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Seismic and sequence stratigraphy of the Palaeocene carbonates at the western margin of Cyrenaica platform, NE-Libya.

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ABSTRACT

The work of this research focuses on seismic sequence stratigraphy of the Palaeocene succession in the western margin of Cyrenaica Platform. The availability of a good seismic and well data provided the opportunity for testing seismic and sequence stratigraphy techniques in the area. This area, geologically, lies on a hinge-line between the subsiding Sirte Basin to the west and the stable Cyrenaica Platform to the east. The immediate objective of this research is to better understand the stratigraphic and facies variation within the Palaeocene sequence in this area.

By the end of the Palaeocene the major tectonic rifting event which formed the Sirte Basin had almost ceased. The subsequent history of the basin was represented the post-rift depositional phase of basin development. The carbonate platform on the western margin of the Cyrenaica Platform contains a record of composite relations between the factors that controlled carbonate platform deposition during the Tertiary.Evolution of this carbonate margin is an excellent example since it clearly shows how the history of this type of margin is dominated by interaction between regional effects, and governed by thermal subsidence consequent upon extension. The shelf edge is the most sediment-starved part of the margin, and given suitable climatic conditions, carbonate deposition can occur at rates equal to subsidence thus maintaining and building the platform. The most important facies and stratigraphic relations of Palaeocene sequence are analysed and discussed in terms of platform development and the principal factors that influenced patterns of sedimentation and the production of carbonate. Furthermore, the sequence stratigraphic and seismic facies study of this interval explain the Paleocene geological history of the Sirte Basin, an essential step in any Hydrocarbon exploration program.

1. Introduction

The area of study is located on the western flank of the Cyrenaica Platform and in a location affected by tectonic elements such as the hinge-line between Sirte Basin and Cyrenaica Platform (Fig. 1). During the late Cretaceous and Tertiary, this area was located on a broad differentiated carbonate platform, that bordered the northern (Tethyan) margin of the African continent (Del Ben and Finetti, 1991; Buxton and Pedley, 1989). The stratal relations and lithofacies preserved in the stratigraphic record document the complex interaction of tectonic uplift and subsidence, eustatic sea-level changes, sediment supply, and climate as envisaged by Vail (1987). The principal objective of this study is to define the lateral variations of the Palaeocene depositional sequence in western margin of Cyrenaica Platform using the seismic stratigraphic technique. In addition, to determine the controls on Palaeocene deposition during the post-rift, thermal subsidence phase of passive margin and basin evolution in a carbonate setting.

Furthermore, Paleocene carbonates in the western margin of Cyrenaica Platform constitute one of the potential petroleum producing intervals that warrant exploration consideration. Carbonate platforms and their associated sediments may form prolific petroleum source and reservoir systems and offer a range of subtle stratigraphic play types and lateral facies variations. Sequence stratigraphic analysis is important for studying the development of carbonate platforms (e.g., Handford and Loucks, 1993).

The sequence stratigraphic and seismic facies analyses of this interval explain the Paleocene geological history of the basin, an essential step in any exploration plan.

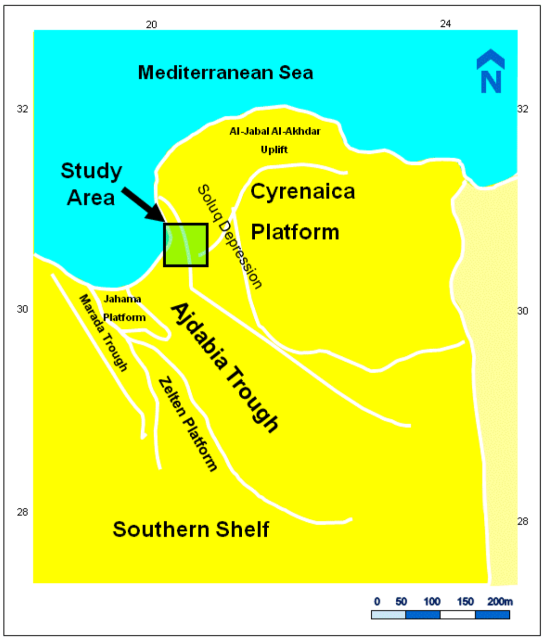

Fig.1. Map of the northeast of Libya shows the location of the study area.

However, the Paleocene sequence is highly discontinuous, and its spatial variations are difficult to define solely from well information. The exploitation of available seismic data for lithological characteristics is thus a key point in the exploration of this sequence. In addition, seismic stratigraphic interpretation in the western Cyrenaica Platform has an importance for rift basin margins, and provides an opportunity to examine deposition and stratigraphy of a carbonate platform on the southern margin of the Mediterranean basin in particular.

Many studies have been carried out on the geology of Sirte Basin, and Cyrenaica region. Tertiary rocks in the Sirte Basin have been studied and described by Berggren, (1974), who divided the sequence into a number of stratigraphic units. Gumati and Kanes, (1985); Gumati and Narin (1991) analysed the subsidence and sedimentation rates of the Sirte Basin and their relation to facies distribution. El-Shari, (2005) used the backstripping technique in the area to separate the subsidence of the sedimentary basin caused by sediment and water loading, from that caused by the tectonic driving force. The relationship between the stratigraphy and structural setting across the hinge-line in passive continental margins has been studied by El-Shari (2008). The Palaeocene facies distribution in the Sirte Basin has been described by Conley (1971); Brady *at el.* (1980) and Bezan (1996).

2. Database methodology

The seismic data over the studied area pointed to a basin-to-shelf depositional setting. In such an area, lateral and vertical changes in geology are expected to reflect different depositional environments. The available seismic and well data from southern margin of Cyrenaica Platform enables seismic facies analysis and the application of sequence stratigraphic concepts. The stratigraphic interpretation approach in this study integrates well logs and seismic reflections to interpret lithofacies, and subsequently the depositional system. A large number of seismic profiles have been analysed to delineate chronostratigraphic units, and to infer the different types of palaeoenvironment under which these units were deposited. About 2300 km of 2D and 200 square km of 3D of seismic reflection data tied to nineteen wells have been used (Fig. 2). They are from a diversity of vintages and demonstrate large variations in quality. Data quality decreases clearly in areas of complex structure, most particularly the deeper areas of the Agdabia Trough toward the southwest. Lithological logs and horizons top data are available for all of the wells in the database. Different wire-line logs are available for most of the wells, which include sonic, density, gamma ray, and other composite logs.

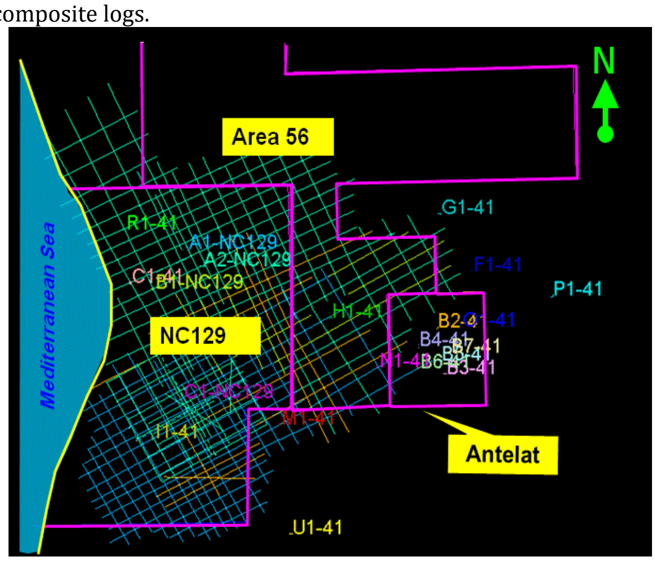

Fig. 2. Seismic lines and boreholes used in the study.

Determining the boundaries of the Palaeocene sequence was based on regional interpretations of all available seismic data. The sequence stratigraphical significance of these boundaries is assessed later, in conjunction with well data and current carbonate sequence stratigraphic models. Based on the internal seismic reflection parameters such as the configuration, continuity, amplitude, frequency, interval velocity and external form of each seismic facies, the Palaeocene seismic sequences were analysed and mapped. Seismic facies were later used to predict lithological and stratigraphic variations within the sequence, based on their particular position within the sequences, lateral relationships to other seismic facies, and the nature of their boundary surfaces.

3. Regional tectonic and depositional setting

In the late Cretaceous, stretching phase in the central Mediterranean, resulted in tectonic effects on the upper Sirte margin, and on the Sirte Basin, with regional marine flooding over the whole north African plate (Finetti, 1985 and Del Ben & Finetti, 1991). During this time, the Tibesti-Sirte arch collapsed, starting with the formation of the NW-SE oriented Agdabia Trough associated with concurrent collapse of the Cyrenaica western margin. The crustal stretching in the Sirte Basin led to major rifting and the development of grabens, in which the syn-rift sediments were deposited. During late Cretaceous and early Tertiary times, there was a major marine transgression in the area coincident with the general eustatic high stand of sea-level at this time (Pitman, 1978). This widespread marine transgression was associated with intense rift-related subsidence throughout the late Cretaceous in the western Cyrenaica. The first phase of extension and initial subsidence was followed by widespread thermally driven subsidence through the Tertiary period (El-Shari, 2005).

A widespread marine transgression, following basin sub-sidence, can be seen in the basin from Palaeocene to late Eocene time. The Palaeocene transgression and facies distribution in the Sirte Basin has been described by Conley (1971); Brady, Campbell and Maher (1980) and Bezan (1996). Along major horsts, carbonate banks and reefs under open marine conditions developed. This carbonate is interbedded with shale in some places, indicating transgressive and regressive sedimentary cycles. However, the Palaeocene carbonate facies are confined to the platform, while the deep open marine facies are restricted to the structural low areas. The Palaeocene sequence reservoirs contain the large amounts of hydrocarbon found in the Sirte Basin. In the eastern basin for instance, the bioclastic coral-rich boundstones and grainstones of the Upper Sabil Formation form the main reservoir (Spring and Hansen, 1998).

On the western margin of the Cyrenaica Platform, NW-SE trending normal faults were activated in the late Cretaceous time. The normal faults occurred at the basin margin and influenced basin development in the post-rift stage. From Palaeocene to Middle Eocene time, more normal faulting occurred, mainly as reactivation along a hinge-line between the Sirte Basin and Cyrenaica Platform (El-Shari, 2008). Relatively rapid thickening of the syn-rift sequence is observed at the hinge-line. The post-rift section produced a relatively simple sedimentation pattern in which the section shows an overall thickening towards the basin centre to the southwest. The transgression, which began in the late Cretaceous, seemingly ended in the early Palaeocene, initiating the Palaeocene platform.

4. Palaeocene seismic stratigraphy

The identified seismic features in this interpretation are compatible with the structural style of area. Variations in lithology, and the development of faults, which introduce discontinuities in the reflectors, mostly control the continuity of the seismic events. Most of the observed faults are extensional normal of a NW-SE trend, and downthrown toward the southwest (basinward). The trend of these faults appears to be compatible with the regional geological setting of area. Most faults are truncated by the top middle Eocene sequence reflector, although minor displacements are observed on some faults above this level. However, the position and nature of the fault planes at depth is hardly recognised on the available seismic sections (Fig. 3).

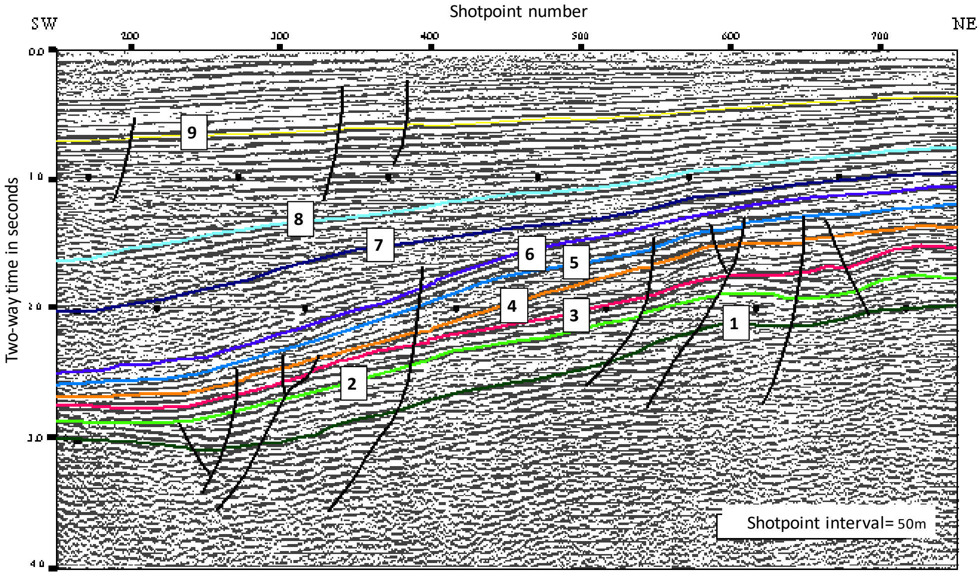

Fig. 3, Seismic interpretation along line NC129-87-08 (dip line). The boundaries between the sequences shown as following; (1) base Palaeocene sequence, (2) top Palaeocene sequence, (3) top Lower Eocene sequence I, (4) top Lower Eocene sequence II, (5) top Middle Eocene sequence, (6) top Upper Eocene sequence, (7) top Lower Oligocene sequence, (8) top Upper Oligocene sequence, (9) top Lower Miocene sequence. Note that all faults are of extensional type and mostly downthrown in the direction of the basin (after El-Shari, 2008).

(i) Areal Distribution

The Palaeocene sequence is regionally traceable in the whole area. The isopach map of the sequence is shown in Fig. 4. This map generally represents very significant lateral change in the thickness of the sequence. It is thin in the southeastern part, and thickens around the edges of this area. The maximum thickness of the sequence is 1200 m (3937 ft.), which is encountered in the area to the west of the paleo-shelf margin. The isopach map show a major thinning of the Palaeocene sequence in the area around well M1-41, which represent the minimum thickness of about 100 m (328 ft.). Possibly pre-existing topography in this area may be responsible for this significant decrease in sequence thickness.

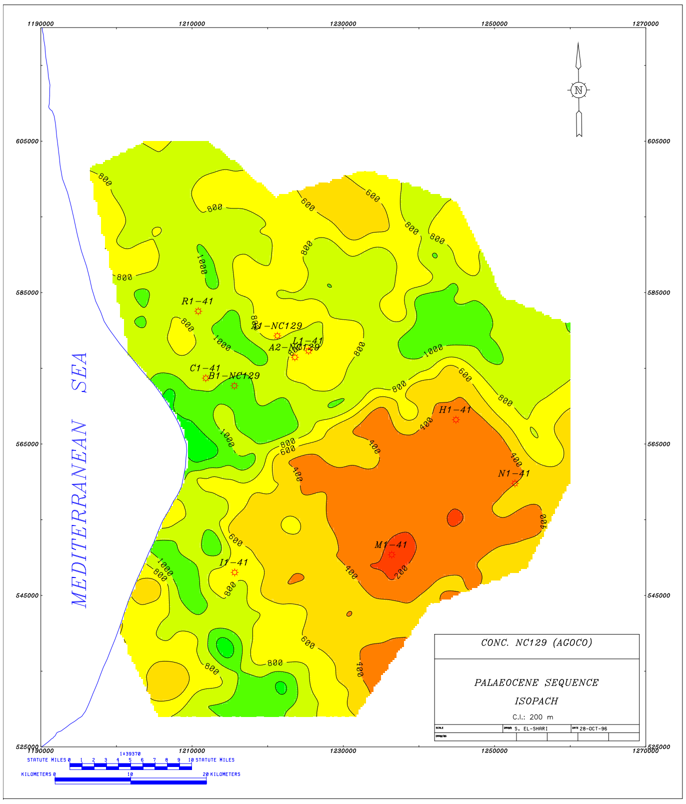

Fig.4, Isopach map of the Paleocene sequence at the western margin of the Cyrenaica Platform.

(ii) Bottom and Top Boundaries

The lower boundary of the Palaeocene sequence cannot be followed easily throughout the study area due to the relatively low seismic reflection quality associated with this boundary and the discontinuity related to structural disturbances where a large number of faults clearly dissect the sequence (Fig. 3). The lateral continuity of this reflector is poor on the platform, while on the slope the reflector is relatively much stronger. Despite the fact that the seismic stratigraphy is very uniform at this level, the seismic reflections in the southwestern part of the area indicate predominantly erosional truncation of the underlying strata at the lower sequence boundary. The Upper boundary of the sequence is well developed throughout the area. This boundary is characterised by an unconformity with erosional truncation of underlying strata (Fig. 5).

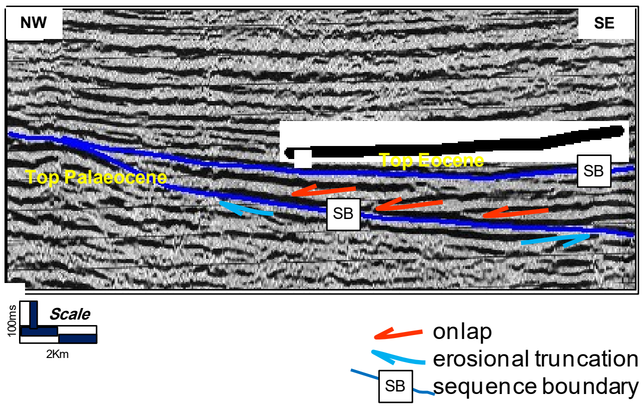

Fig. 5. Interpreted seismic profile (part of seismic line NC129-87-03) (strike-line) showing the pinch-out of the Lower Eocene sequence I against a palaeotopograpic high of the Palaeocene sequence. Clearly seen are onlapping terminations against the top Palaeocene sequence boundary.

(iii) Internal Seismic Character

The sediments of the Palaeocene sequence have a prominent progradation pattern, terminated by erosional truncation at the top boundary, and the internal configuration is characterised by variable-amplitude and variable-continuity. The internal seismic reflection within the sequence is characterised by subtle truncation below and slight onlap toward the Cyrenaica Platform in the most parts of the area.

At the extreme southwestern part of the area (slopewards), downlapping reflection patterns in the sequence are recognised. A set of high amplitude, mounded structures occur basinwards (southwestwards) (Fig. 6) which show typical downlapping reflectors onto the basal sequence boundary. The reflectors within these mounded structures are relatively high amplitude and variable continuity. The downlapping units are prograding from fault scarps throughout the basin. The overall unit is wedge-shaped, generally 150 ms at its thickest part and up to 10 km in length. Hummocky clinoform reflectors, characterised by discontinuous high amplitude reflectors, occur within these mounds. This unit may be interpreted as high-energy mass flow deposits, which became detached from the basin margin by movement on the basin bounding faults. However, the wedge-shaped external geometry of the unit, as well as the hummocky internal seismic configuration does not support this interpretation. Fontaine *et al.* (1987) suggested mass flows are characterised by chaotic reflections interposed between the parallel continuous reflections of pelagic deposits.

Therefore, this unit is interpreted as submarine fan deposits, which are associated with a normal fault and contain downlapping, high to medium amplitude, discontinuous reflectors. However, there is no well data to support this seismic interpretation and there is no evidence of any canyon feeders to these fans. These fans are suggested as being associated with periods of sea-level fall. Such systems have been taken by Mitchum, Vail and Thompson (1977) as an indication of lowstand sea level depositional systems. Their mounded appearance shows that they were deposited by high depositional energy. These fans may have developed during late syn-rift subsidence phases of basin development.

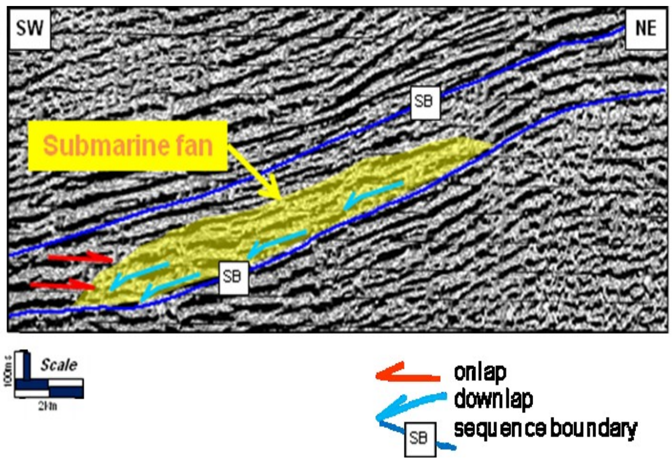

Fig. 6. A set of high amplitude, mounded structures occurs basinwards (southward), show downlapping reflectors onto the basal sequence boundary, which interpreted as submarine fan.

In the slope area, this unit is onlapped by later Palaeocene layer reflections, which are characterised by parallel, continuous, high amplitude reflectors. In the platform area, the Palaeocene sequence reflections are generally parallel or sub-parallel with variable amplitude and discontinuous reflection configuration. In the northern shelf area, growths of discrete organic build-ups or grainstone shoals have been recognized. A mound shape and onlap of surrounding reflections seismically identify these reefal constructions. They are interpreted as reefal build-ups forming towards the basin margins on a carbonate ramp during early Palaeocene time (Fig.7).

(iv) Well Data

The whole sequence is penetrated only in nine wells in the area (A1-NC129, I1-41, M1-41, C1-NC129, C2-NC129, C3-NC129, D1-NC129 E1-NC129, F1-NC129, and G1-NC129). The well data show that dolomite is the predominant lithology in the sequence over the investigated area (Fig. 8.).

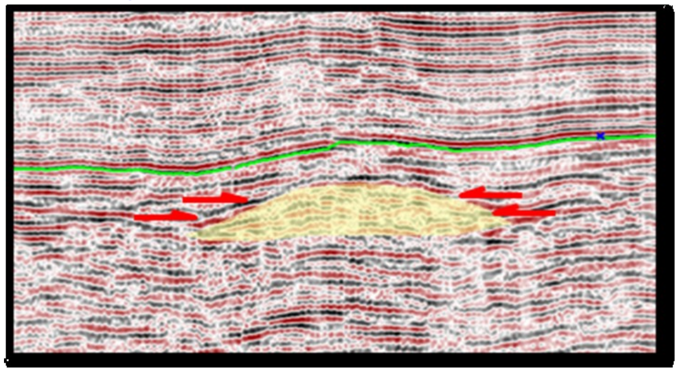

Fig. 7, A mound shape and onlap of surrounding reflections interpreted as reefal build-ups forming on a carbonate ramp during early Palaeocene time

Limestone and anhydrite beds occasionally occur within this sequence. The dolomite is interbedded with some intervals of anhydrite in the area of well I1-41. Wireline logs have consistent profiles across the interval. Typically, the gamma ray and sonic log indicate that the Palaeocene sequence is lithologically uniform. A sharp uphole decrease in sonic and common decreases in gamma values mark the upper boundary of the sequence. In I1-41 a sharp peak of increasing gamma ray values is noticed within the interval. This peak may define a candidate-flooding surface within the sequence.

(v) Facies Interpretation

The overall picture suggests that the Palaeocene sequence is dominated by a regressive trend. The lithologies of dolomites, and some anhydrites, suggest deposition in a very shallow, near-shore, restricted-to-lagoonal and supratidal environment.

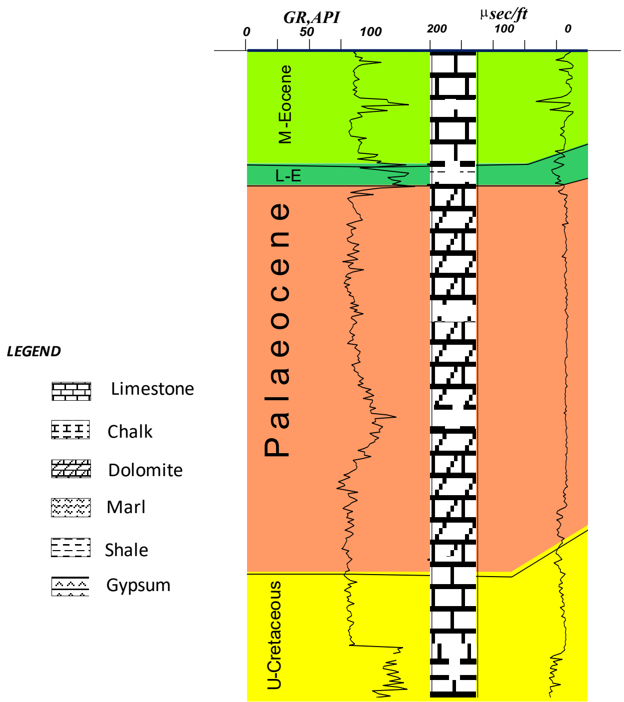

Fig. 8. Summarized lithology of the Palaeocene sequence in Well I1-41.

The time of dolomitization development on the platform probably reflects late highstand-early lowstand of relative sea-level or widespread subaerial exposure of the Cyrenaica Platform. During the late highstand, when carbonate progradation is at a peak, evaporites may be deposited in the inner part of the platform. This is followed by a relative sea-level fall, which completely exposes the carbonate platform and generates a sequence boundary in the basin.

During the lowstand, the marginal carbonates may be extensively dolomitized. The dolomitization is commonly associated with leaching of the metastable skeletal grains and generation of moldic, vuggy and intercrystalline porosity. This could generate an unconformity, which formed prior to the deposition of Lower Eocene sequence. However, the Palaeocene sequence is the most potential attractive hydrocarbon reservoir in the area. Combined structural and stratigraphic potential reservoirs may exist (Fig. 9).

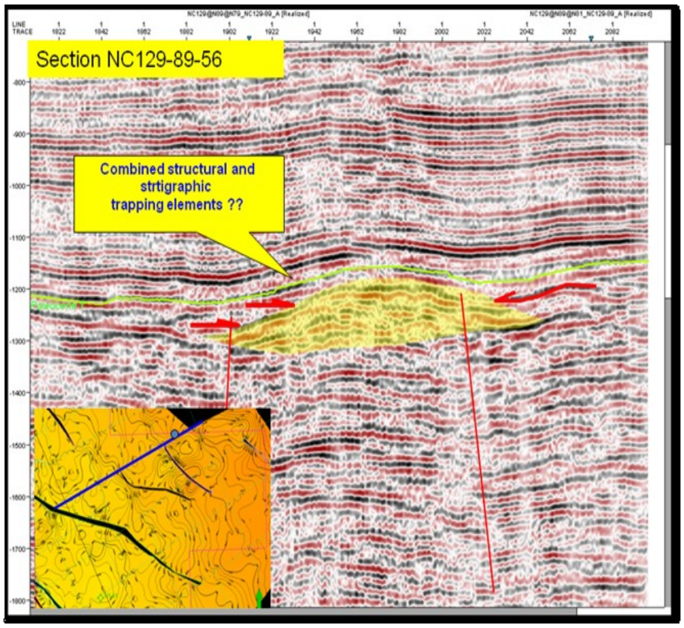

Fig. 9. Possible combined hydrocarbon traps developed within Palaeocene Sequence.

5. Conclusion

This study investigates the seismic facies analysis and depositional environmental interpretation within the Palaeocene sequence at the western margin of Cyrenaica Platform. This research contributes through a depositional model of the area to a better understanding of sedimentation on the southern margin of Mediterranean basin during Palaeocene time. Generally, the passive continental margins of the southern Tethyan seaway were the sites of extensive colonisation by carbonate platforms that developed in the Palaeocene time. The dominance of carbonate sedimentation is largely a function of an arid climate and a subdued stable hinterland providing little clastic sediment supply. This situation enhanced the rate of carbonate production along the North African margin.

The Palaeocene section in the area mainly consists of a prograding carbonate shelf with rimmed platform morphology and palaeo-slopes along the western margin of Cyrenaica Platform. The seismic and well data suggest that the Palaeocene sequence is dominated by a regressive trend, and was deposited during the early stage of thermal subsidence. Increased relief between the Agdabia Trough and Soluq Depression in the Palaeocene resulted in slope instability and debris flows on the flank of the basin. The seismic data indicate that debris fans developed during early Palaeocene time, associated with periods of sea-level falls. These fan deposits may have developed during late syn-rift, transitional and initial thermal subsidence phases of basin development.

The time of dolomitization in the sequence may have been during late highstand-early lowstand of relative sea level or widespread subaerial exposure of the Cyrenaica Platform. The other important stratigraphic feature in the Palaeocene sequence is the growth of discrete organic build-ups or grainstone shoals in the northern shelf area. A mound shape and onlap of surrounding reflections seismically identify these reefal constructions. They are interpreted as reefal build-ups forming towards the basin margins on a carbonate ramp during early Palaeocene time.

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