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Tectonic evolution of Andaman Inner Forearc basin and its implication in hydrocarbon exploration.

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Abstract:

Based on the newly acquired 3D seismic data and integration of this data with existing well data and 2D seismic data in the inner fore arc part of Andaman Oceanic Island Arc system, two phases of evolution, accretionary prism phase (upper Cretaceous to Oligocene) and forearc phase (Early Miocene to Recent) have been proposed for the Andaman Inner Forearc basin situated on SE Asian region of Eurasian plate.

In the accretionary prism phase, most of the sediments are trapped in the trench and are involved in the process of accretion onto the overriding plate which eventually leads to an outerarc formation towards the close of Oligocene. This phase is characterised by complex thrusting and folding towards the trench side and normal faultingand associated deformation towards the volcanic front side responsible for the large structural trap formation in the area. In this phase, a thick prism of sediment containing good source rock (Eocene) and potential reservoir rock (Oligocene turbidite) has been identified in the area around present day deepwater. This source and reservoir combination constitute the first speculative petroleum sysyem, i.e, Paleogene-Paleogene (!) in the basin with the critical moment for oil towards the close of Mid Miocene and make the paleogene as the prime target. These sediments have been deposited in the deep water setting in the form of pelagite and turbidite with input from Sibumasu continental mass for the lower part of prism (upper Cretaceous to Eocene) and from Bengal fan and Irrawady delta for the upper part of prism (Oligocene). The study envisages short distance and vertical migration in this phase. The migration remains a critical risk for the propects in this phase.

In the forearc phase, most of the sediments are trapped in the arc-trench gap. This phase has been divided into two stages, i.e, ponded fill stage(Miocene) and sag fill stage(Post-Miocene).

Ponded fill stage is inundated by a number of tectonic events and dominantly by a turbidite fill and mudflow deposits.The ponded fill stage is started with an extensional event leading to half graben formation on sedimentary sequence of previous phase and compartmentalisation of forearc basin. This was followed by a quiescent period when carbonate sedimentation in shallow water to outer shelf has taken place and then two compressional events, one towards close of Mid Miocene and other towards the close of Miocene leading to inverted structures and thin skin thrust-fold belt. In this stage, two important reservoirs (carbonate and clastic) in Miocene and one potential source rock have been deposited. With the reservoirs and source rocks of this phase and previous phase, two more petroleum system,i.e.,Paleogene-Neogene (.) and Neogene-Neogene(!)

have been identified. The study also envisages short distance and vertical migration in this stage. The Neogene source rock has just entered in the early phase of oil window in

the area of study. Therefore, the Mid Miocene carbonate with charge from Paleogene source rock is considered as the primary target and Mid Miocene clastics are considered as the secondary target in the area with reservoir as well as charge as the critical risk.

Sagfill stage is characterised by the passive fill of the basin with pelagite and has little hydrocarbon potential.

Andaman forearc basin has hydrocarbon potential in Paleogene and Miocene sequences with hydrocarbon charge as the critical risk in accretionary prism phase and both charge and reservoiras the critical risk in fore arc phase. Prospects overlying the kitchen holds more promises than the prospect away from kitchen. Probable kitchen area in the forearc is located around the present day deepwater area. Therefore, prospects close to the present day deep water are worth probing.

Although the viability of the fore arc area as a hydrocarbon province remains dependent upon the factors that can be confirmed only by drilling well, the shear size of the structural traps, envisaged stratigraphy and disposition within the basinal framework are sufficient to mean that the area VIII is perhaps one of the most attractive candidates for exploration of thermogenic play in the Andaman fore arc irrespective of first well results in the area.

Introduction

The Andaman basin is situated towards southeastern part of Bay of Bengal around Andaman-Nicobar chain of islands (between 6^0 N to 14^0N Lat and 91^0E to 94^0E Long.) and is a part of Oceanic Island Arc system that extends from Sumatra (Indonesia) Islands in the south to Myanmar (Burma) in the north ***(Figure-1)***.The basin has six major geotectonic elements like, as identified from west to east, Trench, Inner Slope, The Outer Fore Arc, The Inner Fore Arc Basin , Volcanic Arc and Back Arc, each with different hydrocarbon potential.

In the Andaman basin, eleven prospects have been drilled, nine in the Outer Fore Arc High and one each on Inner Slope and Volcanic Arc. First prospect (AN-1) drilled on The Outer Fore Arc area is having a very small hydrocarbon accumulation in Middle Miocene carbonate. Rest of the prospects was dry. All these prospects are situated in the shallow water part in the Andaman sea. After the exploration setback in shallow water opportunities in Inner Slope, the Outer Fore Arc and Volcanic Arc area, the focus has now shifted to deep water frontier areas, the Inner Fore Arc Basin and Back Arc area, of Andaman sea. ONGC has acquired a good quality of 3D seismic data in different campaigns (I, VII, III, VIII, IV ,IX, V & VI) along the Inner Fore Arc Basin and Back Arc area . The present study has made use of these high quality seismic data of VIIIth campaign in particular and other seismic campaign in general, situated in the inner fore arc area, and demonstrate the structural prospectivity of **the Inner Fore Arc Basin** in the framework of its **tectono-sedimentary evolution and source rock maturity modeling**. The present study has also assessed the hydrocarbon prospectivity of the Inner Fore Arc basin on the basis of structural and stratigraphic analogy.

Structural Interpretation

The study area is a part of Andaman Inner Volcanic Arc, which is a asymmetric basin deepening towards the accretionary prism in the West and shallowing towards Volcanic arc in the East ***(Figure-2)***. As per the present study the Inner Fore Arc is separated from the accretionary prism by a near vertical fault active during Neogene time after the deposition of Early Middle Miocene carbonate but gradually rises towards Volcanic arc. The Inner Fore Arc is dominated by extensional faults both longitudinal and transverse in nature. The transverse extensional faults compartmentalize the Inner Fore Arc basin into number of segment ***(Figure-3)*** with differential subsidence where as the longitudinal faults are of enechelon (left stepping) nature brought out for the first time in the present study. However, earlier study indicates that the adjoining geotectonic elements like the accretionary prism dominated by strike slip and thrust faulting (Ananthanarayan et al., 1981) back arc setting by strike slip and normal faulting and volcanic arc mainly by normal faulting.

Interpretation of 3D seismic data (horizon mapping, horizon slice of dip azimuth cube and coherence cube and time slices) in the study area brings out large structural prospects at Oligocene and Middle Miocene levels and two fault systems, i.e. Paleogene extensional fault system (NW- SE, N-S & NE-SW direction) and Neogene (Upper Miocene) compressional fault system oriented in NE-SW direction ***(Figure-4)***. There are imprint of structural inversion along Paleogene fault systems due to the compressional force active in the Miocene period. Neogene compression is thin skin in nature and has resulted into a south

verging fold-thrust belt ***(Figure-5)***.

In Salin subbasin in Myanmar in the north and Timor Basin in the south of study area, two fault system i.e extensional in older section and compressional in younger section are considered as the structural analogue.

Stratigraphic Interpretation

In the absence of well control in the inner fore arc area, it is difficult to provide a detailed stratigraphy of the area. However, based on the seismic data, the stratigraphy of the area has been divided into two mega sequences such as Paleogene and Neogene mega sequences**.** The base of the strong reflector corresponding to Early Middle Miocene carbonate base demarcates the Paleogene from Neogene in the area ***(Figure-6)***.

Paleogene Mega sequence: Paleogene is having low frequency, high amplitude, discontinuous seismic reflection character. This undifferentiated Paleogene may be equivalent to Baratang Formation (upper Cretaceous to Eocene in age) and Port Blair Formation (Oligocene). This unit is quite thick and having reservoir and source rock potential in the drilled wells in the adjoining accretionary prism and inner slope basin ***(Figure-7)***. However, the base of this sequence is not seen in the drilled section. Similarly the Paleogene base is not clearly seen in the Inner Fore Arc area in the seismic data. It makes the interpreters in wrongly estimating the thickness of the Paleogene in the inner fore arc area. However, the present study assumes a large thickness of the Paleogene***(Figure-8)*** of about of about 2200 to 6500m in the study area and also expects reservoir and source rock potential. Paleogene sediments mainly consists of pelagites and turbidites.

The Paleogene analogue in the adjoining inner fore arc basins ***(Figure-9)*** indicates thick Paleogene (about 10 km thick in Salin subbasin in Myanmar in the north)

Neogene Mega sequence: Neogene is composed of Early Middle Miocene at the bottom followed by Mid Miocene MTC (Mass Transport Complex), Upper Miocene clastic and Post Miocene clastic unit.Neogene sediments consists mostly of deep water turbidites and pelagites. The Early Middle Miocene carbonate is about 80-880m thick and is correlatable with the carbonate in the outer fore arc (gas bearing) and also with volcanic arc area. The MTC Unit (Middle Miocene) is characterized by transparent seismic character and is 400 to 1600 m thick in the study area. Post Miocene unit is not of interest from hydrocarbon point of view in the study area and appears to be passive fill of pelagic deposits with sub marine fan complex toward top.

Proposed stratigraphy of the area is presented in ***Figure-10.***

Reservoir Depositional Model

Well and seismic data indicate the presence of reservoirs at three stratigraphic levels (Paleogene clastics, Early Middle Miocene carbonate and Mid Miocene clastics). While constructing the regional model, the study has considered the regional geology of the Myanmar and Sumatran fore arc basins and existing plate reconstruction (Daly et al., 1991, Curray, *1991)* of Indian plate.

Paleogene clastic reservoirs**:** For building a clastic dispersal model, the Paleogene section has been divided into Baratang and Portblair Formations. Baratang Formation has been further subdivided into two sequences, one of Upper Cretaceous to Palaeocene age and the

other of Eocene age.

As per the earlier work, depositional set up for Baratang varies from shallow to deepwater and provenance from Volcanic Arc/Sibumasu continental mass/Bengal and Nicobar fan. However, the existing plate reconstruction at the end of Palaeocene indicates that the Andaman area is a part of SE Asian plate and close to subduction zone between Indo-Australian plate and SE Asian plate of larger Eurasian plate. The above setting suggests, deep water set up for Up Cretaceous-Palaeocene sequence of Baratang Formation with clastic input from North and NE (SE Asian plate, ***Figure-11a***).

The existing plate reconstruction at the end of Eocene indicates the bending of subduction zone with north-south orientation adjacent to Andaman region. During Eocene, the Andaman region is a part of overriding plate and close to trench. Indo-Burmese range north of Andaman and an island chain came into existence during this time. The above setting, therefore, suggests deep water set up for Eocene sequence of Baratang Formation with clastic input from North (Indo-Burmese range) and East (island arc system) (***Figure-11b***).

Earlier work on sediment dispersal model for Portblair Formation indicates various depositional set up from Shallow water /Shallow to Deep Water /Deep Water & varying provenance as Bengal fan /Irrawaddy delta /NE /Bengal fan and Indo-Burmese range / Sediment from Himalayan.

However, as per the existing plate reconstruction at the end of Oligocene, the Andaman area is still situated close to subduction zone. Proto-Irrawaddy delta in north of Andaman and Bengal fan in NW had come into existence during this time. This overall association suggests a deep water set up for Oligocene sequence (Portblair Formation) with clastic input in the form of turbidite from North (Proto-Irrawaddy delta) for inner forearc and NW (Bengal Fan) for outer fore arc area (***Figure-11c***).

Early Mid Miocene carbonate reservoir: Drilled well data show that there are two areas (A-9 and A-11) having good carbonate development. In other areas, the carbonate is represented by shale or shale with thin limestone bands. As per paleontological study this carbonate is of Early Middle Miocene age and paleobathymetry varying from middle to outer shelf to bathyal except for A-11carbonate which is of inner shelf to middle shelf.

This Early Middle Miocene carbonate has been encountered in exploratory well in the M-8 exploration block adjacent to our seismic campaign area I & Yadana field in North (***Figure-1***). Based on the analogues of adjacent area and geo-scientific data, two types of carbonate facies (shallow water platform with build ups and deep water carbonate with off platform build ups) over a ramp profile have been envisaged in the fore arc area of Andaman region (***Figure-12***). Isopach of Early Mid Miocene carbonate/or its equivalent facies indicates the presence of a thick carbonate/or its equivalent facies in the range of 100-600m.

Mid Miocene clastic reservoir**:** A high amplitude seismic anomaly towards the top of MTC unit is envisaged in the area (***Figure-13)***. This may be a reservoir unit in the area. AAA attribute in the interval of MTC has brought the area of high amplitude unit in the form of a fan with input from NE direction (***Figure-14).*** This reservoir is envisaged to be a submarine fan complex. This unit is down lapping over MTC probably indicating a force regression corresponding to late FSST/a normal regression unit corresponding to LST ***(Figure-15).***

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Tectonic evolution of Andaman Inner Fore Arc

The Andaman island arc system evolves from Late Cretaceous to Recent through well known plate scale processes like subduction, magmatic intrusion and backarc spreading, leading to the development of various sub basins, viz. trench basin, inner slope basin, fore arc basin (outer fore arc and inner fore arc), intra volcanic arc basin and back arc basin**.** The present study has analysed the development of inner fore arc basin and proposes a two phases of evolution, accretionary prism phase (Upper Cretaceous to Oligocene) and forearc phase (Early Miocene to Recent) on the basis of contrasting structural and stratigraphic characteristics of the basin.

The accretionary prism phase: In incipient stage of Andaman island arc system, the subduction of Indo-Australian oceanic plate below Eurasian oceanic plate leads to the accretion of deepwater trench sediments as a prism (accretionary prism complex) onto the overriding Eurasian oceanic plate which eventually led to the formation of outer fore arc close to Oligocene. This initial period of growth of a thick accretionary prism qualify as a distinct phase (**the accretionary prism phase)** in the development history of inner fore arc basin. During this phase, the snout of lower plate does not subduct to such a depth to form a sub areal mountainous chain of volcanic arc of tholeiitic and basaltic type (*Coleman, 1978)*. This accretionary prism forms the basal tectono-stratigraphic unit of Neogene fore arc basin.

The Sumatran fore arc has a Mesozoic accretionary complex underlying the fore arc sequence (***Figure-9)***.

In the inner fore arc of Andaman Island arc system, accretionary prism is of Paleogene age and is the first major event in the development of Andaman inner fore arc basin. The structure of this phase is characterized by complex thrusting and folding towards the trench side and perhaps much simpler extensional faulting and related deformation away from trench (***Figure-9)***. ***There is high strructural prospectivity in this phase***. The Paleogene megasequence in this phase is having good reservoir being deposited in deep water setting in the form of submarine fan complex with input form SE Asian continental mass and Indo-Burmese range. This is also having a major source rock (Paleogene). During this phase the sediments are mostly land derived from the overriding plate and travel right upto the trench.

The fore arc phase: In the fore arc phase, a structurally and stratigraphically different sequence overlies the accretionary prism. This sequence is thought to have been developed in the space between outer arc and volcanic arc after their full development. The period from the full development of outer arc and volcanic arc constitutes as **the fore arc phase.** During this phase, the snout of lower plate has subducted to a such depth to form a sub areal mountainous chain of volcanic arc of andesitic type. This phase has been divided into two stages (***Figure-16)*** i.e., ponded fill stage (Miocene) and sag fill stage (Post-Miocene) based on the presence of a major unconformity at top of Miocene, nature of sediment fill and contrasting deformation style.

Ponded fill stage is characterized by a few tectonic events and dominantly consists of turbidite fill and mudflow deposits. The ponded fill stage has started with an extensional event leading (faults extending NW-SE, N-S & NE-SW direction) to formation of half

graben filled with deep water clastics on sedimentary sequence of previous phase and east west compartmentalization of fore arc basin in lower middle Miocene. This was followed by a quiescent period when carbonate sedimentation with reservoir potential in shallow water to outer shelf has taken place and followed by compressional events, towards the close of Miocene leading to a thin skin thrust-fold belt (***Figure-16)***. The post Early Middle Miocene sediments are mainly deep water clastics with a MTC having source rock potential at the bottom and reservoir (prograding unit) potential at the top.

The Sag fill stage during post Miocene is characterized by passive filling with mainly pelagite showing marine onlap**.**

Petroleum System

A preliminary study has been made to identify the elements in proved petroleum system and occurrence of other petroleum system if any.

Source rock: Source rock study of six wells (A-8, A-9, A-1, A-7, A-5,and A-4) indicates existence of two source rocks (Paleogene and Neogene) in the area. Paleogene source rock is generally having type-III kerogen with TOC values varying from 1.4-3.6% and HI values from 96-465 mg HC/g TOC. Neogene source rock generally having type-III kerogen with TOC values varying from 1.4-1.6% and HI values of 150 mg HC/g TOC .

Reservoirs: Reservoirs at three stratigraphic levels are anticipated. Paleogene coarser clastic is potential reservoir in the area and is distributed within Baratang Formation (lower unit of Paleogene) and Portblair Formation (upper unit of Paleogene). These upper cretaceous to Paleogene coarser clastics (sands) have been tested in well A-1 showing poor reservoir character. However, these reservoirs are primary target in the Myanmar inner fore arc basin. The upper Oligocene being a global regression, good coarser clastics (sands) reservoirs in the upper part of Oligocene (Portblair Formation) having most of the oil fields in inner fore arc setting in Myanmar are anticipated to form potential reservoir in the study area.

Early Middle Miocene carbonate is another potential reservoir in the area and is well developed in A-9 area and A-11. The porosity of this reservoir varies from 7-14% in A-9 area to 25% in A-11. This reservoir is having gas accumulation in A-1.

The Mid Miocene clastic is another reservoir corresponds to a seismic anomaly at the top of MTC unit.

Seal: Since the Andaman fore arc basin has evolved under deep water set up in its most of depositional history, the stratigraphy of the area is dominated by finer clastics. The 80% of the stratigraphic column of drilled wells are finer clastics. Therefore, there is no dearth of top seal in the area.

Generation-Migration-Accumulation: Petromod-II 2D application has been used for the 2D genetic modelling. A cross section of thirteen layers with two source rock, three reservoirs

and corresponding seals are considered as the input for the G-M modelling (***Figure-17)***.
For constraining heat flow values, vitrinite reflectance data and present day temperature data of well A-3 located on western side of block in outer fore arc was used. Petromod-II 1D application has been used for estimating the thermal history.
The estimated geothermal gradient for Andaman deepwater area is in the range 1.5°–2°C/100m. Heat flow values 55mW/m^2 are used for period 40MYbp to 15Mybp, then

reduced to 50mW/m^2 at 10 Mybp to 35 mW/m^2 at present. Thermal history for the period 40-65 Mybp is assumed to be same as at time 40 Mybp. Hence, heat Flow value of 55mW/m^2 during this period appears to be reasonable as this is close to the global average for forearc setting.
With the above input in the Petromod, it is observed that the middle part of Paleogene source rock has entered in onset of hydrocarbon generation at 23-26 Mybp at the corresponding paleo depth of source rock 3500-3600m. Later, it entered in peak oil stage during the period 12-14 Mybp with the corresponding paleo depth of source rock 5600-6100m. It has entered in the wet gas stage from 6-11 Mybp. The present day transformation ratio for this layer varies between 72-91%.
The upper source rock layer of Middle Miocene age has attained maturity for generation of hydrocarbons at places and present day depths are around 6500-6800m. The present day transformation ratio of this layer varies between 6-11%.

On the basis of above study, two petroleum system event charts one for Paleogene and another for Neogene have been prepared (***Figure-18 & 19)***. Paleogene petroleum system event chart indicates that Paleogene source rock is likely to charge Paleogene reservoirs and Middle Miocene reservoir.
Neogene petroleum system indicates that in some part Neogene source rock has entered in early stage of oil window and might have entered in the peak stage in other part of fore arc basin.

The present study therefore indicates existence of three petroleum system such as
Paleogene-Paleogene (!), Paleogene-Neogene(.) and Neogene-Neogene(!)

Conclusions

Two phases of evolution in inner forearc basin, accretionary prism phase (Upper Cretaceous to Oligocene) and forearc phase (Early Miocene to Recent) have been proposed. In the accretionary prism phase, most of the sediments are trapped in the trench and are involved in the process of accretion onto the overriding plate which eventually leads to an outerarc formation towards the close of Oligocene. This phase is characterised by complex thrusting and folding towards the trench side and simpler normal faulting and associated deformation away from trench responsible for the trap formation in the area. Large structural prospectivity exist in this phase. A thick Paleogene section with a combination of source and reservoir rock is envisaged around area VIII, IV, III and VII. Input for lower part of Paleogene (Baratang Formation) is mainly from south east Asian land mass with *subordinate amount from volcanic arc. Input for upper part of Paleogene (Portblair Formation) is mainly from proto-Irrawaddy delta in the forearc area and from Bengal fan in the outer arc area.*

Fore arc phase is divided into two stages namely Ponded fill stage (Miocene) and Sag fill stage (Post Miocene) based on a major unconformity at top of Miocene, nature of sediment fill and contrasting deformation style. Two primary reservoirs in Middle Miocene are anticipated. For Middle Miocene carbonate two depositional setting corresponding to two structural units, shallow water in Volcanic arc and deep water in Forearc have been

envisaged. Shallow water carbonate over the volcanic arc is extensive from Sumatra to Myanmar offshore area as evidenced by the presence of shallow water carbonate in Sumatra, AN-11 (Andaman) and Yadana field in Myanmar. This carbonate is considered as the main source for redeposited deep water carbonate in fore arc. The Middle Miocene clastic reservoir is envisaged as a submarine fan complex. This phase is also associated with number of structural prospect.

Two probable source rocks, one in Paleogene and other in Neogene (Middle Miocene) are encountered in the drilled wells in the adjoining outer arc area. Paleogene and Neogene source rocks are of Type III with average TOC of 2% and HI of 200mgHC/g TOC.

2D migration and generation model indicate existence of three petroleum systems, one known and two speculative i.e Paleogene-Neogene(.), Paleogene-Paleogene (!) and Neogene-Neogene (!).

Paleogene source rock has entered in peak oil stage during the period 12-14 Mybp. The upper source rock layer of Middle Miocene age has just attained maturity for generation of hydrocarbons at places.

Hydrocarbon charge by short distance migration has been invoked in the basin with long distance migration as the critical risk factor. Therefore, prospects overlying the kitchen hold better promises than the prospect away from kitchen. Probable kitchen area in the fore arc is located around the areas-IV, VIII and III.

Although the viability of the fore arc area as a hydrocarbon province remains dependent upon the factors that can be confirmed only by drilling well, the shear size of the structural traps, envisaged stratigraphy and disposition within the basinal framework are sufficient to mean that the area VIII is perhaps one of the most attractive candidates for exploration of thermogenic play in the Andaman fore arc irrespective of first well results in the area.

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