

Cenozoic Subsidence and Lithospheric Stretching Deformation of the Ajdabiya Trough Area, Northeast Sirt Basin, Libya*

H.B. Ghanoush¹, J. Imber¹, and K. McCaffrey¹

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¹Structural Geology Group, Department of Earth Sciences, University of Durham, Science Site, South Road, Durham DH1 3LE, UK (ghanoush@hotmail.com)

Abstract

The Ajdabiya Trough is a failed rift that represents the deepest part of the Sirt Basin, Libya ([Figure 1](#)). It is postulated that more than 7000 m of Mesozoic-Cenozoic sediments accumulated in this depocenter (Rusk, 2001; Hallett, 2002). The Ajdabiya Trough has significant petroleum potential. However, most exploration activity has focused on the relatively shallow basin flanks and adjacent platforms. As a result, the structural and stratigraphic development of the central Ajdabiya Trough is poorly known. The aim of this study is to use 2D seismic reflection profiles, potential field data and information from exploration wells to illustrate key features of the tectonic evolution across the Ajdabiya Trough. In particular, these data are used to determine the tectonic subsidence during the latest syn-rift (Cretaceous to Palaeocene) to post-rift periods, and to estimate syn-rift crustal stretching. Our study builds on previous research by Gumati (1981), Gumati and Kanes (1985), van der Meer and Cloetingh (1993) and Abadi et al. (2008).

Subsidence is calculated by assuming 1D Airy isostatic equilibrium, which allows backstripping based on sedimentary thicknesses, horizon ages, lithologies, and paleo-water depths obtained from well information and crosschecked against sediment isopach and structural maps. The combination of these two approaches allows quantification of tectonic and total subsidence and their relationship to fault activity during the syn- to post-rift stages. The syn-rift sedimentary package has not been encountered or entirely drilled in most of the wells. For this reason, a pseudo (synthetic) well derived from 2D seismic interpretation has also been modeled. In addition to the syn-rift package, the location of the pseudo-well was chosen in order to evaluate the history of the deepest parts of the basin, which are not yet drilled.

Geologic Setting

The Sirt Basin is the youngest intracratonic rift basin in Libya, formed by active subsidence and block-faulting ([Figure 1](#)) accompanying the collapse of the Sirt Arch in late Early Cretaceous time (Hallett, 2002). The subsidence of the basin reached a climax during Paleocene and Eocene times (Gumati and Kanes, 1985; Abadi et al., 2008). The Precambrian basement and Early Paleozoic sediments of the basin were

fragmented and subsided differentially to depths of more than 6000 m (Gumati and Schamel, 1988). According to Tawadros (2003) onset of subsidence in the eastern part of the former Sirt Arch started in the Middle Triassic, likely along ENE to NE trending faults in Cyrenaica Platform ([Figure 1](#)). The main collapse of the Sirt Arch occurred later, during the Early Cretaceous (Hallett, 2002). During the Late Cretaceous and throughout the Tertiary, the deep troughs in the Sirt Basin received large quantities of organic-rich shales, evaporites and clastic materials. At the same time, the uplifted blocks were the site of carbonate deposition, with reef development on the flanks and crests of the highs (e.g. Hallett, 2002). The southeastern part of the Sirt Basin was a siliciclastic, dominantly fluvial environment while the offshore penetrations show a marine carbonate-dominated depositional environment. The Ajdabiya Trough formed the connection between these two environments. To the south, the Sirt Basin is less disturbed and shallower; its continuation is marked by a thin succession of Early Tertiary sediments (Conant and Goudarzi, 1976).

Evidence from the eastern Sirt Embayment shows the presence of Triassic and Jurassic rocks forming the oldest part of the syn-rift sequence, and the same situation may be present in other parts of the Ajdabiya Trough. The main syn-rift deposition occurred in the early Cretaceous when the pre-Upper Cretaceous, Nubian (Sarir) Sandstone ([Figure 2](#)) accumulated in rift troughs and topographic lows on the irregular pre-Cretaceous surface and passing into a quartzitic facies in the northern Ajdabiyah Trough. Rifting waned during the Late Cretaceous and the entire Ajdabiya Trough basin experienced thermally-induced basin-wide subsidence and a thick succession of homogeneous mudstones with subordinate limestones were deposited (Gir and Gailo formations; [Figure 2](#)). The post-rift sequence represents 90% of the total sediment thickness that reach about 7000 m in the basin centre (Hallett, 2002).

Methods

Crustal thickness (Moho depth) is an important control on subsidence. A low-amplitude, positive Bouguer gravity anomaly exists over the Ajdabiya Trough, possibly attributed to an elevated Moho beneath attenuated crust. Gravity and magnetic modeling ([Figure 3](#)) has therefore been used to estimate crustal thickness variations. Moho depths along variable gravity and magnetic profiles are extracted at regular spacing of about 1.8 km interval over a total length of 180 km each ([Figure 3](#)). The commercial software package GM-SYS was used with initial estimated densities (Libyan Gravity Compilation Project, 2001; Makris and Yegorova, 2006; Casten and Snopek, 2006; Essad, 1978). Values of susceptibility are adopted from Witte, (2008). For modeling purposes, the lithospheric column was divided into different layers, comprising mantle, lower crust and upper crust. The latter includes Palaeozoic, Mesozoic and Cenozoic sediments.

Tectonic subsidence has been estimated by backstripping well data following standard procedures (e.g. Watts, 2001), using a sea level curve from Kominz (1984) and Haq et al. (1987) and exponential porosity-depth relationships characteristic to each lithology (Sclater and Christie, 1980). Paleo-water depths have been inferred from lithological variations in different domains within the Sirt Basin close to the trough. It is inferred that water depths never reached values greater than 200 m (656 ft) (Bezan, 1996; Muftah, 1996). Errors estimated for paleo-water depth are interpreted as less than 50 m (164 ft), using data from Barr and Weegar (1972), Eliagoubi and Powell (1980), Megerisi and Mamgain (1980), Ashour (1996), Barbieri (1996), El Sogher (1996), Muftah (1996), Tmalla (1996). Data obtained from wells B1-12, C1-12, and EE1-6 are based on unpublished joint study report between the Libyan Petroleum Institute and Utah University (Regional Chronostratigraphy of the Cretaceous Sections of the Sirt Basin Libya).

The subsidence analysis is based on five wells mainly located along structural highs where water depths were <100 m (Abadi et al., 2008). Wells located in the trough margins are: LL1-6 (Zelten Platform), A1-114 (Jahama Platform), Q1-31 (Amal Platform), U1-41 (Northeast Ajdabiya Trough), A1-119 (central Ajdabiya Trough) ([Figure 4](#)). Apart from the A1-119 well, exploration boreholes have not penetrated the proposed syn-rift sequences related to the period of Jurassic-Early Cretaceous rifting within the Sirt Basin. Within this poorly-constrained central region a synthetic well (PW-360) has been constructed by combining the lithology from the available wells, and the geological interpretation of the seismic line 05NC213-0360 located at the middle of the study area ([Figure 5](#)). In this case, uncertainties could occur during the conversion of seismic data from time to depth, and from other input parameters such as age constraints, stratal thickness, lithology, porosity, and paleo-water depths. In all cases, where the syn- and post-rift sequences have either been partially eroded (Gumati and Schamel, 1988) or not been drilled in their entirety, the estimated tectonic subsidence represents a minimum value.

Results

Crustal Structure

A Moho depth of ca. 26 km is estimated beneath the Ajdabiya Trough ([Figure 4](#)). The Moho is 26 to 33 km deep in the centre of the trough and sharply deepens towards the northeast and southeast where it remains around 35-40 km. Other work suggests a Moho depth of ca. 23 km below the Sirt Basin (Marone et al., 2003). To the north of the Ajdabiya Trough, within the offshore Sirt embayment, the Moho is present at 30 km depth (Marone et al., 2003). This suggests that the region could be an extension of the northern African margin beneath the Mediterranean Sea, an idea supported by its shallow bathymetry. Our estimates of Moho depth show that the mantle is obvious and elevated beneath the Ajdabiya Trough and distinct from adjacent regions. This elevated Moho is consistent with rifting and crustal thinning beneath the Ajdabiya Trough.

Total and Tectonic Subsidence

The subsidence observed can be resolved into two components: isostatic subsidence caused by the response to sediment- and water-loading; and tectonic subsidence, due to rifting of continental crust and subsequent thermal cooling. A maximum total subsidence of about 5.5 km is recorded in the northeast part of the Ajdabiya Trough (U1-41 well), while in the northwest the total subsidence does not exceed 3.0 km ([Figure 6](#)). In the southeast, the maximum total subsidence recorded is about 4.5 km. In the southwest, Ajdabiya Trough subsidence in the footwalls of the Early Cretaceous faults relates mainly to isostasy. Syn-rift subsidence illustrates the combined effect of two components, which are isostasy and normal faulting. This is the case in the well A1-119 drilled on a basement high of a tilted block and the pseudo well (PW-360) constructed at the centre of attached half-graben ([Figure 5](#)). Backstripping of A1-119 ([Figure 6](#)) yields a very low subsidence during the syn-rift cycle (~0.5 km) and subsidence rate (15 m/Myr), which are not representative of the thick syn-rift series preserved in the grabens and half grabens across the Ajdabiya Trough ([Figure 5](#)).

In the hanging walls, where faulted-block movements are important, isostasy effect is limited and subsidence is largely driven by normal faulting, as shown by the pseudo well PW-360 curve ([Figure 6](#)), where the subsidence rate is 50 m/Myr, 3 times higher than in A1-114. In the northeast part of Ajdabiya Trough, subsidence rates correspond to 85 m/Myr in well U1-41. The minimum values observed in well A1-119 and the other wells drilled on platforms and structural highs surrounding the Ajdabiya Trough may account only for the upper part of the syn-rift,

preserved in structural highs and in footwalls of master faults. This indicates a substantial increase of syn-rift subsidence rates towards the depocenter of the trough, in agreement with extension trend mentioned by previous investigators (e.g. Abadi et al., 2008). Post-rift subsidence can be divided into three phases characterized by different subsidence rates. The curves show a relatively slow to moderate subsidence from 100 to 65 Ma, and a more rapid and uniform rate during the periods 65-55 Ma and 37.0-33.0 Ma. These two phases of more rapid subsidence, corresponding to phases of fault activity at the and late Paleocene-early Eocene (Gumati, 1982; Gumati and Nairn, 1991; van der Meer and Cloetingh, 1993). The early post-rift period (65-54.8 Ma), shows abrupt moderate to high basement subsidence during the Paleocene, comprised between 0.5 km for U1-41 and A1-119, 0.7 km for A1-114 and 0.8 for Q1-31. The associated subsidence rates are also relatively moderate to high, 30 m/Myr, 50 m/Myr, 50 m/Myr and 75 m/Myr respectively. This phase corresponds to the deposition of Paleocene carbonates. Following the early post-rift, the Middle to Upper Eocene post-rift phase (50-33.7 Ma), is characterized, along an entire domains, by an increase of subsidence rates (40-80 m/Myr). For the period (33.7-0 Ma) post-rift accelerated subsidence occurred during the Early Oligocene at the western part of Ajdabiya Trough (80-100 m/Myr), as observed in wells A1-114 and LL1-6. Fault analysis during this period show that there is a dramatic decrease in the number of active faults and fault growth rate, which indicates that no active brittle crust extension occurred during the post-rift period. Regional slow subsidence due to thermal cooling began to occur during Late Oligocene.

However, a period of rapid subsidence occurred in the northern Ajdabiya Trough from Late Miocene (about 10 Ma) to the present as observed from well U1-41 and A1-114. The analysis shows that the syn-rift and post-rift sequences in the Ajdabiya Trough were affected significantly by basement structural relief. There is a ca. 1000 m syn-rift sequence correlated with the basement structural relief, and post rift sequences of more than 4000 m in sag or thermal subsidence stage.

Stretching Factor

We calculated the crustal stretching factor for the Ajdabiya Trough ([Figure 7](#)) as the ratio of the initial crustal thickness (~35 km) to the final crustal thickness, as inferred from gravity and magnetic modeling ([Figure 4](#)) and showed values ranging from 1 near basin shoulders to 1.3 in the depocenter. Abadi et al. (2008) derived an amount of 1.263 in southern Ajdabiya Trough for 98.9-83.5 Ma stretching phase followed by thermal subsidence until 65 Ma. We also measured extension using fault heaves from the seismic line 05NC213-0360. Calculation is based on offsets of marker horizons. Extension length and rate for basement horizon is presented in [Table 1](#).

Discussion

Decompaction and backstripping are used to quantify the tectonic subsidence of the Ajdabiya Trough area. Uncertainties in the input parameters are related mainly to constraints on stratigraphic resolution and water depths. The key issue is that the subsidence data must be used in conjunction with other lines of evidence in order to determine basin controlling mechanisms. The tectonic and basement subsidence curves for the Ajdabiya Trough obtained in this study correlate well with subsidence curves obtained from studies in the Sirt Basin (Gumati, 1985; Gumati and Kanes, 1985; van der Meer and Cloetingh, 1992; Ceriani et al., 2002; Abadi et al., 2008). The subsidence curves ([Figure 6](#)) show linear and exponential profiles during the interval of 90-0 Ma, probably related to syn-rift and thermal subsidence (McKenzie 1978). The subsidence of the Ajdabiya Trough depocentre resembles that of a passive continental margin characterized by medium to high subsidence rate at 20-100 m/Ma (Allen and Allen, 2005). From the Middle Eocene onward, fault-related differential subsidence abated. Fault mapping using

2D seismic data shows that the trough bounding faults exhibit negligible throw across the Tertiary reflections and do not cross cut the above reflections, which means that there is no clear and significant growth in the Cenozoic strata. This along-strike variation in the timing of faulting is also reflected in sediment accumulation, with the thickest accumulations in the northern part of the trough occurring up to the Eocene reflector.

The subsidence is punctuated by periods of decelerating subsidence rates from Early Cretaceous to Miocene time related to periods of tectonic quiescent or change in tectonic regime. For instance, during the Maastrichtian, the depositional environment shallowed upward regressive carbonate facies cycles of the Upper Cretaceous to Danian (Kalash Formation). It is documented that the Sirt Basin undergoes compression during Middle-Late Eocene tilting the basin northward, causing abrupt subsidence in the north and uplift on the basin southern shoulders, possibly driving the latest stage of regional minor subsidence (van der Meer and Cloetingh, 1993; Anketel, 1996). Capitanio et al. (2006) suggested that an abrupt growth of tensile boundary force was recorded in the Sirt Basin, ~55-48 Ma, could have been induced by the avalanching of the Hellenic slab in the lower mantle after ~20 Myr of stagnation on the 660 km discontinuity.

Conclusions

- 1) Backstripping analysis of five wells and seismic data provides new constraint on the development of the tectonic subsidence of the Ajdabiya Trough during Late Cretaceous to Miocene.
- 2) The subsidence is affected significantly by basement structural relief and increases gradually towards the north.
- 3) Subsidence patterns indicate deposition in a flexurally loaded sag basin which migrated northeastwards with time.
- 4) The subsidence induced a change in the basin configuration during the Cenozoic as expressed on the subsidence curves as a different change in subsidence pattern.
 - A convex-upward profile denoting a short and rapid subsidence phase and a subsidence rate that increases through time at 100 m/Ma corresponding to deposition of the Late Pliocene to Early Eocene sequences during the interval of 55-50 Ma.
 - Another convex-upward profile is noticed on the subsidence curve during the interval of 37 to 10 Ma expressing a long phase of rapid subsidence with a subsidence rate that increases through time at 40-100 m/Ma corresponding to deposition of the Upper Eocene to Middle Miocene sequences.
- 5) There may be a period of stability or uplift between convex upward subsidence curves attributed to possible compression and inversion during the period of rapid subsidence. The tectonic subsidence is attributed to thermal contraction following heating and thinning of the crust at the time of rifting.

- 6) Gravity modeling provided evidence of mantle upwelling and crustal thinning which accelerated the subsidence rates and raised the positive gravity anomaly at the center of the trough.
- 7) The subsidence curves show an anomalous subsidence pattern both for the Oligocene and the Miocene, and reflect a period of post-rift thermal subsidence. Gumati and Kanes (1985), van der Meer and Cloetingh (1993), and Abadi et al. (2008) have also pointed to the anomalous subsidence pattern in the same period, with apparent subsidence acceleration.
- 8) The Oligocene-Miocene subsidence increases to about 700 meter in magnitude, which was not predicted by previous works despite existing models of lithospheric stretching (van der Meer and Cloetingh, 1993; Abadi et al., 2008).
- 9) Stretching and extension factors suggest that the excess subsidence is caused by surface and subsurface loading of a lithosphere with an effective elastic thickness in the range of about 25-35 km, with Mesozoic and possibly a middle phase of Tertiary stretching to have occurred.
- 10) In the late stage, the basin subsidence patterns reveal a tilting to the northeast toward the Mediterranean Sea. However, no fault activity in this interval is observed, which indicates that the basin subsided because of sediment loading and thermal relaxation.

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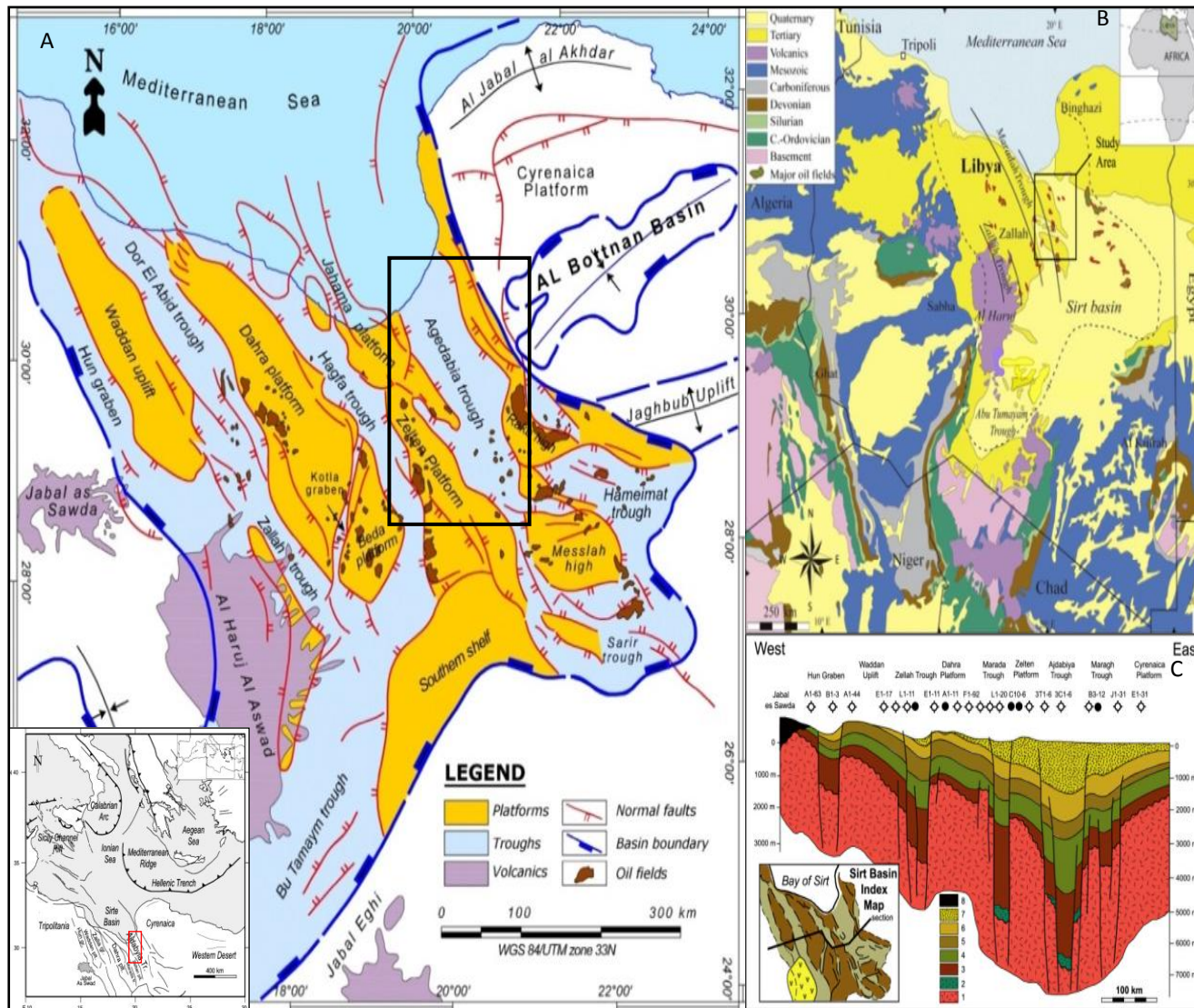


Figure 1. A) Structural map of the Sirt Basin. Inset shows regional tectonic setting with Ajdabiya Trough indicated in red. (B) Shows the surface geology and the outline of the Sirt Basin (dotted line) (Abouessa et al., 2012) and the location of the Ajdabiya Trough (rectangle). (C) Geological cross section across the Sirt Basin modified from Abuhajar and Roohi (2003) and Guiraud et al. (2005). (1) Precambrian basement and Paleozoic quartzites; (2) Lower Mesozoic(?) sandstones; (3) Upper Cretaceous; (4) Paleocene; (5) Lower Eocene; (6) Middle Eocene; (7) Upper Eocene to Recent, (8) Cenozoic volcanics.

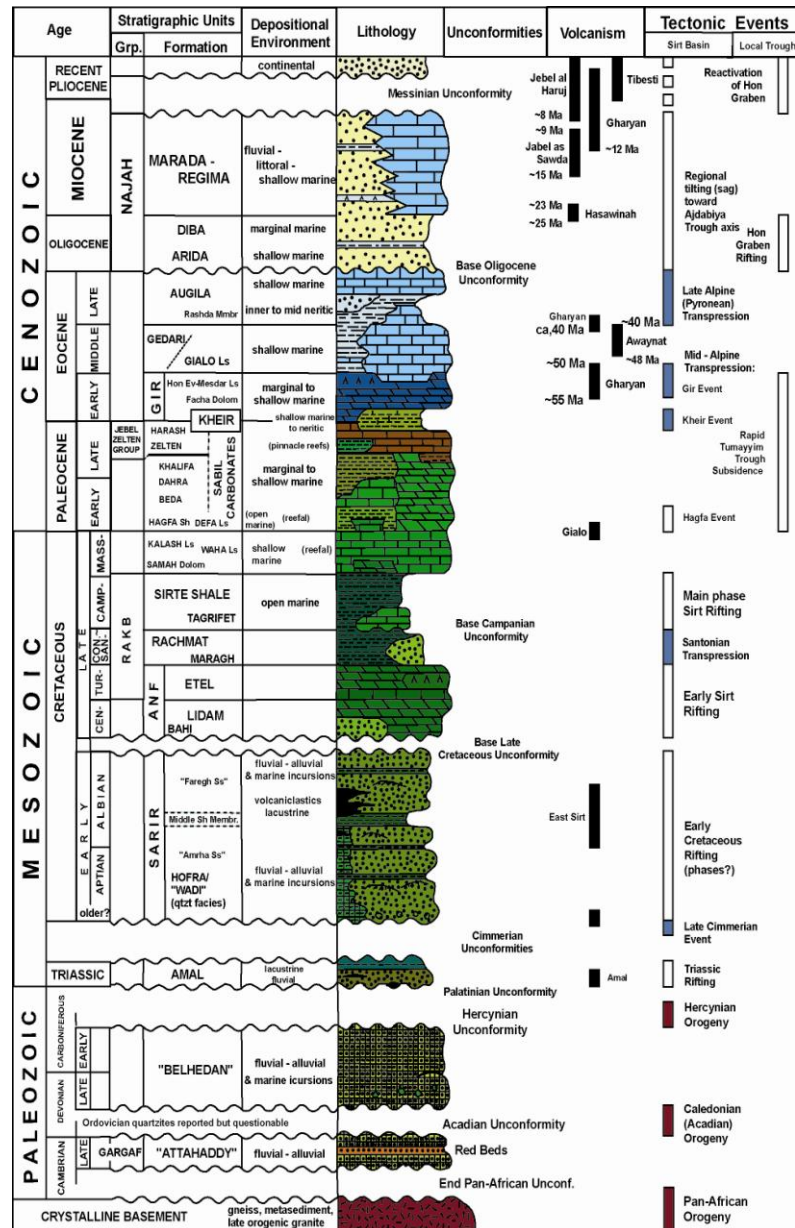


Figure 2. (A) Phanerozoic tectono-stratigraphy of the Sirt Basin, Libya. Vertical bars: black, volcanism, with radiometric ages where known; white, rifting or post-rift sag basins, (modified from Guiraud et al 2005), (B) Stratigraphy of the Eastern Sirt Basin including Ajdabiya Trough.

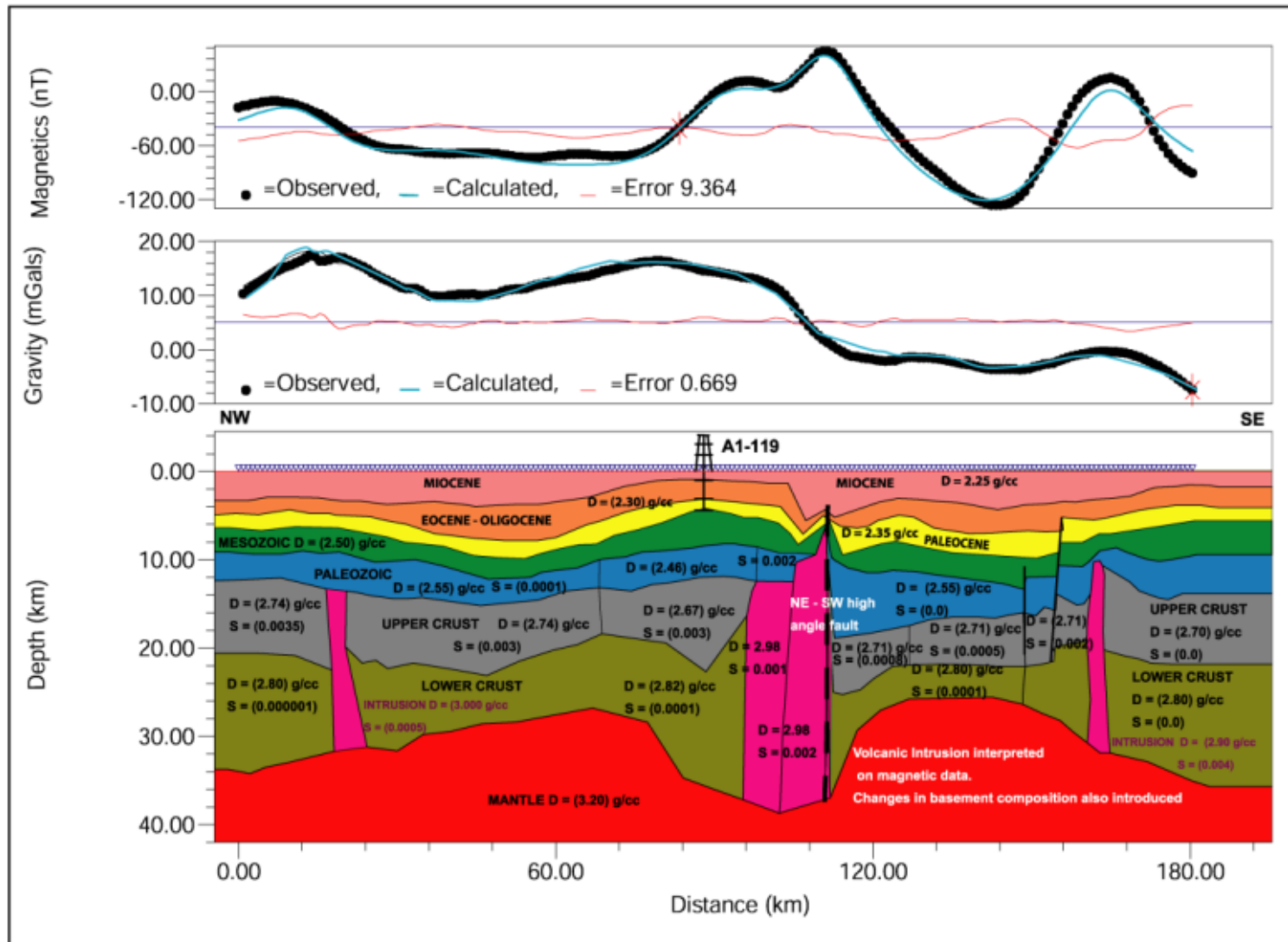


Figure 3. Gravity and magnetic model of the central Ajdabiya Trough. Densities in g/cm^3 are adopted from various sources (Libyan Gravity Compilation Project, 2001; Makris, and Yegorova, 2006, Casten and Snopek, 2006). Published values are mainly based on analysis of well logs (density and sonic) and core sample analysis from the Sirt, Ghadames, Murzuk, Jefara and Cyrenaica areas (Essad, 1978); magnetic susceptibilities are given parenthetically with some constrains from local and regional studies. The modeled gravity and magnetic anomalies are shown with unconstrained intrusive bodies. Crustal thickness varies under Ajdabiya Trough indicating stretching and undulations formed due to sediment loading and subsidence.

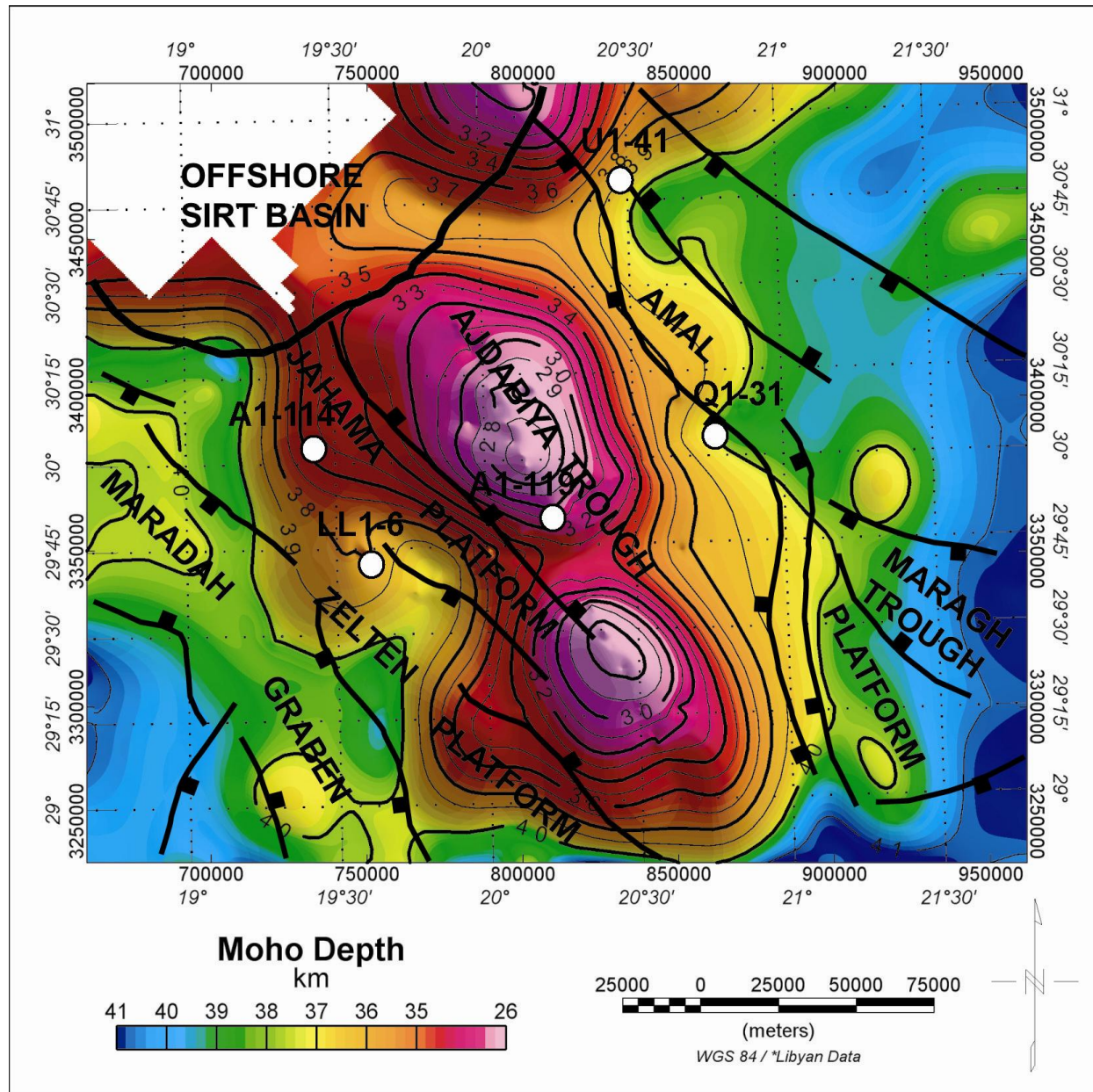


Figure 4. Moho depth map for the Ajdabiya Trough and adjacent areas inferred from gravity and magnetic modeling.

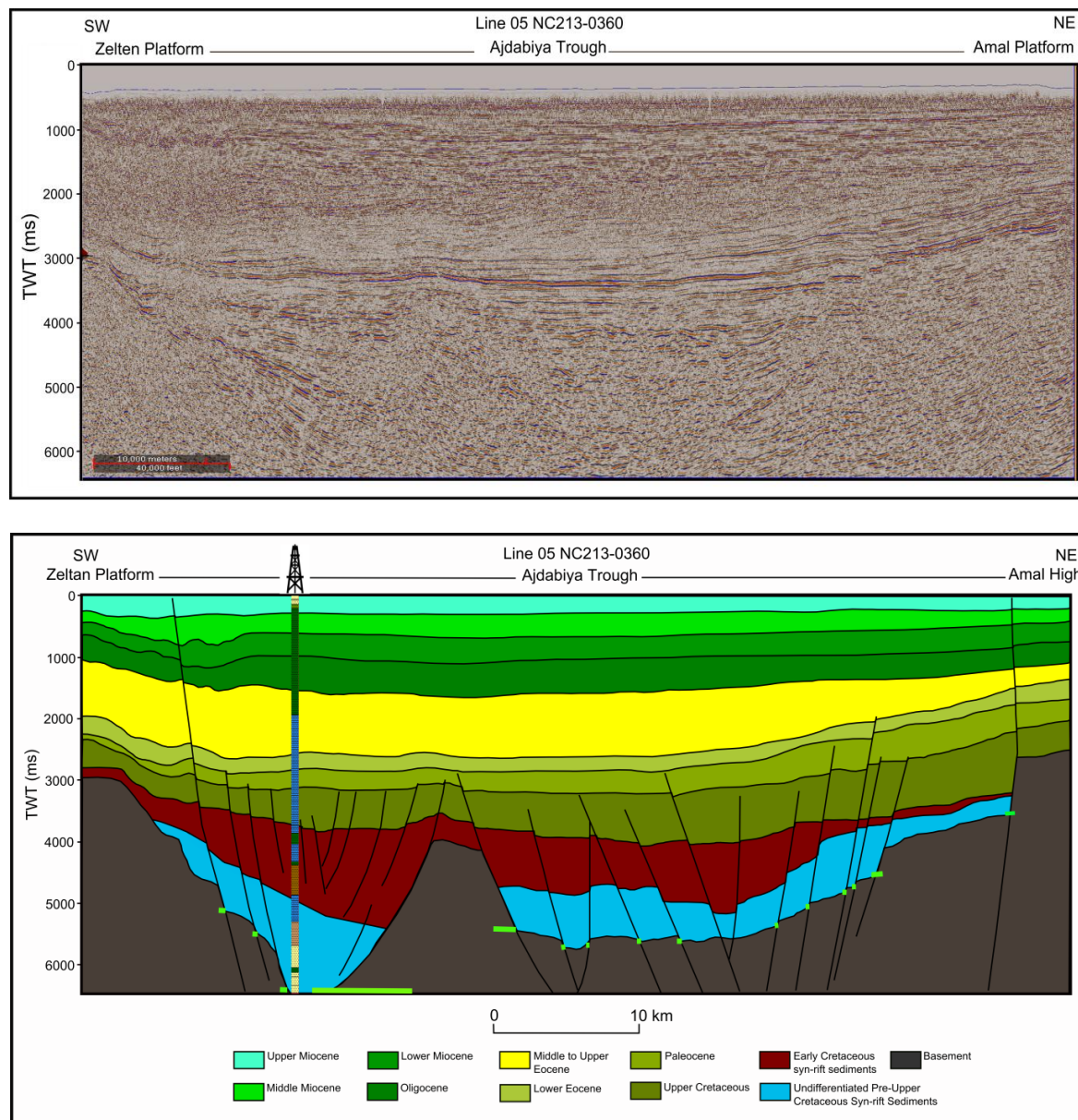


Figure 5. Seismic line 05NC213-0360 running across the Ajdabiya Trough. (A) Original seismic line; (B) Line drawing of the main reflectors with geological interpretation. Green lines are areas where fault heaves were measured for extension factor prediction. Vertical column is the synthetic well used in the subsidence calculation.

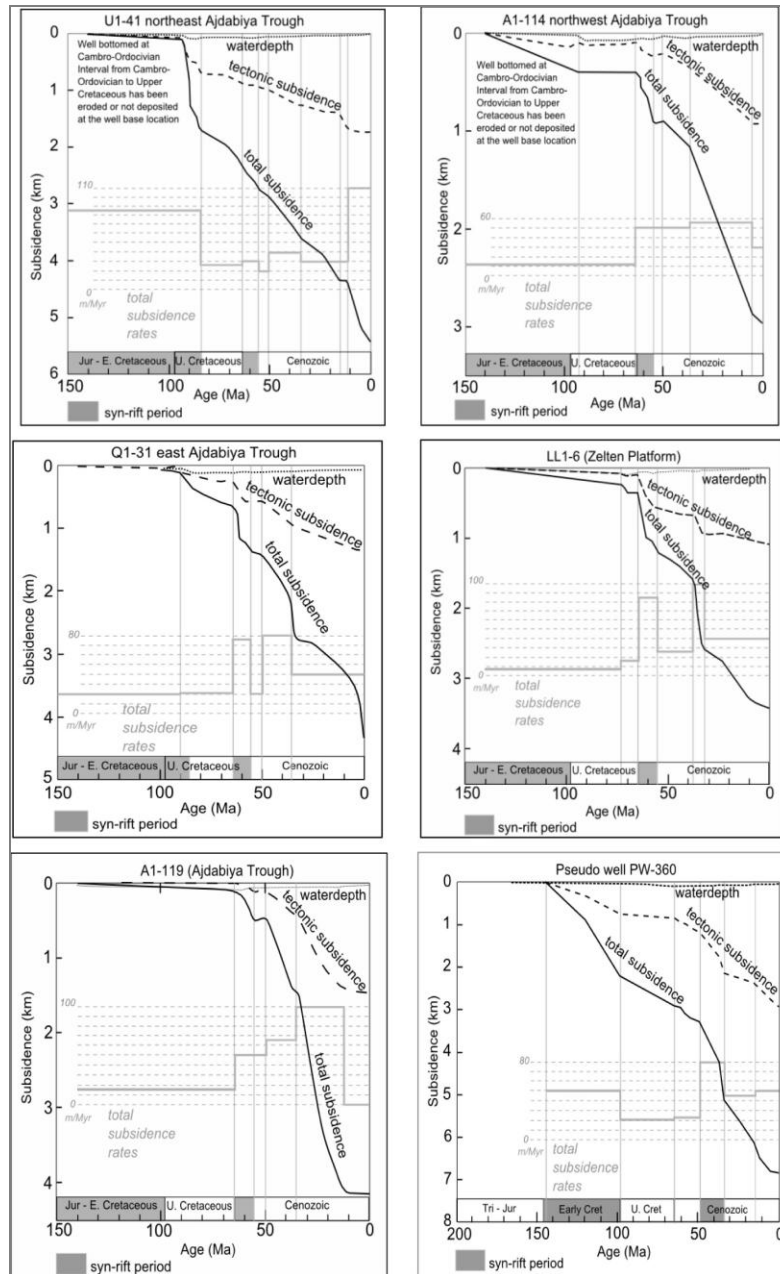


Figure 6. Subsidence curves inferred by backstripping of wells U1-41, Q1-31, A1-114, LL1-6, A1-119 and the pseudo well PW-360.

Extension factors for the basement horizon caused by normal faulting in the southern Ajdabiya Trough, along seismic line 05 NC213-0360 .							
Region	Length (km)	Period	Extension Length (km)	Extension rate (%)	Total extension length (km)	Total extension rate (%)	Stretching factor (β)
South Ajdabiya Trough	85	Basement	18.0	21.17%			~ 1.3

Table 1. Extension factors for the basement horizon caused by normal faulting in the southern Ajdabiya Trough, along seismic line 05 NC213-0360.