Zohr – A newborn carbonate play in the Levantine Basin, East-Mediterranean

Paolo Esestime[1*], Ashleigh Hewitt[1] and Neil Hodgson[1] **address the characteristics and the distribution of the emerging carbonate play proven by the recent Zohr-1 gas discovery in Egypt.**

The Levantine Basin in the East-Mediterranean is proven as a prolific hydrocarbon province, with numerous gas fields and discoveries, including several of giant reserve size extending from the over-explored Nile Delta of Egypt and offshore Israel in the south to underexplored Cyprus and Lebanon to the north and east. Many of the gas discoveries to the east are biogenic in origin, although a thermogenic source underlies the Nile Delta, as evidenced by minor oil discoveries and, especially in the pre-Pliocene, ubiquitous gas condensate discoveries (Figure 1).

Historically, exploration of the Nile Delta targeted siliciclastic plays since AGIP (now ENI) made the ground-breaking discovery of the Abu Madi Field in the Nile Delta of Egypt in 1967. The Abu Madi gas condensate play was followed offshore with the Baltim discoveries and throughout the 1970s and 1980s this play was exploited, following Miocene channel deposits, broadly deposited during the Mediterranean drawdown of the Messinian Salinity crisis, located in shallow water. IEOC (an ENI subsidiary) drilled deeper targets in the 1980s and found over-pressured gas in Middle Miocene sands in the El Temsah field discovery. In the 1990s exploration in the Delta moved on to target Pliocene turbidite play-fairways in ever deeper water (eg discoveries of Ha'py (Amoco) and Rosetta (BG)), and more recently Early Miocene and Oligocene targets have yielded good results in the Nile Delta for BP (Raven Field) and others. Early Miocene clastics have proved prolific offshore Israel, where, in water depths greater than 1500 m, Early Miocene deep water turbidites provide the reservoirs for more than 30TCF in Noble's Tamar and Leviathan gas discoveries alone.

Although carbonate plays had been targeted close to shore at the edges of the Levantine basin, there had been no significant successes in this play due to the variability of reservoir and the difficulties of constraining source and seal. The Eastern Mediterranean looked like a clastic play basin, with, after 40 years of exploration, recoverable reserves of ca 120TCF.

However, in the summer 2015 ENI made yet another game-changing discovery. After two disappointing wells in Cyprus targeting Miocene siliciclastic deposits, IEOC (the Egyptian subsidiary of ENI) drilled a new play, in 1500 m close to the Egypt/Cyprus border. At the base of a thick sequence of Messinian evaporates, IEOC had identified an early to middle Miocene structure, which was drilled by the Zohr-1 well. This discovery was found to hold a 628 m gross gas column, 430 m net pay and gas in place preliminary estimated at 30 TCF. Recoverable reserves in this one discovery are therefore around 25% of all the exploration successes in the prolific Levantine basin over the previous 40 years. Indeed, this well has bucked the trend of exploration as the reservoir is provided by Early-Middle Miocene limestones, in a carbonate reef and lagoon build-up at the southern margin of a very large carbonate platform (Figure 2).

The discovery of a carbonate build up so distal from the modern Nile Delta suggests a new model for the paleogeographic evolution of the Levantine Basin may be required. It had been assumed that with the exception of the brief Messinian salinity crisis, north of the Nile Delta deep water conditions had prevailed across the basin during the Neogene. However, the Zohr carbonate build up requiring shallow water conditions during the Early to Middle Miocene, indicates the presence of a basin north of the Nile Delta, and this paper concerns the discussion of what this basin high might be comprised of, how it developed, how

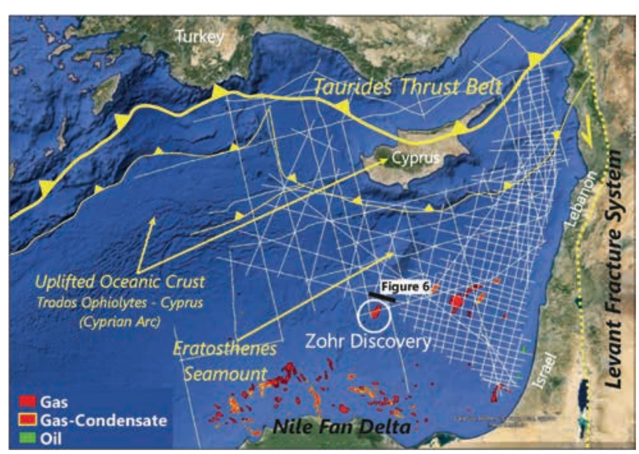

Figure 1 *Map showing the main regional structures related to the Paleogene-Neogene shortening and the hydrocarbon discoveries. The white lines show the Spectrum`s 2D seismic library used for this study.*

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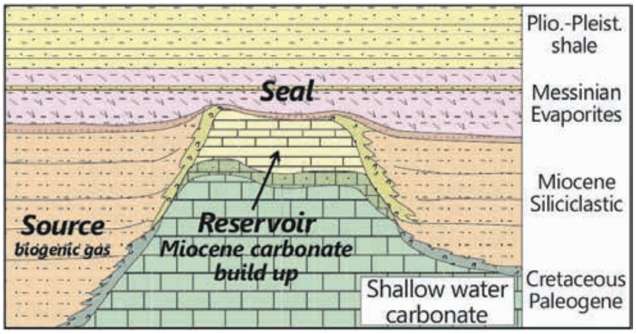

***Figure 2** Geological sketch of the Zohr Discovery reprinted from ENI press release.*

widespread it might be and therefore what might be the consequence for future exploration potential.

Through the interpretation of a regional 2D seismic grid, as both pre-stack time and depth migrated data located over the area between Zohr and south Cyprus, we present a regional interpretation showing the extension and the evolution of the structural high that spawned this incredible gas resource. We have also considered the relationship between the Zohr build-up, its multiple analogues, and the evolution of the Eratosthenes high during the Mesozoic and the Tertiary, and its relationships with the main continental margin of Africa and Arabia.

Stratigraphy and petroleum system

The stratigraphic development of the Levant Basin is shown in sequences of carbonate and siliciclastic deposits both from deep and shallow water environments (Figure 3). These units contain several petroleum systems, including source rocks and reservoir intervals, vertically stacked from the Triassic to the Miocene and the Pliocene.

The Mesozoic section is well known from the onshore geology (Hawie et al., 2013) and the wells drilled in the nearshore areas of Israel (i.e. Yam-Yafo-1). The interval displays several source rocks, postulated on a regional basis (Renouard, 1955; Graham et al., 2001). Likewise most of the Neo-Thetian realms, the Levant Basin displays a Triassic section of shallow carbonate, siliciclastic, dolomites and evaporites, frequently associated to anoxic environments and black shales. Additional source rocks may be present in the Jurassic; the deepwater equivalents of the waxy-coal-bearing delta sequences exposed onshore North Sinai, and associated to a restricted circulation in the pelagic depocentres. Pelagic shales and marls and cherty limestones are dominant during the Cretaceous, intercalated to siliciclastic input, mainly associated to eustatic oscillations. The Upper Cretaceous unconformity (Santonian) marks the beginning of the convergence in the Taurides Thrust-Belt and the deposition of organic-rich shales, regionally extended and correlated to the asphalt and oil accumulations in the Dead Sea (Tannenbaum and Aizenshtat, 1985).

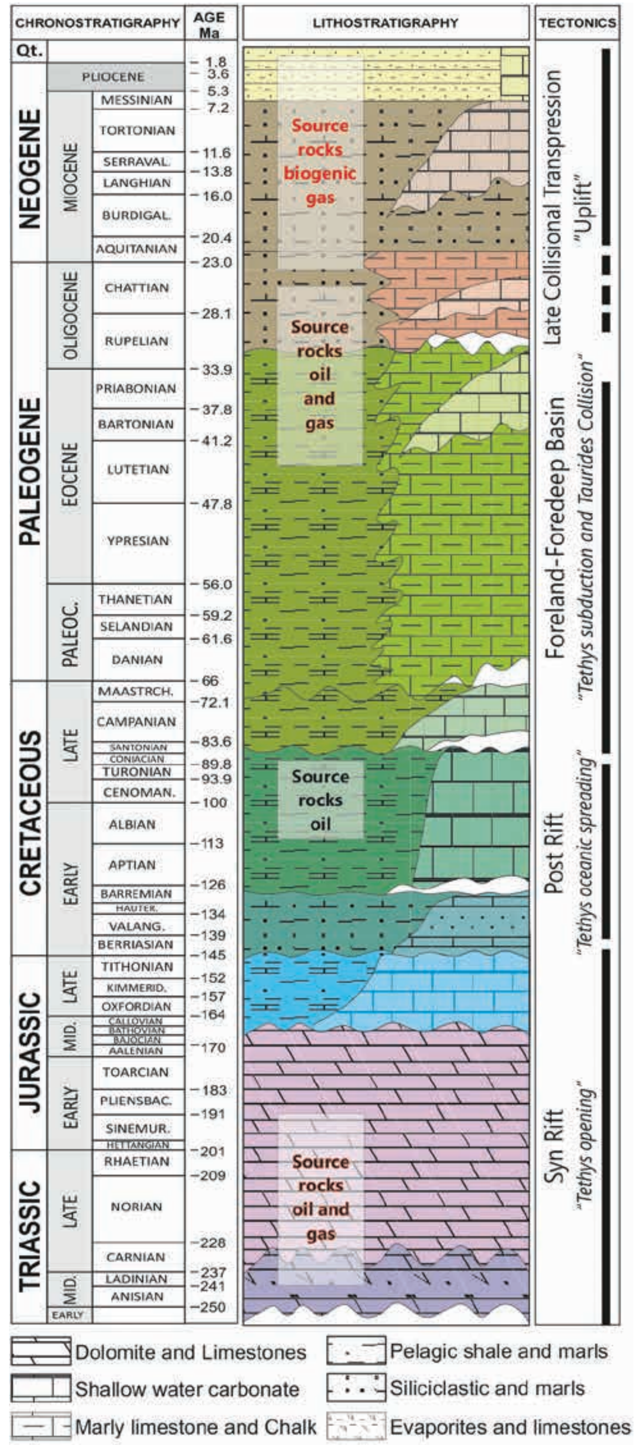

***Figure 3** Simplified stratigraphy of the Levant Basin and surrounding continental margins.*

During the Cenozoic, the Levant evolves as foreland and foredeep basin of the Taurides Thrust-Belt. Siliciclastic inputs occur locally from the basin margins, which are affected by recurrent uplifts. The North Levant is affected by the initial subsidence, related to the subduction phase in the Late

Cretaceous and the Paleogene. Coarse-grained deposits repetitively flood the pelagic domain since the Eocene, during the Oligocene and the Miocene. The source rocks of biogenic gas are widely spread, while oil sources are restricted to pelagic marls and shales, more frequent in the Oligocene.

The Messinian salinity crisis sealed the Miocene cycle in the deep basin under approximately 2000 m of evaporites, while shallow water areas are deeply incised as a consequence of the sea level drop. Finally, the Pliocene-Quaternary, will reach a notable thickness only in the cone of the Nile Delta (Figure 1) where clastic supply is dominated by the Tertiary northward flow of the Nile.

Regional geological frame

The Levantine Basin comprises the easternmost Mediterranean Sea, representing a discrete remnant of the Neo-Tethys Ocean. This ocean formed after the separation of the continental margins of Europe-Asia and Africa-Arabia initiated during the Permo-Trias, and completed by Early Jurassic rifting and the subsequent phase of Cretaceous drifting (Golonka, 2004).

The Permo-Trias rifting is characterized by extensional faults, oriented NE-SW NNE-SS, which shaped the architecture of the continental margins (Gardosh et al., 2008; 2010).

The initial marine transgression of the rift dates back to the Triassic syn-rift stages, when the first shallow water carbonate were deposited with locally developed evaporites and minor siliciclastic. Yet from the Jurassic, post-rift subsidence led to deep water pelagic sedimentation in the basin centre continuing through the Cretaceous such that carbonate platforms were confined to the continental margins, and only locally could carbonate reefs develop on basement highs. The pelagic sedimentation in the basin during the Cretaceous and Paleogene comprised deep water and detrital limestone, chalk, marls and shale. Siliciclastic input was present locally since the Mesozoic in both shallow and deep water, associated to variations of the drainage of the nearby landmasses.

From the Late Cretaceous, the subduction in the Taurides Arc consumed the northern oceanic crust of the Arabian Plate, brought the continental block of Arabia and Anatolia to collide by the end of the Oligocene and during the Miocene, closing the open sea way to the Persian Gulf to the east. In the Oligocene the slowdown in the migration of the allochthonous frontal thrust caused by this collision led to an end of the subduction phase, yet was replaced by the formation of large-scale folding. The convergence of course continued with the uplift of oceanic thrust ophiolite of the Troodos Terrane of the Cyprian Arc and the reactivation of previous discontinuities along the continental boundary of Arabia i.e. Levant Fracture System (Geological Survey Department of Cyprus, 1995; Beydoun, 1999).

The constrained nature of the Eastern Mediterranean meant that whilst the foreland-foredeep subsidence in the Oligocene created the deep Northern Levant Basin, the area to the west, still part of the Arabian and African continent, was affected by repeated uplift. This then generated a large platform area during the Late Oligocene–Early Miocene,

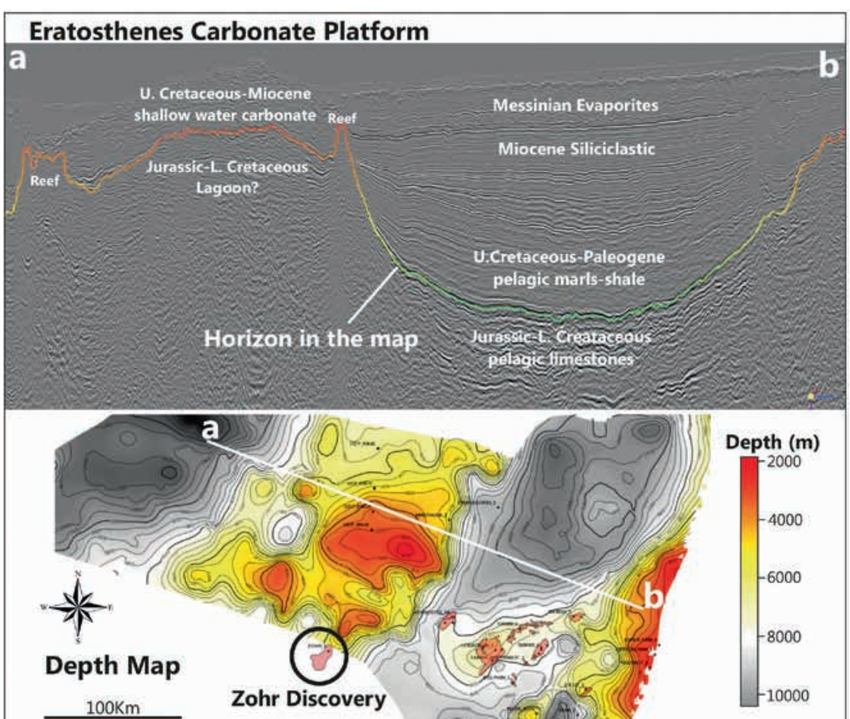

Figure 4 *Pre-stack Depth Migrated section and related Depth map of the Eratosthenes Carbonate Platform.*

and it was at the edge of this uplifted carbonate platform, in shallow water, that the 100 km^2 Early Miocene Zohr structure began to grow.

Whilst the Northern Levant Basin became filled with the coarse clastic basin floor fan sediments supplied by the Nile Delta, the area of the platform to the north supported largely carbonate deposition, with the development of large reefs and lagoon structures. These large reefs were not necessarily located at the platform margin, but took up interior positions reflecting intra-platform topographic heterogeneities. Initially, the Early Miocene clastic supply across the Southern Levant platform (providing the Tamar and Leviathan reservoirs), continued to be transported into the Northern Levant basin where up to 1000 m of coarse clastic turbidites are thought to be accumulated. It was during this phase that towering over the northern margin of the basin, and indeed on intra-pelagic basement highs, the carbonate build-ups were forming that provide the Zohr, and analogue structures. Early to Middle Miocene carbonate build ups comprise an outer rig of porous carbonate – the high energy reef

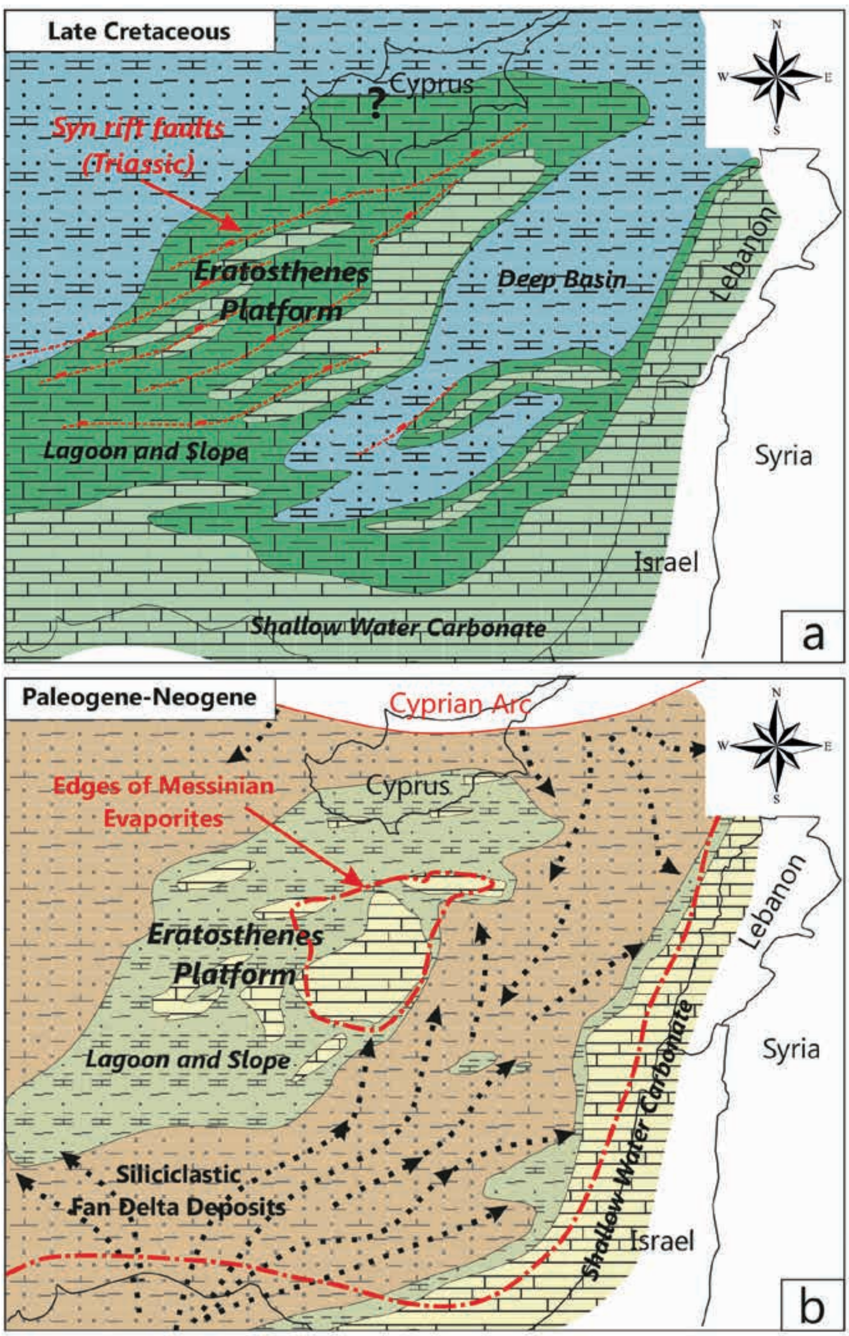

***Figure 5** Paleogeographic maps of the Eratosthenes Platform during the Cretaceous (a) and Paleogene-Neogene (b).*

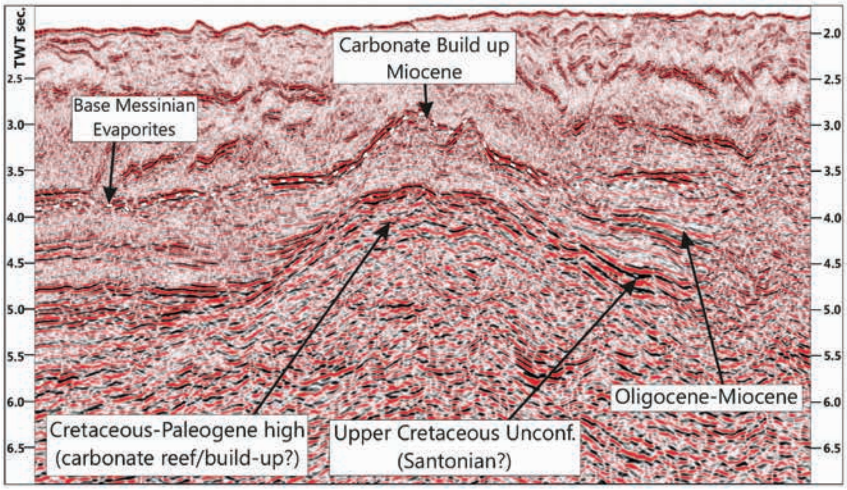

***Figure 6** TWT section across a Miocene carbonate build-up along the margins of the Eratosthenes Platform. The section is located in Figure 1.*

part of the structure, which surrounds a shallow-water low-energy back-reef and lagoon facies. The published RFT plot for Zohr which is very linear over 628 m, suggests that not only is the reef facies very porous, but there is also a high degree of connectivity within the reservoir. The build-up is surrounded by late Miocene mudstones, and capped by a seal of thick Messinian evaporites. The Oligocene-Miocene mudstone surrounding the carbonate build-up is the probable source for the biogenic gas in Zohr. Although the potential involvement of thermogenic gas is not precluded, the published gas pressure gradient (0.26 g/cm^3) suggests that the gas is dry, mostly methane, similar indeed to the offshore Israel gas accumulations that are reportedly biogenic in origin. The thick Messinian salt unit that provides the seal to Zohr is probably a thickened mobile salt unit. Much of the Mediterranean below 1500 m of current water depth shows approximately 2000 m of halite-rich evaporites; regional tectonic shortening and sediment loading in the Nile Delta have thickened up this Messinian sequence over Zohr producing an effective seal for the prospect.

The Eratosthenes Carbonate platform

The Eratosthenes Seamount has been reconstructed as a SW-NE trending platform extending off the Northern Levant (Figures 4, and 5a). This regional high is covered by Cretaceous-Neogene shallow water carbonate (ODP wells) and from seismic data is interpreted to be controlled by SW-NE trending normal faults related to the syn rift stage. During the Paleogene-Neogene, the Eratosthenes Platform suffered the inability to continue to absorb the rotation and northward movement of Africa by the collision of the Arabian and Anatolian plates. Such regional evolution might lead us to expect more Zohr type carbonate build ups on this platform (Figures 4 and 5b). Slow, no doubt punctuated subsidence through the Early Miocene created the accommodation space not only for the Zohr reef to grow, but also numerous other carbonate build ups that formed across the Eratosthenes Carbonate platform. These are now mapped across the Eratosthenes Platform, and the onshore areas of Cyprus (Figure 5).

These carbonate build-ups are expressed in a number of forms with the atoll-like ring-reef with lagoonal core being the most prevalent (Figures 4). One such feature of this form lies north of Zohr and maps over a 500 km^2 area (Figure 7).

Assuming that small topographic highs within the platform were the seeds for reef growth, a morphological high within the basin may have recurred several times, in particular during the Oligocene-Miocene shortening active along the Taurides thrust-front of the Cyprian Arc (Robertson, 1998, Hawie et al., 2013) (Figure 1). Shortening and uplift created shallow water conditions, developing carbonate build ups, as observed on the Eratosthenes Platform, and the onshore areas of Cyprus (Figure 5). The shallow water carbonate appears as a high amplitude seismic event that becomes discontinuous and chaotic towards the crestal positions. This confirms the platform was periodically exhumed and drowned by sea level changes creating favourable conditions for numerous Zohr-style build ups elsewhere on the platform.

The Eratosthenes platform played a fundamental role in the siliciclastic dispersal during the Oligocene-Miocene, allowing shallow water carbonates to persist on the platform high whilst causing the Nile sourced turbidites to be deflected to the east into the deeper Levant Basin along the coast of Israel and Lebanon (Figure 1 and 5b).

A striking similarity exists between the Troodos Ophiolites and the High to the Gorringe Bank fold/thrust structure described in Sartori et al. (1994); Zitellini et al. (2009), in the Atlantic offshore of Gibraltar. In the Levant Basin, even accounting for the Neogene shortening, the short distance between the Troodos Ophiolites and the Eratosthenes Platform suggests that this platform belongs to a highly stretched continental crust, at the extreme edges of the African-Arabian continents, where the crust changes from continental to oceanic. That assumption is consistent with the detrital and pelagic

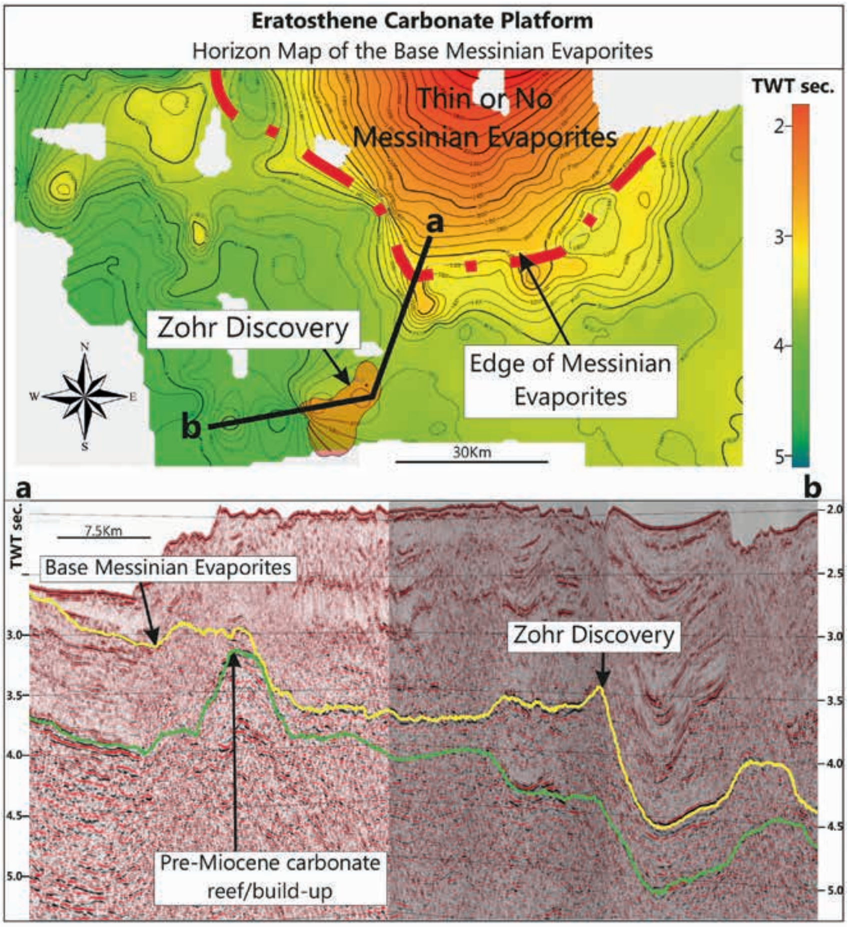

Figure 7 TWT horizon map and seismic section showing several culmination of carbonate build-ups from the Miocene and older, which surround the Eratosthenes Carbonate Platform.

limestones deposed on the Troodos Ophiolites, and organized in shallowing upwards sequence from the Upper Cretaceous to the Miocene. In effect, the uplift of the Cyprian Arc might have created the bathymetrical conditions which allowed the Eratosthenes Carbonate Platform to grow laterally onto the nearby oceanic crust. It should be noted that the PSDM seismic data suggest at least 5-6 km of carbonates lie over the structure of the Eratosthenes "Seamount", and we expect Mesozoic carbonate to be extended on the Eartosthenes Carbonate Platform.

Conclusion

The Zohr discovery in Early to Middle Miocene carbonate reefal build-up sits on the southern margin of an exceeding large platform area we called the Eratosthenes Platform (Figures 4, 5a, 5b). Previous authors refer to part of this platform as seamount, however, there is no evidence of volcanic origin, and rather we interpret a thick carbonate sequence to have been deposited on the feature that has been locally deformed to create a structural high. Regional scale compression of the northern margin of the African plate and oceanic obduction/buckling in the Troodos Ophiolites (Cyprus) during the Paleogene-Neogene led to the formation of numerous carbonate build ups, distributed along the Eratosthenes margin, which forms the play-type recently proven in the Zohr Discovery (Figures 6 and 7).

The eastern margin of the Eratosthenes Carbonate platform played a fundamental role in siliciclastic sedimentation during the Early Miocene. On the platform, shallow water carbonate build-ups accumulated in a clastic starved environment, whilst to the east in the Northern Levant foredeep, Nile sourced coarse clastic turbidites were accumulated.

As the hydrocarbon system for Zohr comprises a biogenic gas source from the enclosing Oligocene and Miocene shales, and a top seal from ubiquitous thick Messinian halite, there is a high probability that the Zohr play is very repeatable on a very large scale both in Egypt and Cyprus. The opportunity exists to discover sufficient gas, quickly, in these very large (30-100TCF) resource potential features, to rewrite the play book for the development of the gas industry in the Eastern Mediterranean.

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