9th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2012"

P-308

Structural Modelling with Qualitative and Quantitative analysis to understand Crustal architecture along a regional profile in Western Offshore Basin, India

Jatindra Kumar Samal*, Ranjit Shyam and Saumitra Gupta, *ONGC*

Summary

Detailed structural analysis has been carried out along a regional seismic profile extending to deep water, South of Mumbai High, Western Offshore Basin, India. Qualitative modelling has been attempted by critically evaluating different growth features like progradational wedges/fans and stratal disposition with respect to structural elements. Quantitative structural modelling has been carried out by using Move software to determine regional consistent values for depth to detachment of the fault systems and its implications on crustal extension have been determined in the present study. The analysis has helped out to develop a comprehensive structural model to understand the kinematics and tectonic evolution of the basin. Different extensional structural features such as Basement involved normal faults, Paleocene asymmetric rifts, extensional folding and related structures formed due to propagation of basement faults through variable mechanical stratigraphy of overlying sediments and complex hanging / foot wall deformation have been identified. Seaward Dipping reflectors (SDR) indicating volcanic flows deposited within the rifts bounded by listric faults have also been identified. The structural model proposed in the present study will help to asses the risk involved in hydrocarbon exploration. The quantitative understanding of depth of basal detachments of normal faults at different crustal levels will give insight into the extensional tectonics of western continental margin of India. The present study will aid in developing viable models for deep water exploration.

Keywords*: Extensional Structures, Seaward Dipping Reflectors (SDR's), Structural Modelling, Inclined Shear, Detachment Surface, Continent Ocean Boundary (COB).*

Introduction

The western continental margin is considered to have evolved consequent to rifting of Madagascar and Seychelles from Indian Peninsula (during Late Cretaceous and Latest Cretaceous-Paleocene).A series of horsts and grabens resulted in response to rifting along the dominant basement tectonic trends (NNW-SSE, NE-SW and ENEWSW) (Fig 2). The northernmost part of the western continental margin was first to be subjected to continental rifting and crustal subsidence in late Triassic (Biswas, 1988) and then process of rifting gradually advanced towards south and by cretaceous time all the rift related horsts and grabens came into existence. The deposition during early rift phase started with continental environment which changed gradually to paralic and finally to pulsating marine conditions, punctuated by basic lava flows in the terminal stages towards the end of Cretaceous and early Paleocene. Most of the rift related regional and local horsts and graben systems were covered by sediments by the end of early rift phase and the continental margin became less intricately differentiated. The end of early rift phase is marked by a basin wide unconformity, clearly depicted on seismic sections and dated on paleontological evidences as close of Middle Late Paleocene in the Bombay offshore Basin. The post rift phase witnessed passive subsidence of continental margin, tilting of depositional surface basin ward due to thermo tectonic adjustments.

AAF Block, A&AA Basin, Luit Bhawan, ONGC, Cinnamara, Jorhat, Assam, India
E-mail: jatinsamal@gmail.com

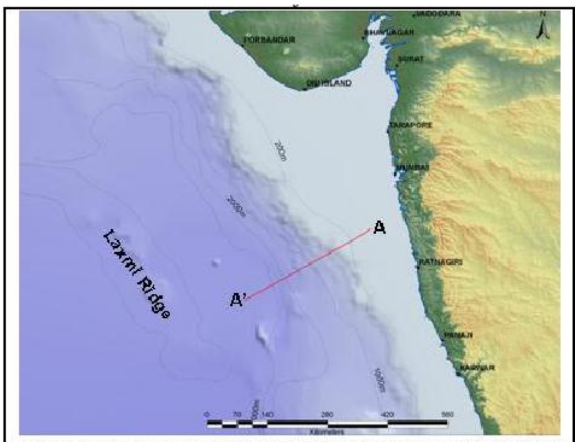


Fig 1: SRTM image showing location of the studied Section (AA')

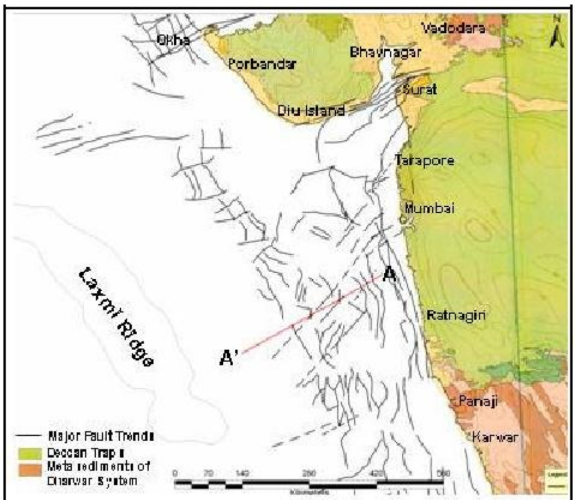


Fig 2 : Major tectonic elements of Western Offshore Basin along with Onland Geology. Ref: Modified after Bhowmick et al, 2008

Objective and methodology

In the present study, an attempt has been made to analyse extensional structures and their evolution along a regional profile of 326km covering shelf to ultra deep water setup.(Fig-1) High resolution post stack depth migrated seismic profile (Fig 3B) has enabled to study deep crustal phenomena by quantitative structural modeling using Move software. Modelled detachment surface was constructed from the derived detachment depths for individual faults to understand the process of extension through simple shear mechanism (Fig 8). An attempt has also been made to study the extensional tectonics related to magmatism and propose an integrated model of continental extensions along the western continental margin of India and delineation of Crustal boundaries.

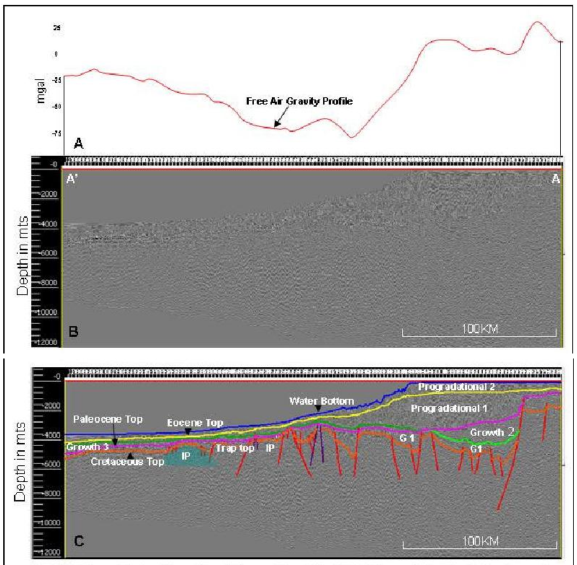


Fig 3: A: Free Air Gravity profile of the section AA', B: Uninterpreted seismic depth section C: Interpreted Seismic section. Abbreviations: IP- Igneous Protrusion, G1-Growth 1

Analysis

Stratigraphic

Broadly two mega sequences i,e Paleocene rift and younger post rift sequences have been identified considering Cretaceous trap top as bottom most correlatable reflector. The regionally unconformity surface separates younger passive margin progradational sequences from the older rift sequences. Different tectonic phases has been identified by mapping syntectonic growth sequences. Typical Paleocene syn rift wedges have been mapped along the profile. Three Syntetctonic growth packages have been identified. Initial growth packages (1&2) are related to the continental rifting stages (Fig 3C). Transparent to chaotic seismic package representing distal mud flows (Growth 3) over Eocene surface indicates tectonic upheaval during late Eocene period towards continental side.

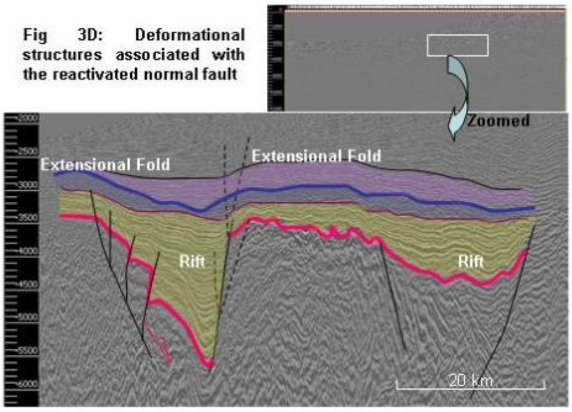
Seismo facies

The seismo facies indicating volcanic flows have been studied. Sea ward dipping reflectors (SDR's) representing sub aqueous volcanic flows during Cretaceous have been documented (Fig 9A). Several igneous intrusions and domal protrusions were identified in the study. The high amplitude stand outs within Paleocene rifts may also represent different episodes of volcanic activities.

Structural

Mainly two types of extensional structures i.e rotated half grabens or horst and graben, extensional folds (Fig 3D) developed within post rift sequence due to the extensional reactivations of basement related faults. The structural interpretations were validated from different structural analogue models.

Fig 3D: Deformational structures associated with the reactivated normal fault



Structural Modelling

Quantitative structural modeling was carried out using Move software by M/S MVE to find out basal detachments of major Paleocene graben building faults. High angle extensional rift building faults generally becomes low angled downward and detached at brittle ductile transition within the upper crust or at the boundary between upper crust & lower crust. The crustal rheology plays important role in the development of rift structural style and the depth of detachment (Fig 4).

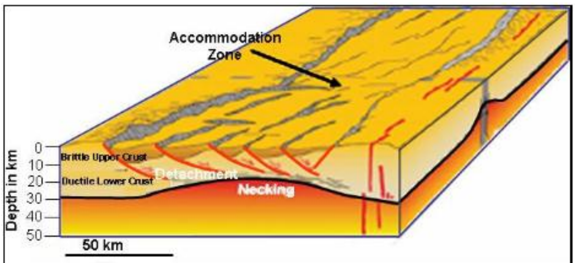


Fig 4: Detachment surface separating brittle & ductile crust. Case study from Gulf of Suez. (After Khallil & Mc Clay, 2001)

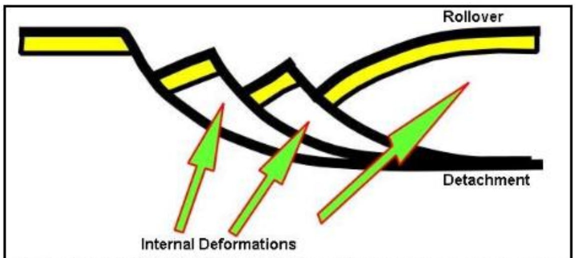


Fig 5: A listric fault implies a rotation of the hangingwall, which is controlled, by the depth of detachment plane

The hanging wall geometry depends upon the shape of the normal fault (Fig 5). The Depth to Detachment is calculated using the area balance method by applying inclined shear algorithm (Fig 7). At optimal shear angle the fault becomes horizontal at the level of detachment. For this to work, there must be an enclosed, triangular area between the Regional, the hanging wall and the fault plane (Fig 6). In the present study five major fault planes of the rifts were reconstructed and depth of detachment was determined for each fault. Finally a modeled detachment surface was constructed joining all the above detachment depth points (Fig 8). Different extensional processes like pure shear, simple shear and combination mode has been proposed to explain the geometry of extensional structures and their causative. Magmatism and related extension has been extensively studied by different workers through different physical and numerical models. Simple shear mode of extension due to uprising magmatic bodies / mantle up warping with the development of rifts having detachment within the crust and over magmatic bodies have been well documented in the literature. In the present study similar rifting / extensional style could also be documented.

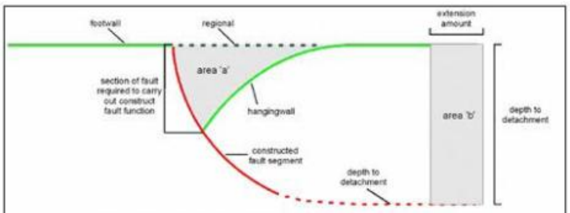


Fig 6: Principle of calculating depth of detachment

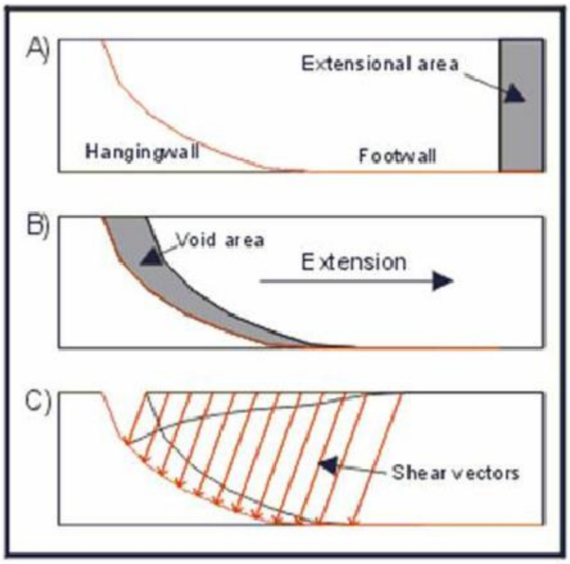


Fig 7: Principle of Inclined shear. A) Initial state showing amount to be extended B) Area of extension equals to area of void C) Shear vector controls how hanging wall elements collapse down onto fault plane. Ref: MOVE by M/S MVE

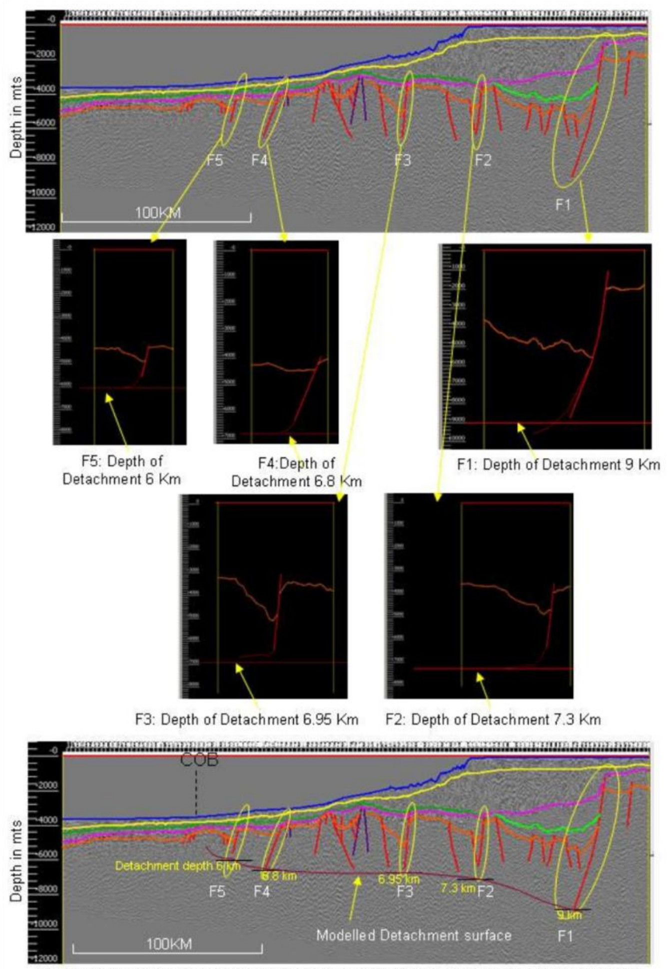
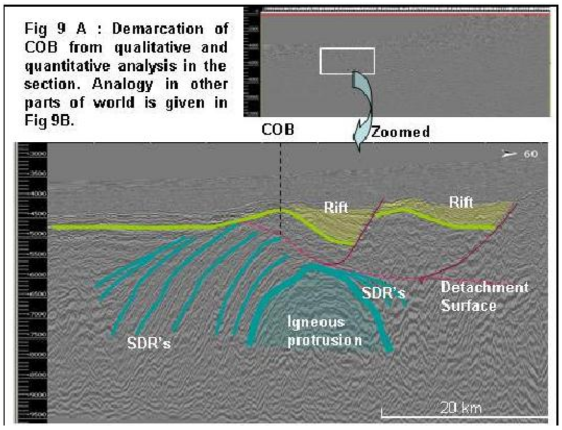


Fig 8: Determination of detachment depth using Move software by MVE and finally determining the modeled detachment surface.

Continent Ocean Boundary (COB) delineation

Fig 9 A : Demarcation of COB from qualitative and quantitative analysis in the section. Analogy in other parts of world is given in Fig 9B.



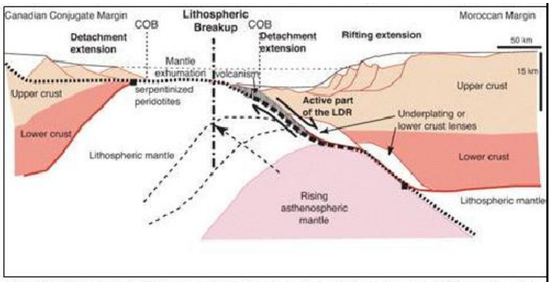


Fig 9B :2D-Model of the conjugate margins of Morocco and Nova Scotia demarcating COB. Ref: Maillard Agnes et. Al, 2006

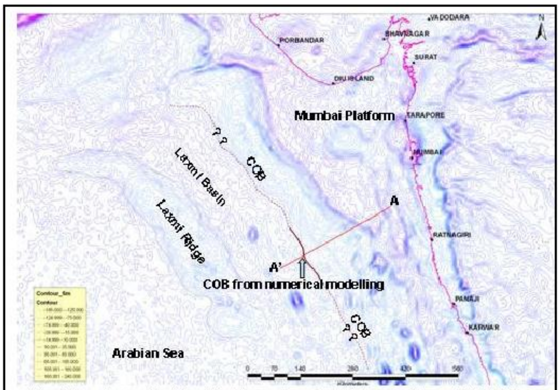


Fig 10 : Free Air Gravity Map showing demarcation of COB from qualitative and quantitative analysis in the studied section. Gravity data source: Topex

Demarcation of the ocean ward extension of the continental basement (thinned continental crust) of the Indian Peninsula is of vital significance to hydrocarbon exploration. All along the western margin owing to a relatively younger magmatism, the zone of continentocean boundary (COB) is rather difficult to identify. COB is poorly constrained along the WCMI which may be due to overprinting of with few more regional tectonic / magmatic events succeeding the formation of the continental margin. In the present study, COB has been demarcated by integrating the structural style, geometry of the lower detachment surface, Free air gravity data and magmatic seismic facies (Fig 9, 10). The point where the modelled detachment surface derived from numerical modelling (Fig 8) emerges out may be considered as the domain of brittle/ elastic continental crust. This demarcation through modelling helps immensely in validating the continent Ocean boundary identified from the qualitative analysis.

Conclusions

Cretaceous to paleocene magmatism has significant role in the formation of extensional rift structures in the Western Continetntal margin. The demarcation of COB could help in prioritising the exploration areas having rifted structures and optimal heat flow for hydrocarbon generation. The structural model proposed in the present study will aid in assessing the risk involved for hydrocarbon exploration. The present study helps in predicting the geometries of structures from observed deformed geometries. The quantitative understanding of depth of basal detachments of normal faults at different crustal levels will give insight into the extensional tectonics of western continental margin of India. The present study will help in developing viable models for deep water exploration. Similar work if carried out along other profiles could help in prioritizing the area of exploration interest.

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Acknowledgement

We express our sincere thanks to the management of ONGC for their kind permission to present and publish this paper. We are grateful to Sh S. K. Jain, Basin Manager, A & AA Basin for his encouragement and support. We are indebted to Sh. R. N. Dwivedy for his valuable suggestions and constant encouragement. The views expressed in this paper are solely of the authors and not necessarily of the organization in which they are working.