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Prospectivity of rift fill sequences in Krishna-Godavari Basin (a case study of Kaza-Nandigama area)

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Summary

This paper pertains to the 3D area of Kaza-Nandigama area falling in West Godavari Sub Basin . 3D seismic data of Kaza-Nandigama area was acquired , processed and interpreted by ONGC. Authors have mapped 9 horizons from Lower Cretaceous to Oligocene top in the entire volume to decipher the structural configurations and for extracting the stratigraphic information in all sequences with an emphasis on rift fill sequences. The presence of hydrocarbons have been established in this area by wells on Kaza Horst and Bantumili Graben which produced gas from Upper and Lower Cretaceous sequences respectively. The rift fill sequences of Nimmakuru area are seen extending up to Kaza Horst. Sediments in these sequences are expected to be prospective at favourable entrapment conditions. Prospectivity to this effect has been discussed in Krishna Formation and older sequences in this corridor for hydrocarbon exploration. Fluvial channel system appears to be prevailing during Lower Cretaceous period as seen in the amplitude and inversion attribute studies of rift fill sequences and gas producing well in Nandigama area is situated in one of these channels. There is a lot of exploration potential left in these channels.

Introduction

The passive margin basin captures some of the stratigraphic complexities of rift basins because it focuses on the entire depositional environment, i.e. faulting, deposition, isostasy, erosion, and transport of sediments. The basin rift is filled axially by sediments transported from footwalls around fault scarps into the hanging wall depressions and through fluvial channels present at Cretaceous period. Kaza Nandigama area lies in the on land part of the KG basin to the South-West of Bhimavaram-Tanuku Horst (Fig.1)

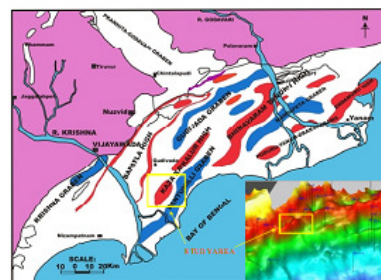


Fig. 1 Tectonic map of study area

The study involved sizeable 3D and 2D seismic data acquired and processed by in-house field parties and processing centre. The seismic data was integrated with



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well data and other available geo-scientific data within 3D volume and nearby areas. The study resulted in identification of a number of prospects.

Background

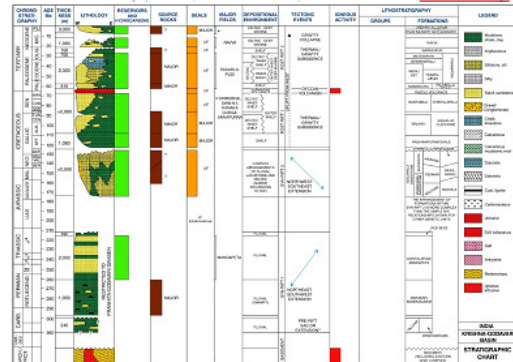
Regional Geological setup

The Krishna Godavari Basin is a passive margin basin comprising of a number of North East – South West trending horsts and grabens. Tectonically, the basin can be divided into three sub basins, namely the Krishna, West Godavari and East Godavari Sub Basins which are separated by the Bapatla and Tanuku Horsts respectively. The West Godavari Sub Basin is further separated by Kaza – Kaikalur Horst into the Bantumilli and Gudivada Grabens (Fig 1). The onland part of East Godavari sub basin has been further differentiated into the Mandapeta Sub Basin on the West and Narsapur Sub Basin on the East by the Yanam Ridge. The offshore part of the East Godavari Sub Basin is the Godavari Offshore Sub Basin. (Fig.1)

The depositional environment of Krishna – Godavari Basin is controlled by a series of rifting phases. The early-rift phase in the Permo – Triassic produced a fluvial and brackish water environment. The main rift phase during the early Cretaceous resulted in deltaic to fluvial conditions prevailing in the area. The initiation of main rift phase in the middle Jurassic resulted in the formation of a North East – South West trending West Godavari sub-basin which was filled with synrift sediments. Continued tectonism at the end of the Jurassic resulted in the formation of the Kaza high, a central horst which bisects the West Godavari sub basin. The Early Cretaceous period saw continued continental dominated deposition, although marginal marine conditions became increasingly common, with open marine incursions evident towards the end of the rift phase (Barremian age). The end of rifting and onset of thermal subsidence is marked by an erosional unconformity followed by a basin wide flooding and blanketing of synrift sediments by the marine

Raghavapuram shale. The generalized stratigraphy of Krishna Godavari basin is given in chart 1

GENERALISED STRATIGRAPHY OF KRISHNA-GODAVARI BASIN
Chart 1



Exploration Status

The study area falls in KG basin covering part of Gudivada Graben, Kaza Horst, part of Kaikalur Horst and part of Bantumilli Graben (Fig 1). The main horst block i.e. Kaza - Kaikalur Horst separates the Gudivada Sub Basin into Gudivada Graben in the North West and Bantumilli graben in the South East. Wells have been drilled on Kaza Horst, in Bantumilli Graben and Gudivada Graben to explore the hydrocarbon potential of the area. Hydrocarbons have been discovered from well on Kaza Horst, well in Nandigama area in Bantumilli Graben and hydrocarbons were indicated in some other drilled wells in the area. A few wells in Angaluru area, North Kaza area and Vinnakota area just in the North and Nimmakuru area in the West of present study area drilled in Gudivada Graben have gone dry. Lower to Upper Cretaceous sands were encountered in these wells and red beds of possible Jurassic age were reported in wells Nimmakuru wells. These wells were dry perhaps due to lack of proper entrapment conditions.

The details of hydrocarbon discoveries and indications are given below:



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- On Kaza Horst, presence of gaseous hydrocarbon in the sands within Raghavapuram shale of Cretaceous age is established by the Kaza well along with water and little condensate .
- In Bantumilli Graben, Nandigama well produced commercial quantity of gas with condensate from Nandigama arenaceous unit .
- In another Nandigama well, a sand in the Nandigama arenaceous sequence was tested having feeble gas only.
- In one more Nandigama well feeble gas was observed while testing object within a sand pack above Nandigama arenaceous unit and was identified for chemical/hydro-fracturing. On chemical fracture, the well produced gas.
- In a few other Nandigama wells traces of oil and gas were observed .
- In few Nandigama wells no activity was observed while testing sands within Nandigama Formation.

The presence of non commercial quantity of hydrocarbons has also been established from the sands within Raghavapuram shale of Cretaceous age in Mukkollu well. The Mukkollu well was drilled with the objective to explore hydrocarbon potential of sands within Raghavapuram shale and Kanukollu sandstone / rift fill sediments. However the rift fill sediments were completely absent in this well as the well was actually drilled in a fault zone below Raghavapuram Formation and Raghavapuram shale is directly resting over the basement. A sand within lower shaly sand pack of Tirupati Formation was tested in this well which gave minor gas and condensate.

Petroleum System

Source and hydrocarbon potential

The results of the geochemical studies of Nandigama well indicate that Raghavapuram shale could be the source rock facies in the deeper part of the basin. In many

areas the juxtaposing Raghavapuram shales with the Nandigama Formation act as source. In Bantumilli Graben, the Raghavapuram shale unit possesses fair to good organic matter and is thermally mature to generate potential hydrocarbons in the area. The argillaceous sequences within Nandigama Formation occurring at deeper levels can also be considered as source .

Reservoir

The main reservoirs are the thick sands within the Nandigama arenaceous unit, sands within Nandigama argillaceous unit, sands within Raghavapuram shale and Tirupati Formation.

Seal and Migration

The reservoirs are either sealed intraformationally or by the overlying Raghavapuram shale. Trapping within these plays consists of rift phase generated fault blocks and horsts, drape anticlines and stratigraphic features. Migration into these reservoirs would have been relatively easy utilizing sandstone carrier beds and rift generated fault system.

Plays

The various formations that comprises of rift fill sequences consist primarily of fluvial to proximal deltaic sandstones and provide reservoirs to several fields. Deposition was restricted to the developing syn-rift grabens with the ensuing complex horst and graben (sub-basin) setup resulting into complex vertico-lateral facies variations and resultant reservoir geometries . Erosion of uplifting rift shoulders lead to the development of alluvial fans and fan deltas along the flanks of horst blocks. As reservoir geometries are concerned , it is thought they would consist of complex interactions of both stacked and isolated channel sandstones, distributary mouth-bars and delta front deposits. It being a prolific hydrocarbon producing basin , it encompasses a number of fields . However present interpretation of the 3D Seismic volume led to the identification of several structural and stratigraphic prospects in the form of fault closures, minor four way closures and Channel/Fan configurations within Lower Cretaceous rift sequences and Upper Cretaceous sequences.



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Present study

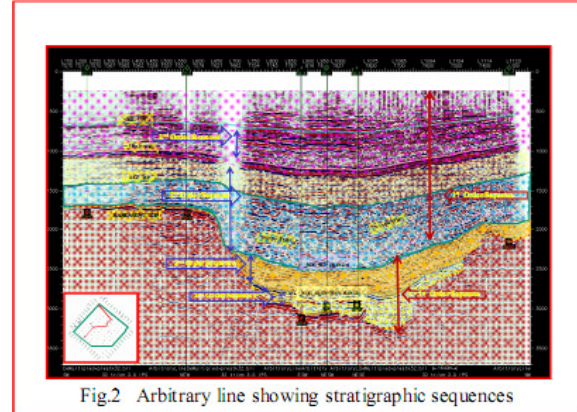
Evaluation of the area included structural as well as stratigraphic interpretation using Landmark software and inversion studies were carried out using Hampson-Russell software. Volume based studies were carried out on Geoprobe software. A number of structural/stratigraphic prospects have been firmed up during the study.

Structural interpretation and mapping

Sequence stratigraphy in the study area and correlated horizons

The stratigraphy in the present study area ranges from Lower Cretaceous rift sequences to Upper Cretaceous post rift sequences and younger.

The Lower Cretaceous rift fill sequence in this area is known as Nandigama Formation in Bantumilli Graben area and is sub divided into two major units namely Nandigama arenaceous unit in the lower part and Nandigama argillaceous unit in the upper part. Nandigama arenaceous unit is approximate time equivalent of Gollapalli Formation. In Gudivada Graben, time equivalent of Nandigama Formation is known as Krishna Formation. As present study is grossly within 3D volume, single horizon has been tracked on top of rift fill tracking phase of the event which is referred to as Nandigama top throughout the study. However the reference of Sand 4 in context with Gudivada Graben is understood as Krishna Formation while describing prospectivity of rift fill sequences with the help of maps. The stratigraphic sequences present in the study area are shown with the help of transparent colours with their names in an arbitrary seismic line in Fig .2 as described below.



1st Order Rift Sequence (Late Jurassic – Early Cretaceous):

The sequence between horizons Basemenand Nandigama top (Sand-4 top) is the 1st order synrift/riftfill sequence which constitutes the total unit of Nandigama Formation in the present study. There is a school of thought that the High Gamma-High Resistivity (HGHR) marker close to Nandigama Formation top is rift fill top. But HGHR marker is better seen in Kaikukur-Lingala area rather than present study area. Therefore, in the absence of proper HGHR marker, Nandigama top is being considered as rift fill top in the present context. This sequence is sub divided into two 2nd order sequences as described below .

Lower 2nd Order Sequence (Late Jurassic – Barremian top?):

The unit between the horizons basement and top of Nandigama arenaceous unit (Sand-2 top) is a 2nd order rift sequence. This sequence is Nandigama arenaceous unit in present study area.

Upper 2nd Order Sequence (Barremian top? – Aptian / Albian top):

This sequence is between horizons top of Nandigama arenaceous unit (Sand-2 top) and Nandigama top (Sand-4 top) which marks the end of rift fill sedimentation. This sequence is Nandigama argillaceous unit in present study area.



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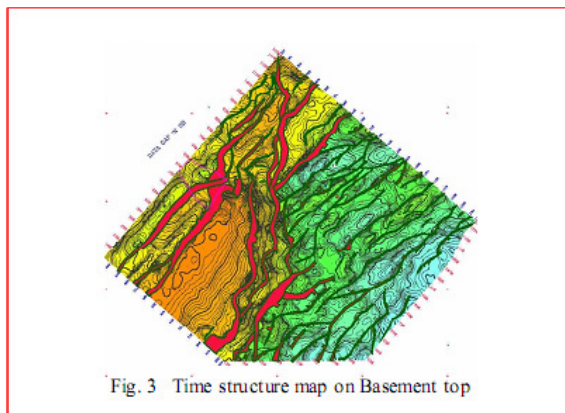


Fault interpretation

Basement controlled faults are well defined extending up to the end of Lower Cretaceous clearly depicting rift geometry in the area. However, fault interpretation became difficult in the post rift Upper Cretaceous sequences. Some of the basement related faults appear to have been reactivated and extended into post rift section upto Tirupati Formation. The coherency attributes could be used only on top of basement and for Lower Cretaceous sequences and it's quality deteriorated in Upper Cretaceous sequence. A coherency attribute map along basement was generated to decipher the Basement fault plane configuration. However, faults have been correlated for all stratigraphic levels from Basement to Raghavapuram top and fault polygons were generated. In general the major faults are trending in NE-SW direction with some intervening cross faults. These polygons were used for subsequent structural mapping.

Time Structure Mapping

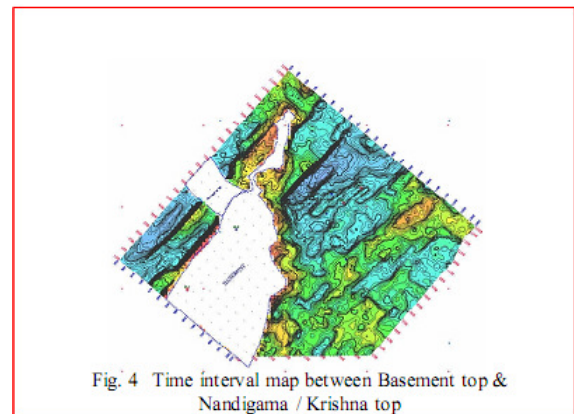
Time structure maps have been prepared after correlation of above levels corresponding to Basement top, Sand-2 top, Sand-3 top, Sand-4 top. Coherency slice at basement level imaged numerous rift faults in turn it helped to bring out tectonic framework of the area. The basement map reveals the tectonic framework along with structural elements (Fig. 3). The map depicts base of the overlying rift fill sequences. The Nandigama / Krishna top map provides upper bound of rift fill sequences. These maps



led to the identification of various prospects in the form of fault closures and small four way closures in Lower and Upper Cretaceous sequences from Sand-2 top to sand-4 top.

Depth and Interval Mapping

Time structure maps have been migrated to depth maps with the help of available interval velocity field. Isochronopachs and Isopachs have also been prepared from the maps generated above. Thickening of sediments in the eastern flank of Kaza high has been observed with a prominent orientation of NE-SW direction indicating sediment input from North - East (Fig. 4). Isochronopachs and Isopachs have also been created for different units within the rift fill indicating major highs and lows.



Depositional Model

To bring out the nature of hydrocarbon distribution at different stratigraphic levels, their lateral continuity and entrapment, log correlations have been carried out along various profiles. The inferences drawn are as follows:

- In Kaza area Upper Cretaceous sequence is directly resting over the Basement as seen in well on Kaza Horst.
- In Nandigama area, Nandigama arenaceous unit is present over the Basement with intervening thin



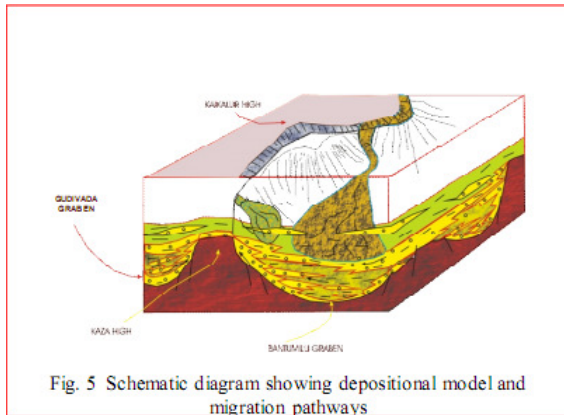
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shales. The top of this unit is marked by shift in SP, Resistivity and Sonic logs.

- The pack above Nandigama arenaceous unit is mostly argillaceous which is called Nandigama argillaceous unit. Thin discrete sand occurrences are seen towards the top of this unit.
- The sands within Nandigama argillaceous and bottom Nandigama arenaceous pack show the typical box type, serrated box type and fining up log signatures. The sands are discrete in nature and do not have extensive lateral continuity.

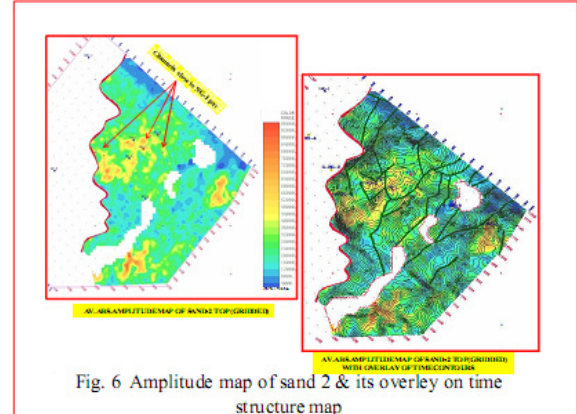
A conceptualized geological model considering isopachs of different units in rift fill a sand dispersal pattern was worked out as shown in Fig.5 . The terrigenous input into accommodation formed by rifting of the basin is shown from North-East direction and from uplifting rift shoulders.



Stratigraphic Interpretation

Amplitude studies

Average amplitude extractions using the correlated horizons have been carried out. Several Channel / fan features have been identified within Lower Cretaceous rift fill sequences in Bantumilli as well as Gudivada Grabens.



The amplitude map of horizon Sand-2 top indicates that the Lower Cretaceous pay sand of Nandigama well is a channel sand which was not penetrated perhaps by other Nandigama wells in the area . The amplitudes of Sand-2 top were gridded for better continuity and corresponding maps are shown in Fig 6. The amplitude map of horizon Sand-4 top exhibits amplitude anomalies in Gudivada Graben . One of these anomalies shows a channel like feature in the northern flank of Kaza Horst and this is associated with a possible DHI on seismic. The other amplitude anomaly is situated further North in Gudivada Graben.

Seismic Inversion

Inversion of the PSTM 3D seismic data had been carried out on Hampson-Russell software and acoustic impedance volume was generated after calibrating the 3D seismic volume with logs in HR software for understanding the reservoir distribution in the 3D area. The available logs were conditioned and processed before inversion had been carried out.

The impedance values of KAZA pay sands of Upper Cretaceous age are observed to be in the range of 8000 to 8400 (g/cc)*(m/s) and those of Nandigama wells (the Lower Cretaceous rift fill sands in Bantumilli Graben) are higher in the range of 9000 to 10500(g/cc)*(m/s). It is also observed that these impedance values are further higher in basinal side indicating presence of reservoirs in deeper parts.



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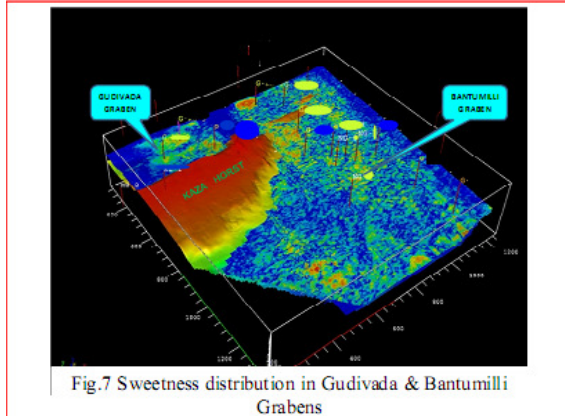
Impedance maps have been generated corresponding to correlated horizons and the maps indicate that the geometry and extension of the reservoirs of the drilled wells are conformable to those of amplitude studies.

Sweetness Attribute studies

The 3D seismic volume was loaded in Geoprobe and volume based studies were carried out. Sweetness attributes for correlated horizons were generated. The sweetness map of sand 2 establishes the channel like configuration of Nandigama pay as seen in the amplitude maps. The channels/fans seen in the amplitude maps of Sand-4 are confirmed by the sweetness maps indicating the presence of reservoir/possible hydrocarbons in those features which are untested so far.

Prospectivity analysis

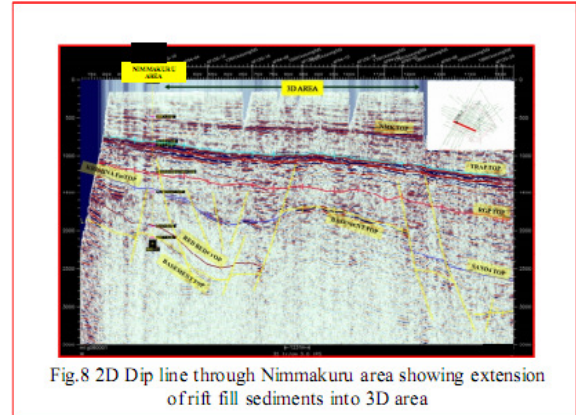
The sweetness map of Sand 4 is shown in Fig. 7, indicating prospectivity of Gudivada and Bantumilli Grabens. Based on above studies a number of prospects have been identified. The details follow:



Strati-structural prospects

Nimmakuru wells were drilled in the northern rising flank of Gudivada Graben towards west of the present 3D volume as shown in the Fig.8. Sands of 1 order Nandigama / Krishna Formation rift fill sequence of Lower Cretaceous age and red beds of Jurassic age are

encountered in these wells. These wells were dry perhaps due to lack of proper hydrocarbon entrapment. But, the oil and gas bearing Kaikukur and Lingala wells are situated in the northeastern part of the Gudivada Graben establishing it as a commercial hydrocarbon rich graben. Moreover, the area between Nimmakuru wells and Kaza



wells, towards South of the Gudivada Graben, still remains to be fully explored. Above stated rift sands are expected to extend into the present study area as seen on 2D seismic dip line (Fig.8). The correlated horizon Sand-4 top close to the probable rift fill top exhibits a 3 way closure against the binding fault of Kaza Horst as seen in the time map. The average amplitude, inversion and sweetness distributions along this horizon revealed a channel with possible hydrocarbon accumulation trapped against the fault in the form of a DHI. The hydrocarbon prospectivity of this prospect can be tested by drilling of an exploratory location on this fault closure in line and cross line to test the rift fill play as primary target. The adjacent well in Mukkollu area, which was targeted for rift fill sands, was in fact drilled in a fault zone and did not penetrate any rift sediments as per the drilling results. This prospect will be structurally up dip for rift fill sequences as compared to Mukkollu well Fig. 9. Additionally, the Kaza pay (Sand6) and sands below Raghavapuram top are also of interest at this location. The details of this prospect are elaborated in a prospect mosaic in Fig. 10.



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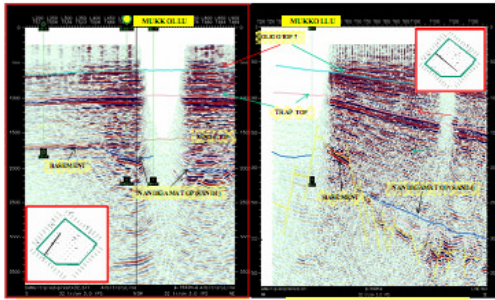


Fig. 9 RC line & in line through Mukkolli (in fault zone)

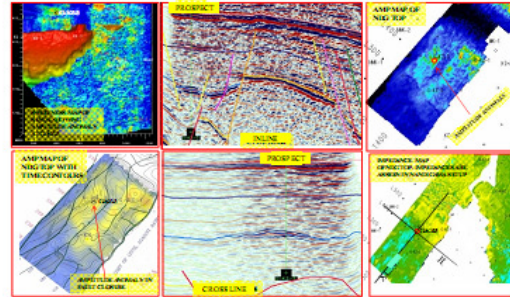


Fig.11 In line & cross line through prospect with amplitude & inversion attribute maps of Nandigama top showing anomaly

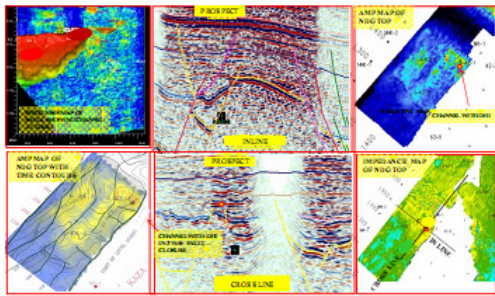


Fig.10 In line & cross line through prospect with amplitude, inversion & sweetness attribute maps of Nandigama / Krishna top showing DHI associated with channels

Nandigama / Krishna top (Sand-4) level forms another three way fault closure in the western flank of the Kaza Horst. A set of faults separate the sediments encountered in the Nimmakuru wells and those expected in above fault closure. Further, the amplitude, inversion and sweetness studies exhibit a fan like feature in the above stated fault closure of Sand-4 (Fig. 11). The fan feature in the Lower Cretaceous Formation as primary target deserves an exploratory merit. Besides the above mentioned stratigraphic fan feature, structural plays of deeper sands are also envisaged in this prospect. Besides this the prospect will also test the potential of Upper Cretaceous sands of Raghavapuram and Tirupathi Formations.

The amplitude, inversion and sweetness distributions on levels Sand-4 and Sand-5 exhibit strong anomalous features truncating against the fault in the western part. These anomalies appear to be DHIs with a flat spot on seismic in line and cross line. The prospect is to test the prospectivity of above anomalies in Lower as well as Upper Cretaceous sequences. The details of prospect are shown in Fig. 12.

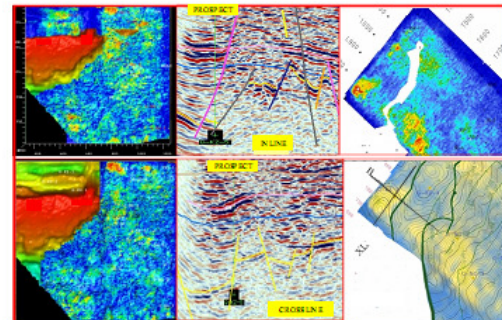


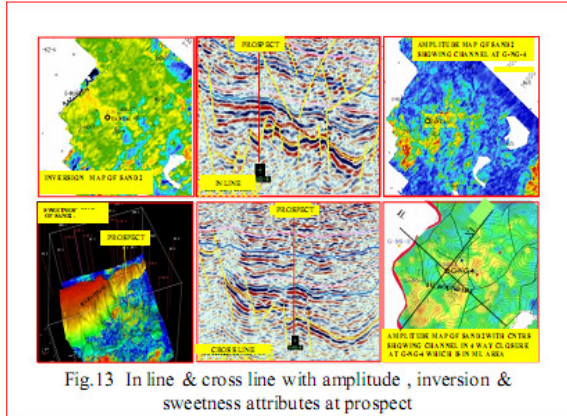
Fig. 12 In line & cross line through prospect

Stratigraphic prospects

The mapped level on top of Nandigama arenaceous unit

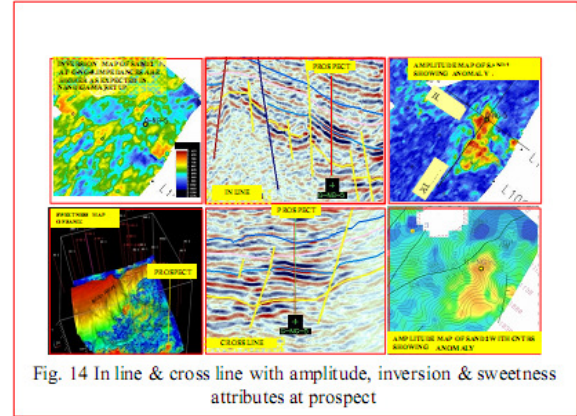


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revealed a small four way closure towards North of drilled Nandigama well. As stated in the details of location, the attributes of Nandigama arenaceous top (Sand-2 top) are showing channel levee features in the Bantumilli Graben. One of these anomalous channel features is situated within this four way closure. Another well did not penetrate this feature and a clear fault separates this anomaly from Nandigama well in which this unit produced commercial gas. The mapped level of Sand-3 top also exhibits a fault closure at this place. The probing of these channel sands along with other Lower Cretaceous rift sands will establish possible hydrocarbon accumulations. Fig.13 elaborates the details of this prospect.

The same amplitude, inversion and sweetness attributes of Nandigama arenaceous top (Sand-2) revealed a strong anomalous feature in the North-East part of the 3D volume (Fig.14). An exploratory location may be drilled to test this feature primarily, along with other sands of Lower Cretaceous, on the crossing of seismic in line and cross line. Though, horizon Sand-2 exhibits a fault closure against the northern fault at this feature, the entrapment is envisaged to be stratigraphic in nature with lateral and vertical seal being provided by shales as seen on the impedance slice.



Conclusion and Recommendations

- The rift fill sequences of Nimmakuru wells of Gudivada Graben are seen extending up to Kaza Horst. Sediments in these sequences are expected to be prospective at favorable entrapment conditions.
- Fluvial channel system seems to be prevailing during Lower Cretaceous period as seen in the amplitude and inversion attribute studies of rift sequences and gas producing Nandigama well is situated in one of these channels. There is a lot of exploration potential left in these channels.
- As understood a well in Mukkollu area did not encounter any rift fill sequence, a large area comprising of Krishna Formation requires probing in Gudivada Graben West of Kaza Horst.

References

Contreras. J and Christopher H.S., Evolution of stratigraphic sequences in ultisegmented continental rift basins: Comparison of computer models with the basins of the East African rift system.