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Multiple Phases of Tectonic Inversion, East Java Sea Basin Indonesia, and Potential Analogues in Pakistan

Muhammad Amir Bhatti[1], Muhammad Iqbal[1] and Moin Raza Khan[1]

ABSTRACT

Inverted basins are structurally very complex as they generally preserve overprints of extensional and compressional tectonics. Intensity of inversion within any basin could vary from partial inversion to total inversion depending upon the tectonic environment, location and stratigraphy of the basin. Amount of inversion could be expected to vary within the fold belts from mild in the external parts to the severe total inversion in its interior.

East Java Sea Basin reveals an excellent example of multiple phases of tectonic inversion where multiple tectonic inversion episodes are well preserved in the tectono-stratigraphic record of the basin. Synthesis of data shows that the intricate tectonic history of the mentioned basin has experienced extension followed by compression (positive inversion-the change from subsidence to uplift), another phase of extension (negative inversion-change from uplift to subsidence) and presently is in compressional phase (positive inversion). These inversion structures are well resolved at seismic scale and can be identified as pre-rift, syn-rift and post rift (syn-inversion) mega-sequences. Timing as well as the degree of inversion varies within the basin from south to north.

Inversion related basins are commonly distributed around the globe and are petroliferous; however, within Pakistan still some reluctance exists in applying the term inversion despite the fact that the orogenic Sulaiman & Kirthar foldbelts and Badin extensional basins were initially part of passive margins of northward drifting Indo-Pakistan Plate which has subsequently experienced compressional tectonics during Tertiary period. The overprint of extentional tectonics is preserved at places.

Analyzing the inversion tectonics of East Java Sea Basin, analogous structural configuration can be inferred in the western fold belt (Kirthar and Sulaiman foldbelt) Pakistan which will enhance our understanding of the geology of the region and its hydrocarbon prospectivity.

INTRODUCTION

Tectonically inverted basins were recognized by Lamplugh (1920) and Stille (1924) long before Glennie and Boegner (1981) first used the term 'Inversion'. Structural inversion takes place when the basin controlling extensional faults reverse their movement during compressional tectonics and to a varying degree the basins are turned inside out to become positive feature (Cooper and Williams, 1989). As such, basin is inverted from a net extensional to net compressional, by changing the fault mode, or vice versa. However, there is no precise definition of basin inversion (Buchanan, 1995) because it is a process which occurs in a wide range of tectonic settings, therefore, it becomes difficult to give it a universal definition. Basins can show inversion by way of just folding without any fault reactivation. As described above positive inversion is accommodated dominantly by folding and faulting. The capability of any fault to reactivate in response to changing stress environment depends primarily on the orientation of the fault to the dominant stress direction, dip of the fault planes and amount of friction along the faults (Coward, 1994).

Most of the basins experience inversion, one way or the other, during their tectonic history. To recognize inversion structures Cooper and Willams (1989) used the concept of 'regional' to describe the type of inversion (positive or negative). It is the regional elevation of any marker horizon if the effects of compression (folding, faulting) or extension is removed.

Coward (1994) gave a detailed account of the inversion tectonics in western fold belt, Pakistan. According to him misinterpretation of folds and thrusts as being related to thin-skinned shortening rather than the inversion of a sedimentary basin can have far reaching implications for the structural interpretation of a region. This may lead to: (i) use of the wrong method in section construction (ii) incorrect calculations of the amount of orogenic shortening, and (iii) incorrect assumptions about the nature of structures at depth, both directly beneath the fold/thrust belt and further back within the hinterland of the mountain belt. He further recognized the importance of inversion tectonics for petroleum exploration as it will modify the interpretation of the burial history of a sedimentary basin which can complicate calculations of the timing of maturation and generation. Inversion may also result in up-lifting that could generate secondary porosity by weathering or karstification due to complete or partial exposure of the rocks. Reactivation of older faults may affect the sealing potential of the faults etc.

Tectonic history of a basin can be inferred from the stratigraphy and structural style observed on well, seismic and outcrop scale. With ever improving seismic resolution, now small scale observations such as reversal of fault movements, slight variation of strata thicknesses across the faults can be made. Effects of different tectonic episodes are preserved in the stratigraphy of the basin in the form of mega-sequences. It is very important to understand such events to have detailed insight of the basin controlling tectonic processes and tectono-stratigraphic history of the basin.

East Java Sea basin located to the ENE of Java and to the

[1]Pakistan Petroleum Limited, Exploration Department,
PIDC House, Dr. Ziauddin Ahmed Road, Karachi, Pakistan.

North of the volcanic islands of Bali, Lombok and Sumbava Besar (Figure-1) is one such example where the basin has experienced multiple phases of basin inversions. It is a Cenozoic back-arc basin framing as a result of Indo-Australian oceanic plate subduction under the continental Eurasian plate, farming an east west volcanic arc in the form of islands (Bali, Java, Lombok etc.). This active normal convergence between the two plates has produced an orogenic belt of Andean type (Simandjuntak & Barber, 1996). Structural features evolved as a result of multiple inversions are well preserved and can be observed at seismic scale.

Stratigraphy of the basin is well established as many wells have penetrated the entire sedimentary sequence down to the acoustic basement. Stratigraphy can be divided into three prominent tectonically controlled mega-sequences based on their seismic character, style of deformation and depositional geometries. Thick Upper Cretaceous sequence has formed over the basement (megasequence-1) as a result of early rift related basin formation events followed by compression that resulted in folding and faulting of this megasequence-1. The compressionally deformed Upper Cretaceous package then deformed by extension in the form of differential regional subsidence from early Eocene to early Oligocene (Matthews et al., 1995) resulting in the deposition of thick syn-rift sediments as growth strata on the hanging wall side of half grabens (megasequence-2). Regional positive inversion of the Eocene deposition (megasequence-3) started in the early Miocene that continued till today, as evident from sea floor highs. This recent phase of positive inversion is not uniformly distributed within the study area and is controlled dominantly by thickness of the Upper Cretaceous megasequece-1 and movement along basement, which involved Sepanjang fault zone in the central basement high area.

1.1 Objectives

The objectives of this article are to analyze the evolution of inversion related structures, their identification, distribution and kinematics involved at megasequence level. Possibility of inversion related structures in Pakistan inferred by previous workers are also briefly discussed.

1.2 Data Base

Data base consists of fairly close grid 2D seismic, covering an area of approximately 950 Sq.km. NS lines are the dip lines and EW lines are the strike lines. Quality of data was fair enough for this study.

2. Regional Tectonic Setting

East Java Sea Basin lies in an area of complex tectonic environment. The current physiography of the basin and surrounding areas of Indonesian Archipelago is believed to be developed as a result of interaction between three major lithospheric plates since Neogene. These include the NNW moving Philippine plate, NNE moving Indo-Australian plate and stationary or slowly SE moving Eurasian plate (Figure-2a and 2b, Simandjuntak and Barber, 1996) This basin is a Neogene back-arc type, formed as a result of convergence and subsequent subduction of Indo-Australian plate under the Sundaland in the south with direction of convergence normal to the subduction trace leading to Sunda orogeny.

The volcanic island of Bali, Lombok and Sembava Besar are the part of the extensive magmatic arc positioned above currently subducting oceanic crust of the Indo-Australian plate.

The basin was affected by the relative movement of the three major tectonic plates and experienced a complex history of initial extension followed by differential basin subsidence and later tectonic inversion (Hamilton, 1979). The reason for recent positive inversion is still not clear, however, it is proposed that this compression could develop in the hinterland when smooth down going oceanic plate is interrupted by topographic irregularities, resulting in accumulation of strain in the hinterlands that was previously releasing along the subduction zone (Simandjuntak, 1996).

The pre-Neogene history of this basin relates to the earlier pre-collisional settings of the micro-continents. These micro-continents were part of the northern margins of Australian continent that has separated in Mesozoic or Palaeogene time. The Mesozoic sedimentary sequence that consists of Upper Cretaceous megasequence-1 within the east Java Sea basin represents the pre-collisional history of the basin.

3. Stratigraphy of the area

Based on the structural and sedimentary depositional history of the basin, the stratigraphy can be broadly divided into three mega-sequences.

The Upper Cretaceous pre-rift megasequence-1, Eocene-Middle Oligocene syn-rift mega-sequence-2 and Lower Miocene to Holocene, syn-inversion mega-sequence-3. Brief description of these sedimentary packages is as follows;

3.1 Upper Cretaceous Megasequence-1

The oldest sedimentary unit is of Upper Cretaceous (Campanian to Maastrichtian) age that consists of mudstone, with interbedded siltstone and sandstones. Their time equivalent clastic sediments crop out on-shore southwest Sulawesi where they are termed as Balangbaru formation (Hasan, 1991). This sequence lies over the deformed acoustic basement which is characterized by variety of lithologies including meta-sediments, quartzite and chert. (Matthews et al. 1995). Top of this package is marked by a regional peneplane surface in the form of an angular unconformity (Figure-3 and 4). Seismic data indicate that the maximum thickness of this package is in the form of preserved synclines under the Tertiary angular unconformity surface in the area of basement lows. This megasequence is thickest, up to 3 km in the northern part of the basin (Matthews et al. 1995).

The seismic data delineated compressionally deformed folds and fault system characterizing the Upper Cretaceous Megasequence-1.

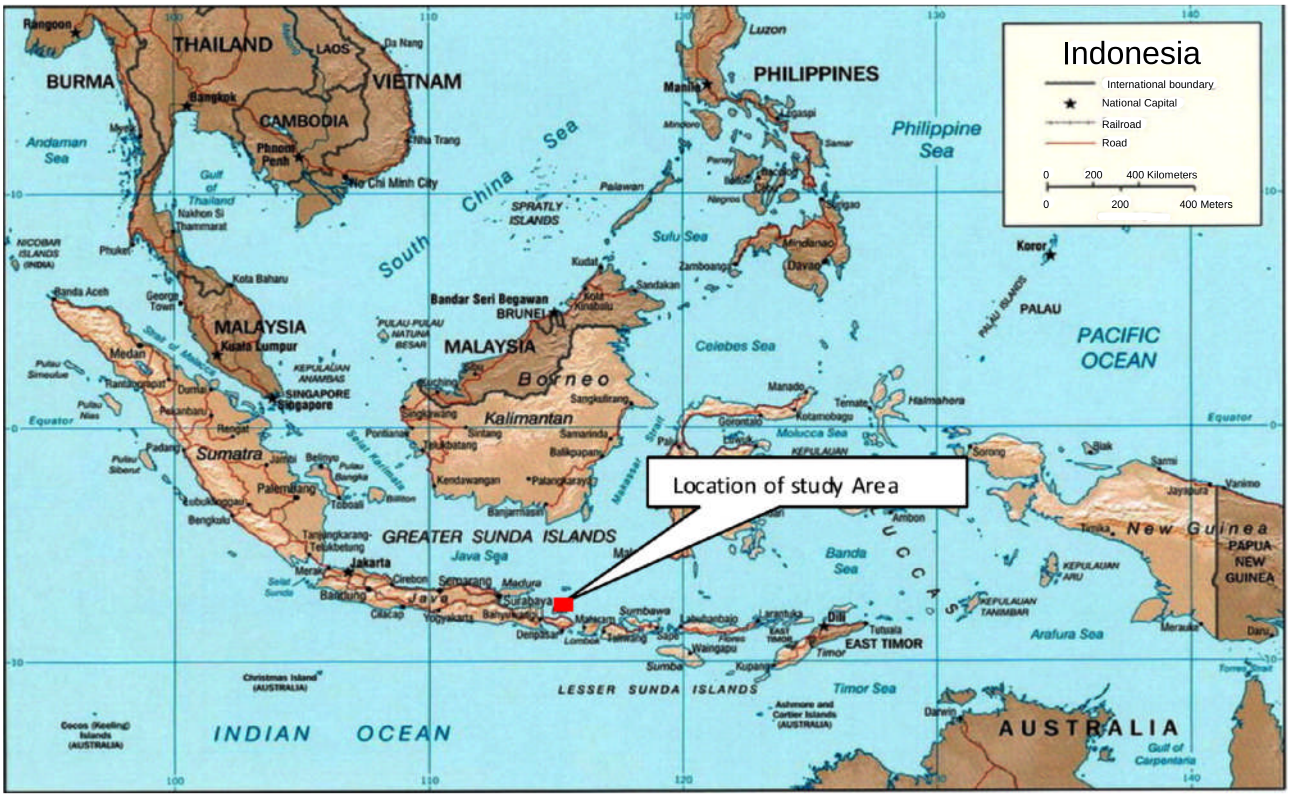

Figure 1- Location of the Study Area, East Java Sea Basin.

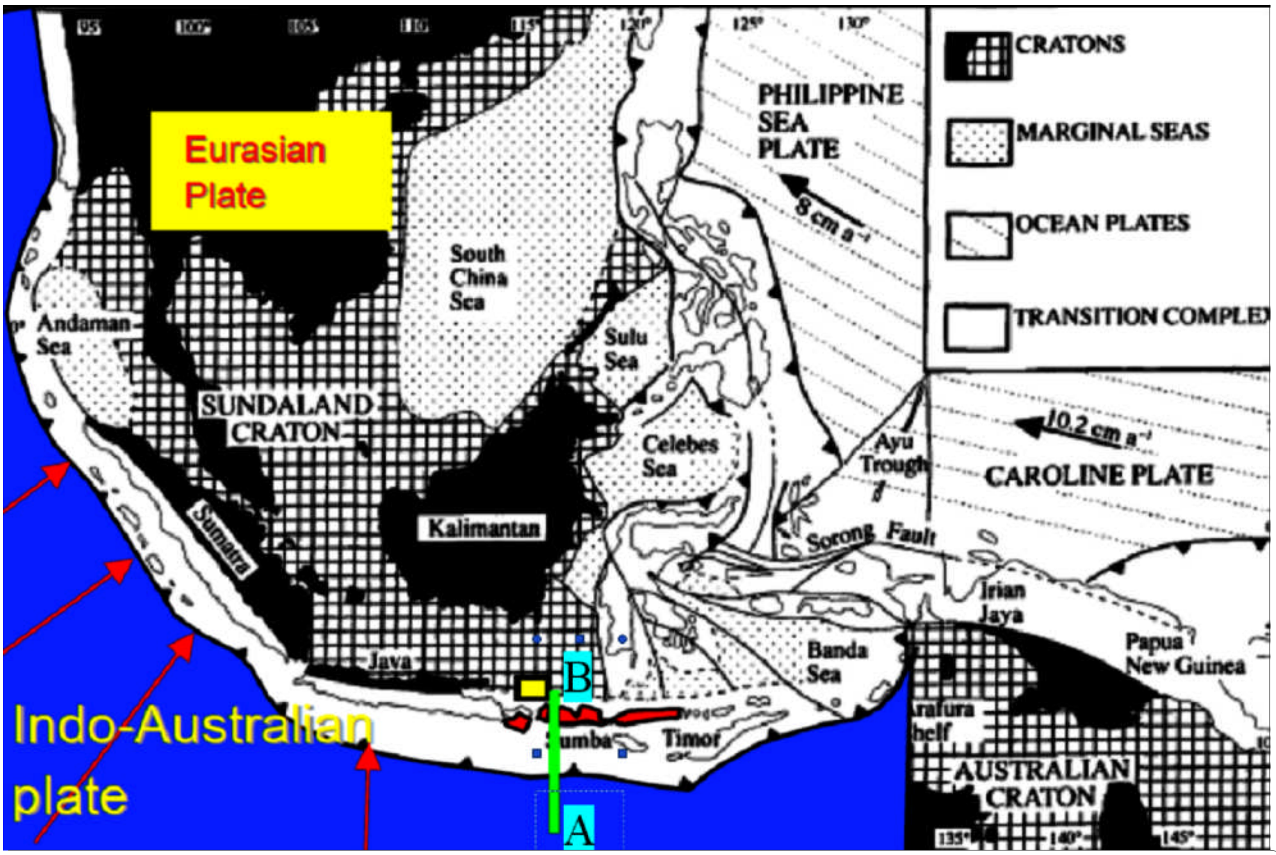

Figure 2a - Regional tectonic map of East java Sea Basin and Indonesian archipelago (After Simandjuntak and Barber, 1996).

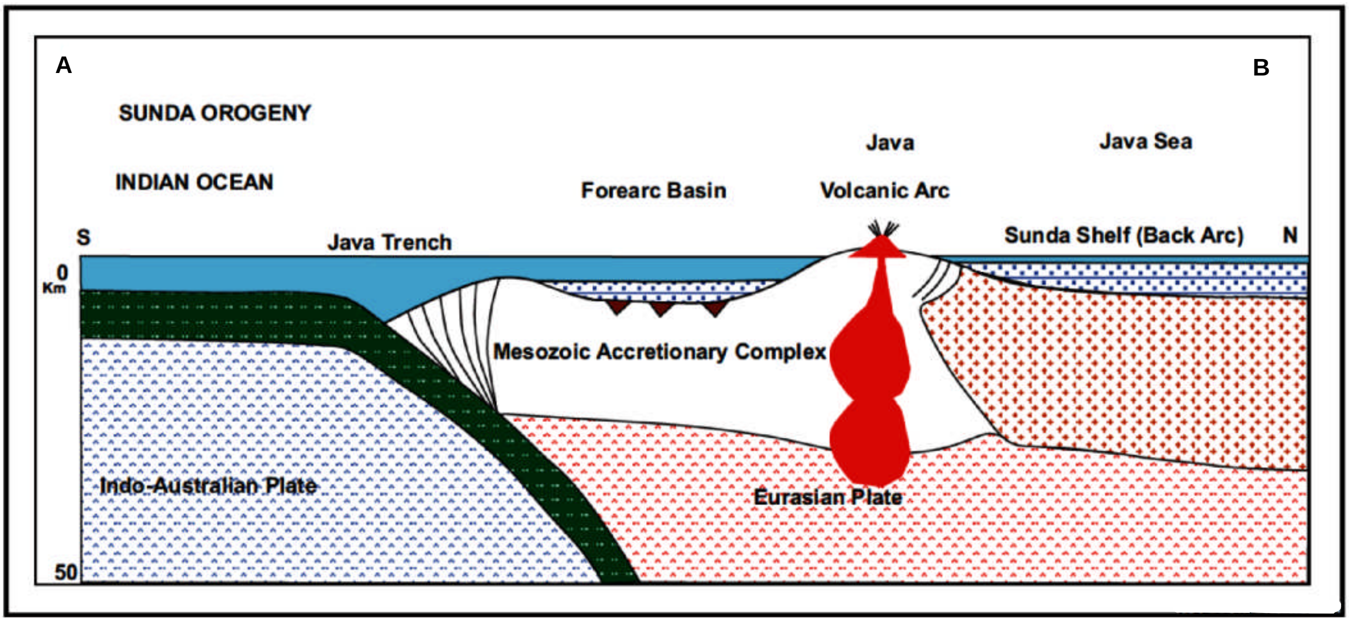

Figure 2b - Schematic cross section showing the subduction of Indo-Australian plate under Eurasian plate, forming the volcanic arc of Andean type.

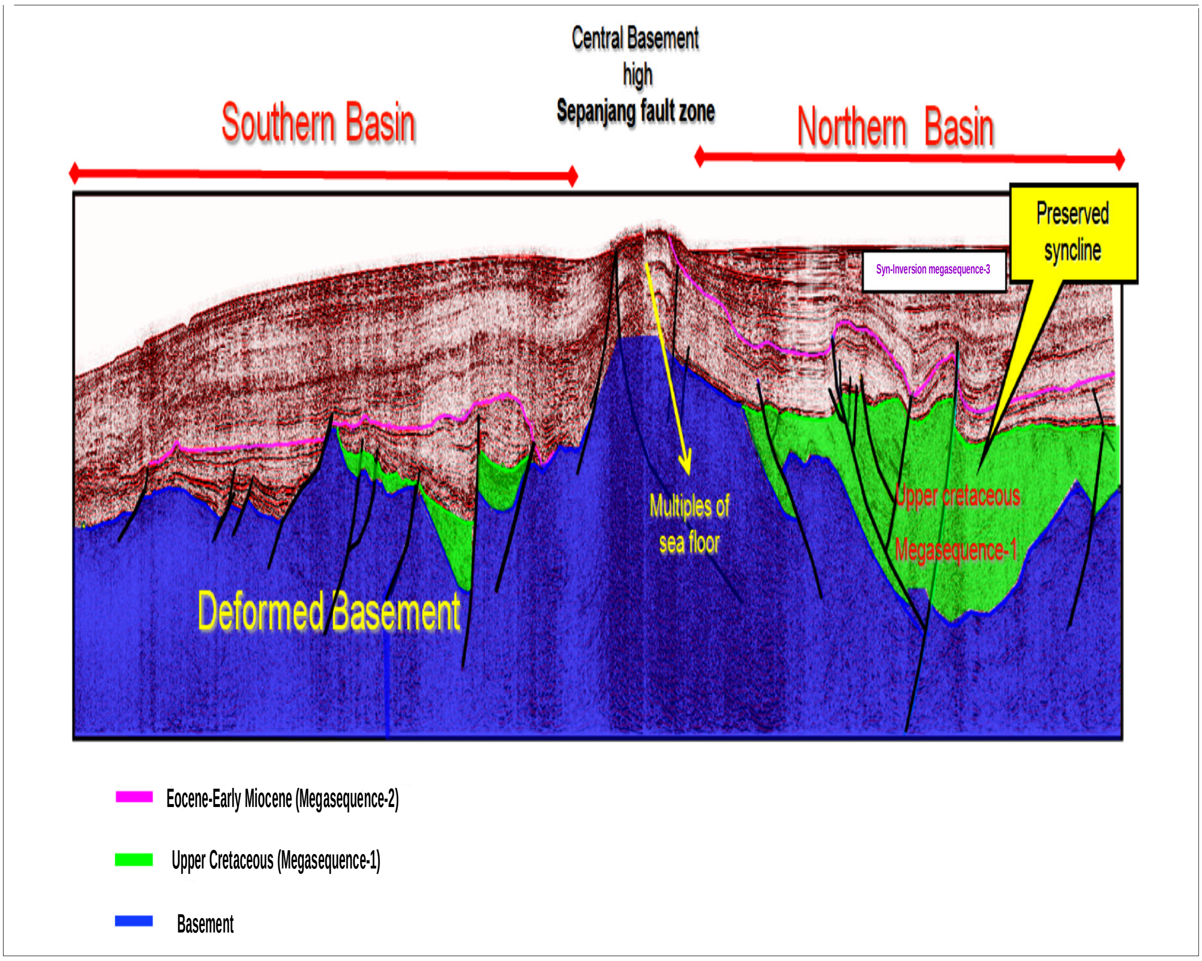

Figure 3 - N-S regional seismic line showing megasequences-1, 2 and 3.

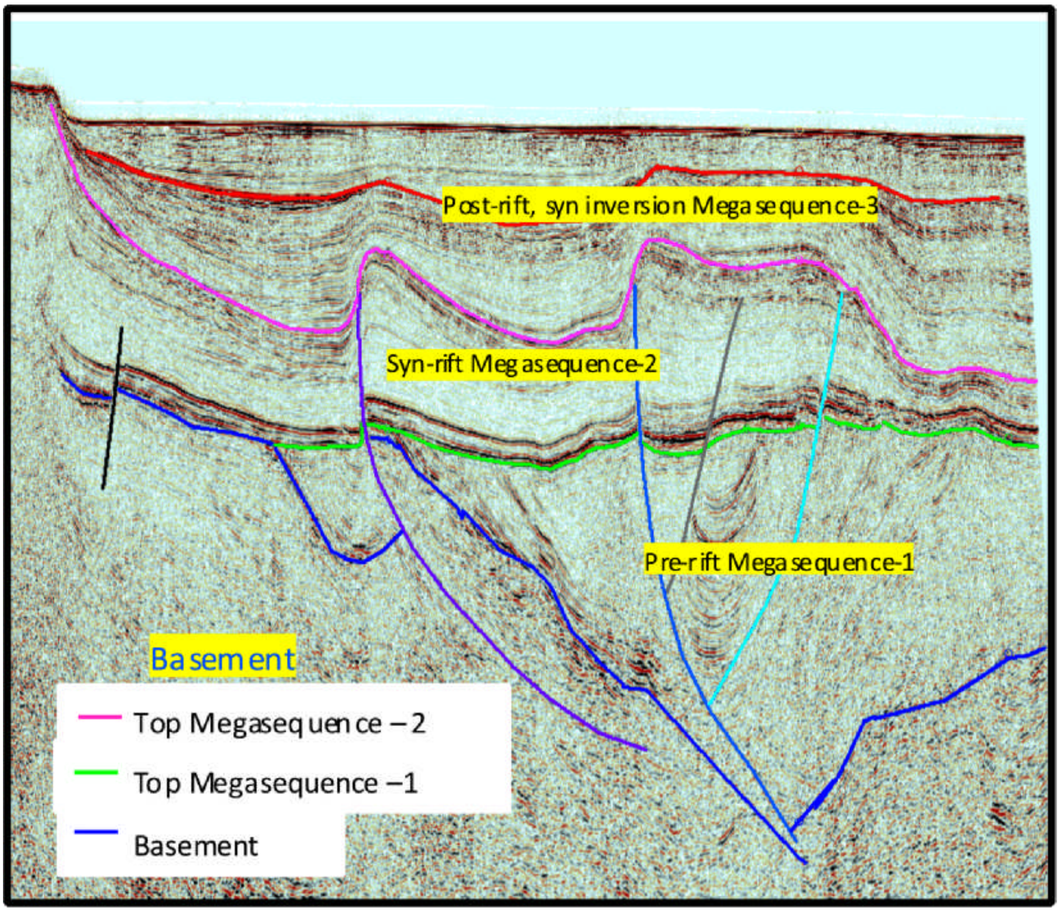

Figure 4 - Seismic section showing Pre-rift, syn-rift and post rift megasequences.

3.2 Eocene to Lower Miocene Mega-sequence-2 (M2)

There is no evidence of Paleocene deposition in this area and M2 lies unconformably over the upper Cretaceous angular unconformity.

M2 consists of transgressive syn-rift deposition that has later on undergone inversion. This mega-sequence consists of fluvial clastics, passing upward into coals, carbonaceous mudstones and occasionally distributary channel sandstones of early to middle Eocene age. These are successively overlain by shelf mudstones with minor interbedded sandstones and limestones, deep marine mudstones and calcareous mudstones. Top of M2 is the top of Prupuh limestone, which also marks the initiation of regional inversion shown by the on-lapping of younger strata onto the Prupuh limestone which has folded into gentle anticlines especially in northern sub-basin (Matthews et al., 1995)

3.3 Lower Miocene to Holocene Mega-sequence-3 (M3)

M3 shows progradation with dominantly clastic deposition in the west and carbonates in the east of the basin (Matthews et al., 1995). It shows onlaping onto the top synrift Prupuh limestone suggesting syn-inversion origin.

4. Seismic Interpretation

Four stratigraphic levels, top basement, top Cretaceous (M1), top Lower Miocene Syn-rift sequence (M2) and Top sea bed were selected for interpretation/mapping on the basis of their structural significance and importance in the tectono-stratigraphic history of the basin. Formation tops were correlated using well to seismic tie (company propriety). Top basement can be observed as top of seismically transparent zone, without any coherent reflections. Top Cretaceous (M1) is present as an angular unconformity thus lacks any continuous reflection. Top M2 sequence marks the top of syn-rift deposition. Top sea bed was mapped to observe any active structuration.

5. Geometry of the Basin

Basement surface shows an EW trending basin immediately south of the island of Lombok. Southern most part of the basin is the northern flank of the volcanic arc. A basement high that crops out in the western part of the basin is known as Sepanjang fault zone (Figure-3 & 5; Matthews et al., 1995). This basement high separates the basins into two sub basins namely, the northern sub-basin and the southern sub-basin. The geometry and deformation style of both sub-basin

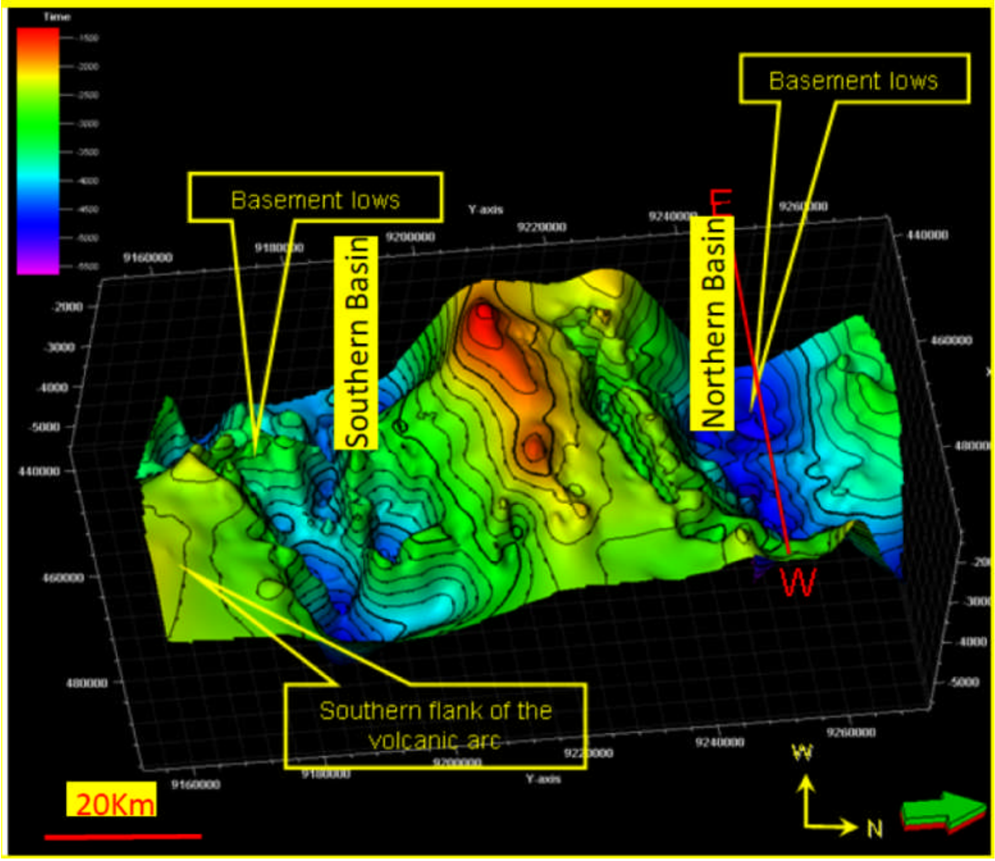

Figure 5 - Top Basement surface showing the geometry of the basin.

are significantly different from each other. Topographic high at sea bed level shows that current phase of compression is still active resulting in compressing the basin in north-south direction.

6.0 First phase of Inversion(Negative)

Upper Cretaceous M1 sequence deposited on a previously deformed and metamorphosed basement was further deformed during a compressional or transpressional event prior to erosional truncation and deposition of Eocene syn rift clastics. The exact timing of the formation of these large amplitude folds in the form of anticlines, synclines and compression associated faults is not known but generally they are considered to be of late Cretaceous or early Paleocene age (Matthews et al., 1995).

It is important to explain the term inverted faults; in the current text it means reactivation of previously formed normal faults in reverse mode (Figure-6). The beginning of extension or negative inversion in this part of the basin is observed at the time of early Eocene as Paleocene is missing in this area. Net extensional displacement by re-activation along the major pre-existing reverse faults along with sedimentation occurred from Eocene to Early Oligocene time resulting in the deposition of thick syn-rift growth strata on the down thrown side of the possible pre-existing inverted faults. The distribution and thickness of these growth strata depends on orientation and displacement along these faults. The depocenters of these syn-rift packages are located where maximum displacement along these inverted faults has occurred. The isochron map for M2 shows its thickness variation along the faults and therefore indirectly the amount of displacement along these inverted faults during the extensional phase (Figure-7). Geometries evolved as a result of this deposition during displacement can be very important as it preserves information about the timing of fault re-activation and rate of sedimentation. These informations are important to estimate the petroleum potential of the basin and risk evaluation.

6.1 Second phase of inversion (Positive)

End of Oligocene marks the end of rifting phase. The basin once again went under compression and negative inversion started. The major rift related faults started inverting, by changing the sense of slip and uplifting of syn-rift growth strata (Figure-6 & 8). All the positive inversion may not be entirely accommodated by reactivation of rift related faults, flexure and folding has also played its role to accommodate the stress.

The basin finally bulges out and the syn-rift local depocenters become topographic highs (Figures-6 and 8). All the highs on top M2 surface are the inverted syn-rift depocenters associated with positive inversion of the basin.

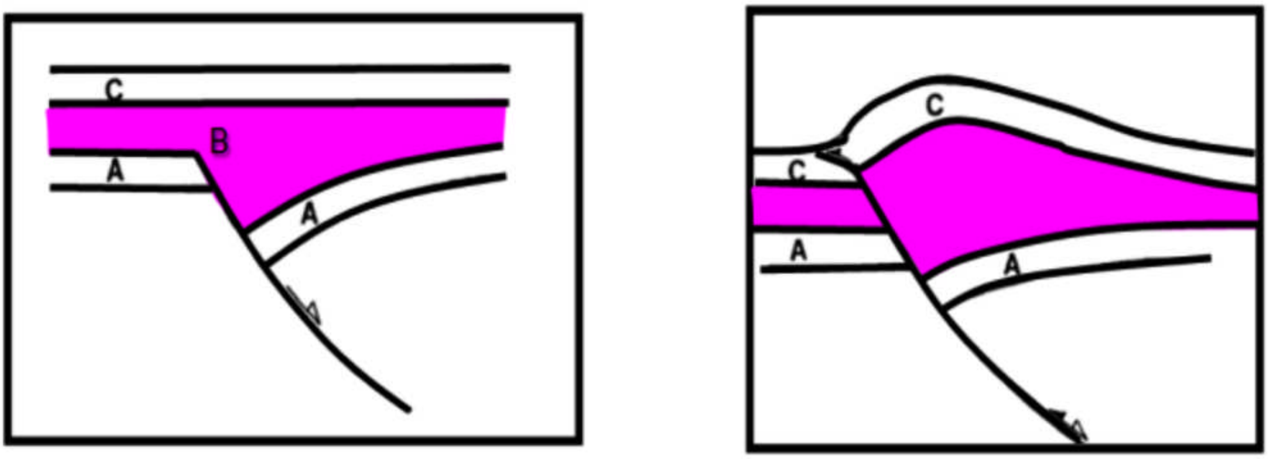

Figure 6 - Model showing geometry of positive inversion structures.

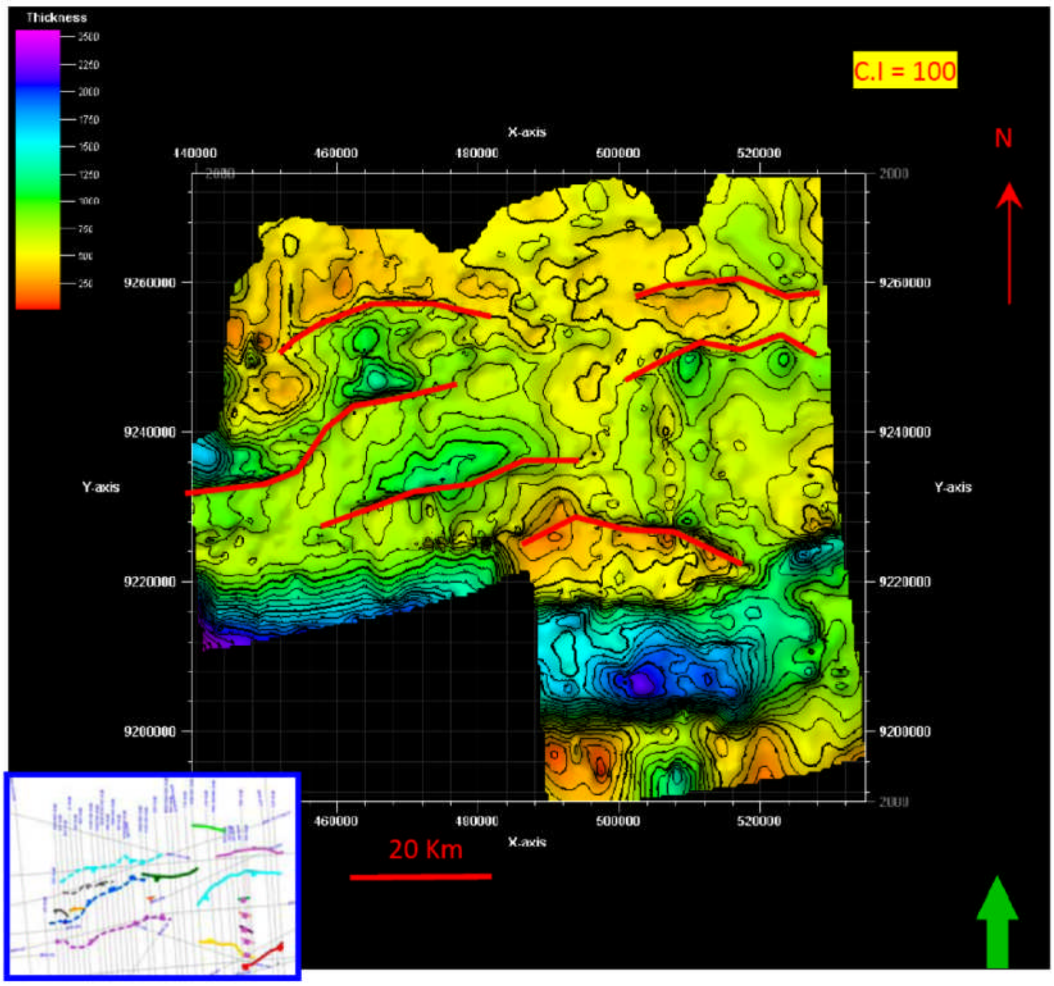

Figure 7 - Isochrone map of Eocene-Early Miocene syn-rift megasequence-2 shows trend of Eocene faulting.

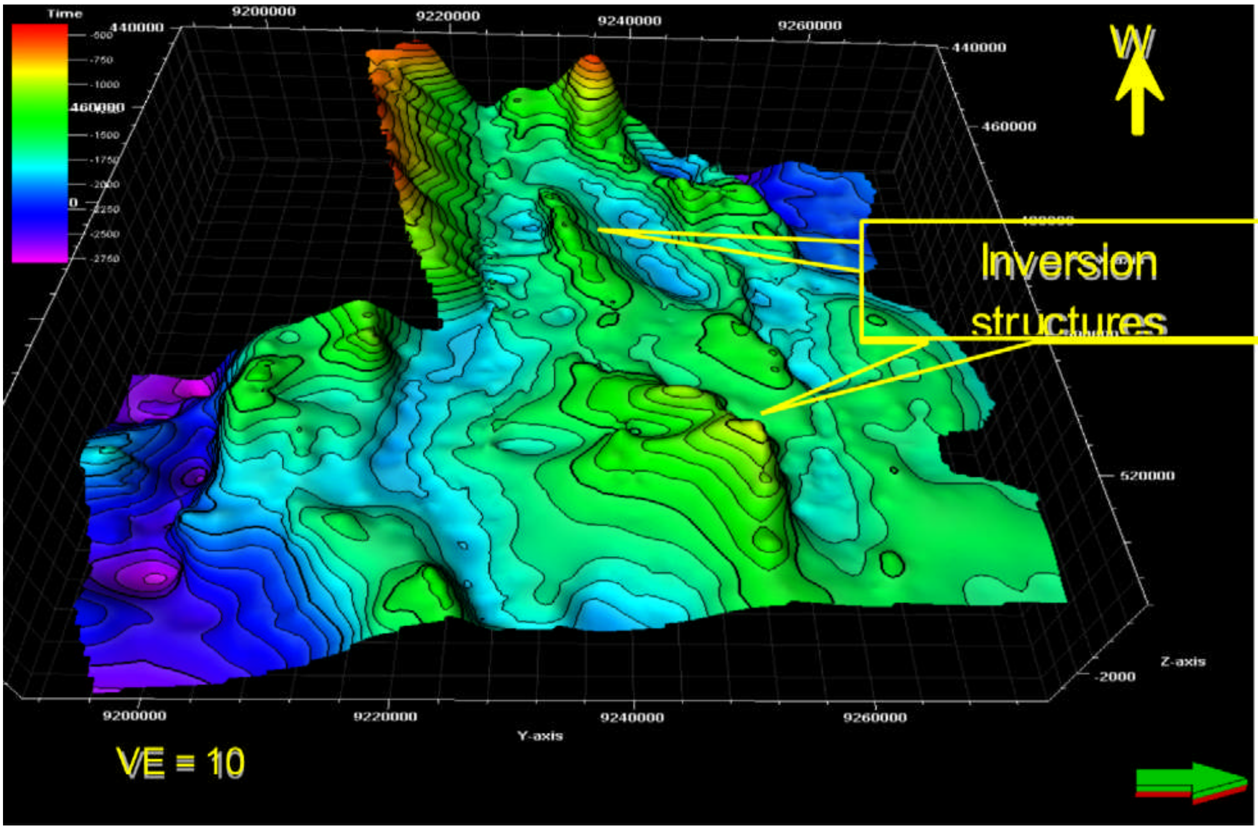

Figure 8 -Time contour surface at top M2 level showing the geometry of positive inversion structures.

7.0 Inversion along the faults

During the recent phase of positive inversion, stress is predominantly accommodated by inverting the pre-existing faults rather than developing new faults or shortcut faults. All the faults at top M2 level shows net reverse movement whereas at top M1 (Upper Cretaceous) some of the faults still show net extension along their strike. The central basement high Sepanjang fault zone, plays a very important role by accommodating most of the compression and hence separating the two sub basins. Latest active phase of positive inversion is not uniformly distributed within the basin. Southern sub-basin show very mild inversion as all the faults at top Cretaceous level still show net Extension, where as in northern sub-basin most of the faults are totally inverted and show net compression (Figure-3). Western part of the northern sub-basin has experienced more positive inversion as all the faults are inverted from net extension to net compression at all levels, whereas in eastern part some of these major faults still show net extension at top upper Cretaceous level along their strike (Figure-9).

8. Hydrocarbon prospectivity of East Java Sea basin

The first significant hydrocarbon production from Indonesian reefal carbonates began in 1952 (Nayoan et al., 1981). Carbonate mounds developed over the Oligocene-Miocene inversion related highs are the potential reservoir targets for hydrocarbon exploration in East Java Sea basin. Off mound facies are Marls and chalks with occasional shallow water carbonates debris derived from the mounds.

9. Inversion Tectonics in Pakistan

Review of published literature reveals examples of inversion tectonics from the Sulaiman and Kirthar fold belts of Pakistan. Such structures are related to reactivation of deep seated Mesozoic extensional faults and their conversion to reverse/thrust (inverted normal faults) due to Tertiary compressional tectonics.

Ahmed et al., 1991 considered that the Sibi basin is an inverted extensional basin in which the pre-existing normal faults of Mesozoic rift were reactivated during Oligocene-Early Miocene time and inverted to high angle reverse faults (Figure-10) due to the combined effect of compression from (i) Sulaiman fold and thrust belt in the north & east (ii) left lateral transform movement in the west in Kirthar fold belt. The inversion has also affected the Cenozoic section.

Hedley et al., 2001 analyzed and established relationship between sequence stratigraphy and tectonics of the Kirthar fold belt, Pakistan. It is an area of broad buckle folds separated by narrow synclines and were previously interpreted as the result of thin skinned tectonics terminating abruptly eastwards in a major passive back thrust.

Hedley, et al 2001 reinterpreted the area based on observations of active strike-slip component along with

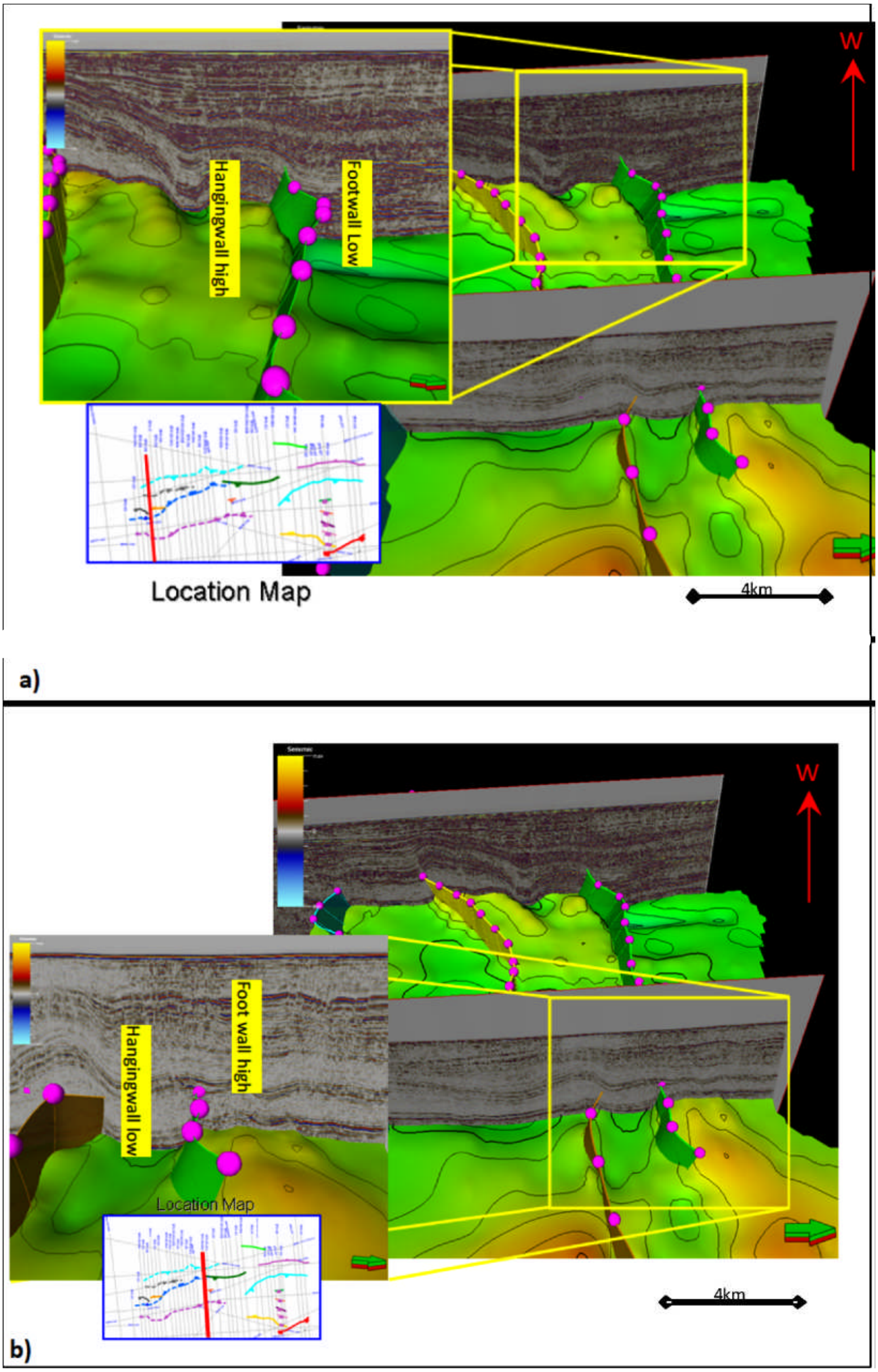

Figure 9 -3D surface, showing the reversal of throw along strike of the fault at top Cretaceous level in EW direction across the northern basin.

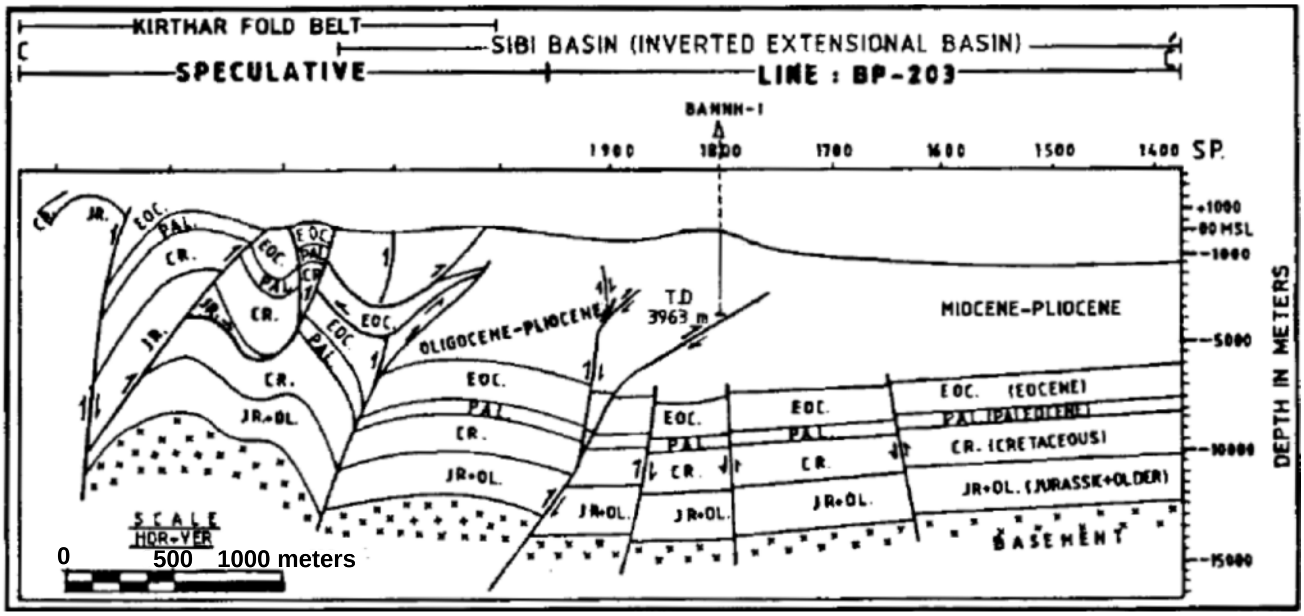

Figure 10 - Structural cross-section across Bannh well in Sibi basin showing inversion of pre-existing normal faults of Mesozoic rift to high angel reverse faults (after Ahmed et al., 1991).

compression. They proposed an oblique slip type of thick skinned model, possibly involving inversion along pre-existing extensional faults developed on the Indo-Pakistan Plate passive margin (Figure 11).

Their model explains that evolution of the Kirthar fold belt is the result of positive inversion along early Cretaceous syn-rift faults. Local highs developed as a result of positive inversion would have controlled the facies distribution within the basin and should be considered during hydrocarbon prospectivity evaluation of this region.

These are very important observations, suggesting that basement is involved in these inverted structures. Positive gravity anomalies follow the trend of the Sulaiman and Kirthar fold belt also suggest the involvement of the basement in structural deformation (Figure-12). This would mean that there are chances of finding older petroleum system above the basement and below the existing Cretaceous plays in Kirthar Fold belt. PPL is pursuing this play in their Khuzdar Block.

The inversion and thick-skinned tectonics are not necessarily the same thing but generally they often do coincide. Usually the structures termed as thick skinned are the result of inversion of previous structures like the Central Apennine (Italy). Following features are common in such tectonic regimes (1) thrust faults are steeper but do not steepen downwards necessarily; (2) there is less lateral continuity in both folds and stratigraphy (3) there may be inliers of stratigraphic packages, other than the principal one, undergoing deformation; (4) folds wavelengths may be much more viable locally, and less related to the thickness of the deforming succession (5) there may be major stratigraphic changes between principal thrust faults, especially near the base of the upper plate succession, since each major thrust originally separates two different depositional basins, the base of the succession may contain coarse clastics and local evaporates; (6) the footwall succession may be variably eroded and discontinuous: the upthrown sides of the original extensional faults would have been exposed to erosion; (7) faults are likely to cut across bedding in their footwalls, which may not cut across bedding in the upper plate than are low angle thrusts; (8) less control of the footwall succession on fold and thrust style, but more control of basement-involved faults; (9) there may be major vertical faults offsets that are unrelated to local stratigraphy ; and (10) the total shortening and the rate of shortening are both 20-25 % of the same features calculated for thin-skinned tectonics. Iqbal (2004 Ph.D thesis un-published) quoted the concept of inversion tectonics of Coward (1994) for the structures of the Sulaiman, Kirthar and Kohat regions. Coward (1994) concluded that " example of reverse faults and folds, which have previously been interpreted as thin-skinned thrusts, but which may warrant re-interpretation as thick-skinned inversion structures, include parts of Appennine of Italy, the Zagros Ranges in Iraq and western Iran (Ameen, 1992), and the Kirthar, Sulaiman and Kohat ranges in western Pakistan" (Coward, 1994: 300-301).

Conclusions

Excellent example of basin inversion from East Java Sea Basin helps structural geologists to understand and appreciate the evolution and significance of inverted basins. Multiple phases of inversion in East Java Sea basin reveals its dynamic tectonic history and structural control during sedimentation leading to structural evolution. Structures developed as a result of these processes are complex and careful interpretations are required.

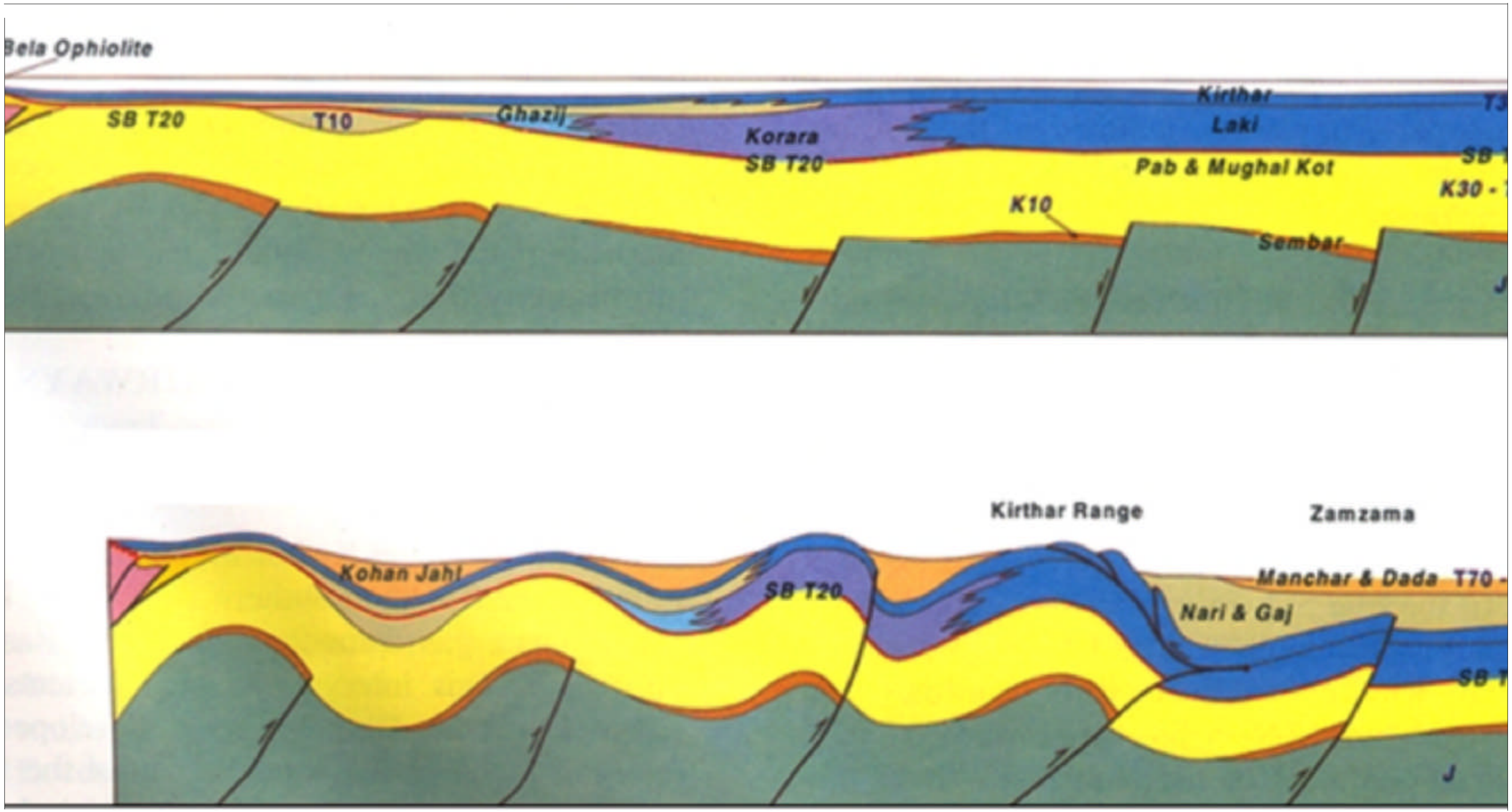

Figure 11 - Structural model for the evolution of Kirthar fold belt, showing positive inversion of Late Jurassic rift related faults (After Hedley, et al., 2001).

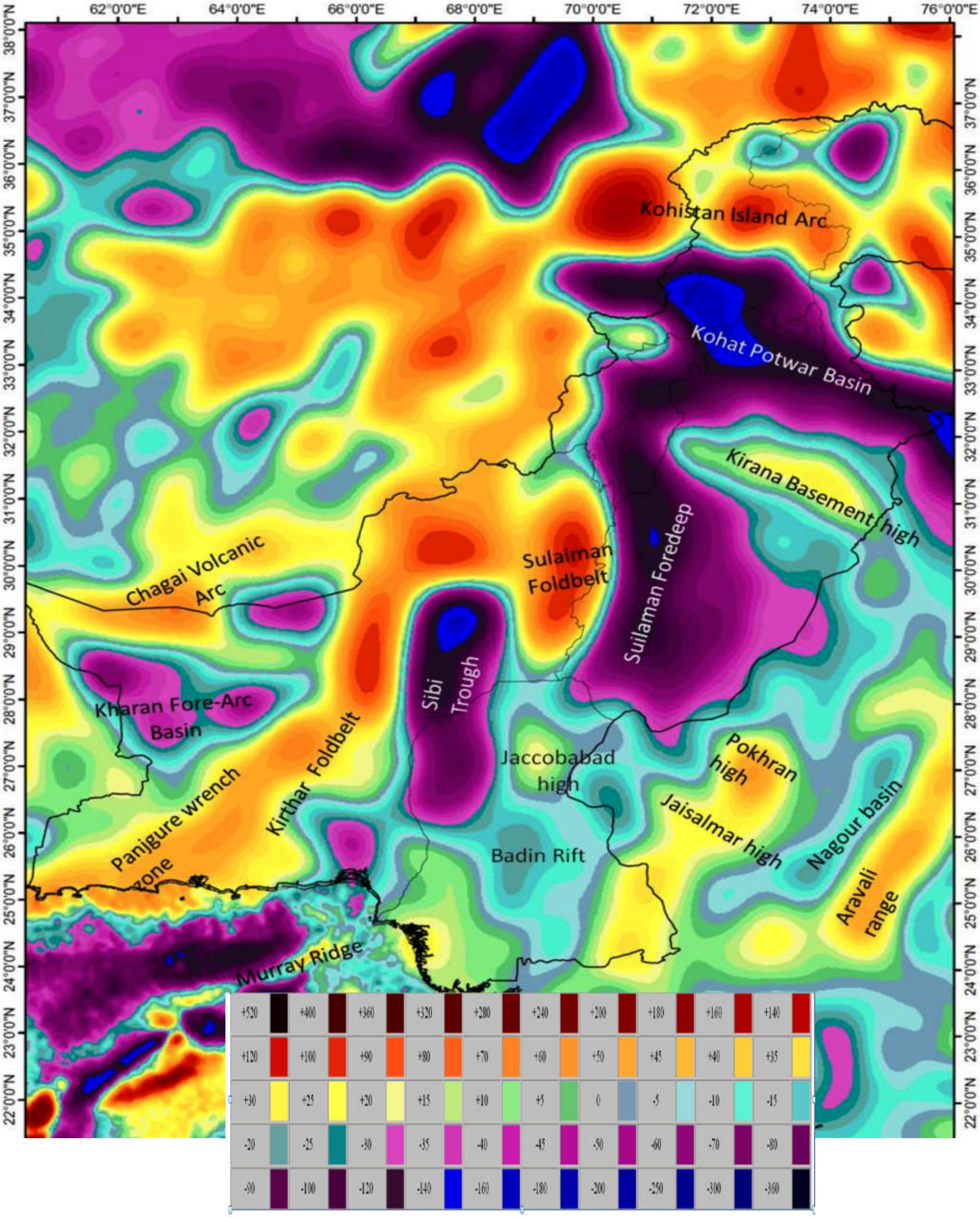

Figure 12 -Regional satellite gravity anomaly map showing Basement involved tectonics in Sulaiman and Kirthar fold belts of Pakistan. (after Sandwell and Smith, 1997).

The present structural configuration of Pakistan is also a result of very complex tectonic processes of rifting, drifting of Indo-Pakistan Plate and finally its collision with Eurasian Plate. Uplift of Himalayas in the north and very rapid deposition of molasse in the Indo-Gangetic Plain in the south is the outshoot of collision tectonics. As a result of tectonic pulses basin inversion took place in geological past. These events have been preserved in the geological record of the region.

In view of the important role of inversion tectonics in understanding basin development and evaluation of its hydrocarbon prospectivity, it is recommended to conduct another round of structural interpretation of previously interpreted thin-skinned tectonic regimes. Data in public domain from outcrops, modern satellite images, wells and sophisticated seismic reflection profiles will greatly assist us in such integrated study.

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