant remains) sandstones with conglomeratic intercalations at the base which rest unconformably on the quartz-syenite complex (Luger *et al.*, 1990). However, the formation is much thicker elsewhere in the Nogal region and ranges in thickness from 1001 m (Nogal-1) in graben locations to 172 m (Burhisso-1) on the platform (Table 2).

At the Nogal-1 and Kalis-1 wells, the Jesomma Formation consists of interbedded limestones and claystones at the top grading to interbedded sandstone and shale towards the base. Core data from the Kalis-1 well over the interval 1346-1348 m show that the formation consists of marginal marine, fine-grained, subangular, well-sorted sandstones with good to fair porosity (Overmyer and Cowen, 1990). Abundant carbonaceous material, mostly woody plant fragments, are present in laminated black shales, and small wave ripples are observed in the core (Fig. 6b). This marginal-marine section marks the transition to the overlying Auradu Formation (Granath, 2001).

The Cenozoic succession

Paleogene shelf carbonates of the Auradu, Taleh (or Gypsum-Anhydrite Series) and Karkar Formations are exposed over large areas in the Nogal region (Fig. 2). A marine transgression flooded across northern Somalia and Yemen during the Early Paleocene. This is recorded by the transition from the Jessoma clastics to the marine carbonates of the Auradu and Umm-er-Radhuma Formations. These gave way to more evaporitic conditions and deposition of the Taleh Anhydrite in the Middle Eocene. A further transgression in the Late Eocene was accompanied by the deposition of a marine limestone with chert bands (Karkar Formation, Fig. 7f). These Paleogene sediments rest conformably upon the Jesomma Formation. The Paleogene succession consists of comparable facies both in the Nogal Basin and in the surrounding platform areas.

Paleocene – Early Eocene: Auradu Formation

The Auradu Formation is exposed over much of the Nogal region. In the Huddun area north of the Nogal Basin, the formation is present in two discontinuous and fault-dissected ranges (the Hagrin-Bur Anod-Hagraajin and Shileh Madu ridges: Fig. 2) which form striking morphological features. The formation is present in wells drilled in the Nogal region and subsurface data show that it ranges from 421–571 m thick (Table 2). The Auradu Formation maintains a fair lithological uniformity and thickness throughout the study area, indicating deposition during a tectonically quiescent time interval. However, the formation is slightly thicker in the Nogal-1 well than it is in wells drilled on the platform (Fig. 5). It is ~300 m and 330 m thick respectively at Bur Dab and Gorei.

In the Huddun area (Fig. 2), the Auradu Formation consists of at least 250 m of thick-bedded and massive, nodular, grey to white and pink, finely-crystalline fossiliferous limestones with iron-stained concretions (Fig. 7c). At the base, the formation is composed of 50-60 m of well-bedded limestones and marls, overlain by ~120 m of brown to grey, nodular marly limestone. At the top, the formation consists of 70-80 m of well-bedded limestones with thin marly horizons. In the Nogal-1 well, the Auradu Formation consists of moderately argillaceous limestones with minor interbeds of claystone deposited in a shallow-marine environment with limited open-marine influence (Poppendeck and Cowen, 1990).

The lower boundary of the Audaru Formation was not observed in the Huddun area. However, at Bur Dab and Gorei, the formation rests conformably on the Jesomma sandstone. At Huddun and elsewhere in the Nogal region, the unit is overlain, apparently conformably, by the Taleh Formation.

Limestones of the Auradu Formation are assigned to the Paleocene to Early Eocene (MacFadyen, 1933; Mackay *et al.*, 1954). Luger *et al.* (1990) suggested that Auradu limestones contain ostracods and larger foraminifera (*Lockhartia* and *Orbitolites*) indicating a Late Paleocene to Early Eocene age.

Early–Middle Eocene: Taleh Formation

The Taleh Formation evaporites are exposed over wide parts of the north and south Nogal Valley and the surrounding area (Fig. 2), and typically weather to undulating, flat-topped hills which are bare of vegetation. The formation is 104–338 m thick in the Nogal region (Table 2); it is 140 m, 160 m and 285 m thick in the Gorei, Bur Dab and Las Anod areas respectively (Mackay *et al.*, 1954). However, the Faro Hills-1 well intersected 338 m of the Taleh Formation.

The formation consists of massive to banded gypsum, irregularly bedded with chalky gypsiferous limestones, white marls and anhydrite (Fig. 7d). The unit is barren of fossils. In the Nogal-1 and Kalis-1 wells, the formation consists of interbedded anhydrite and dolomite with minor interbeds of claystone (Overmyer and Cowen, 1990; Poppendeck and Cowen, 1990). Cores from the Kalis-1 well over the interval 447-450 m (Fig. 6b) show that the formation consists of brown argillaceous dolomites and microcrystalline, massive anhydrite (Overmyer and Cowen, 1990).

The Taleh Formation conformably overlies the Auradu limestone with a boundary which is often transitional; its upper boundary with the Karkar Formation is conformable and transitional (Fig. 7e). The formation was deposited in a predominantly intertidal-supratidal environment (Boeckelmann and Schreiber, 1990). The age of the formation is not constrained. However, from the ages of the underlying (Auradu) and overlying (Karkar) formations, the Taleh has been dated as Early to Middle Eocene (Boeckelmann and Schreiber, 1990).

Middle Eocene: Karkar Formation

Outcrops of the Karkar Formation are usually covered by thin red soil with a vegetation cover that disappears where gypsiferous soils prevail. In the Huddun and most of the Nogal region, the formation is the youngest unit exposed at the surface, and the eastern side of the Hagrin Range north of Huddun (Fig. 2) is composed entirely of Karkar Formation sediments. The formation consists of chalky nodular limestones and marls with interbedded gypsiferous shales (Fig. 7f). In some locations the upper section contains sequences of marly limestone and thin-bedded fine-grained limestones with gypsum lenses. The lower section consists of chalky nodular limestones with shales.

The Karkar Formation has an average thickness of ~100 m. In the Ainabo and Las Anod areas, the formation is 80 m and 139 m thick respectively (Mackay *et al.*, 1954). The formation is erosionally absent in wells drilled in the Nogal Basin and surrounding area (including Nogal-1), except the Faro Hills-1 and Kalis-1 wells which intersected 104 m and 306 m of Karkar Formation respectively (Table 2). In the Kalis-1 well, the formation consists of gypsum interbedded with dolomite, limestone and chert (Overmyer and Cowen, 1990); at Faro Hills-1, it consists of limestones with shale and anhydrite layers (Amerada, 1957). A major unconformity which is considered to be associated with the initial rifting of the Gulf of Aden is responsible for the absence of the Karkar Formation and Upper Eocene sediments from large parts of the Nogal region.

The lower boundary of the Karkar Formation is well exposed in the Nogal region (Fig. 7e), and the formation rests conformably and gradationally on the Taleh Formation. The upper boundary of the formation was not observed in the Nogal region, but the boundary is a discontinuity over most of northern Somalia.

The Karkar Formation was deposited in a supratidal to open, shallow-marine environments. Over most of northern Somalia, the formation is entirely of Middle Eocene age on the basis of a good foraminiferal assemblage. In the extreme NE of northern Somalia, the formation may range up to Late Eocene (Azzaroli, 1952; Azzaroli, 1958).

Oligocene – Miocene: Nogal Group

During the Oligocene–Miocene, the west-central part of the Nogal Basin underwent rapid subsidence with the development of a half-graben system and the reactivation of Cenomanian–Maastrichtian faults which resulted in the formation of fault blocks and possibly flower structures along wrench faults. At the same time, at least 877 m of predominantly continental sediments of the Nogal Group were deposited in a narrow down-faulted basin (Fig. 5, Table 2). These sediments are probably time-equivalent to those of the Daban Group which outcrop along the coastline of the Gulf of Aden (Ali and Watts, 2016). The section intersected by the Nogal-1 well consists of interbedded sandstones and claystones, with 107 m of gypsum and anhydrite just below surface which probably represent the deposits of a salt lake (Poppendeck and Cowen, 1990). However, the eastern part of the Nogal Basin did not undergo the same subsidence as indicated by the Kalis-1 well which did not penetrate an Oligocene–Miocene succession.

AEROMAGNETIC DATA

Figs 3a and 3b show the magnetic anomaly and AS maps. The AS map shows the presence of NW-SE oriented anomalies that run from north of the Burhisso-1 well to the NW corner of the study area (Fig. 3b). The middle high-magnetic zone west of the Faro Hills-1 well is located exactly where the seismic data (Fig. 8) indicate the presence of a sub-basin. However, the magnetic anomaly and AS maps do not show this sub-basin, nor do they illustrate the main Nogal Basin. Another high magnetic zone coincides with the quartz-syenite outcrop near Gorei (Figs 2 and 3). Therefore, the NW-SE trending magnetic anomalies are interpreted as plutonic bodies that were intruded during the Early Cretaceous (118-127 Ma), probably contemporaneously with the pre-Cenomanian uplift event. Other, weaker NW-SE anomalies are observed to the SE of the Nogal Basin (Fig. 3b) and may have a similar origin.

The NW-SE trend of the magnetic anomalies coincides with the regional trend of the Late Jurassic rift basins in northern Somalia and Yemen. This trend lies along the Nogal-Erigavo Arch where pre-Cenomanian deformation is interpreted to have removed the Upper Jurassic and Lower Cretaceous succession. Therefore, it is possible that the plutonic bodies are related to the pre-Cenomanian deformation phase.

The magnetic anomaly and AS maps also show a NE-SW trending line through the Bur Dab-1 well which separates higher frequency magnetic anomalies to the NW from lower frequency anomalies to the SE (Fig. 3). This trend has been interpreted as being due to a reactivated SE-verging basement thrust or to the presence of volcanics within the sedimentary column (Harms *et al.*, 1989). Alternatively, it may reflect an old suture zone with a different basement composition.

In northern Somalia, two different basement outcrop areas can be distinguished (i) the Borama-Hargeisa-Burao area to the west, where high-grade metamorphic rocks, migmatites, orthogneisses and metagabbros are exposed; and (ii) the Erigavo-Bosaso area to the east, where the low-grade Inda Ad Series rests unconformably on crystalline basement (Farquharson, 1924; Greenwood, 1960; Greenwood, 1961; Mason, 1962; Mason and Warden, 1956; Mason *et al.*, 1959). The basement of northern Somalia consists of Proterozoic terranes which were amalgamated during Neoproterozoic island-arc and microcontinent accretion events, which led to the formation of the Afro-Arabian margin of Gondwana (Al-Husseini, 2000; Husseini, 1989; Loosveld *et al.*, 1996; Sassi *et al.*, 1993; Warden and Daniels, 1982; Warden and Daniels, 1984). Thus, the suture zone observed in the magnetic anomaly and AS maps may indicate a change of basement type from the Inda Ad Series in the SE, as documented by wells drilled in the Nogal region and outcrop data to the north in the Mait area, to igneous and high-grade metamorphic basement in the NW.

SEISMIC MAPPING AND STRATIGRAPHY

Seven sedimentary sequences have been defined in the Nogal region (Figs 8–12) and are: Nogal Group (Oligocene-Miocene to Recent); Taleh and Karkar Formations (Lower to Middle Eocene); Auradu Formation (Paleocene to Lower Eocene); Jesomma Formation (Maastrichtian); Gumburo Formation (Cenomanian to Campanian); Bihendula Group (Upper Jurassic); and Adigrat Formation (Lower–Middle Jurassic). Surface and isopach maps for each formation in time and depth domains were generated (Figs 13–16). These sequences are described in the following section.

The Kalis-1 well constrained all the sedimentary sequences present in the eastern part of the basin. The Nogal-1 well TD'd at 3273 m and identified the majority of the reflector surfaces (up to top-Gumburo) within the western part of the Nogal Basin. Therefore, all the formation tops below the Gumburo (including top-Bihendula, top-Adigrat and top-Basement) are not constrained by well data, and seismic data did not clearly image the formations. In addition, the seismic lines do not have sufficient quality to define possible Upper Jurassic graben structures, and interpretation of formations in the western and central parts of the basin is challenging. Furthermore, all the wells drilled in the Nogal region, except the more recent Nogal-1 and Kalis-1 wells were drilled on platform areas, and it is

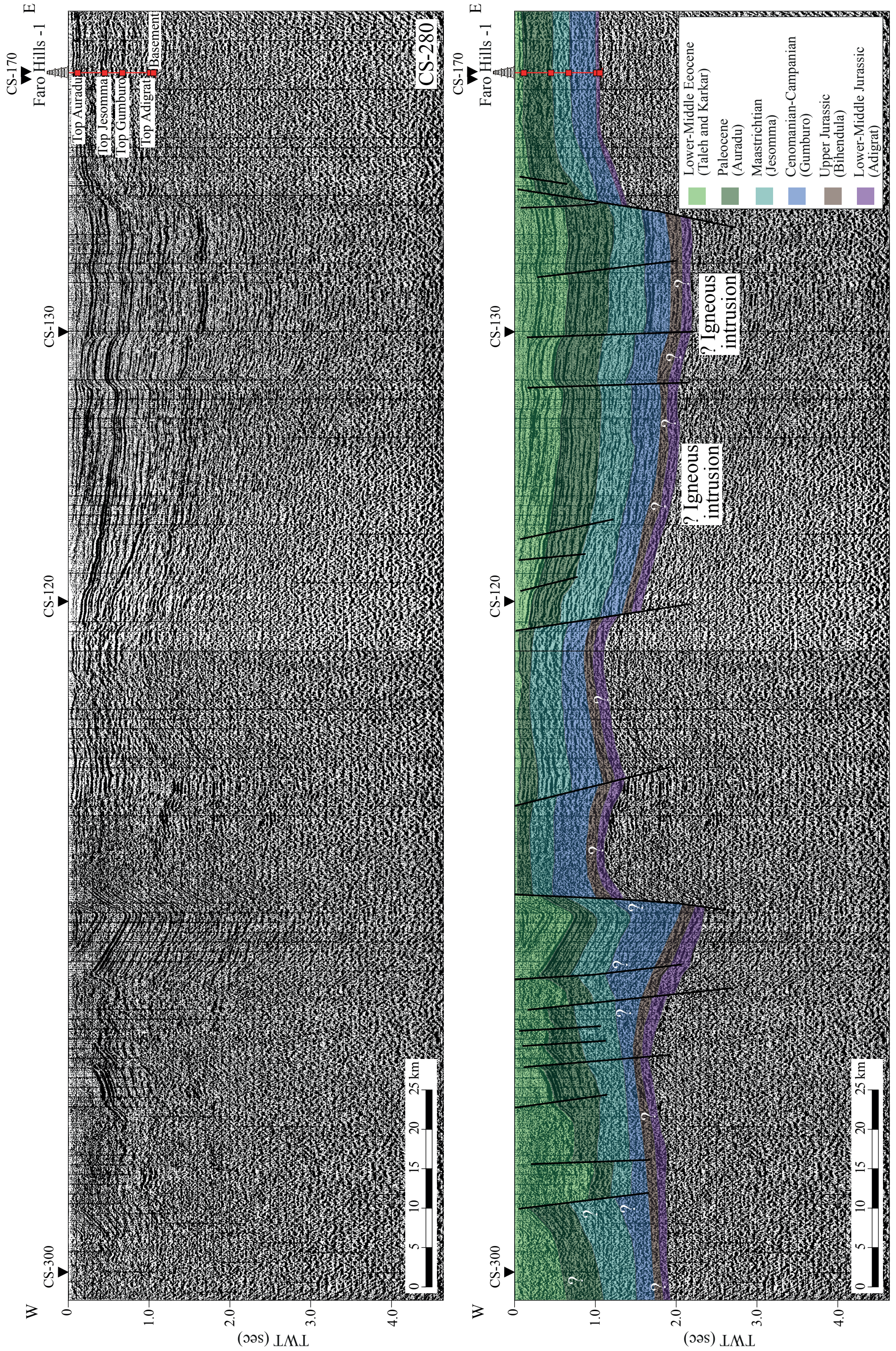

Fig. 8. (a) Uninterpreted and (b) interpreted seismic reflection profile CS-280, which crosses well Faro Hills-1 and a sub-basin. For location of the seismic profile, see Fig. 1. The inverted triangles show line ties.

therefore difficult to correlate the platform stratigraphy to the graben areas.

The seismic profiles show that a branch of the Nogal rift extends to the NW of the main Nogal Basin. For example, seismic line CS-280 (Fig. 8) shows half grabens (with less sedimentary cover than the main Nogal Basin, as imaged by CS-155 in Fig. 9) which seem to have developed contemporaneously with, and are oriented parallel to, the main Nogal Basin. These seismic lines indicate the possible existence of further graben areas which could be *en échelon* extension features of the main Nogal Basin.

Basement

The Kalis-1 well penetrated the basement corresponding to the Inda Ad Series at a depth of 2831 m (Fig. 5, Table

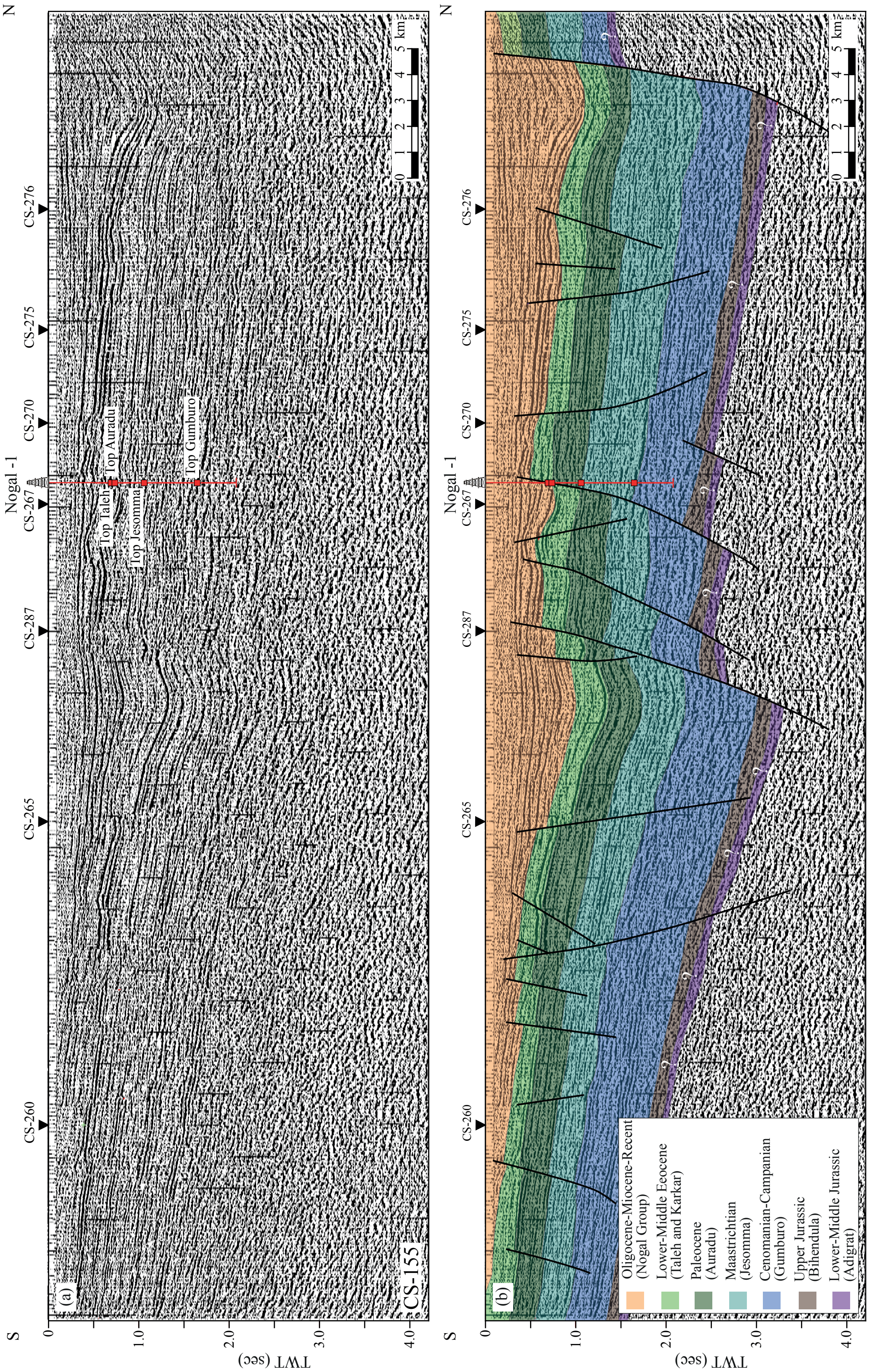

Fig. 9. (a) Uninterpreted and (b) interpreted seismic reflection profile CS-155, which crosses the Nogal-1 well and the main Nogal Basin. For location of the seismic profile, see Fig. 1. The inverted triangles show line ties. Well-to-seismic tie and the lateral continuity of seismic horizons allowed identification of seven mappable stratigraphic sequences. The seismic line shows a major tilted block.

2). At this location the VSP data indicated that the Inda Ad Series is non-reflective (Overmyer and Cowen, 1990) due to the weak acoustic impedance contrast between the Adigrat sandstones and the quartzitic basement; no strong seismic reflection is observed at top-basement (Figs 8–12). The strong reflectors beneath top-basement in seismic line CS-229 (Fig. 10) are interpreted as multiples and not as intra-basement primary reflectors. The basement is characterized by noisy and ambiguous reflectors that are contaminated with numerous multiples. As there is a lack of well data for basement in the western and central parts of the basin, it was difficult to map the top-basement reflector or any of its internal structures in the seismic lines.

In line CS-155 (Fig. 9), the depth of top-basement is not well defined since well Nogal-1 did not penetrate

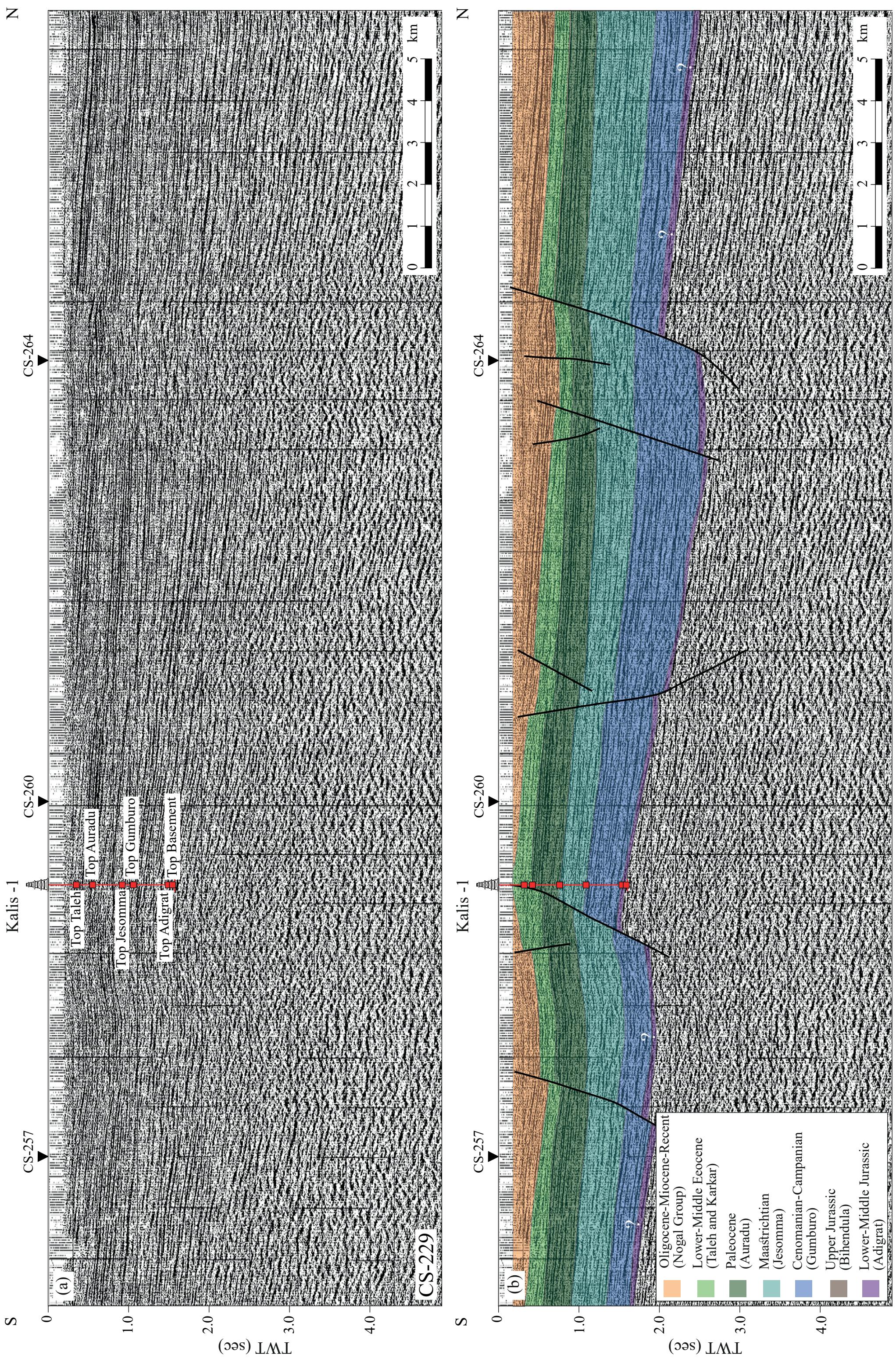

Fig. 10. (a) Uninterpreted and (b) interpreted seismic reflection profile CS-229, which crosses the Kalis-1 well. For location of the seismic profile, see Fig. 1. The inverted triangles show line ties.

it, and it was determined using intersection points with seismic lines which passed through wells Faro Hills-1, Yaguri-1, Las Anod-1, Burhisso-1, and Kalis-1. The greatest depth of top-basement was ~7800 m in the centre of the Nogal Basin next to the northern border fault (Fig. 13). In lines CS-280, CS-155, CS-299 and CS-185 (Figs 9-11), the basement is cut by major faults which were probably reactivated during rifting events.

The seismic data (e.g. line CS-280; Fig. 8) do not show any evidence of the plutonic bodies which were interpreted from the aeromagnetic data (Fig. 3), because the seismic signal significantly has deteriorated at the depths below the Gumburo Formation at which the plutonic bodies may be expected to occur. The discrepancy between the seismic and magnetic anomalies could be explained

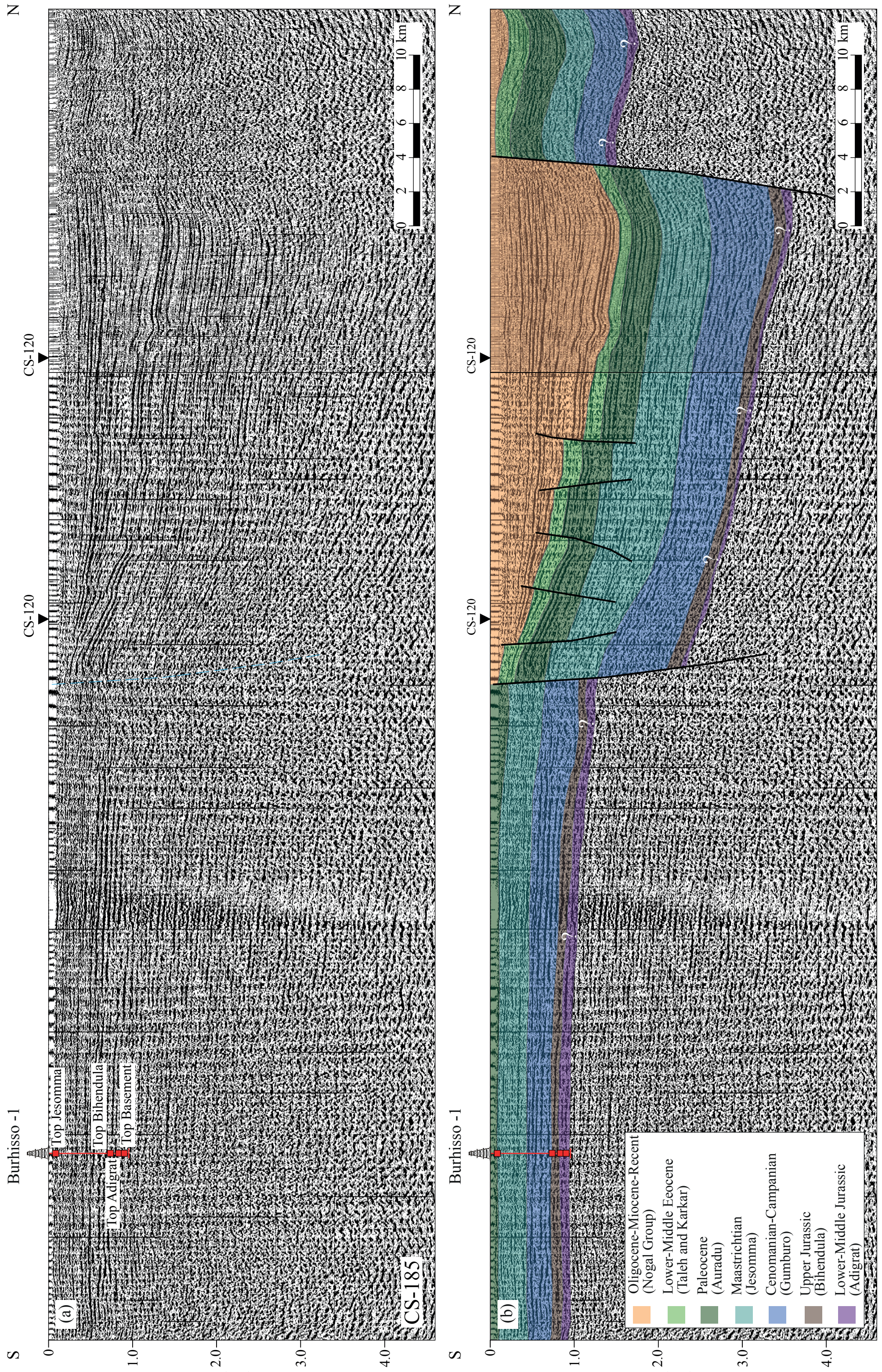

Fig. 11. (a) Uninterpreted and (b) interpreted seismic reflection profile CS-185. For location of the seismic profile, see Fig. 1. The inverted triangles show seismic profiles that cross this profile.

if the plutonic bodies have a similar composition to the quartz-syenite body which is exposed near Gorei, with densities and velocities which are similar to those of the sedimentary rocks and particularly of the carbonates of the Bihendula Group and Gumburo Formation. Consequently, there will be little acoustic impedance contrast between the carbonates and the intrusive bodies.

Adigrat Formation

The deepest sedimentary sequence in the Nogal region is interpreted as the Adigrat Formation. Although seismic data do not clearly image the formation or the Inda Ad Series, there appears to be ~0.1 sec TWT of sedimentary section between top-basement and top-Adigrat as shown in Figs 8–12. However, the presence and thickness of the Adigrat Formation in the centre and western parts of the basin is extremely uncertain due to a lack of well penetrations. In line CS-229 (Fig. 10), the reflector representing the top-Adigrat is laterally continuous, but the top-Adigrat in line CS-155 (Fig. 9) is less clear. The Nogal-1 well did not penetrate the Adigrat Formation and the top of the sequence was therefore extended from intersection points with other seismic profiles. The sequence appears to have an almost constant thickness of ~150 m throughout the Nogal region (Fig. 15), possibly indicating that it represents a pre-rift succession. The greatest depth of the top-Adigrat is at about 7600 m in the centre of the basin and adjacent to the northern border fault (see Fig. 13).

Bihendula Group

We interpreted that the Bihendula Group is restricted in the western and central parts of the Nogal Basin. However, the interpretation of this unit is very difficult. Seismic line CS-260 (Fig. 12) shows that the horizon can be interpreted to terminate in the central part of the basin before it reaches seismic line CS-229 (Fig. 10). The Kalis-1 well, which is situated on line CS-229, did not encounter the Bihendula Group (Fig. 5). According to the well data, only the Las Anod-1, Yaguri-1 and Burhissio-1 wells penetrated the lowermost part (the Bihen Formation) of the Bihendula Group. Furthermore, seismic profiles in the north of the Nogal Basin (e.g. CS-280, Fig. 8) together with the Faro Hills-1 well show that the Bihendula Group is absent in the footwall blocks. However, seismic profiles (e.g. CS-280) indicate the occurrence of ~100 – 300 m of Bihendula Group above the Adigrat Formation in graben areas, and the group is therefore expected to be preserved in the central-western part of the Nogal Basin. Lack of penetration at well Nogal-1 means that the Bihendula Group could not be identified with confidence. In addition, the reflection identified as the Bihendula Group could be part of the Gumburo Formation or could be a multiple, as observed in the in the Kalis-1 well (Overmyer and Cowen, 1990); therefore the Upper Jurassic may be missing from the entire area.

Nevertheless, a horizon representing top-Bihendula Group was extended from seismic line CS-260, which passes through the Yaguri-1 well (Fig. 12). This reflector is laterally continuous to discontinuous, and the internal geometry of the sequence consists of discontinuous reflectors. The top of the sequence is interpreted to be eroded, probably as a result of pre-Cenomanian uplift. The group does not show a significant variation in thickness, but is slightly thicker in the centre of the basin probably because its upper part is present (Fig. 15). The deepest top of the Bihendula Group is at 7382 m, with an average thickness of 370 m (Figs 13 and 15).

Gumburo Formation

This sequence contains more laterally continuous reflectors than those in the Jurassic succession, and the top of the sequence is a laterally continuous reflector that can be traced across the profiles. Internally, the sequence exhibits high-amplitude, continuous to discontinuous reflectors. The reflectors are clearer and more continuous in line CS-229 than in line CS-155 (Figs 9 and 10).

The sequence rests unconformably on the Bihendula Group, and gradually thickens towards major domino-style normal faults. There is a greater increase in thickness towards the normal fault located at the centre of the basin than towards the northern border fault, as seen in line CS-155 and the isopach map (Figs 9 and 15e). The thickness of the formation in the central basin depocentre is about 2800 m, and the formation top is at 5500 m. In the footwall of the northern border fault, the thickness of the formation is approximately three times less than that in the hanging wall. In addition, the sequence is ~ 500 m thick (0.3 sec TWT) at the centre of the sub-basin west of the Faro Hills-1 well (Fig. 8), indicating that the faults grew synchronously during deposition of the formation. In addition, localized horst and graben structures are observed within the sequence, which probably suggests reactivation of the Cenomanian-Maastrichtian faults during Oligocene-Miocene rifting (Figs 8–12).

Jesomma Formation

The top of this sequence is a prominent, readily traceable reflector of high amplitude and medium continuity across most of the study area. Internally, the sequence has variable amplitude, discontinuous, low-frequency reflectors as well as a chaotic pattern (Figs 8–12). The sequence generally increases in thickness in an NNE direction, where there are major normal faults, at the centre and western parts of the basin and towards the northern border fault (Fig. 16). However, it is clear that the increase in thickness is greater near the northern border fault than at the basin-centre faults (Figs 14 and 16). In addition, the increase in thickness is prominent in the western and central parts of the basin, as the offset of the border fault becomes smaller to the east of the basin (Fig. 16). These observations therefore suggest that deposition of the formation was controlled by the movement of normal fault system as the basin rapidly subsided as a result of rift-related extension that was initiated during deposition of the Gumburo Formation. The average thickness of the formation is ~2000 m, and the deepest point of the top-Jesomma is 3880 m (Figs 14 and 16).

Auradu Formation

The top of the sequence is generally characterized by a strong and high amplitude, continuous reflector.

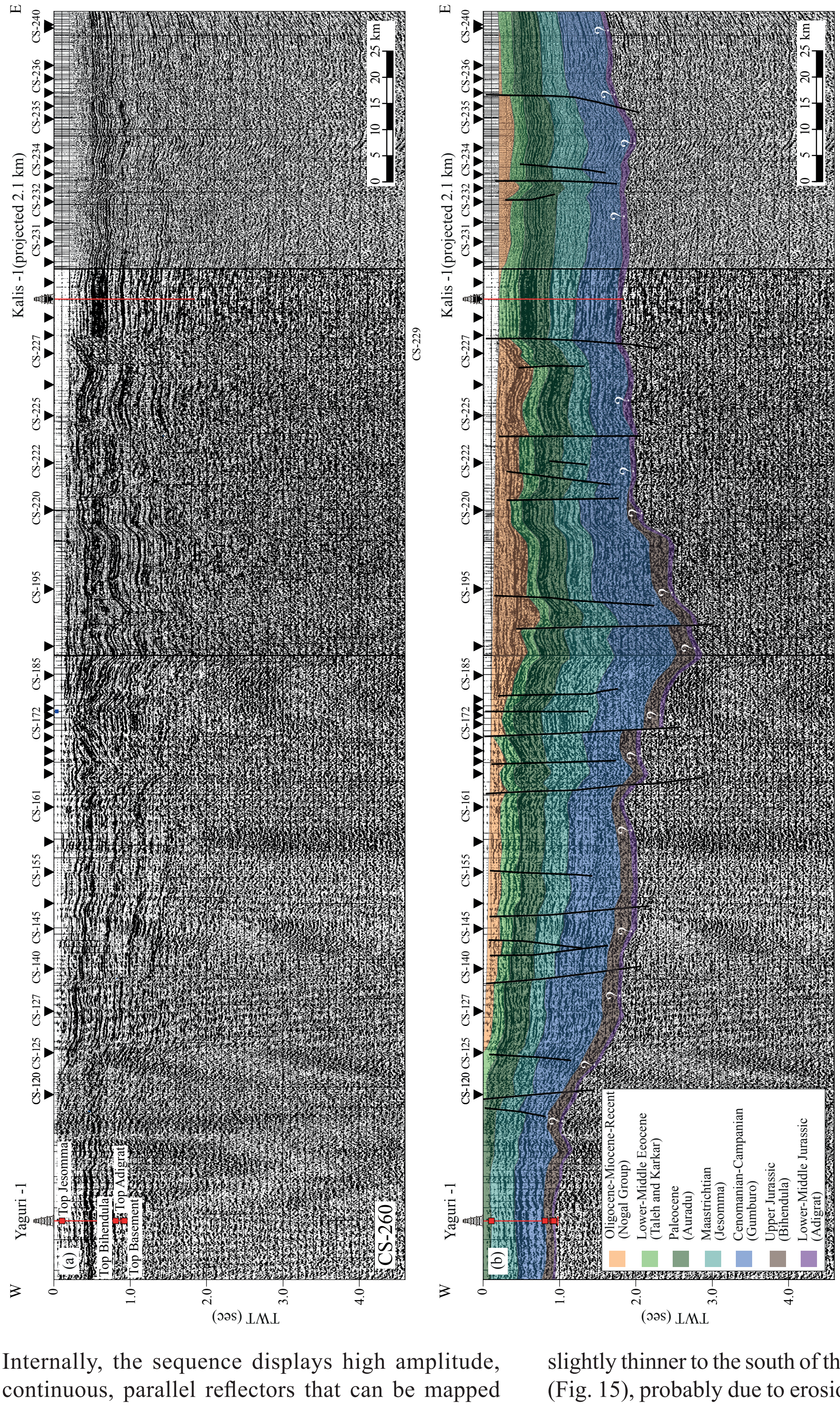

Fig. 12. (a) Uninterpreted and (b) interpreted seismic reflection profile CS-260, which crosses the Yaguri-1 well. For location of the seismic profile, see Fig. 1. The inverted triangles show line ties.

Internally, the sequence displays high amplitude, continuous, parallel reflectors that can be mapped throughout the seismic sections. The boundary between the Jessoma and Auradu Formations seems to be conformable as the reflectors above and below the boundary are parallel. The sequence has a constant thickness of ~650 m both in the basinal and platform areas of the Nogal region. However, the formation is slightly thinner to the south of the southern border fault (Fig. 15), probably due to erosion of its top-most part.

Taleh and Karkar Formations

It was not possible to distinguish the Karkar from the Taleh Formation on seismic, and both formations were therefore grouped together as Taleh Formation in the interpretation for this study. Their characteristics are

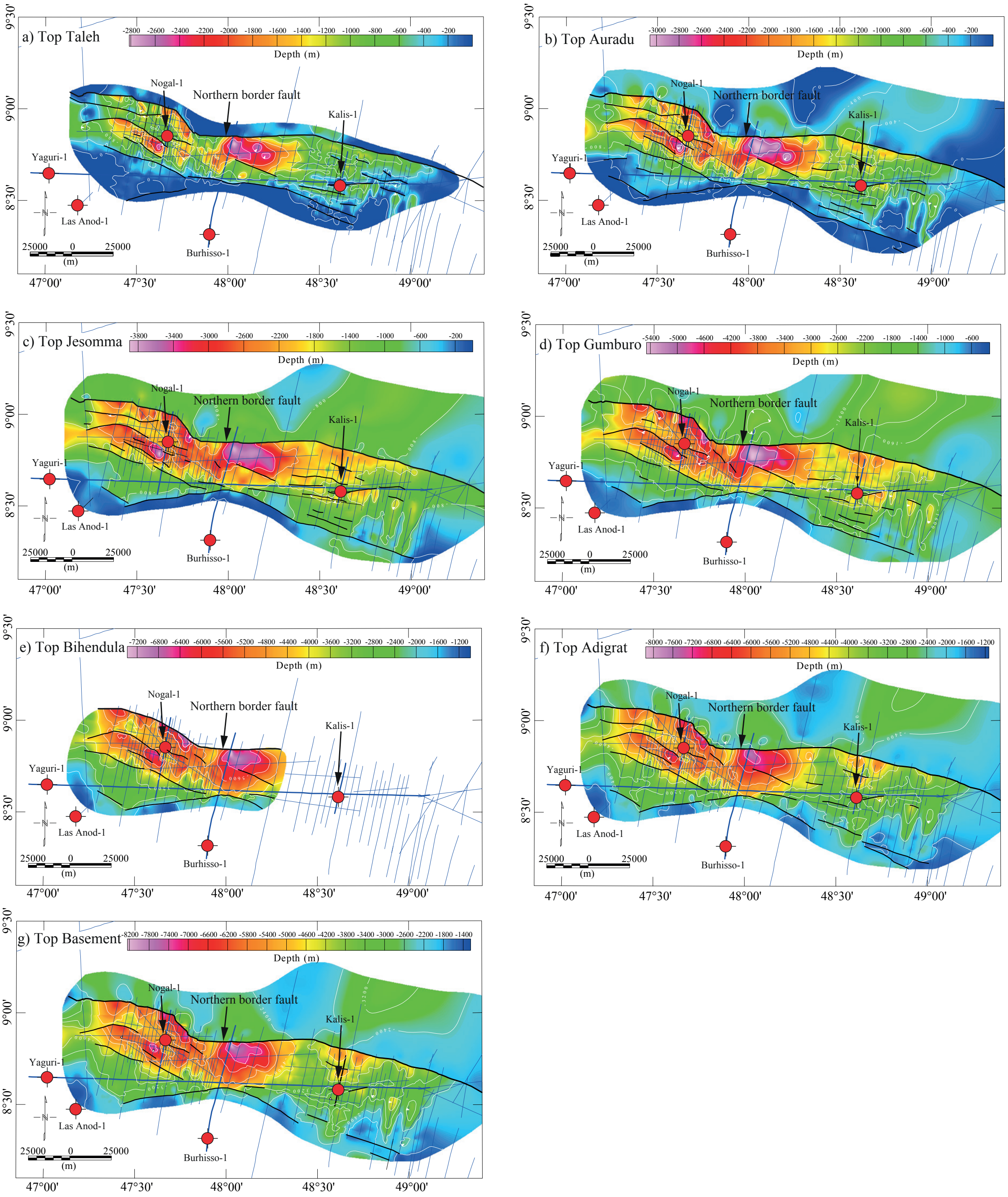

Fig. 13. Depth structure maps of formation tops. (a) Top Taleh (b) Top Auradu (c) Top Jesomma (d) Top Gumburo (e) Top Bihendula (f) Top Adigrat (g) Top Basement. Thick blue lines show seismic profiles presented in Figs 8–12.

similar to those of the Auradu Formation although they are thinner than the latter. The average thickness of the unit is ~400 m, and there is no major interpreted variation in thickness throughout the basin (Fig. 15) although it is thinner in the footwall of the border faults. This is probably because erosion was enhanced in uplifted footwall areas, and the eroded sediments were then redeposited in the hanging wall as the Nogal Group. Therefore, the unit together with the underlying Auradu Formation was interpreted as a post-rift sequence deposited after the Cenomanian–Maastrichtian rifting event.

Nogal Group

The sequence exhibits strong and clear, continuous and sub-parallel reflectors. It is only recorded in wells at the centre of the Nogal Basin (e.g. Nogal-1) and there is no evidence of it in platform areas. The seismic

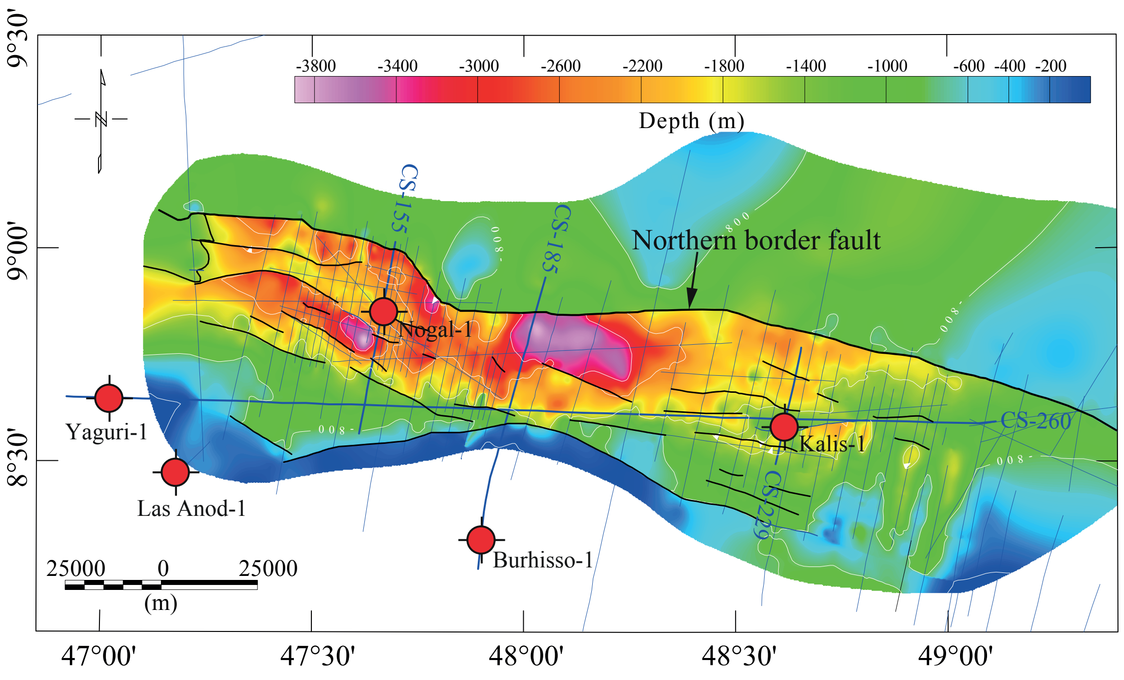

Fig. 14. A larger scale depth structure map of the Top Jesomma. Thick blue lines show seismic profiles presented in Figs 8–12.

data indicate a major unconformity as the Oligocene-Miocene Nogal Group onlaps the Eocene Taleh–Karkar Formations at the margins of the basin (Figs 8 and 11).

Furthermore, the seismic profiles (Figs 9–12) indicate that reflectors in the lower part of the Nogal Group are generally parallel to the Taleh and Auradu Formations at the centre of the basin. This observation suggests that an initial sagging accommodated Early Oligocene continental sediments. However, as fault-controlled subsidence increased, a WNW-ESE trending half-graben developed, bounded by a south-facing fault system to the north and a more flexural margin in the south. The graben is floored by several northeasterly tilted fault blocks, subsequently filled and buried by predominantly continental sediments of the Nogal Group, while the adjacent platform was uplifted and partially unroofed. Its internal structural architecture suggests it was formed during a discrete phase of faulting, block rotation and mild transpressional deformation along the boundary faults and subsequently healed and partially buried by flat-lying Pliocene-Pleistocene sediments.

Well Nogal-1 penetrated 877 m of the Nogal Group which consists of interbedded gypsum, limestones shales and sandstones (Poppendeck and Cowen, 1990). The sequence shows major thickness changes across syn-depositional faults. It thickens towards the northern border fault and is ~1300 m thick (0.9 sec TWT) and ~2170 m thick (1.5 sec TWT) in the NNE of seismic profiles CS-155 and CS-185 respectively (Figs 9 and 11). Its maximum thickness is ~ 2800 m, which occurs at the centre of the basin (Fig. 15), and the thickness increases are related to the rifting phase related to the opening of the Gulf of Aden. The Nogal Group gradually thins and disappears outside the basin due to erosion or non-deposition (Figs 9, 11 and 15). The area east of line CS-220 did not undergo this phase of rifting with same intensity.

Fault Interpretation

Seismic data indicate that a major period of growth of the Nogal Basin occurred in the Oligocene–Miocene with the development of significant half-grabens (Figs 9–11). Reactivation of Cenomanian–Maastrichtian faults resulted in the segmentation of the graben area into a series of tilted fault blocks. In addition, the seismic profiles suggest that major normal faults cut through the entire sequence, except in the shallow ?Pliocene–Pleistocene Nogal Group.

Both complex border faults and basin interior faults are observed in the Nogal Basin, and in general can be grouped into three sets: the northern border fault; the central fault with associated minor faults; and the southern border fault (Figs 13–16). The northern and southern border faults correspond to the faults which bound the basin, and form domino-style normal structures with rollover anticlines in their hanging wall blocks (Figs 8–12). The northern border fault trends WNW-ESE while the southern border fault shows an east-west trend; these trends are consistent with the rift axis. The northern and central faults dips towards to SSW; however, the southern border fault dips in

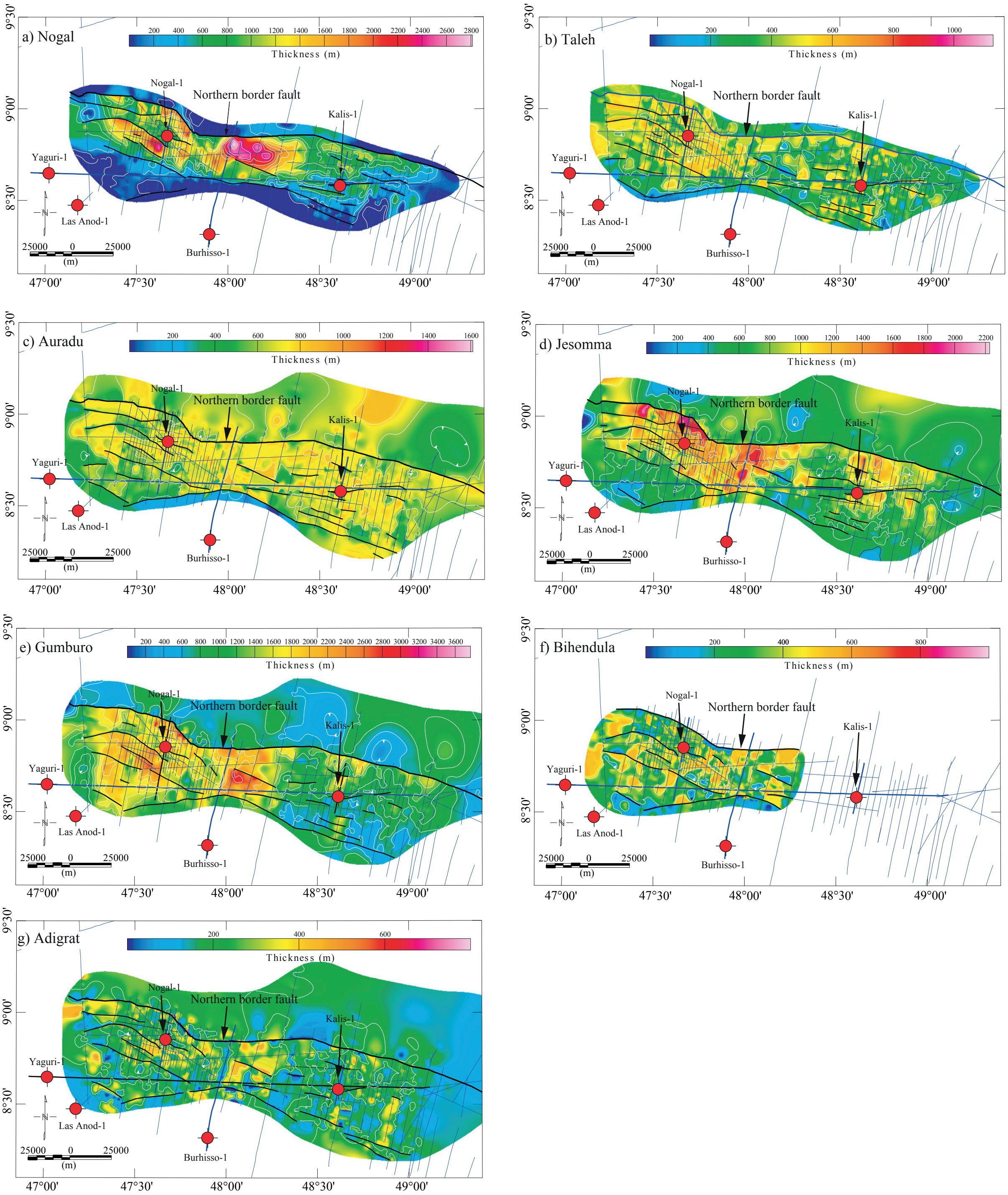

Fig. 15. Isopach maps (in depth) of the (a) Nogal (b) Taleh (c) Auradu (d) Jesomma (e) Gumburo (f) Bihendula and (g) Adigrat Formations. Thick blue lines show seismic profiles presented in Figs 8–12. The thickness maps of all the formations were generated by subtracting each subsequent depth surface map.

an NNE direction and the throw is much smaller than those of the central and northern faults. Most of the minor faults show reverse polarity against the northern and central major faults. The isopach maps (Figs 15 and 16) show thickening of the Upper Cretaceous Gumburo and Jesomma Formations along northern border and central faults and complimentary uplift of the margins.

In the western and central parts of the basin, the northern border fault has a large-scale throw (~1 sec TWT, approximately 3000 m), but the offset becomes less towards the eastern part of the basin (Figs 9, 10 and 11). The throw on the rift-bounding faults in the sub-basin to the NW of the main Nogal Basin is estimated to be ~1000 m (Fig. 8). Seismic line CS-280 shows that the Gumburo Formation is faulted against the Basement, and the Jesomma and Auradu Formations are faulted against the Adigrat and Gumburo Formations (Fig. 8).

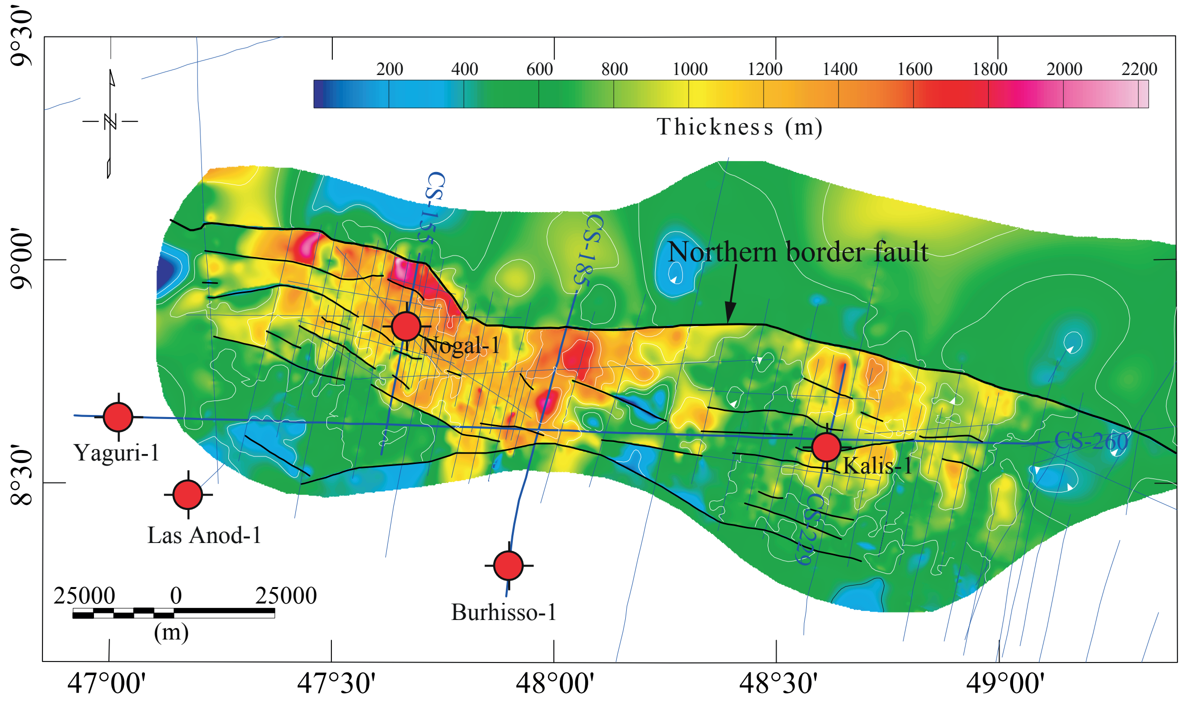

Fig. 16. A larger scale isopach map of the Jesomma Formation. Thick blue lines show seismic profiles presented in Figs 8–12.

DISCUSSION

Tectonic evolution of the Nogal Basin

The main graben area of the Nogal Basin as defined from the seismic data is approximately 250 km long and 40 km wide with a dominant NWN-ESE strike. Its depocentre is at least 7000 m deep and is located south of the northern border fault in the Shileh Madu Range. Other graben areas, which possibly formed contemporaneously, are observed NW of the Nogal Valley; for example, seismic line CS-280 (Fig. 8) shows a half graben which seems to be orientated parallel to the main Nogal Basin.

Structural development and sedimentary filling of the Nogal Basin can be divided into three periods of rift-related subsidence. These are probably related to the late-stage break-up of Gondwana and a rapid increase in spreading rate on the ridges separating the African and Indian plates during the Late Jurassic and Late Cretaceous respectively, and to the opening of the Gulf of Aden during the Oligocene–Miocene. These rifting episodes were interrupted by phases of uplift and erosion. The first two rift episodes are an early Late Jurassic half-graben phase with deposition of the Bihendula Group; and a Late Cretaceous graben stage with continuous subsidence during which the Gumburo and Jesomma Formations were deposited. However, although the regional stratigraphy of northern Somalia supports a model of possible Late Jurassic rifting across the Nogal Basin, seismic and well data as yet only support the Late Cretaceous (Cenomanian to Maastrichtian) rift phase, with a second rift phase in the Oligocene–Miocene to Recent.

In northern Somalia, the Adigrat Formation and probably the lower section of the Bihendula Group (upper Hamanlei) is equivalent to a pre-rift sequence, and shallow-water carbonates of the Bihen Formation mark the transition to a marine environment (Ali and Watts, 2016). Deposition of the middle to upper Bihendula Group occurred during the Late Jurassic rift phase.

The Bihendula Group contains the primary source rock in the basin and its preservation is therefore critical for the petroleum system (Ali and Lee, *in press*). Seismic data in the western and central parts of Nogal Basin could neither identify top-basement nor conclusively resolve events (e.g. unconformities) in the interval between top-basement and top-Gumburo. Consequently, the occurrence of an Upper Jurassic source rock based solely on the present seismic data may be disregarded, although this may change if future well or high-resolution seismic data show that rift-related subsidence began in the Late Jurassic. This subsidence could preserve at least some of the section which was otherwise eroded during pre-Cenomanian uplift. Thus, the Faro Hills-1 and Kalis-1 wells, for example, show that the Upper Cretaceous Gumburo Formation rests directly on a thin Adigrat basal conglomerate. Hence, the Upper Jurassic successions are either missing or may be preserved only in localised grabens in the western and central parts of the Nogal Basin. It is therefore plausible that the Upper Jurassic rift sediments were removed by the pre-Cenomanian uplift event or by the Erigavo-Nogal Arch which developed during the Late Jurassic; hence Upper Jurassic rift-fill facies were not deposited in the Nogal Basin. The Upper Jurassic sediments that may have been eroded in the Nogal region were possibly deposited further east, as the Cotton-1, Sagaleh-1 and Garad Mare-1 wells penetrated thick sequences (up to 780 m of the Cotton Formation) of Early Cretaceous age. The origin of the pre-Cenomanian uplift event and the Erigavo-Nogal Arch is not known but it might be associated with regional-scale tectonic uplift flanking the Gondwana rifted margin. Alternatively, the uplift event may have resulted from a regional thermal doming related to plutonic bodies that intruded during the Early Cretaceous.

The aeromagnetic data identified high magnetic zones with a NW-SE orientation which are interpreted to represent plutonic bodies of similar age to the quartz-syenite intrusion (i.e. 118–127 Ma) at Gorei. Moreover, the seismic data show no indication of intrusive bodies within the sedimentary cover. However, all of the sequences imaged by seismic profile CS-280 (Fig. 8), west of Faro Hills-1, could be interpreted Late Cretaceous and younger, assuming the intrusions are same age as that at Gorie. This interpretation is based on the lack of acoustic impedance contrast between the sedimentary sequences and the quartz-syenite intrusions which are not therefore detected in the seismic data. The intrusive bodies may be contemporaneous with the pre-Cenomanian uplift that resulted the Erigavo-Nogal Arch.

The stratigraphy of the Gumburo and Jesomma Formations is consistent with a rifting episode that post-dates the pre-Cenomanian uplift. The seismic profiles and surface and isopach maps suggest that sedimentation was fault controlled, and the Gumburo and Jesomma Formations show characteristics of syn-rift sequences (Figs 8–16) with significant thickness variations across the rift (Figs 8–16). Compared to sections in footwall locations, the Jesomma Formation is more than three times thicker, and the Gumburo Formation more than two times thicker, than equivalent sections in the Faro Hills-1 well (Fig. 5). Thickness variations are also evident within the rift across faults (Figs 8–16). These two syn-rift sequences in general consist of sandy carbonates and sandstones, and are the most important potential reservoir units in the basin (Ali and Lee, *in press*).

The Paleocene to Eocene Auradu and Taleh Formation are consistent with post-rift deposition, with constant thicknesses throughout the Nogal region (Fig. 15). These units may serve as a regional seal because they are composed of tight limestones and evaporites, respectively (Ali and Lee, *in press*). The Karkar Formation and upper part of the Taleh Formation are eroded in many parts of the Nogal region due to Oligocene uplift and unroofing (Figs 8 and 9).

The Nogal Group which overlies the Taleh Formation is thicker (up to 2800 m) in the centre of the Nogal Basin (Fig. 15a). The group is absent in well Kalis-1 (Fig. 5) and adjacent platforms. However, its thickness is generally less than 800 m in the western part of the basin (Fig. 15a). The group correlates well with other Gulf of Aden depocentres in northern Somalia, such as those in the Daban Basin (Ali, 2015). Deposition of the Nogal Group was controlled by growth faults related to the development of the Gulf of Aden rifting event (Figs 9–11). The middle to upper part of the group represents a post-rift sequence since it shows little variation in thickness (Fig. 9).

Structural Trends in the Nogal Region

The geometry of the major faults in the Nogal Basin in general form a half-graben structure (Wernicke, 1985). The Upper Cretaceous synrift sequences and overlying Cenozoic have similar WNW-ESE trends (Figs 13–16), and the most prominent structural features in the basin are WNW-ESE trending domino-style normal faults together with fault-block ranges in the northern flanks of the Nogal Valley. The northern border fault probably began to develop in the Mesozoic and coincide with the escarpments of the Shileh Madu and Bur Dab Ranges (Fig. 2). The Shileh Madu Range is tilted to the NNE with dips of 5–10°, with stratigraphic throws on south-dipping normal faults of up to 900 m. The Bur Dab Range is tilted SW with dips of 3–10°, and stratigraphic throws on north-dipping normal faults of 600-700 m (Harms *et al.*, 1989; Mackay *et al.*, 1954). During the Cenomanian–Maastrichtian, epeirogenic movements and rifting generated numerous faults, but it is hard to distinguish them from faults reactivated during Oligocene–Miocene rifting. Nevertheless, since the faults displace the Taleh Formation, significant movement must have occurred in late Eocene or Oligocene–Miocene times.

Granath (2001) suggested that the Nogal Basin and associated sub-basins are bordered by NW-SE trending normal faults. In this interpretation, the sub-basins in the Nogal region continue to the Las Dureh and Berbera sub-basins (Figs 2 and 17). However, seismic and outcrop mapping indicate that the faults bounding the northern side of the Nogal graben do not continue to link up with the Las Dureh and Berbera sub-basins. For example, the structural data acquired in the Huddun area and western Nogal region show a series of east-west to WNW–ESE trending normal faults with southerly-tilted fault blocks resulting in half graben systems. These faults separate the uplifted blocks of the Hagrin and Bur Anod-Hagraajin-Shileh Madu Ranges from the down-faulted blocks of the Huddun and Ban Tur Anod Basins (Fig. 2). In the Bur

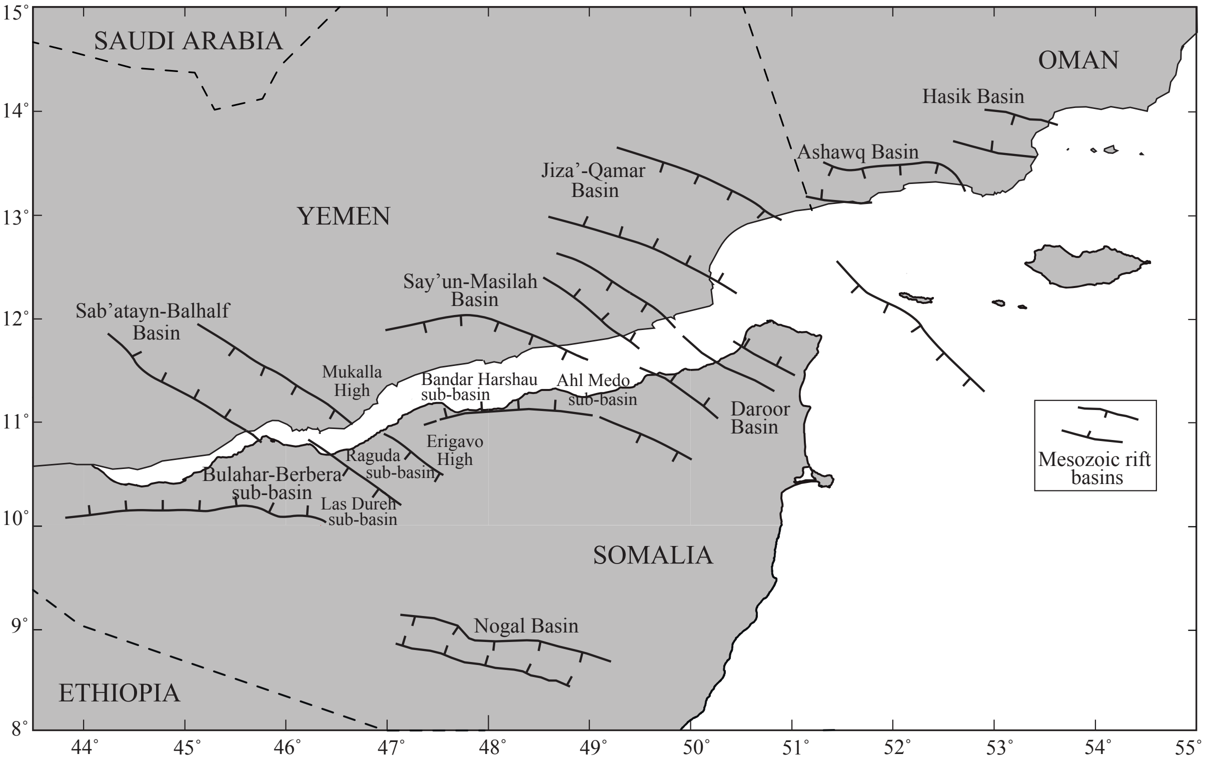

Fig. 17. Reconstruction of the opening of the Gulf of Aden to magnetic anomaly 6 (19.7 Ma), the oldest magnetic anomaly recognised in the Gulf of Aden (modified from Fournier *et al.*, 2010). Also shown are the Mesozoic rift basins in Yemen and northern Somalia (modified from Ali, 2015).

Anod-Hajraajin-Shileh Madow Range, the Aurdau Formation dips gently (6-25°) to the NE; however, in the Hagrin Range, it seems that the Auradu, Taleh and Karkar Formations are flat-lying with some evidence of drag folding to the south where the Auradu dips 5° to the SW.

Mesozoic Rift Basins in Northern Somalia, SE Ethiopia and Yemen

Seismic interpretation combined with well data demonstrate that the Nogal Basin and associated sub-basins underwent multiple tectonic events. The basin formed as a narrow WNW-ESE trending graben as a result of Cenomanian–Maastrichtian and Oligocene–Miocene rifting, probably in the same location as an earlier, Late Jurassic rift. However, the earlier events had a predominantly NW-SE orientation parallel to Mesozoic rift basins of northern Somalia and southern Yemen (Ali and Watts, 2016).

In the Guban Basin, the sedimentary section consists mainly of Upper Jurassic (Oxfordian to Tithonian) Bihendula Group carbonates overlain by Upper Cretaceous Jesomma sandstones and Cenozoic sediments. Due to pre-Cenomanian erosion, the Upper Jurassic Bihendula Group is only preserved in localised graben. Although the Guban Basin trends generally NW-SE, its stratigraphy and tectonics are essentially identical on a regional scale to those of the Nogal Basin.

In the Daroor Basin, two wells drilled recently (Shabeel-1 and Shabeel North; Fig. 2) by Horn Petroleum encountered an identical stratigraphy to that of the Kalis-1 well (Africa-Oil-Corp., 2013). The wells penetrated a thick section of the Upper Cretaceous Gumburo and Jesomma Formations, a thin section of Adigrat Formation, and reached the metamorphic basement of the Inda Ad Series at 3430 m and 3919 m respectively, without encountering the Upper Jurassic Bihendula Group. The absence of Upper Jurassic sediments in these wells may be a result of pre-Cenomanian erosion.

The stratigraphy of the Ogaden Basin, SE Ethiopia, shows many similarities with that of northern Somalia. The lower, middle and upper Hamnlei (Bihen) Formations make up the Lower Jurassic to Callovian syn-rift marine sequence (Hunegnaw *et al.*, 1998). The Callovian–Oxfordian Uarandab Formation (Gahodleh-Wanderer-Daghani) corresponds to the maximum flooding sequence deposited during the break-up transgression, and the Tithonian Gabredarre (Gawan) Formation represents a passive-margin sequence (Hunegnaw *et al.,* 1998*)*. The Cretaceous successions (Gorrahei, Mustahil, Ferfer, Belet Uen and Jesomma Formations) are interpreted to have been deposited in an intracratonic sag basin as a result of activity on shear zones formed by far field stresses generated by the opening of the South Atlantic Ocean (Hunegnaw *et al.,* 1998).

Although now separated by the Gulf of Aden, Yemen and northern Somalia shared a common tectono-stratigraphic history during the Jurassic, Cretaceous and Paleogene (Beydoun, 1970). Reconstructing the Arabian and African plates to their pre-rift position before the opening of the Gulf of Aden shows that rift basins in southern Yemen extended to northern Somalia (Fig. 17). For example, the Balhaf and Sab'atayn Basins appear to be a continuation of the Berbera-Bulahar and Raguda sub-basins; the Erigavo-Nogal Arch is the continuation of the Mukalla High; and the Bandar Harshau and Ahl Medo sub-basins are conjugates of the Say'un-Masilah Basins (Ali, 2015; Beydoun, 1970; Bosworth *et al.*, 2005) (Fig. 17). In addition, Birse *et al.* (1997) suggested that the Late Jurassic extensional NW-SE (140°) lineament that occurs in the Marib-Al Jawf-Balhaf grabens of Yemen extends to the Guban and Nogal grabens in northern Somalia. This trend is also parallel to that of the Masilah and Daroor Basins (Ali and Watts, 2016), and subsurface data demonstrate that these basins are part of a NW–SE striking rift system (Ali and Watts, 2016; Ellis *et al.*, 1996). On the Yemeni side, the entire Jurassic is known to be absent on the Mukalla High where Cretaceous sediments rests unconformably on a peneplained basement.

In Yemen, the orientation and age of the Mesozoic rift basins vary from the west to the east of the country. In western and central Yemen, the Sab'atayn and Balhaf rift basins are oriented NW–SE (Bosence, 1997; Bott *et al.*, 1992; Brannan *et al.*, 1997) (Fig. 17). The earliest syn-rift strata within the Sab'atayn (Marib-Shabwa) Basin are early to mid Kimmeridgian in age (Holden and Kerr, 1997), with maximum subsidence occurring in the Kimmeridgian and Tithonian (Redfern and Jones, 1995). To the east, the Say'un-Masilah and Jiza'-Qamar Basins are oriented progressively more east-west (Beydoun, 1996; Beydoun, 1997; Bosence, 1997; Brannan *et al.*, 1997; Redfern and Jones, 1995) (Fig.17). These basins are relatively younger than the NW-SE oriented basins, with syn-rift deposits starting in the Hauterivian and subsidence continuing intermittently through to the late Cenozoic (Bosence *et al.*, 1996). The change in stress orientation over time has been suggested to relate firstly to the inherited NW-SE Najd trend, which was later translated to an external stress induced by the northward movement of India in the Late Cretaceous together with involvement with the rifting and spreading of the Gulf of Aden (Bosence *et al.*, 1996; Bosworth *et al.*, 2005; Redfern and Jones, 1995; Birse *et al.*, 1997).

Based on the above observations and by analogy with Yemen, it is possible that the WNW-ESE trending Nogal Basin is predominantly a Late Cretaceous rift basin, with little subsidence during the Late Jurassic, as in the Say'un-Masilah and Jiza'-Qamar Basins in Yemen which have a similar orientation as a result of the Erigavo-Nogal Arch which was centred on the region. However, it is also possible that Upper Jurassic rift sequences were deposited but were removed by the pre-Cenomanian uplift event.

CONCLUSIONS

The following main conclusions can be drawn from this study of the Nogal Basin, northern Somalia:

Aeromagnetic data identified high magnetic zones with a NW-SE orientation, which are interpreted to represent plutonic bodies of similar age to that of the Gorei intrusion (i.e. 118–127 Ma) in the Shileh Madu Range. The data also show a suture zone which separates the basement of the Inda Ad Series in the SE from the igneous and high-grade metamorphic basement in the NW.

Interpretation of closely-spaced seismic profiles shows that sedimentation and structural development of the main Nogal Basin and associated sub-basins were strongly affected by rifting events. The sub-basins have a WNW-ESE trend similar to that of Cretaceous rift basins in Yemen.

Seven sequences have been defined in the Nogal Basin: Nogal Group (Oligocene–Miocene to Recent), Taleh and Karkar Formations (Lower to Middle Eocene), Auradu Formation (Paleocene to Lower Eocene), Jesomma Formation (Maastrichtian), Gumburo Formation (Cenomanian to Campanian), Bihendula Group (Upper Jurassic), and Adigrat Formation (Lower–Middle Jurassic).

The Upper Jurassic Bihendula Group, which is the main source rock interval in northern Somalia, is either absent in the basin or preserved only in localised grabens in the western and central parts of the basin.

A major unconformity (pre-Cenomanian) below the Gumburo Formation records a basin-wide uplift and erosional event which removed most of the Jurassic sequences. This uplift formed the Nogal-Erigavo Arch, a NW-SE area where the Upper Cretaceous rests directly on Lower-Middle Jurassic sediments or basement. The origin of the event is not understood but may be associated with regional uplift on the rifted margin of Gondwana.

Seismic data document a well-developed half graben with thickening of the Upper Cretaceous and Oligocene–Miocene sequences towards the northern border fault.

The border fault bounds the basin in the north. The thickness of Cretaceous formations in the footwall block is less than that in the hanging wall, implying that the border fault was active syn-depositionally.

Seismic data suggest an early rift sag phase which accommodated Early Oligocene continental sediments of the Nogal Group. This was followed by a period of strong rotational faulting and tilting, and these structures were subsequently healed and partially buried by flat-lying Pliocene–Pleistocene sediments.

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