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Overview of Overpressure in Bengal Basin, India

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Abstract: Abnormally high formation pressures are encountered worldwide, ranging in geological age from Cenozoic to Paleozoic, within a depth range of few hundred meters to as deep as six thousand meters while carrying out exploratory drilling by E and P companies. Several causes can increase formation fluid pressure i.e. rapid loading of sediments results compaction disequilibrium, thermal expansion of fluids, compression and/or upliftment of strata by tectonic forces, generation of oil and gas from organic matter and its volume expansion due to high thermal stress within the restricted pore volume in subsurface condition. Few global examples on overpressure occurrences have been compiled in the paper with special reference to Bengal Basin. Emphasis has been given on methodology and interpretation on abnormal pressure detection in Bengal Basin with a compiled data package on generated curves (Geologs), charts, tables in a systematic way to understand the depth/stratigraphic horizons proved/interpreted as proved or likely to be within transition and overpressure regime. The integrated analysis indicates that the wells drilled in the east of Eocene hinge zone in the onshore and offshore parts of Bengal Basin have penetrated overpressure formation within Miocene in the depth range of 2800 m to 5340 m and the mud weight used to control this overpressure zone was more than 2.0 sp gr mud. The generated Geologs can be used as reference to understand the regime of transition and overpressure, as a valuable document for exploration drilling planning and monitoring. The generated model curve (modified using available data after Hottman and Johnson,1956 curve) using sonic departure (i.e. $\Delta t_{ob(sh)} - \Delta t_{n(sh)}$) from drilled wells may be used as an additional tool to find out the expected formation pressure gradient and equivalent mud weight in all future wells. The correlation of wells based on the trend of dcs and σ logs will be useful for predicting transition and overpressure top provided all the parameters required for calculating dcs and σ log recorded smoothly during drilling phase. The study has brought out the detail procedure to generate the pressure profile in the future wells. The generation of pressure profile of a well prior to drilling has got immense importance in oil industry. The drilling of the well should be done by maintaining the optimum mud weight generated from the pressure profile. In case, during drilling, formation pressure is more than the mud pressure, resulted gas kicks or worse, blowouts of the well. Excessively high mud pressure can fracture the formation and cause lost circulation. The oil and gas companies, worldwide, attributed 15% losses due to various problems associated with drilling complications, mostly related to improper pressure prediction of a well. The losses include loss of material as well as drilling process continuity, called non-productive time (NPT). The generation of accurate pressure profile reduces drilling problems, cuts exploration and development costs and allows billions of dollars now spent on losses to be better spent-building and replacing reserves.

Keywords: Overpressure, Geologs, Dc exponent, σ log, Electrologs, Bengal Basin.

INTRODUCTION

Abnormally high formation pressures are encountered worldwide, ranging in geological age from Cenozoic to Paleozoic, within a depth range of few hundred meters to as deep as six thousand meters, while carrying out exploratory drilling in various basins by E and P companies. The normal/hydrostatic pressure is defined as the pressure which is exerted by a column of water extending from a stratum tapped by the well to the surface. This pressure is the result of the unit weight and vertical height of a fluid column. Mathematically, this can be expressed as:

$$P = p.g.D$$

where P = Pressure, p = average density, g = gravity value and D = height of the column.

The average hydrostatic gradient encountered during hydrocarbon exploration in any area is 0.433 psi/ft (0.10 kg/cm^2/m) for fresh and brackish water and 0.465 psi/ft (0.1074 kg/cm^2/m).

The sub hydrostatic pressure is defined as the pressure less than the hydrostatic gradient, i.e. when they are below the normal gradient.

Overpressure/abnormal pressure zone is defined as the interval in which pressure exceeds the vertical hydrostatic pressure column of water. The genesis of overpressure is

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likely to be one of the reasons or combined thereof (a) Rapid deposition of sediments, (b) Thin/lenticular permeable layers concealed within exclusive clay/shale or any other impermeable layers, (c) Tectonic uplifted/thrust belt areas and (d) Generation of oil and gas from organic matter and its volume expansion due to high thermal stress within the restricted pore volume in subsurface condition

The Bengal Basin is one of the major sedimentary basins in Indian subcontinent. Ganga-Brahmaputra and cratonic river systems, bringing the sediments from the Himalayas and the surrounding Indian shield area, have converted the area as one of the biggest modern delta system in India. Hydrocarbon exploration in Bengal Basin has become a long history for about five decades. Fifty exploratory wells drilled so far in Bengal Basin (onshore and offshore) have probed sediments of Gondwana to Recent. The overpressured Miocene sediments have been encountered in onland well W-10, the first well drilled by ONGC in mid sixties. During subsequent exploration processes, overpressured zone was encountered in various offshore and onshore wells in the east of hinge zone. Geologically, the overpressure is reported in the siliciclastic Miocene sediments in the deeper basinal part (slope fan, basin floor fan) east of hinge zone which are characterized by high rate of sedimentation. The overpressure in Bengal Basin was reported in the depth range of 2800 m to 5340 m and most of the wells have faced severe down hole complications related to overpressure resulting premature terminations of the wells and/ or loss of time.

OBJECTIVES OF THE STUDY AND DATABASE

The present paper deals with various causes which lead to generation of overpressure. Global examples on high pressure occurrences have been compiled to have an idea to identify the geological set up of the overpressured areas. The wells drilled in deeper part of Bengal basin (east of hinge zone) have penetrated Miocene overpressured sediments and most of these wells have experienced severe downhole complications related to premature termination and/or loss of time. The data related to pressure profile like Dc exponent, σ log, flow line temperature and various electrologs generated in all the overpressure wells of Bengal Basin have been analyzed.

Dc exponent is the normalized penetration rate computed during drilling. Sigma (σ) log also computed during drilling. The basic drilling equation is a depth related function of rock strength which varies due to lithology, compaction/ porosity and the formation pore pressure gradient (FPG). The “dcs” and σ log plot vs. depth in shale intervals on a semi log paper in 5m intervals show a normal trend in formation having normal pressure, the departure from extrapolated normal trend line is the evidence of over pressure formation down below.

Geologs of all the over pressure wells were made using data like dcs, σ log etc and validated by trend observed from the electrologs (Resistivity, Density, Porosity, Sonic) and pressure data (RFT/ SFT/DST etc). During RFT (Repeat formation tester), SFT (Selective formation tester), DST (Drill Stem test) pressure data generated from the tested interval/depth. Formation pressures measurements are done during drilling are recorded in kg/cm^2. This pressure data is multiplied by 10 and then the multiplied value is divided by depth (m) from which the pressure was recorded, the resultant value is expressed in MWE. The input data of different wells have been used to establish the average trend line of the shale acoustic parameter differences vs. formation pressure gradient and equivalent mud weight. The generated model curve (modified using available data after Hottman and Johnson curve, 1956) using sonic departure from drilled wells may be used as an additional tool to find out the expected formation pressure gradient and equivalent mud weight in future wells. Thickness contour map of Transition zone, depth contour map on top of Transition and Overpressure zone have been prepared which will aid prediction of pressure profile and thereby lead to successful completion of overpressure wells. The generation of pressure profile of a well prior to drilling has got immense importance in oil industry. In case during drilling, formation pressure is more than the mud pressure, resulted gas kicks or worse, blowouts of the well. Excessively high mud pressure can fracture the formation and cause lost circulation. The oil and gas companies, worldwide, attributed 15% losses due various problems associated with drilling complications. The losses include loss of material as well as drilling process continuity, called non-productive time (NPT). The generation of accurate pressure profile using different indirect techniques using Dc exponent, Sigma (σ) log, study of Formation Density, Resistivity, Neutron Porosity, Acoustic log as well as direct methods of pressure measurements from RFT/SFT/DST/MDT, use of seismic data like study of interval velocity etc reduces drilling problems, cuts exploration and development costs and allows billions of dollars now spent on losses to be better spent-building and replacing reserves.

REASONS OF OVERPRESSURE

A lot of researches have been carried out by earlier renowned authors on various aspects of overpressure. The various reasons which leads to generation of overpressure (as per Fertl, 1976) are compaction, paleopressure, tectonic activities, digenesis, upliftment, earthquakes, osmosis, adsorption, salt domes, artesian pressure, permafrost environment, tidal disturbances in shelf regions in oceans etc. In addition to this, generation of oil & gas from organic matter and its volume expansion due to high thermal stress within the restricted pore volume in subsurface condition is another factor for generation of overpressure (Hunt, 1995). Compaction is one of the major causes of overpressure worldwide where in the abnormally high fluid pressure are caused by the weight of the overburden and fluid environment, dependent on the rate of sedimentation (Dickinson, 1953). Hubert and Rubey (1959) listed following favorable conditions for development of overpressure: (a) Large total thickness of sediments, (b) Presence of clay/shale, (c) Interbedded sandstone/siltstones, (d) Rapid loading and (e) Geosynclinal conditions. Fertl and Timko (1972) stated that the rapid deposition of predominantly clays and some sand (i.e. high sand/shale ratio), exceeding the structural down wrap, can cause abnormal pressure. According to Rochan (1967), overpressure zones and reservoirs are associated with periods of fast deposition when hydraulic equilibrium accompanying normal compaction is distributed by a restriction to the orderly expulsion of water. As per Fertl (1976), paleopressure can exist in older rocks, which have been completely enclosed by massive, dense and essentially impermeable rocks, or in a completely sealed formation uplifted to a shallower depth. Abnormally high fluid pressures may result from tectonic activities like local and regional faulting, folding, lateral sliding and slipping, squeezing caused by down-dropping of fault blocks etc. Diagenesis in sand/shale sequences is related to alteration of clay minerals, which contribute to the origin of abnormal fluid pressure by increasing the quantity of free water in the subsurface water system. Diagenesis in carbonate sequence contributes to the origin of abnormal fluid pressure by creating permeability barrier in porous sequences. In this way, expulsion of fluids from the rocks is inhibited while the static load continues to increase, as a result, a large potential energy within the pore fluids generated. Formation originally compacted at a particular depth can be uplifted to a shallow depth. In case the original pressures within the formations are retained, such uplift can result in abnormal pressures.

GLOBAL EXAMPLES OF OVERPRESSURE REGIMES

Global search for hydrocarbon, both onshore and offshore, encountered abnormal formation pressures in all continents. They may occur as shallow as only a few hundred meters below the surface or at depths far exceeding 6000 m. Occurrence and magnitude of these abnormal pressure environments have a profound impact on the oil industry.

The overpressured areas of the world (Fig. 1) have been

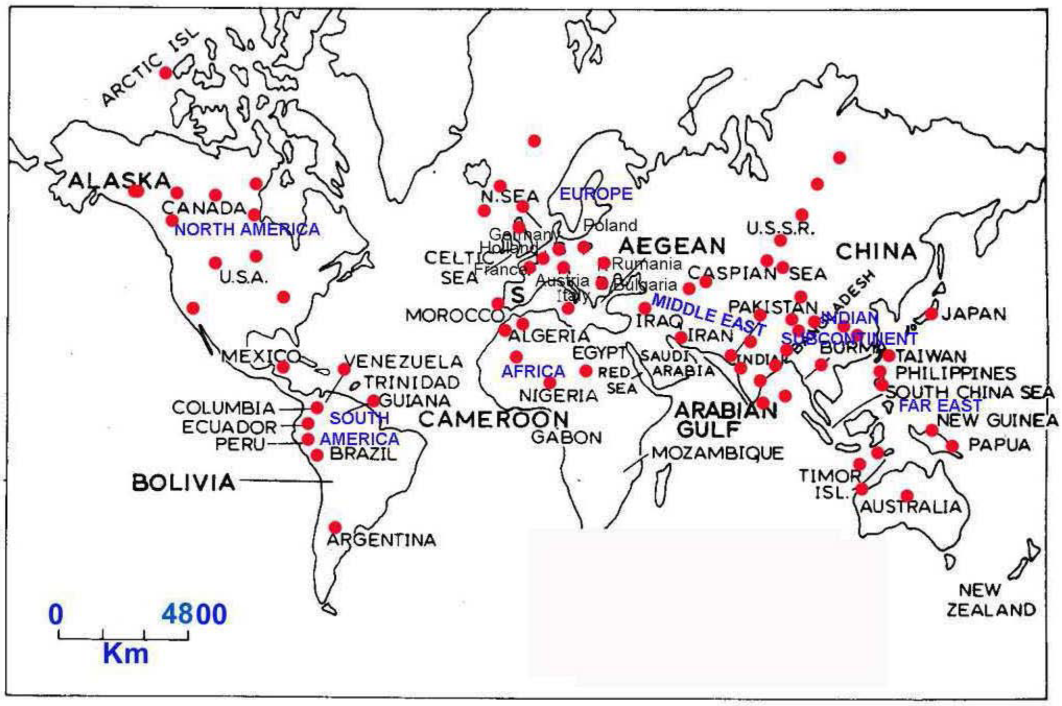

Fig.1. Worldwide occurrence of overpressure (*after* Fertl, 1972, updated).

evidenced in Europe, Soviet Union, North American and South American Continents. Overpressures also exist on the west coast in Columbia, Ecuador, Peru, Bolivia and along the east coast of Venezuela, Guiana, Brazil, Gulf coast, Africa, Far East, Middle East (in several oil and gas producing areas of the Middle East with more than 75% of the Worlds oil reserve), Iran, Iraq, Saudi Arabia, Red sea areas, Oceania Australia, Artic Island and in Canada. In Asian subcontinent, overpressure horizons occur in India, Pakistan, Bangladesh and Myanmar region. In Pakistan, overpressure regimes occur in Potwar, Khaur, Dhulian, Kot Sarang, Balkassar and Joyamair fields, Mahesian structure, Chak Beli Khan, Bains structure, Adhi structure and Indus offshore basin. In Myanmar, overpressure is known to occur in the Tertiaries in Irrawady and Chindwin river basins in onshore as well as in the Gulf of Matraben in offshore. In Bangladesh, all the gas fields occur in the overpressure environment at deeper levels. Wells drilled in the Sylhet structure in the northern Bangladesh and in Titas field adjoining the Tripura folded belt, extreme overpressure conditions exist.

Overpressured Areas of India

The major areas where overpressures have been encountered includes Bengal basin, Himalayan foothills, areas adjoining the Schuppen belt of Assam and Arunachal Pradesh, Cachar, Mizoram and Tripura in the north eastern India, South Kadi and South Malpur areas of Cambay basin, Godavari basin on the east coast of India, offshore areas in Bombay and Andaman-Nicobar basin. Overpressure regions of India have been divided into following categories on the basis of their occurrence (Fig.2, updated after Pressure regime in Oil and Gas exploration by Bhagwan Sahay, 1999):

A. Overpressure primarily due to compaction and partly digenesis
   a) Bengal Basin, (b) KG Basin, (c) Cambay Basin, (d) Bombay Offshore Basin
B. Overpressure due to tectonic phenomena
   (a) Himalayan foothills, (b) Jammu area
C. Overpressure due to the combined effect of compaction initially and later due to tectonics, uplifts etc
   (a) Schuppen Belt and adjoining areas of Assam and Arunachal Pradesh, (b) Cachar area of Assam and Tripura-Mizoram fold belts, (c) Andaman Nicobar Basin

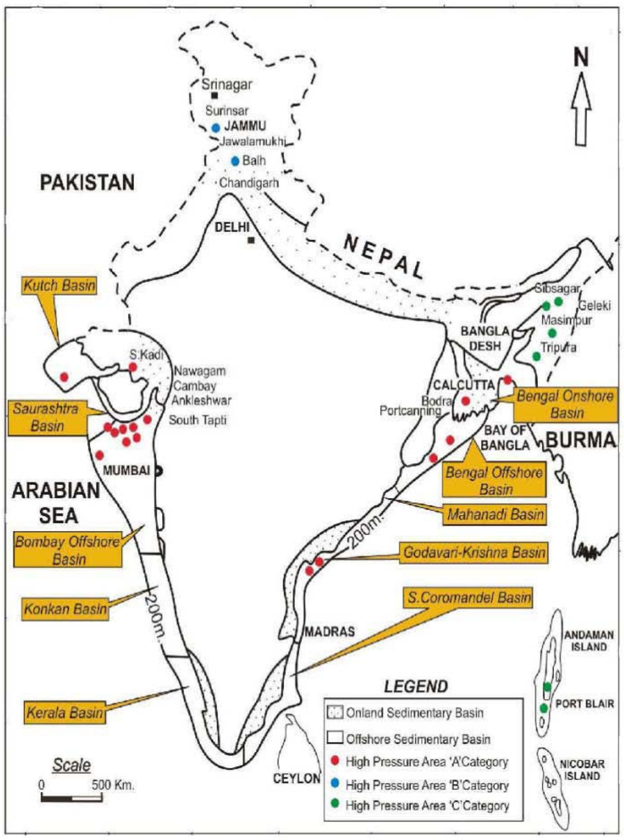

Fig.2. Sedimentary basins of India showing overpressure area (*after* Bhagwan Sahay et al. 1999, updated).

TECTONIC SETUP AND STRATIGRAPHY OF BENGAL BASIN

Bengal Basin, a polyclic basin, has evolved through two tectonic episodes. It initiated as an intracratonic rifted basin within Gondwanaland during the Paleozoic- Mid Mesozoic time and received the continental Gondwana sediments. This phase of basin development ended with widespread volcanic activity during which basaltic and andesitic sheet flows (Rajmahal trap) covered the Gondwana sediments. The second phase of basin formation took place when Indian Craton separated out completely from the Gondwanaland and kept on moving northwards. During this journey of the Indian plate, the Pericratonic part having loaded with Gondwana sediments sagged eastward and received colossal volume of sediments from Late Mesozoic through Tertiary to Recent times. During its northward journey, it collided with the Uresean plate and resulted folding and thrusting of Tethian sediments to build the Himalayan orogenic belt. The Indian plate further moved northward and ultimately collided with the Burmese plate, the former subducting below the latter and the Pericratonic basin gradually coalesced with the geosynclinals sediments of the Assam-Arakan basin along a line whose present day surface manifestation is roughly along the alignment of Swatch-of-no-ground at the head of Bay of Bengal and Schuppen belt of NE region through northern part of Tripura.

Bengal Basin is subdivided into four NE-SW trending tectonic zones (Fig.3) from west to east:

1. Narrow basin margin zone with two trends of major lineaments corresponding to Eastern Ghat (NNE-SSW) and Dharwarian trend (NW-SE to NNW-SSE).
2. Wide stable shelf zone that becomes narrower from onshore to offshore.
3. The Hinge zone characterized by sudden increases in slope, which is distinct at Eocene Carbonate (Kalighat Formation) level.
4. Deep basin with huge thickness of Neogene sediments.

The Gondwana sediments are restricted in the grabens of Bengal Basin and are covered by Basaltic and Andesitic lava flows (Rajmahal Trap). After a major hiatus, the marine transgression took place during Maestrichtian period, resulted in the deposition of Dhanjaypur Formation (Fig.4) which aerially restricted in immediate west of Eocene Hinge zone and basinal side which is overlain by considerably thick Bolpur Formation consisting of trapwash at the bottom and dominantly aeranaceous facies of fluviatile deposit towards top. During Early Paleocene time, the basin witnessed the transgressive phase when shale and silt with argillaceous limestone were deposited (Ghatal Formation). The late Paleocene sediments (Jalangi Formation) are represented by coarse to medium grained arkosic sandstone with occasional thin and carbonaceous dark gray shale. During Eocene‘ period, a thick carbonate sequence was deposited. This episode of carbonate deposition gave rise to distinct basin architecture of wide carbonate platform, narrow slope (Hinge zone) and deeper basin during Eocene period. The sedimentation rate increased drastically during Mio-Pliocene period due to the emergence of Proto-Himalayas in the north. This has resulted in the higher sedimentation rate, which changed the shelf break from NNE-SSW in Oligocene period to more or less, east-west at present time.

OVERPRESSURE WELLS IN BENGAL BASIN

Exploratory drilling in Bengal Basin was initiated by Indo-Stanvac Petroleum Company (ISPP) during 1957-1960. Ten wells were drilled out of which only one well i.e. W-7 was drilled down to 4042 m in the deeper basinal part (east of hinge zone). The deepest section in this well was drilled with mud sp.gr 1.71 suggested the presence of overpressure in the bottom section below 4030m. ONGC drilled its first well W-10 in 1966 in the deeper basinal part, which encountered overpressure zone for the first time in the basin within late Miocene at around 3775 m. Due to various down hole complication related to overpressure, the well was terminated at 4197 m that took nearly three years time for drilling. In the year 1975, the well W-11 was drilled to explore a fault closure prospect within Pliocene to a depth of 3700 m in which evidence of overpressure reported below 3540 m. Natomas-Carlsberg group drilled two wells W-12 and W-13 in offshore area in the year 1975-1976. Out of these two wells, W-12 encountered transition top around 3048 m and overpressure top at 3640 m. This well was drilled with 1.62 sp.gr mud around 3048 m and 2.17 sp.gr mud around 3668m. To the southwest of W-12 in the shelf side, W-13 was drilled in which no abnormal pressure was encountered and 1.53 sp.gr (maximum) mud weight was used to drill this well. ONGC subsequently drilled three onshore wells namely W-22, W-26 and W-29 in the deep basinal part, one well W-36 on the hinge zone and all these wells encountered overpressure within Miocene sediments. In the offshore part, ONGC drilled its first two well W-30 and W-32 to probe the growth fault related feature within Miocene sediments which also encountered overpressure within Miocene sediments. Three more wells W-28, W-37 and W-34 were drilled in Bengal offshore, W-28 and W-37 encountered over pressures within Miocene but no abnormal pressure was encountered in W-34 (shelf side of hinze zone) in which maximum 1.6 sp.gr mud was used. In the year 2005, ONGC took up drilling of one well W-45 targeted to 5000 m to probe Miocene slope fan prospect. In this well, transition top was encountered at 3560 m and over pressure top was encountered at 4278 m (MWE 2.12 sp gr). The well could not be drilled down to target depth and was terminated at 4400 m due to severe down hole complications related to abnormally high pressure and ultimately mud weight was increased to 2.28 to control the well, resulting into a high quantum of non-productive time.

In view of above, a thorough understanding regarding formation pressure regime in PreMiocene/Miocene sections (east of hinge zone) is paramount importance for further exploratory drilling operations and its successful completions considering the earlier experiences and observations. A total of eleven exploratory wells are being considered for integrated analysis on abnormal formation pressure in Bengal Basin.

DATA ANALYSIS

The available geoscientific data, which includes details of formations, electro logs (Resistivity, Density, Neutron and Sonic log), dcs, σ log, FLT, pressure data (wherever available) have been integrated in a composite chart (Geolog) for all exploratory high pressure wells. The Geolog of individual wells have been plotted compiling all available

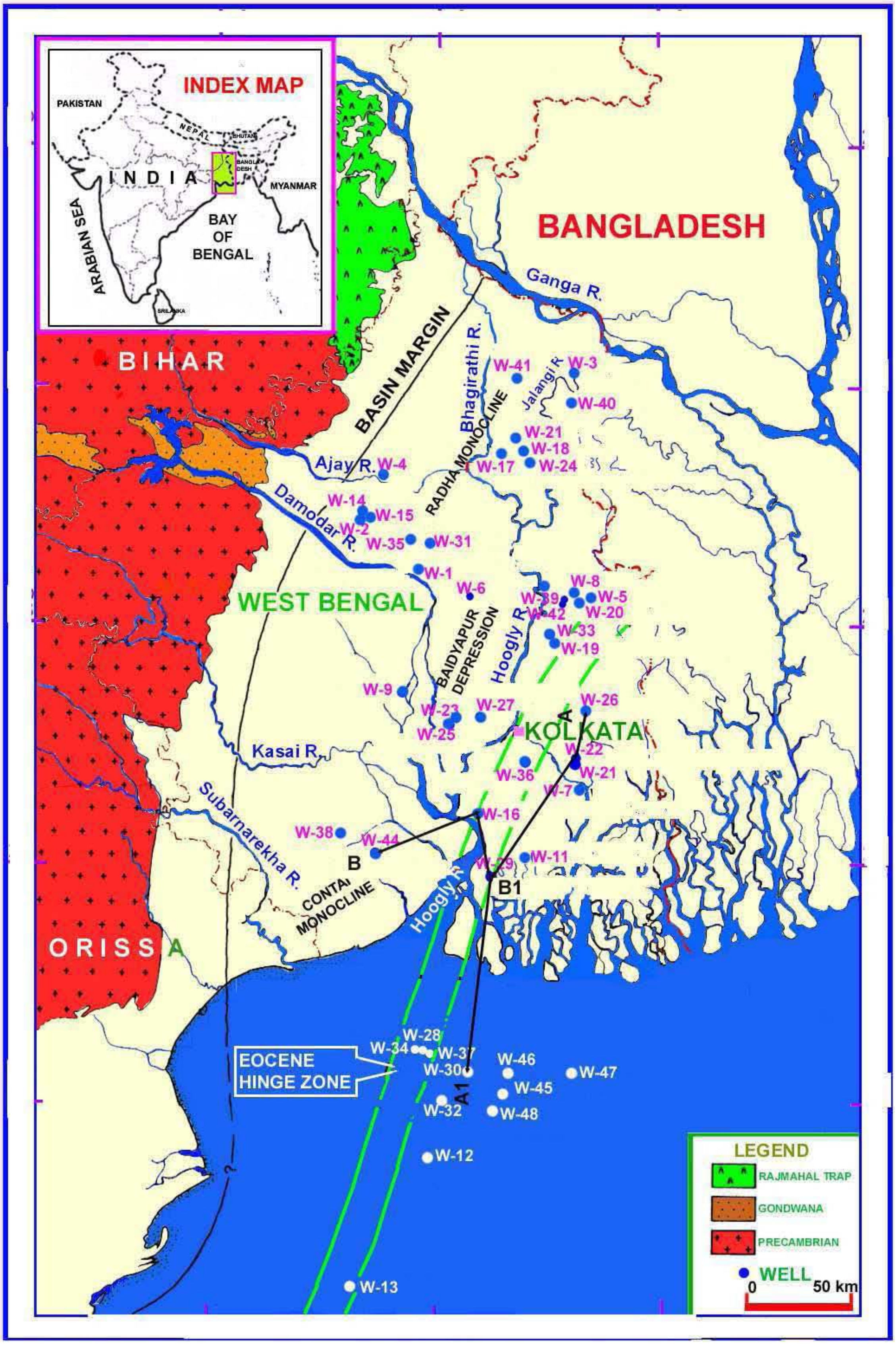

Fig.3. Location map of Bengal Basin with correlation line AA1 and BB1 (ref. Fig.11A and 11b).

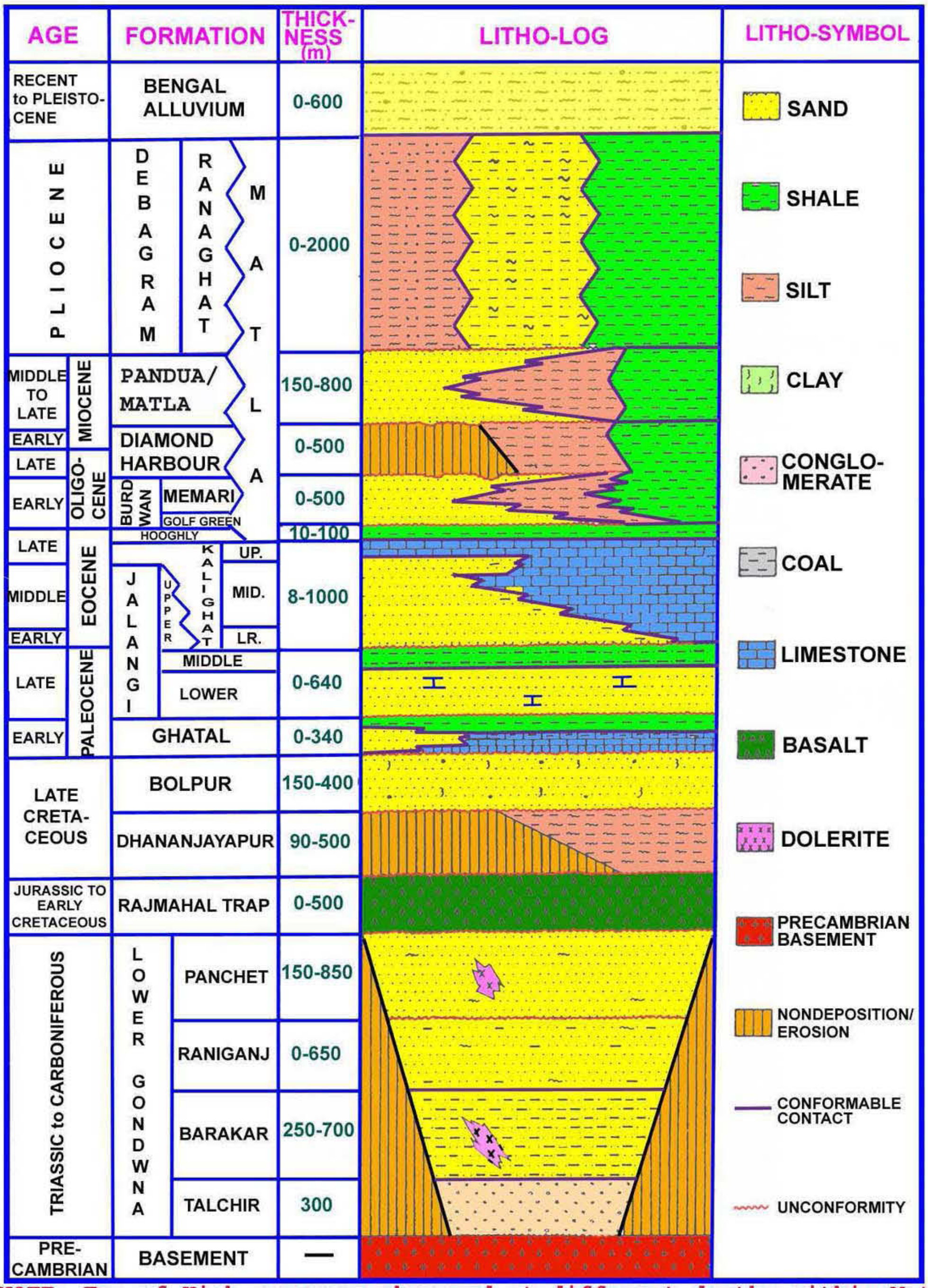

Fig.4. Generalised lithostratigraphy of Bengal Basin. Note: Top of high pressure observed at different depts within Matla Formation of Middle to Late Miocene in wells east of Hinge zone.

geoscientific data (ref Figs. 5 and 6, Geolog plot of W-22 and W-32). Different pressure regimes like normal, transition and overpressure regimes are marked. The major component of overpressure formation is the high rate of sedimentation in the slope and deeper basinal part during different episodic phases of sedimentation in the form of slope fan, basin floor fan and other deeper basinal sedimentary units. Based on Geolog plot, the overpressured data of wells are tabulated in Table 1.

INTEGRATED STUDY OF PRESSURE PROFILE

In a siliciclastic stratigraphic section, the interval velocity increases with depth and the normal trend can be easily

Table 1. Overpressured data of wells

Well Name	Offshore/ Onland	Drilled Depth (m)	Bottomed in	Transition Zone		Overpressure		Thickness of transition zone (m)
				Top (Measured)	MWE (Sp.gr.)	Top (Measured)	MWE (Sp.gr.)	
W-12	Offshore	4073	Miocene	3048 m	1.29	3640 m	1.98	592
No Dc, σ log data available, Transition and Overpressure top taken on the basis of Temp data								
W-16	Onland	5555	Eocene	3175 m	1.25	-	-	-
Well completed with 1.46 sp. gr mud, Transition top taken on basis Dc plot, no over pressure encountered upto D.D (5555 m)								
W-22	Onland	4950	Miocene	3168 m	1.20	3775 m	1.89	607
Based on Dc & σ log plot, Transition and Overpressure top taken, 9 7/8" casing was lowered at 3756 m (RFT 3760 m 1.44 MWE), At 3789 m,RFT-1.88.								
W-26	Onland	5007	Miocene	3400 m	1.31	4171 m	2.06	771
Based on Dc & σ log plot, Transition and Overpressure top taken, 10¾" casing lowered with shoe at 3731 m								
W-29	Onland	5339	Miocene	3400 m	1.31	3864 m	2.01	464
Based on Dc & σ log plot, Transition and Overpressure top taken, 10¾" casing lowered with shoe at 3844 m, at 3864 m, RFT 2.014 MWE.								
W-36	Onland	5826	Eocene	3360 m	1.32	3814 m	1.82	454
Based on Dc & σ log plot, Transition and Overpressure top taken, 10¾" casing lowered with shoe at 3697.25 m, at 3814.5m, RFT 1.825 MWE.								
W-28	Offshore	5079	Eocene	3300 m	1.24	3840 m	1.53	540
Based on Dc & σ log plot, Transition and Overpressure top taken First kick at 3840 m (RFT at 3849 m 1.5 MWE, second kick at 4864 m (2.19 MWE).								
W-30	Offshore	4951	Miocene	3025 m	1.21	3720 m	2.04	695
Based on Dc & σ log plot, Transition and Overpressure top taken, 10¾" casing lowered with shoe at 3706.45 m, RFT at 3717.2 m 2.098 MWE.								
W-32	Offshore	4975	Miocene	2800 m	1.26	3273 m	2.04	473
Based on Dc & σ log plot, Transition and Overpressure top taken, 10¾" casing lowered with shoe at 3255 m, first kick at 3280 m (RFT 1.977 MWE).								
W-34	Offshore	5831.50	Cretaceous	3100 m	1.19	-	-	-
Well completed with 1.56 sp.gr mud, No over pressure encountered upto D.D.								
W-37	Offshore	5575	Eocene	3410 m	1.28	3960 m	1.99	550
Based on Dc & σ log plot, Transition and Overpressure top taken, 9 5/8" casing lowered at 3747 m, RFT at 3981 m 1.99 MWE.								
W-45	Offshore	4402	Miocene	3560 m	1.35	4278	2.12	718
The arenaceous facies overlying the transition zone leads to misguided data of Dc and σ log plot, shift observed in Resistivity and Porosity plot. 9 5/8" casing lowered at 3791 m. At 4400 m, 2.25 sp.gr. mud was used.								

established. The porosity in overpressure regime is more in comparison to the normal pressure regime. The overpressure zone is overlain by transition zone which is overlain by an impermeable layer which restricts the transmission of pressure upwards. The ΔT_{shale} (transit time) decreases downward in a normally compacted stratigraphic section but with the approach of transition zone, ΔT_{shale} values increase and deviates from the normal trend. This concept has been applied in offshore well (W-28, W-30, W-32, W-37 and W-45) and onshore wells (W-26, W-29 and W-36, ref 7 and 8). The departure from the normal trend is taken as the top of transition zone, validated by the actual pressure data available from RFT.

Overpressures in deltaic environments are generally associated with undercompacted shales which exhibit higher transit time. The prediction method consists of relating the amount of abnormality of these shales, expressed in terms of interval transit time. The relationship between the shale acoustic parameters difference (i.e. $\Delta t_{ob\ (sh)} - \Delta t_{n\ (sh)}$) and reservoir fluid pressure gradient (FPG) was plotted by Hottman and Johnson for Miocene and Oligocene formations along the U.S. Gulf Coast area (Fig. 9). The formation pressure gradient (FPG) is multiplied by the subject depth to obtain the formation pressure. For Bengal Basin, such a curve was earlier plotted by Dutta et al. (1984) based on the well data of W-12, W-13 and W-22 and subsequently

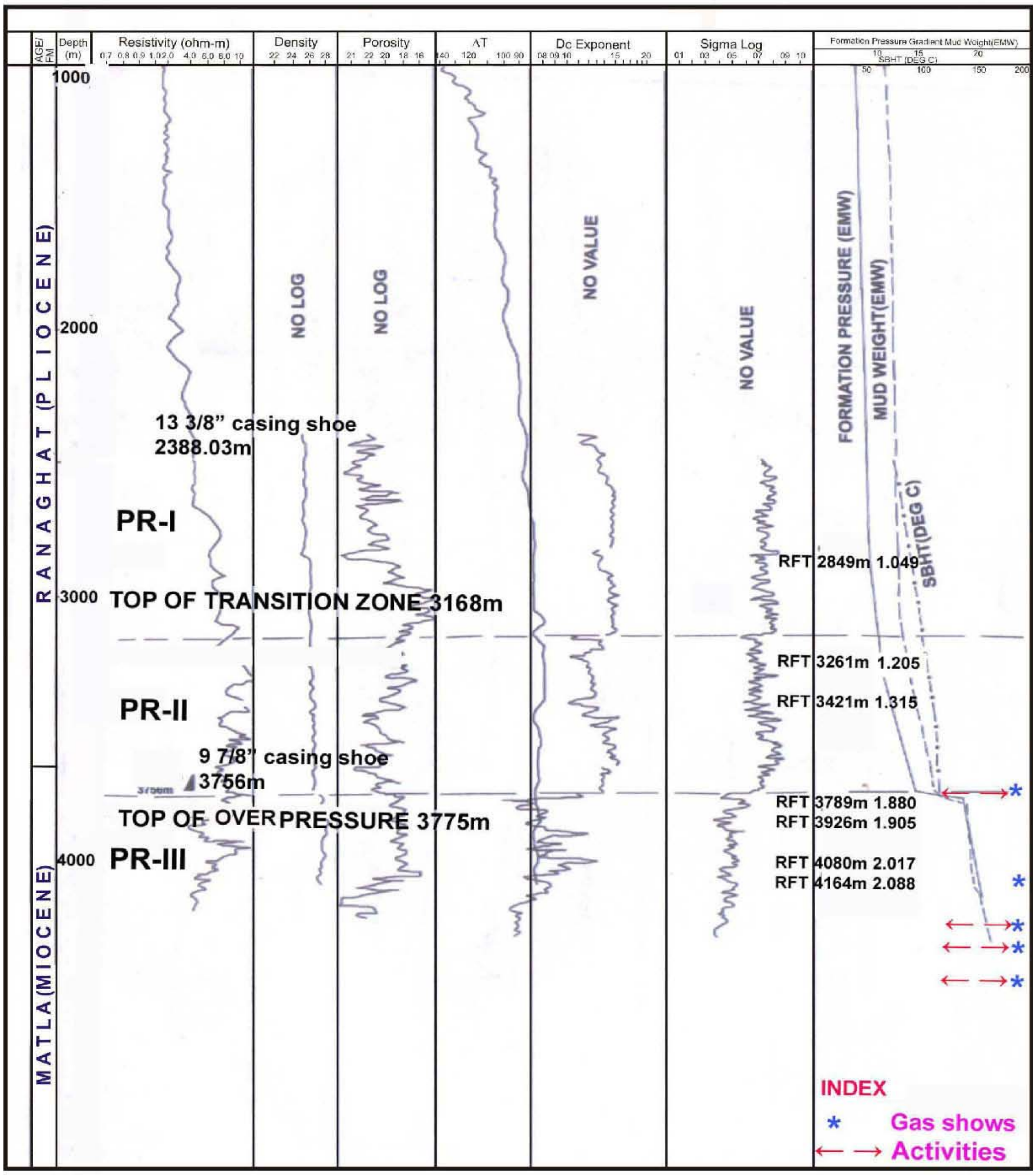

Fig.5. Geolog plot of W-22.

Repeat Formation Tester (RFT):

RFT permits capture of fluid samples from various zones in a well. When brought to surface, the samples can be fed into a high resolution gas chromatograph to give reservoir fluid analysis data. The tester records the pressure and temperature of each sample at the location taken.

Mud Weight Equivalent (MWE):

Formation pressure measurements are done during drilling by RFT, SFT (Selective formation tester), DST (Drill Stem Test) etc which are recorded in kg/cm^2. The hydrostatic pressure gradient in fresh and brackish water is 0.10 kg/cm^2/m. Hence the pressure data obtained during RFT (in kg/cm)^2 is multiplied by 10 and then the multiplied value is divided by the depth (m) from which the pressure was recorded. The resultant value is expressed in MWE.

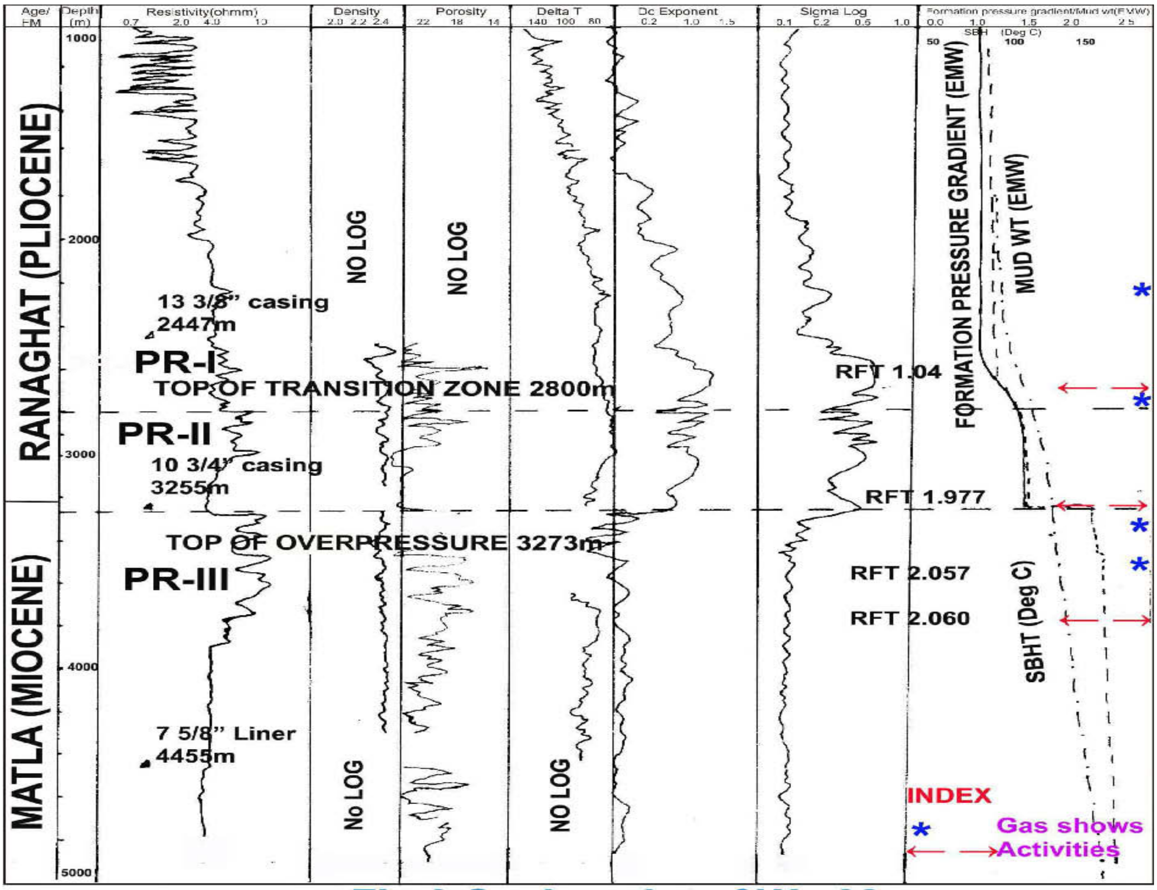

Fig.6. Geolog plot of W-32.

Normal Trend:

Normal trend in a Geolog plot indicates pressure plot where formation pressure is hydrostatic and thus the pressure plot indicates a normally increasing pressure value along with depths i.e. hydrostatic gradient. The average hydrostatic gradient which is encountered during oil and gas exploration in fresh and brackish water is 0.10 kg/cm^2/m.

Transition Zone:

The wells drilled in the deeper basinal part of Bengal basin are having thick pressure transition zone which restricts pressure dissipation laterally as well as vertically. The pressure value in this zone is slightly more than hydrostatic. During drilling, the top of this zone is usually picked up from Composite curves generated by dcs, Sigma log, shale density etc. The sediment in transition zone is lesser compacted with respect to overlying it which is reflected in TShale trend.

Overpressure Zone:

Overpressure zone is defined as the layer in which the pressure exceeds the vertical hydrostatic pressure column of water. The high rate of sedimentation depositing large thickness of clastics represented by dominant clays and interbedded sandstones (high shale/sand ratio) under rapid bottom subsidence are likely reasons of high pressure in Bengal basin.

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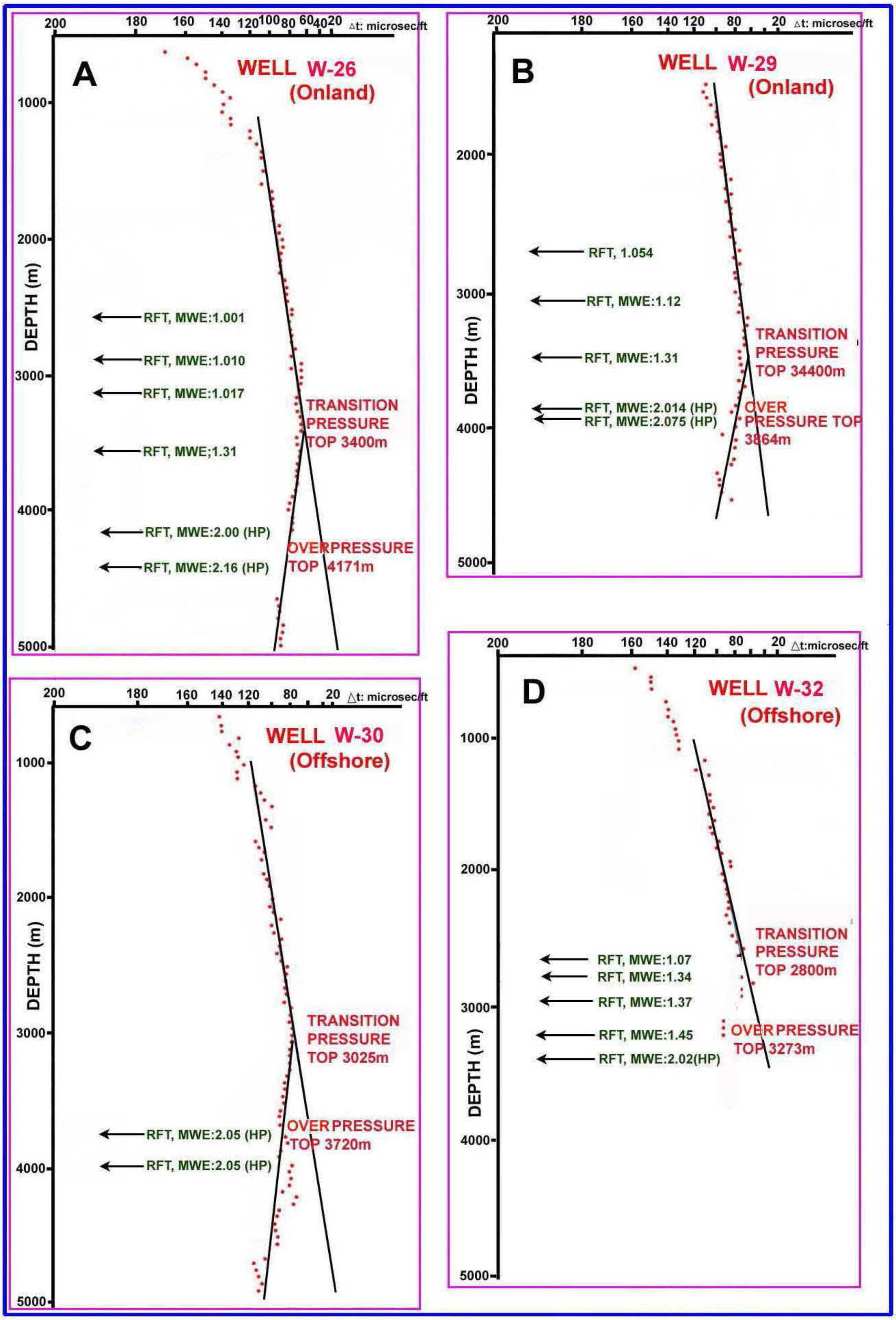

Fig.7. ΔT vs Depth plot showing Transition top.

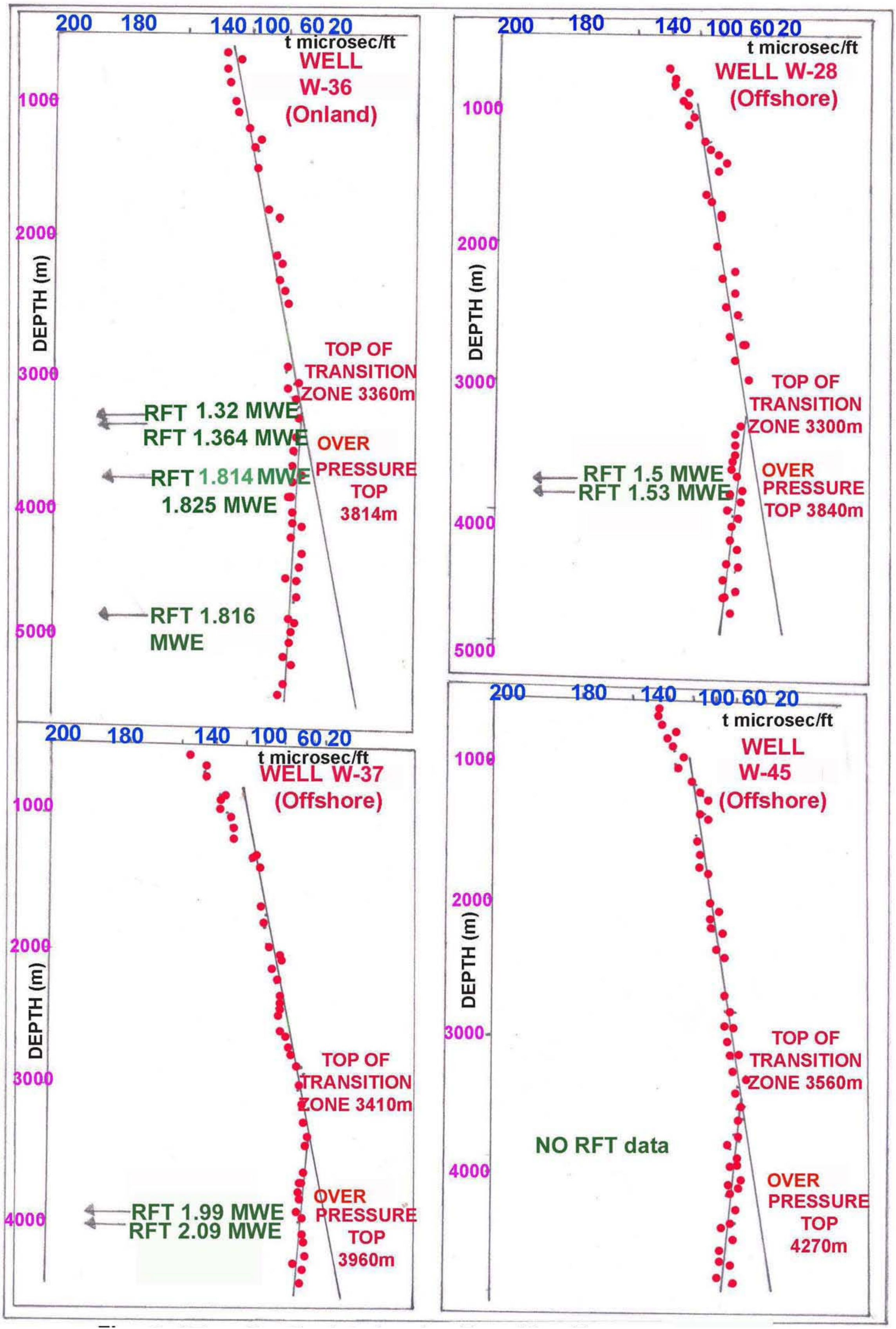

Fig.8. ΔT vs Depth plot showing Transition top.

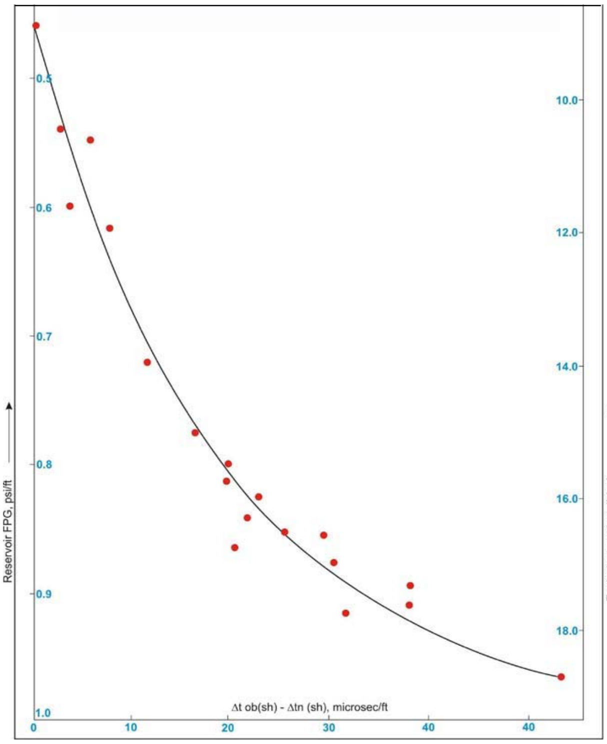

Fig.9. Relationship between the shale acoustic parameter difference and reservoir fluid pressure gradient (*after* Hottman and Johnson, 1956)

by S. Deb et al. (1989) incorporating additional well data of drilled wells W-30, W-32 in offshore and W-26 and W-29 in onshore.

Based on the available data of shale acoustic parameters difference (i.e. $\Delta t_{ob\ (sh)} - \Delta t_{n\ (sh)}$) of subsequent wells (W-36 in onshore and W-28, W-37 and W-45 in offshore), the Hottman's curve is modified by the authors (Fig. 10). The generated model curves using Sonic departure principle (Hottman and Johnson, 1956) in the present study has been prepared to demonstrate the departure from normal to overpressure regimes and the causes of departure indicates presence of high pressure at that depth and the reasons of overpressure are high rate of sedimentation, under rapid subsidence along with large accumulation of clastics dominantly clays with sandstone interbeds. The generated model curve from drilled wells (drilled in deeper part of the basin) may be used as an additional tool to find out the expected formation pressure gradient and equivalent mud weight in all future wells to be drilled in deeper part of the basin. The observed Δt difference in a drilled well will give corresponding FPG from the generated model curve which is to be multiplied by the subject depth to obtain the formation pressure and equivalent mud weight to drill the formation.

Correlation of Wells/Pressure Regimes Based on Dc and Sigma Log

An attempt has been made to correlate onshore wells W-26, W-22, W-29 and offshore well W-30 (Fig.11a). The plot indicates fare correlation in the trend of dcs and σ log plot exist in all the four wells though the distance between the northernmost onshore well W-26 and offshore well W-30 is well over 150 km. Another correlation (W-E) has been made based on dcs and available σ log through onshore wells W-44, W-16 and W-29 (Fig.11b) which indicates occurrence of both transition and overpressure zone in well W-29 (western boundary of hinge zone), occurrence of transition zone in well W-16 (eastern boundary of hinge zone) and in well W-44 (situated in stable shelf zone with normal pressure regime). The correlation line in Fig 11b indicates the pressure response across the hinge zone. As lateral facies variation within Miocene is not uniform in all these wells, the confidence level of lithocorrelation for this thick sedimentary section is not very high in this part of the basin. As such, the online correlation/interpretation during drilling phase may be useful for anticipating transition top and overpressure top provided all the parameters required for calculating dcs and σ log recorded smoothly.

Based on the characteristics of the dcs curves corroborated with formation pressures recorded by RFT/MDT etc, the following generalized pressure regimes (in deep basinal part east of hinge zone) are demarcated for onland and offshore sedimentary sections in Bengal Basin (Table 2).

The thickness contour map of transition zone (Fig. 12) is made utilizing the well data drilled in the deeper basinal side. The thickness contour appear to increase towards basinal part of Bengal Basin i.e. east of hinge zone as depicted in thickness contour map with maximum thickness recorded in well W-45 (718 m) which also indicates that expected overpressures zones are likely to be deeper in deep basinal part. The depth contour map on top of transition zone (Fig. 13) also runs more or less parallel to the Eocene hinze zone except nosal feature around W-30 and W-22 area. The depth contour map on top of overpressure (Fig. 14) runs more or less parallel to the Eocene hinze zone.

CONCLUSIONS

The prediction of pressure profile in future wells of Bengal Basin can be estimated based on the present study. The wells drilled in the east of Eocene hinge zone in the onshore and offshore parts of Bengal Basin have penetrated overpressure formation within Miocene in the depth range

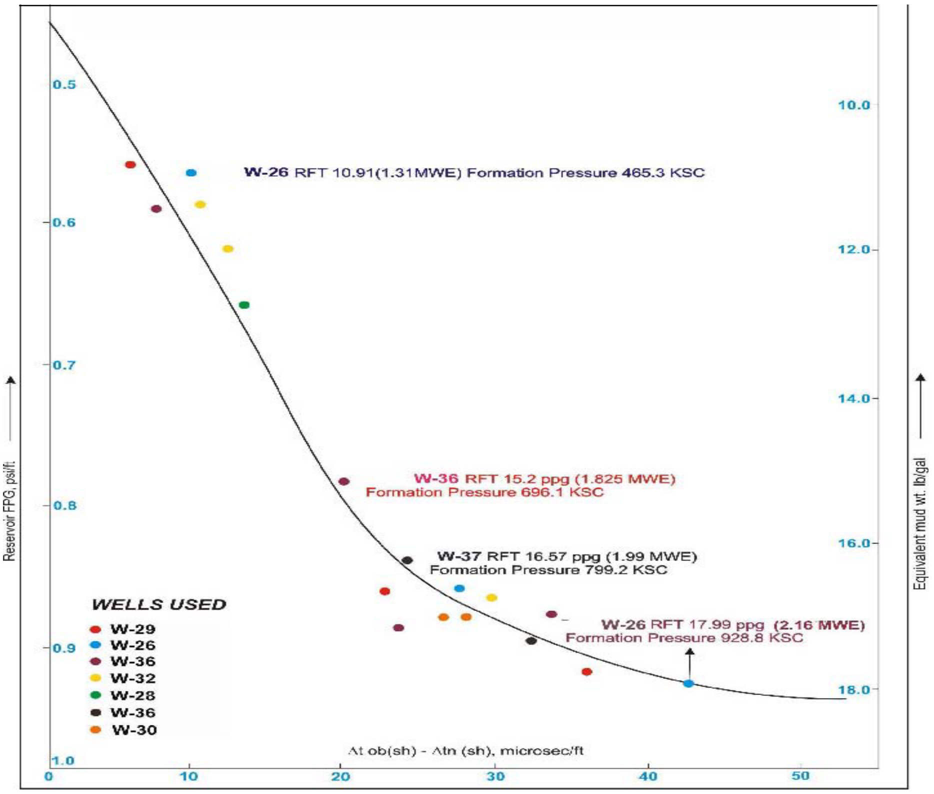

Fig.10. Relationship between shale acoustic parameter difference (tob(sh) - tn(sh) from drilled wells, ref. Figs. 7 and 8) and reservoir fluid pressure gradient (modified Hottmans curve of Bengal Basin).

Repeat Formation Tester (RFT):

RFT permits capture of fluid samples from various zones in a well. When brought to surface, the samples can be fed into a high resolution gas chromatograph to give reservoir fluid analysis data. The tester records the pressure and temperature of each sample at the location taken.

Mud Weight Equivalent (MWE):

Formation pressure measurements are done during drilling by RFT, SFT (Selective formation tester), DST (Drill Stem Test) etc which are recorded in kg/cm^2. This pressure data is multiplied by 10 and then the multiplied value is divided by the depth (m) from which the pressure was recorded. The resultant value is expressed in MWE.

Parts per gallon (PPG):

Pressure expressed in mud weight equivalent (MWE) is multiplied by 8.33 give rise to value expressed in PPG.

KSC:

KSC stands for pressure value expressed in kg/cm^2.

of 2800 m to 5340 m and the mud weight used to control this overpressure zone was more than 2.0 sp gr mud. Most of these wells have faced severe downhole complications related to overpressure resulting premature termination of the wells and/or loss of time. The overpressure zone is mostly associated with the deeper basinal facies (slope fan, basin floor fan) of Miocene sediments which are characterized by high rate of sedimentation under rapid subsidence along with large accumulation of clastics dominantly clays with sandstone interbeds. The overpressure zone is overlain by 500-800 m thick transition zone and lithologicaly characterized by a monotonous argillaceous sediments. Geologs of all the high pressure wells have been made using data like dcs, σ logs etc generated during driiling and are validated by the trend observed from the electrologs and pressure data. The Geologs will be useful to have a clear understanding for overpressure monitoring during future exploratory drilling. The maps/curves generated in the report can be used for detection of transition/overpressure tops with stratigraphic correlation and using the map. The

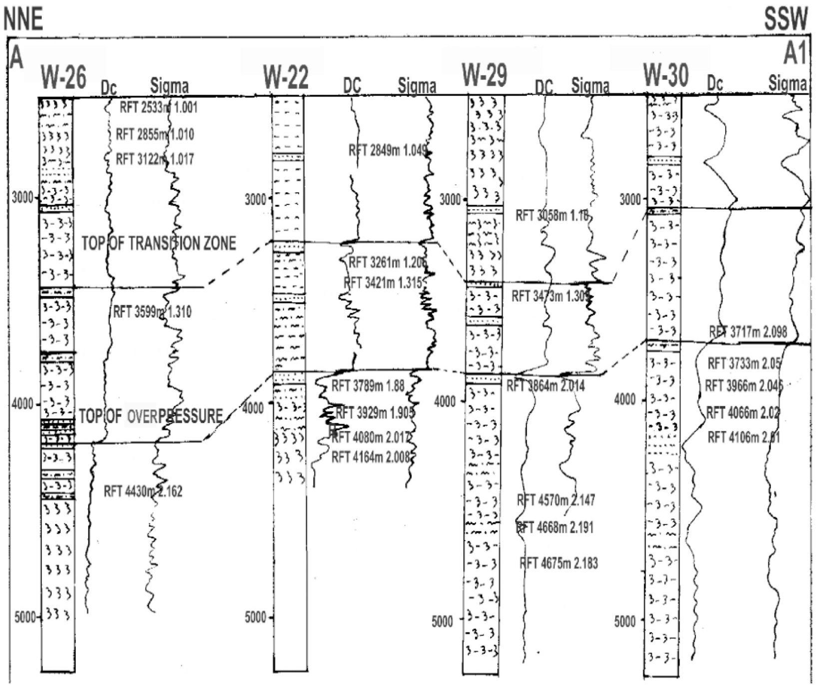

Fig.11a. Correlation of wells (NNE-SSW) on the basis of Dc and Sigma log. *Note:*The correlation of onshore wells W-26, W-22, W-29 and offshore well W-30 indicates fair correlation in the trend of dcs and σ log plot exist in all the four wells though the distance between the northernmost onshore well W-26 and offshore well W-30 is well over 150 km. The top of transition zone in all these wells is marked by change in gradient of dcs and σ log plot. The top of overpressure zone is clearly marked by marked deviation in gradient of dcs and σ log plot.

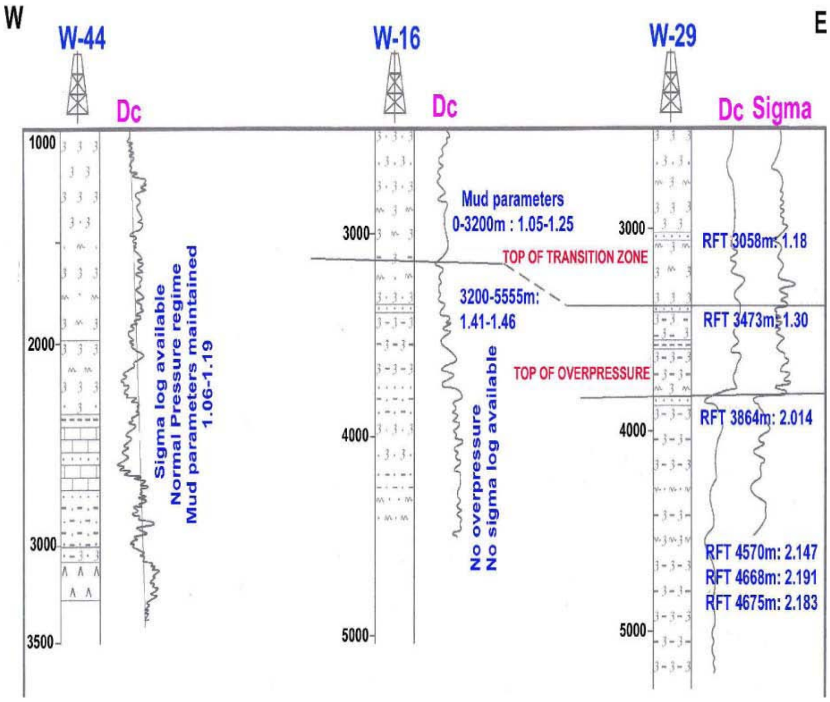

Fig.11b. Correlation of wells (W-E) on the bsis of Dc and Sigma log for pressure response across hinge zone. *Note:* The west-east correlation of onshore wells W-44, W-16 and W-29 indicates occurrence of both transition and overpressure zone in well W-29 (western boundary of hinge zone), occurrence of transition zone in well W-16 (eastern boundary of hinge zone) and in well W-44 (situated in stable shelf zone with normal pressure regime). This correlation line indicates the pressure response across the hinge zone.

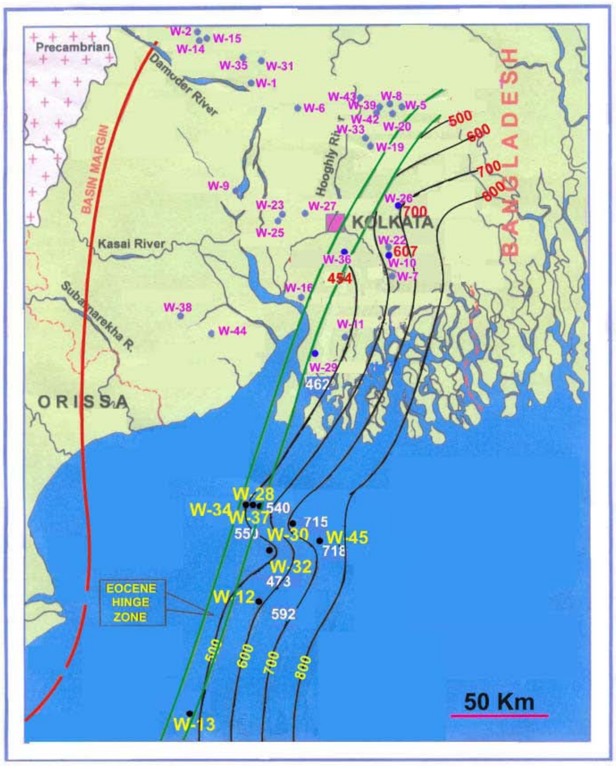

Fig.12. Thickness contour map of Transition zone.

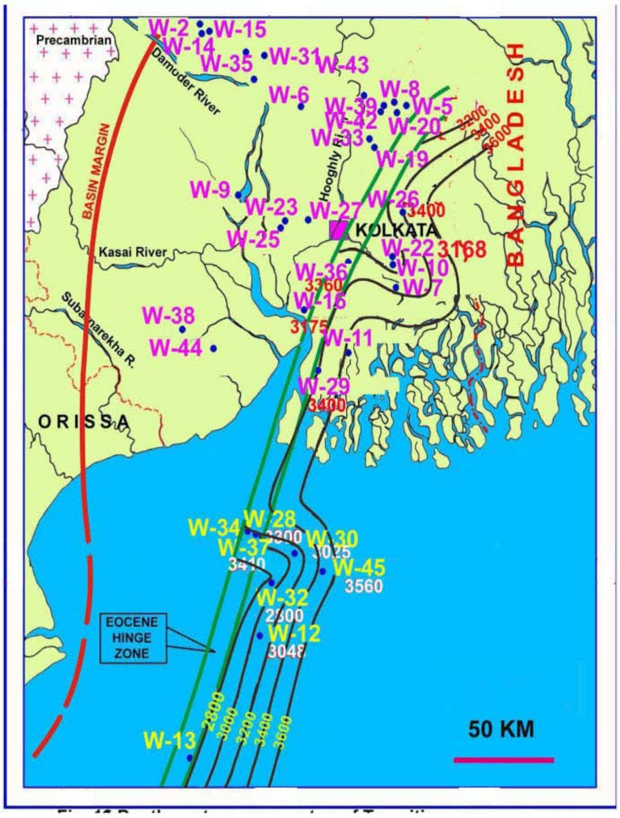

Fig.13. Depth contour map of Transition zone.

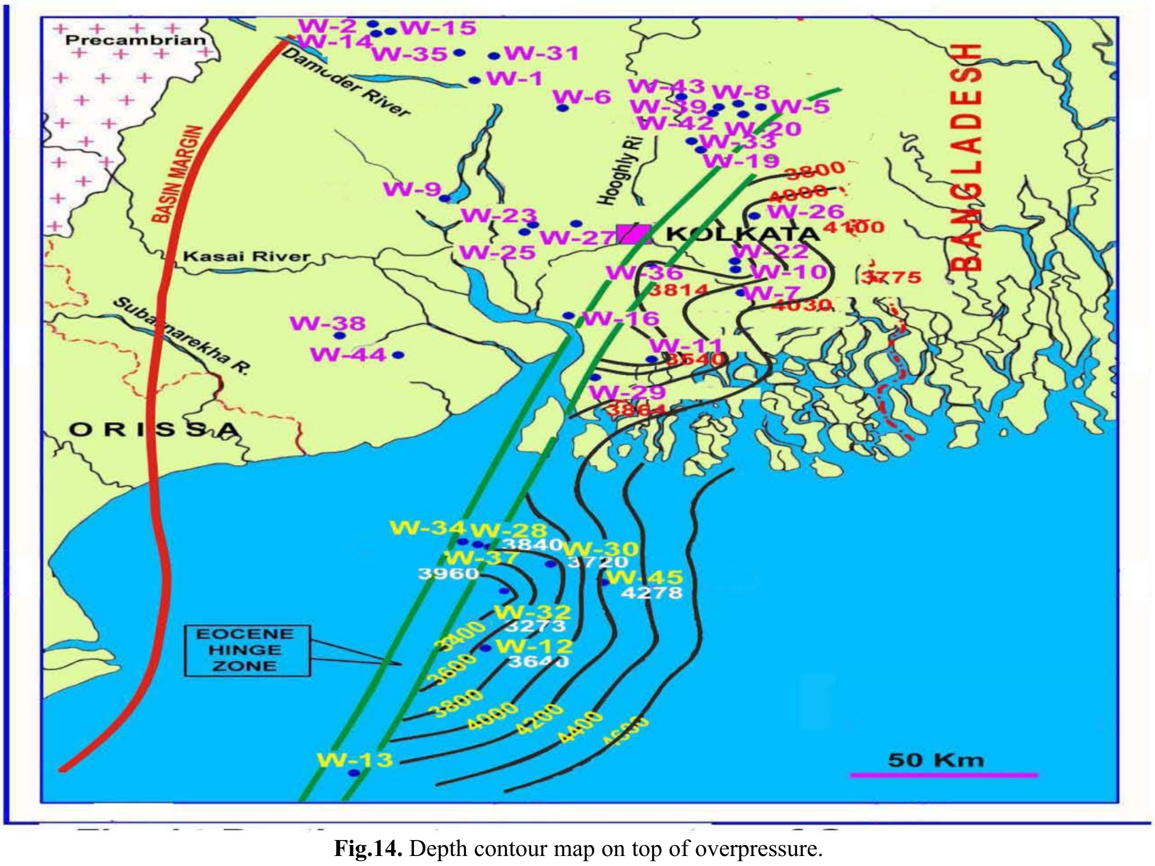

Fig.14. Depth contour map on top of overpressure.

Table 2.

Pressure Regimes	Nature of pressure	dcs characteristics	Remarks
I	Hydrostatic (depth range 2800-3560 m)	Irregular	PR-I can be drilled without any drilling complication
II	Hydrostatic to moderately higher pressure (1.00-1.32)	Normal compaction trend (Transition zone)	Lithologically, PR-II is characterized by thick monotonous finer clastics with a few thin beds of low permeable coarse clastics, which acts as a regional seal for the overpressure formations below and shows marginally higher pressure, ranging upto a maximum limit of 1.32 MWE. The bottom of the PR-II is taken based on the shifting of dcs trend and is correlatable in all the overpressure wells drilled in this basin.
III	Overpressure (1.32-2.19)	Continuous deviation away from the normal trend (over pressure zone)	The PR-III is mostly associated with the deeper basinal facies of Miocene sediments which are characterized by high rate of sedimentation. The formation pressure in this pressure regime ranges from 1.32-2.16 MWE. The dcs log shows a continuous deviation towards left from the normal trend. The major part of the drilling complications due to sudden pit gain, gas/water cut and subsequent well control by increasing mud weight as a statutory measures are limited to pressure regime-III. Drilling breaks followed by pressure kicks in porous intervals are common features of this pressure regime
IV	Overpressure (1.81-2.18), appear in wells Raghunath-1 and SMM-1	Dc exponent trend showed no further increase in formation pressure	This pressure regime has been demarcated on the basis of absence of appreciable change in dcs trend, indicates no further increase of formation pressure expected as evidenced by RFT data.

generated model curve (modified using available data after Hottman and Johnson,1956 curve) using sonic departure (i.e. $\Delta t_{ob(sh)} - \Delta t_{n(sh)}$) from drilled wells may be used as an additional tool to find out the expected pore pressure gradient and equivalent mud weight in all future wells to be drilled in deeper part of the basin. The correlation of wells based on the trend of dcs and σ logs during drilling phase may be useful for anticipating transition top and overpressure top provided all the parameters required for calculating dcs and σ log recorded smoothly. The study has brought out the detail procedure to depict the pressure profile in the future wells. This upgraded resume of pressure regimes will lead to successful completion of overpressure wells and fulfilling the geological objectives within a projected time cycle.

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