

# **Multi-Surface Restoration and Petroleum System Evaluation in the Gulf of Suez\***

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## **Abstract**

A large scale regional study has been carried out at the scale of the Suez rift, using surface restoration. Its aim was to propose a coherent 3D interpretation of geological structures of the Suez rift in order to understand its North-South variations. Results highlight the role of the pre-existing transverse structures on the development of the land-locked basins and salt depocenter in the central and southern Gulf of Suez and Red Sea.

## **Introduction**

Restoration tools are useful in hydrocarbon exploration in improving the geometry of the model and therefore reducing the uncertainty on the prospects that have to be drilled. The computed past geometries may be used to study the evolution of the basin versus time. Restoration is also interesting in solving more academic questions, as for instance the modeling of the paleogeography of the areas and the regional extension and shortening quantification. In this study, we have completed a 3D surface restoration of the synrift series of the Gulf of Suez. This work has various goals: first to have a 3D model of the Gulf where up to now only cross-sections have been prepared, then to get surface restorations in order to understand the various depocenters during rift evolution. Salt deposits exist in the Gulf, as in the Red Sea; it means that there has been periodic isolation from the Open Sea. The southward opening of the Red Sea, at the Afar triple junction, to the Indian Ocean is known to have occurred during the Pliocene; during the Miocene the Gulf was connected to the Mediterranean Sea. However, the salt is younger in the southern part of the Gulf of Suez than in the Mediterranean Sea; so it means that the connection to the Mediterranean Sea was not permanent. Based on the restoration, we discuss when and how the isolation took place and its influence on the petroleum system.

## Gulf of Suez: Geology

### Geological Setting

The Gulf of Suez is the northern tip of the Red Sea (Figure 1). The Gulf itself is about 300 km long whereas the Red Sea is 2000 km long from the Afar triple junction to Suez. Extension started in the Gulf of Suez about 23 Ma, at that time the rifting phase affected both the Red Sea and the Gulf. The extensional rate was fast during the initial phase, between 23 and 15 Ma (Moretti and Colletta, 1987, among others). Around 13 Ma, extension stopped in the Gulf of Suez and then began on the Aqaba-Levant fault (Figure 1), characterised by a sinistral strike slip component (Cochran, 1983). In the Gulf of Suez, a quiescent phase lasted from 15 to 5 Ma and led to the deposition of an evaporitic series. From Quaternary times, the rift trough narrowed, and the uplift of the shoulders accelerated (Moretti and Colletta, 1987). To simplify terms and history:

- R1: the first opening phase, from 25 to 15 Ma; extension and subsidence was active and fast;
- R2: from 15 to 5 Ma, quiescence, infilling to the existing basin;
- R3: the current phase that is contemporaneous with an increase of activity and an oceanization in the Red Sea.

As shown by numerous authors (Moretti and Froidevaux, 1986; Buck, 1986; Steckler et al., 1988), evolution of basin subsidence and rift shoulders uplift are compatible with the secondary convection process (active rifting related to a deep thermal anomaly). The narrowing of the trough and the late uplift of the shoulders are due to the abortion of the Suez branch of the Red Sea rift, when the Aqaba branch became active (Moretti and Chenet, 1987).

The presence of the underlying abnormally hot mantle is confirmed by heat flow, gravity, and uplift rate data (Cochran, 1983; Makris et al., 1991). The crustal thinning is confirmed by refraction data (Gaulier et al., 1988); the upper crustal extension is obvious on the surface as in the subsurface (Figure 2).

The prerift sequence consists mainly of a rather thick and poorly deformed Nubian Sandstone overlying the Precambrian basement followed by a marine Upper Cretaceous (south Tethys margin) and Eocene limestones. Above, the Miocene synrift deposits (R1) range from conglomerate and reef to *Globigerina* marl, depending on the proximity of the crest of the block and/or major normal faults. Later, more restricted marine conditions dominated, with deposition of gypsum and other evaporites (Belayim, South Gharib and Zeit Sequences, R2)--southward, the Post-Zeit Formation, from 5 to 0 Ma, noted here as R3. Northward the evaporites are not younger than the Zeit Formation (Figure 3) and are likely Messinian in age (6 to 5.3 Ma). In addition to the time of evaporite deposition, variation in sedimentation between the northern part of the Gulf (North Darag basin) and the central and south parts have been described (Shutz, 1994)

Today the Gulf of Suez is no more than 60 m deep and disconnected from the Mediterranean Sea, except by the canal, but it was deeper at the beginning, and the fauna collected in the first synrift deposit, Miocene in age, shows that at that time the Gulf was a branch of the Mediterranean Sea. At the opposite end, southward, the connection with the Indian Ocean and the Aden Gulf opened only at the end of the Pliocene (Bosworth et al. 2005).

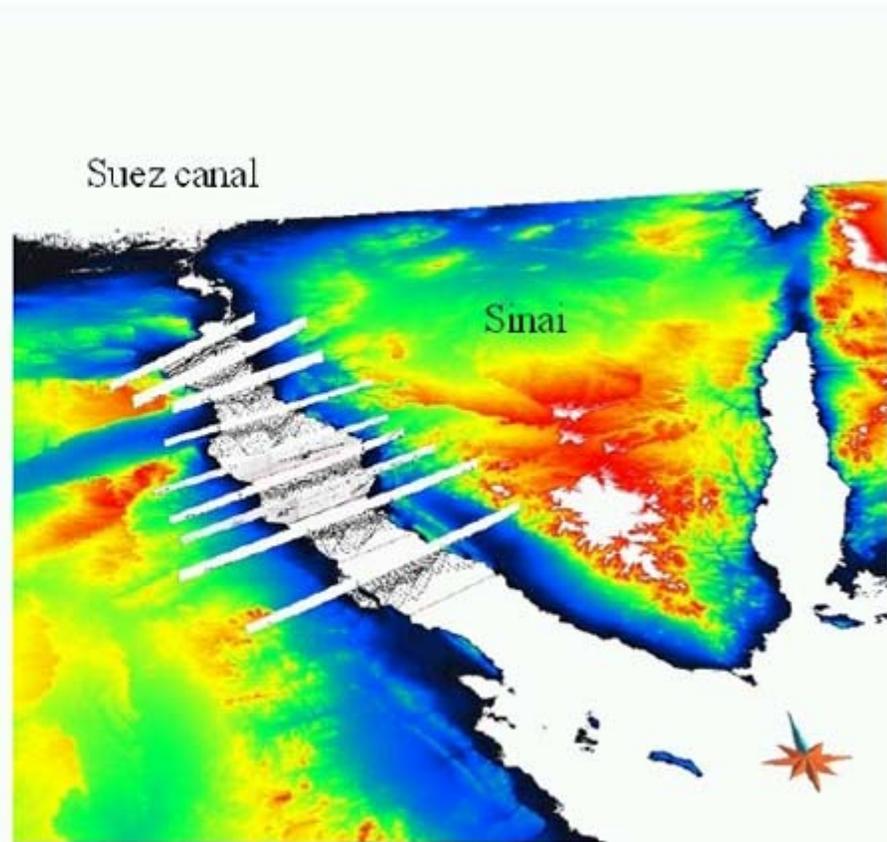
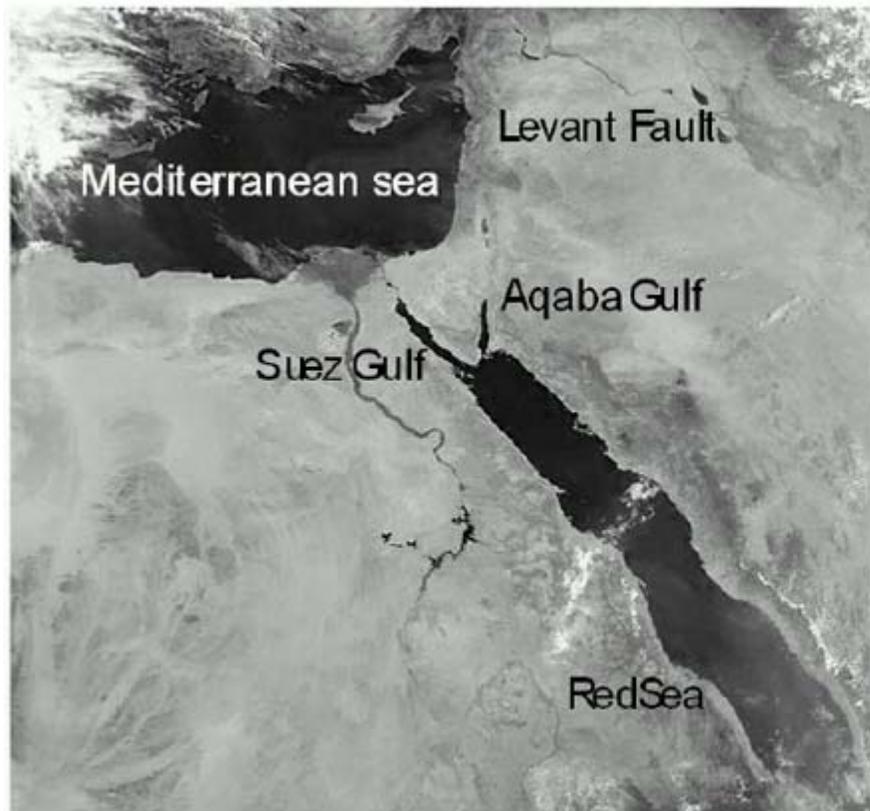


Figure 1: (left) The Gulf of Suez, aborted branch of the Red Sea that now propagates northward through the Aqaba-Levant fault system. (right) The data loaded and georeferenced in Gocad\_KINE3D\_1, including the Digital Elevation model and the cross-sections prepared previously.

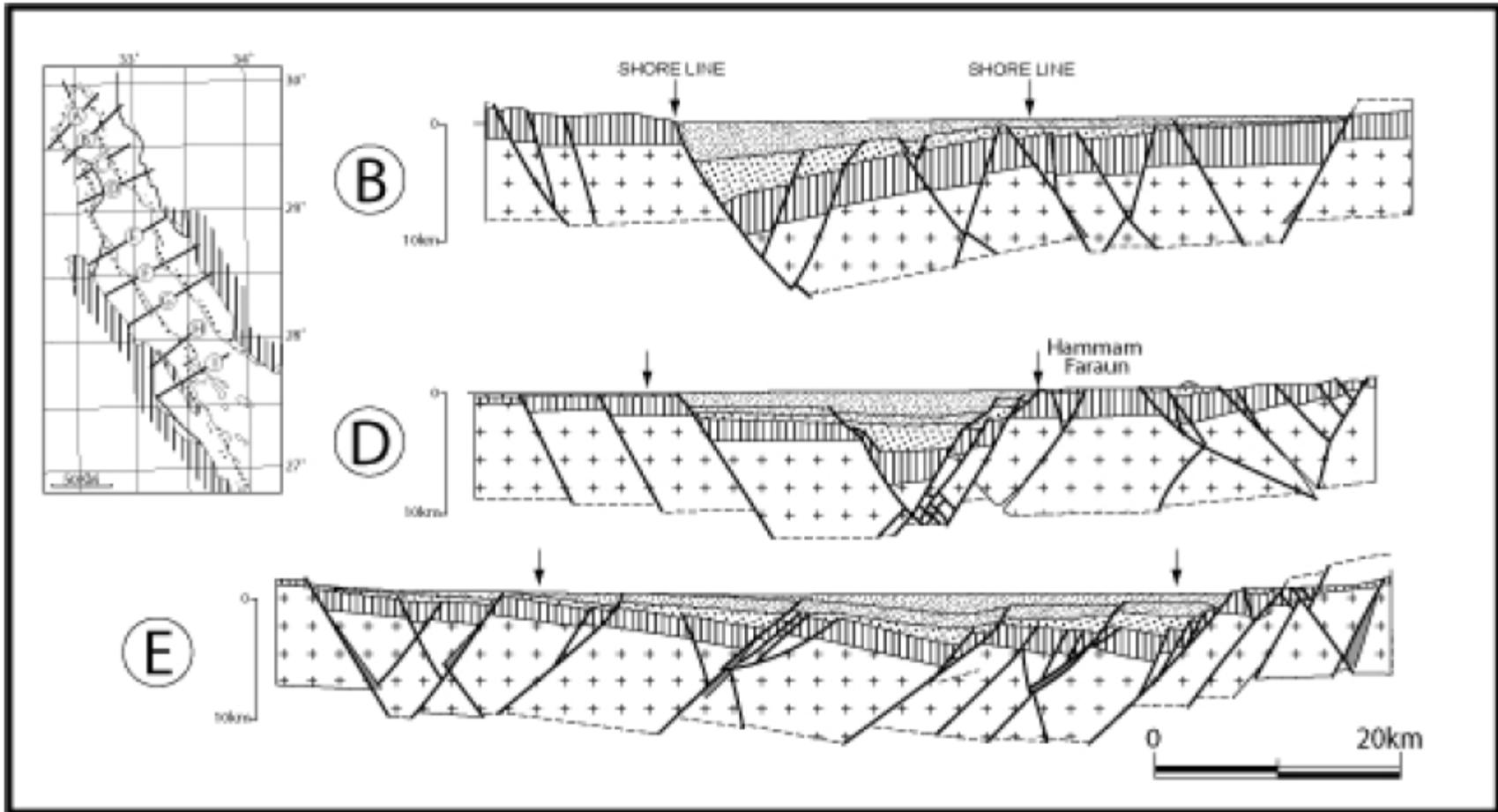


Figure 2: Cross-sections through the Gulf (modified from Colletta et al., 1988). Legend: cross pattern: Precambrian basement; vertical line: prerift sequence; stippled patterns, synrift sequences (R1, R2, and R3).



## Structure

The Gulf of Suez is oriented around N140°, and is rather rectilinear; the majority of the normal faults have this azimuth. The faulted blocks may be tilted up to 30°, but generally no more than 20° (Figure 2); by comparing the uplift of the crest with the subsidence in the half graben, it can be deduced that the rotation is rather rigid (domino style, Angelier and Colletta, 1983), with a decollement level located at about 10 km; i.e., at the upper / lower crust boundary (Moretti and Colletta, 1988).

The original dip of the normal faults is between 60 and 80°. Transverse faults generally have a steeper attitude and accommodate the different vertical displacements affecting the block that they border. Evidences of horizontal displacement along these transverse faults are very rare. Structural analysis shows that the blocks are tilted westward in the northern part of the Gulf, eastward in the center, and westward again in the south (see Figure 1). A subsidence study, based on subsurface data, proved that the tilted blocks were initially very large. They became divided into smaller ones when the tilt angle increased with increasing extension (Moretti and Colletta, 1987). The new faults that appear at this time are parallel to the previous ones and therefore enhance the apparent asymmetry of the Gulf. The switch from east-dipping to west-dipping parts occurs without a major transfer fault but rather by a “twist zone”; i.e., fault offset decrease (Colletta et al., 1988). The northern twist zone is also called the Zaafarana Accommodation Zone by various authors (Younes and McClay, 2002).

Based on the tilt direction of the blocks one may consider the Gulf as segmented into 3 zones: the North where the main faults are tilted eastward (cross-section B Figure 2), the Center where the main faults are tilted westward (cross-section E Figure 2), and the South where the faults are again tilted eastward (not represented here, see Colletta et al., 1988; Patton et al., 1994; Moretti 2004). As already noted, the first synrift sequence, R1, deposited between 25 and 15 Ma during the opening phase, reflects the tilting of the blocks, with reef facies developing at the crest whereas conglomerates fill the trough in front of the main fault. Numerous sedimentological indicators confirm the emergence and therefore the relative uplift of the noses of the tilted blocks (Moretti and Colletta, 1988) that appear to be eroded in the sections (Figure 2).

The balanced cross-sections prepared by Colletta et al. (1988) allow one to quantify the extension that decreases slowly from south to north from 30% to 10%. The backstripping that was performed shows that the tectonic subsidence was almost completed during the R1 phase and that a large part of the Gulf, especially the north and the current borders, are only affected by surface processes, erosion and deposition during the R2 phase (Moretti and Colletta., 1987).

## Petroleum System

The hydrocarbon charge is not a problem for the explorers working in Gulf. Numerous prerift (anterift) and synrift series have high contents of organic matter.

In prerift series, the main source rocks are at the levels of the Upper Cretaceous; this includes the Raha, Wata, and Matulla formations and the limestones of Eocene (Thebes Formation) with initial TOC between 2 and 12% and a potential S2 from 6 to 18 kg / tonne (Alsharhan and Salah, 1997; Alsharhan, 2003). These source rocks are marine (type II). The Cenomanian/Turonian organic-rich strata that are a major source rock from Morocco to

the Western Desert are not present in the south of the Gulf and not always very rich in the North (Raha Formation). In this northern area, the Jurassic deposits (Malha Formation) have also a rather good potential with a S<sub>2</sub> over 20 mgHC/g but a low HI (<400). The Jurassic deposits of the Khatatba Formation are also one of the source rocks of the Western Desert (Metwalli and Pigott, 2005). All the prerift deposits become thinner southward.

In synrift series the main source rock corresponds to the marls of the Rudeis Formation. Its content in organic matter averages 2.5% TOC but can locally reach 4% with a potential around 7kg/t. Usually, the series of the younger Kareem and Belayim formations may have a TOC in the range of 1%. Synrift source rocks are a mixture of type II and type III.

In general terms, synrift source rocks are the dominant ones in the central and southern parts of the Gulf, whereas the prerift source rocks could be the major ones in the north.

Prerift reservoirs are, in most cases, sandstones of the Nubian sequence, which may have excellent porosities, from 10 to 20%. Nevertheless, other sandy units and carbonates could also be good reservoirs. As a matter of interest, there is also a field producing from fractured granites in the nose of a tilted block. In the synrift, the basal formation of Nukhul (sandstones and carbonates) is one of the most common productive reservoirs. Turbidite sandstones from the Rudeis, Karin, and Belayim formations are also good reservoirs.

The high heat flow due to the rifting, as well as the burial in the half graben, favours the maturation of all source rocks. The oil window is around 2.5 km in the south and 3 km northward.

Traps traditionally in this type of environment are the high points of crests of the tilted blocks (Ramadan, October, Belayim, Morgan). The large offsets of the faults may place Miocene source rocks in contact with the reservoirs of the prerift system; fault closures are common. In addition to these purely structural classical traps are more subtle traps, in general both stratigraphic and structural, linked to Miocene sands (Pivnik et al., 2003). They correspond to synrift delta deposits, often in the transfer zone between two blocks. A number of recent discoveries, particularly by Amoco, are on this type of trap. There are also fields of reefs in the synrift series (Ras Gharib, Ras-Bakr, Gemsa).

The general top seal is the evaporites of the middle Miocene to the Messinian. Lateral seals may consist of faults and facies changes.

Up to now, backstripping and 2D cross-section restoration of the Gulf have already been conducted. Let us see the advantages of 3D modelling in understanding some of the geological features: the segmentation and the evaporite deposition.

### **Construction of the 3D model**

In addition to the DEM and the water depth, about 30 cross-sections were loaded and relocated in the geomodeler (Figure 4). The regional ones are from Colletta et al (1988); additional ones are from Patton et al. (1994); and maps published by Sharp et al. (2000) in the Sinai border have been used, as well. The global geological map published by Moustafa (2004) has also been loaded, localized, sized, and projected on the DEM with the KINE3D\_1 facilities (Moretti, 2008).

The Gulf is bounded by a system of large faults that may have very large offsets. The highest point of the Sinai is now 2.7 km high, whereas the basement is commonly more than 8 km deep within the Gulf. The Gulf is oriented N140, the approximate azimuth of the main faults, as displayed in [Figure 5](#). In addition, this stereo diagram shows few faults with another azimuth, close to N-S, that is likely the orientation of pre-existing faults. The visualization of these faults, along with their link with the major rift faults, is one of the main advantages of the 3D modeling versus 2D in this context.

We are not discussing here the full structure of the Gulf but are focused on the northern part and on the paleogeometry at the end of the active rift phase; this corresponds to the base of the evaporitic sequences.

### **Restoration**

Restoration algorithms have been a topic of intensive research for almost 15 years; work has been presented by Gratier and Guillier (1993), JL Mallet and P Jacquemin, both from the LIAD, at the end of the 1990s, Ph.D. research conducted by J. Massot (2002), C. Galera (2002), and more recently P Muron (2006). The surface restoration can be now achieved routinely by various methods in industrial software, such as KINE3D developed by IFP and Earth Decision; these were used for this study.

KINE3D\_2 proposed a multisurface restoration, based on the simple shear or a global approach that preserved the areas and the thicknesses and so-called flexural slip by extension (Moretti et al., 2007). Using the flexural slip one may or not impose the closure of the fault lips; when this method is used, internal deformation is computed to insure this continuity.

[Figure 6](#) shows the current geometry at the base of the south evaporitic sequence (base Belayim Formation) and the restoration of this surface at Messinian time, 5 Ma, when the top of the evaporite was deposited, supposedly on a flat surface close to sea level. The color code represents the depth and range from 0 (red) to -3000 m in the deepest half graben (North Darag, cross-section B; see location of the sections, [Figure 2](#)).

The restored geometry shows that the central part, corresponding to the Wadi Araba structure onshore, was more or less at the same depth as the current outcropping border. Wadi Araba is a major geomorphologic feature that corresponds to an eroded anticline of the Syrian Arc fold system and plays an important role in the Gulf of Suez sedimentation (D. Khaled et al., 2008). The restoration prepared here shows that this arch has isolated the northern graben, 2000 m deeper at the time, from the southern part that was therefore periodically a closed sea, as the current Dead Sea, during the latter part of the Miocene. Note that the given depths for the paleomap are relative; a large uplift happened recently in the Gulf, during the last 10 Ma, and we did not try to restore the eroded thickness on the border to get absolute values.

This restoration has been done with the global flexural slip approach, supposing that the thickness of evaporites did not change during the deformation. In other words, we suppose that there is no active salt diapirism in this area. The sections on [Figure 2](#) show that it is the case for this northern part of the Gulf; diapirism is weak, as expected where the burial of the salt is too small to enhance this phenomenon. It is clearly not the case in the southern part of the Gulf.

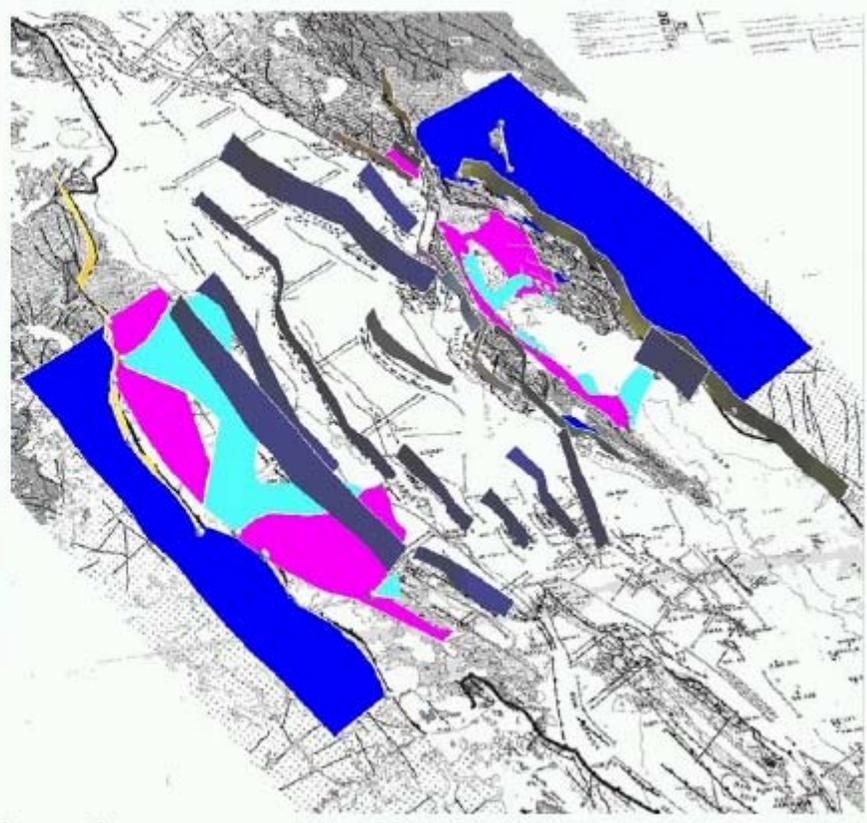
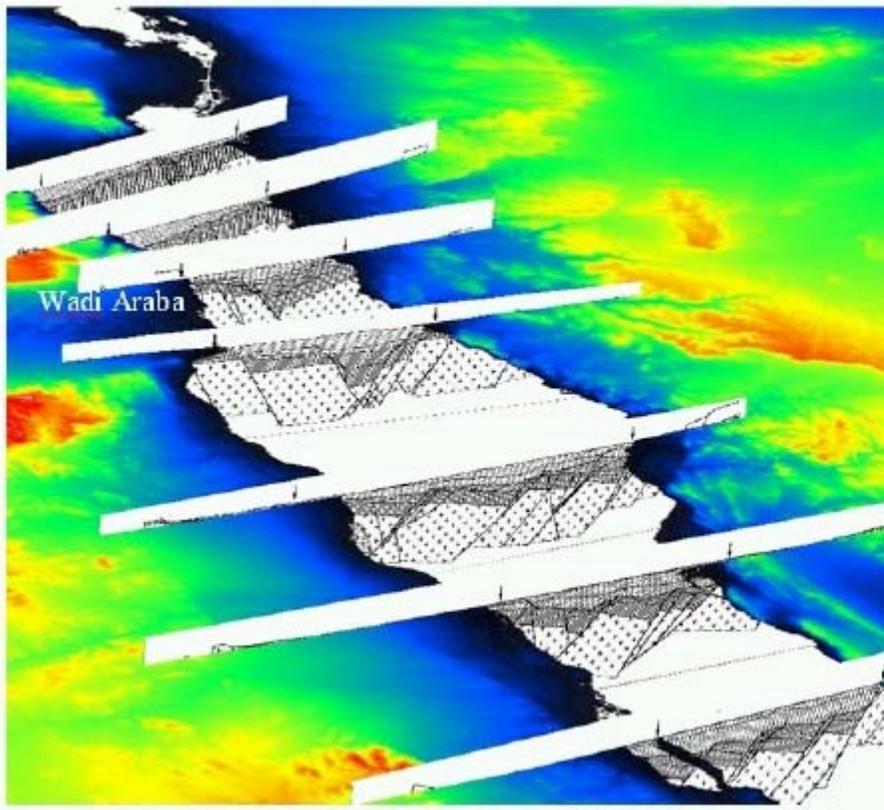


Figure 4: Some elements that have been incorporated in the 3D model. (left) Digital elevation model and cross-sections (for legend, see [Figure 2](#)). (right) Geological map showing the outcrop of the main faults.

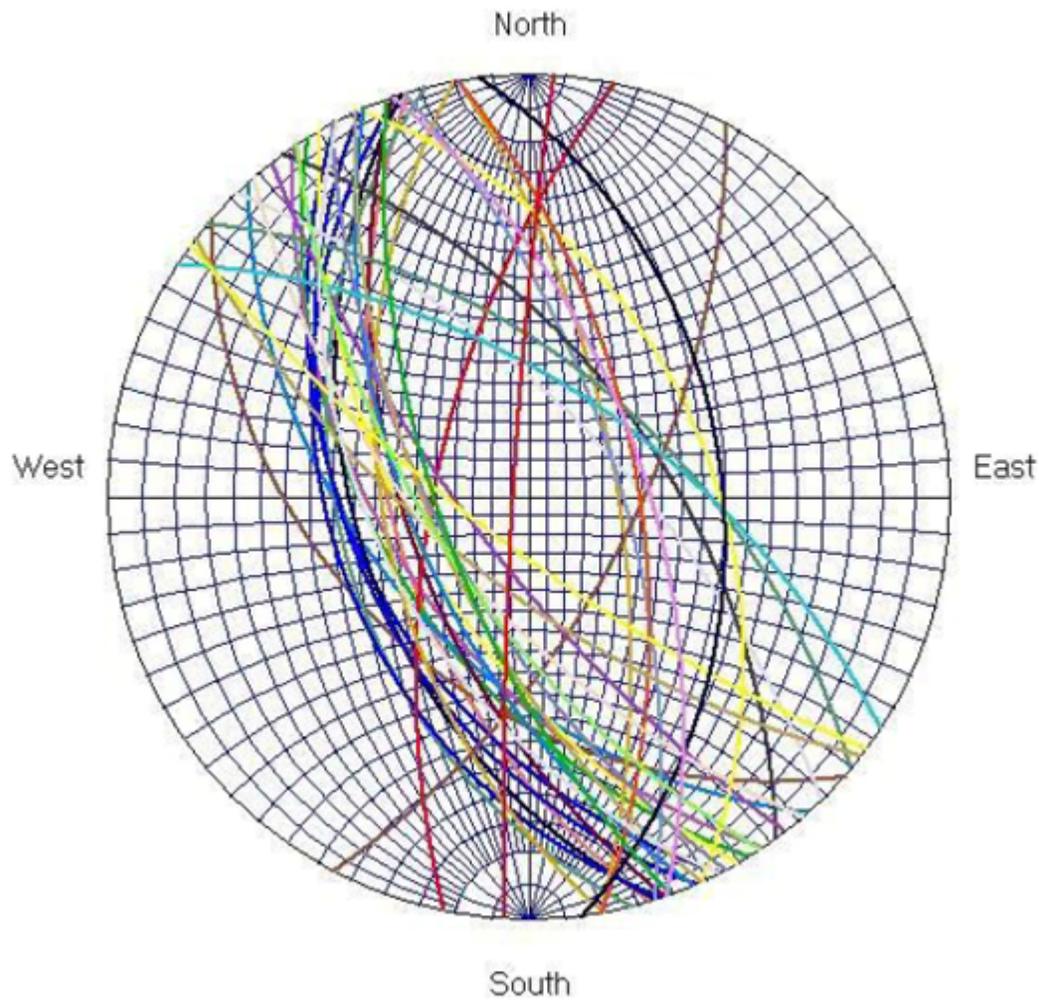


Figure 5: Wulff diagram of the major faults in the northern part of the Gulf; the majority of the faults trend N140° and dip eastward; few dip westward. Note that only two of them have another direction.

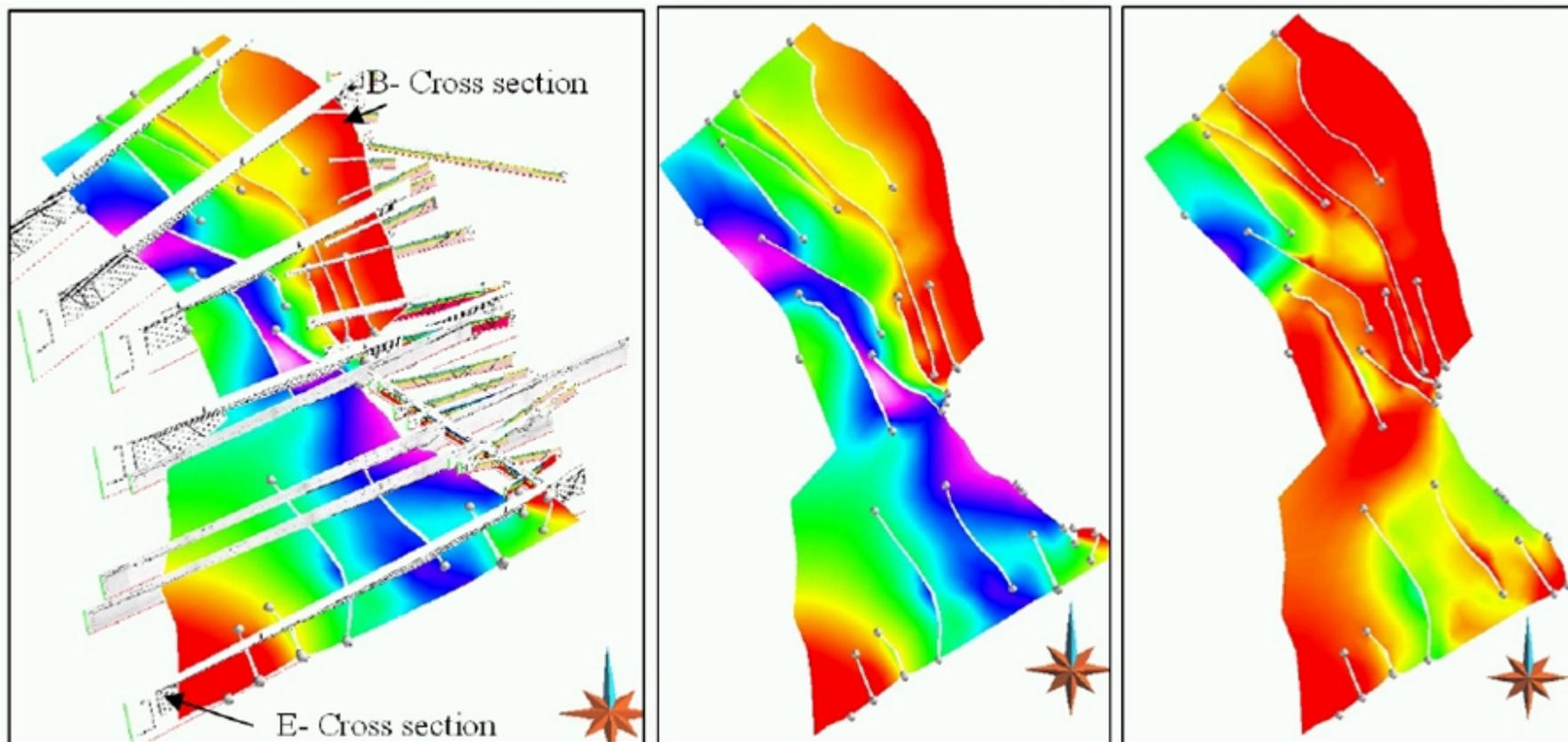


Figure 6: Surface restoration using the flexural slip approach at the base of the evaporites at the time of the Messinian crisis (5Ma). Color code for the depth, Red = zero. (left) 3D view; (center) top view of the current base of the evaporites in the Gulf; (right) restored geometry showing the arch between the two depocenters.

## The Salt Crisis

Salt basin, with thick evaporite deposits, can exist when basins are isolated from the global ocean. Tectonic evolution of the basins and global eustatic variations contribute to the isolation. A salt crisis occurred in the Mediterranean area during the Messinian, when there were no longer connections between the Atlantic Ocean and the Mediterranean Sea (Figure 7). This salinity crisis also affected the sub-basins of the Mediterranean, as the Gulf of Suez and the Black Sea.

As already noted, during Miocene times, the Red Sea was not connected to the Indian Ocean. At the same time, the restoration shown in Figure 6 highlights the existence of an arch that may have isolated the central and southern parts of the Gulf of Suez from the Mediterranean Sea. Because the arch has been very high, depending on the Mediterranean Sea level, the Gulf and the Red Sea were or were not connected; in addition the Mediterranean Sea during the Messinian (~5 Ma) was disconnected from the Atlantic Ocean.

The way in which evaporites accumulated in the Gulf of Suez is linked to the paleogeography of the rift. Isolation of the Gulf, due to the paleogeographical features of the area, allowed an increase in the salt concentration of the sea water. When the south Gulf of Suez - Red Sea basin was isolated, the water budget decreased due to the significant evaporation rate. When the salt concentration reaches high values, salt precipitates. Gypsum is thought to precipitate when the salt concentration exceed 130 g/l, whereas halite deposition starts when concentration exceed 350 g/l (as compared to the 35 g/l of salt concentration in sea water). Numerous connection/disconnection between the Mediterranean Sea and the Gulf of Suez allowed for a significant evaporite mass to accumulate in the Suez Gulf (Gargani et al., 2008).

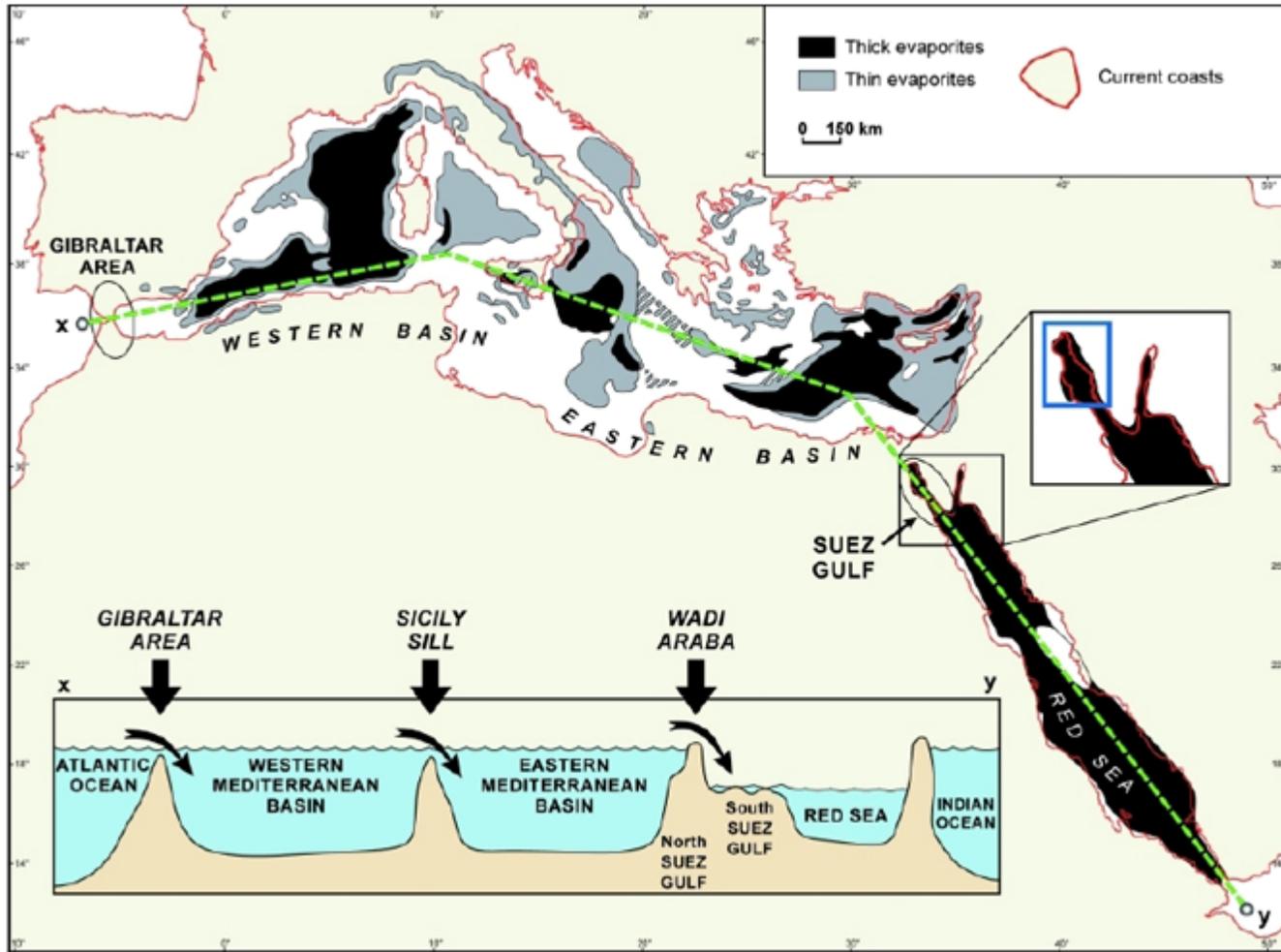


Figure 7: Schematic connection between the open sea and the Mediterranean basins and sub-basins (modified from Montadert et al., 1978; Gargani et al., 2008).

## Conclusion

Based on these multi-surfaces restorations, the geodynamical evolution of the Suez Rift during the last ~15MA has been studied. The study has highlighted the role of the east-west Wadi Araba-Zaafrana synrift structure. Even if the faults are mainly neoformed and have a clysmic (N140) direction, the prerift structures played a role in the formation of the depocenters. They appear to have been significant until the Messinian. In particular the outcropping Araba anticline that prolongates eastward isolated the northern half graben of the Darag area from the south. Following our restoration the arch that constitutes this Araba anticline was outcropping during mid-Miocene and allows for the isolation of the southern part as a closed sea where evaporite deposition may have happened each time that the Mediterranean sea-level drawdown was large.

## Acknowledgments

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