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Influence of overpressure on formation velocity evaluation of Neogene strata from the eastern Bengal Basin, Bangladesh

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Abstract

Interpretation of sonic log data of anticlinal structures from eastern Bangladesh reveals significant variations of acoustic velocity of subsurface strata. The amount of variation in velocity is 32% from Miocene to Pliocene stratigraphic units in Titas and Bakhrabad structure, whereas 21% in Rashidpur structure. Velocity fluctuations are influenced by the presence of gas-bearing horizons, with velocities of gas-producing strata 3–7% lower than laterally equivalent strata at similar depth. Average velocities of Miocene Boka Bil and Bhuban formations are, respectively, 2630 and 3480 m/s at Titas structure; 2820 and 3750 m/s at Bakhrabad; and 3430 and 3843 m/s at the Rashidpur structure. From the overall velocity–depth distribution for a common depth range of 915–3000 m, the Titas, Bakhrabad and Rashidpur structures show a gradual increase in velocity with depth. In contrast, the Sitakund anticline in SE Bangladesh reveals a decrease in velocity with depth from 3000 to 4000 m, probably due to the presence of overpressured mudrocks of the Bhuban Formation. Tectonic compression, associated with the Indo-Burmese plate convergence likely contributed the most toward formation of subsurface overpressure in the Sitakund structure situated in the Chittagong–Tripura Fold Belt of the eastern Bengal basin, Bangladesh.

Keywords: Formation velocity; Overpressure; Sonic log; Bangladesh; Neogene strata; Bengal basin

1. Introduction

It has long been recognized that seismic wave characteristics measured at the earth surface can provide information not only about the attitude and distribution of lithologic interfaces within the earth but also physical properties of subsurface rocks. In fact, much of the knowledge about the interval constitution of subsurface rock has been derived from seismic velocity information. In this study, interval transit time and acoustic velocities are calculated from the sonic logs and are compared with velocity information obtained during seismic exploration in order to predict factors that might be responsible for changes in velocity of subsurface units. In this work, the consideration of normal pressure and overpressure has been taken from published and available literature where abnormal pressure is thought to be 1.6 times greater than the normal pressure (Bradley, 1975). Overpressures are observed in subsurface strata worldwide (Hunt, 1990; Powley, 1990; Osborne and Swarbrick, 1997) and overpressured zones have been frequently reported in exploratory wells drilled in eastern Bangladesh (Khan and Husain, 1980). Maps showing subsurface formation pressure and temperature in the Bengal basin have been prepared from the drilled well data. Finally, an attempt has been made to understand the overpressure phenomenon by comparing velocity data with temperature, depth, and lithologic information from some wells.

2. Regional geology of the Bengal basin

The dynamic nature of the Bengal basin can be attributed to the interaction of three plates; the Indian, Tibetan (Eurasian), and Burma (West Burma) plates. The intensity and pattern of plate-to-plate interaction varied with time, modifying the basin architecture and sedimentation style

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throughout the basin. Basin development began in the late Cretaceous (about 127 Ma) when the Indian plate was rifted away from Antarctica along an inferred northeast–southwest-trending ridge system (Sclater and Fisher, 1974). After plate reorganization at about 90 Ma, the Indian plate began migrating rapidly northward, leading to its collision with Asia, probably initiated during the Eocene between 55 and 40 Ma (Curray et al., 1982; Molnar, 1984; Rowley, 1996). Major uplift of Himalayas may not have begun until the Miocene (Gansser, 1964; Uddin and Lundberg, 2004).

The Bengal basin has two broad tectonic provinces: (1) the ‘Indian platform,’ where thin sedimentary strata overlie rocks of the Indian craton in the northwest; (2) and the very thick basin-fill that overlies deeply subsided basement of undetermined origin in the south and east (Bakhtine, 1966; Khandoker, 1989). These two provinces are separated by a northeast-trending hinge zone (Fig. 1).

The Bengal basin is asymmetric; thickness of sediments increases toward the south and east to more than 16 km (Curray and Moore, 1971; Murphy, 1988). Desikachar (1974) proposed a plate tectonic model of the region where he considered the Bengal basin as a pericratonic basin of the Indian plate. In his view, the Burmese plate has moved toward the Indian plate beginning in the Miocene and overrode the Indian plate to form a subduction zone between the two plates. Today most authors agree that convergence between India and Burma has resulted in subduction of oceanic crust beneath Burma, with the trailing margin of India currently passing obliquely into the foreland of the Indo-Burman ranges (Mukhopadhyay and Dasgupta, 1988; Murphy, 1988; Alam et al., 2003). This convergent margin has been complicated by generally north–south trending right-lateral strike-slip motion (e.g. Kaladan fault, Sagaing fault), possibly throughout the history of the collision (Ni et al., 1989).

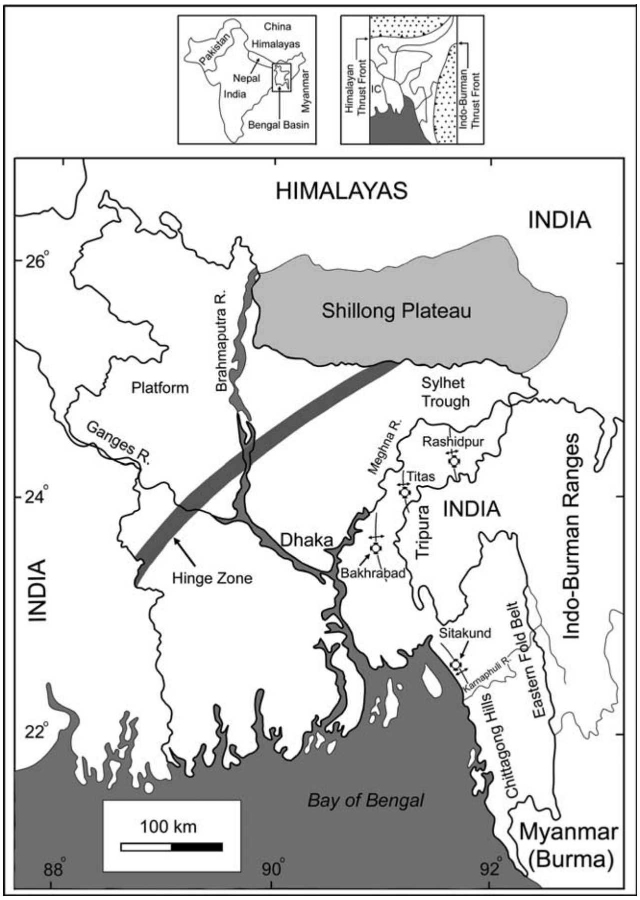


Fig. 1. Location and regional tectonic map showing major tectonic elements of the Bengal basin. Hinge zone separates the shallow Indian platform from the deeper Bengal foredeep. The map shows location of wells for which sonic logs have been studied and well completion reports have been reviewed. Abbreviation: IC: Indian Craton (after Uddin and Lundberg, 1999).

The Sylhet trough is a sub-basin of the Bengal basin in northeastern Bangladesh. It is characterized by a large, closed, negative gravity anomaly as low as −84 mgal (Ali and Raghava, 1985). The Sylhet trough has minimal topography and is actively subsiding. Estimates of the sediment thickness in the Sylhet trough range from about 12 to 16 km (Hiller and Elahi, 1984). The eastern part of the Sylhet trough lies in the frontal zone of the Indo-Burman ranges. The trough is bounded to the north by the Shillong plateau, which is underlain by a basement complex of Archean gneiss, greenstone and late Proterozoic granite.

3. Geology of the study area

The study area covers two important tectonic segments of the Bengal basin: the Sylhet trough in the northeast and the eastern fold belt (also known as Chittagong–Tripura Fold Belt; CTFB) in the east and southeast (Fig. 1). This research deals with four different anticlinal structures: Rashidpur, Titas, Bakhrabad, and Sitakund. Three of those are located in the eastern fold belt of Bangladesh (Fig. 1) and Rashidpur is located at the southern fringe of the Sylhet trough. All but the Sitakund structure has gas-producing wells.

The Titas structure (studied well is Titas-11) lies along the western margin of the eastern folded belt, showing a dome-like structure with a peripheral closure of some $12.87\times19.3\ \text{km}^2$ at 960 m depth. It is asymmetric in shape with a steeper eastern flank. The structure appears to be undisturbed. There are several sand zones in the Boka Bil reservoir, the hydrostatic pressure of which range from 4200 to 4500 psi (Khan and Husain, 1980). The net sand thickness of Titas is 130 m; porosity ranges from 17 to 24% (average 20%) and gas saturation is 55–70%. The field’ was brought under production in 1968 (Khan and Husain, 1980).

The Bakhrabad structure (studied well is Bakhrabad-9) lies in the western continuation of the eastern folded belt (Fig. 1). It is symmetrical in shape and is about 64 km long and more than 6.5 km wide with a total area of 414 km^2. The axial trend of the structure is north–south, curving to the east at the northern end. The structure has four culminations and contains four gas-bearing zones (1826–1854, 1951–2009, 2089–2131 and 2144–2228 m). The net thickness of gas sand zones is 240 m; porosity range is 16–25% (average 22.6%), whereas average gas saturation is 35%.

The Rashidpur (studied well is Rashidpur-4) structure is situated in the eastern fold belt and is a narrow asymmetrical anticline. The structure is about 40 km long and 4.8 km wide, elongated in a north–south direction. Medium-grained sandstone is exposed in the axial part of the anticline and alternating sandstone and mudstone crop out on the flanks. The structure plunges both to the north and south, and its eastern flank is steeper (22–25° dip) than its western flank (10–12° dip). There are two main gas-bearing zones, at depths of 1388–1462 and 2708–2762 m. The net sand thickness for the shallower zone is 64.9 m and for the deeper zone is 65.2 m. Porosity and gas saturation range from 20 to 30% and 55 to 70%, respectively (Khan and Husain, 1980).

The Sitakund anticline (studied well is Sitakund-1), situated at the southeastern part of the Bengal basin, is 70 km long and 12 km wide. This structure is a doubly-plunging and asymmetric anticline (Hossain, 1988). The Sitakund anticline has an axial trend of NNW–SSE and its western flank is steeper than the eastern flank. One prominent feature of this anticline is a major thrust fault on its western flank that runs parallel to the axis of this anticline.

4. Methods

In this research, sonic and lithologic logs are used to interpret subsurface velocity profiles. Well-completion reports have been compared with data obtained from the sonic and lithologic logs. Selection of the four particular wells of this study was based on availability of and permission to use data from the data centre of the Bangladesh Oil, Gas and Mineral Corporation (BOGMC). Sonic logs available for the northern three wells (Rashidpur, Titas, and Bakhrabad) include data from depths of 915–3050 m. Within this depth range, different formations are distinguished by information from BAPEX Corelab Report (1996). Sonic log values are given in microseconds (μs) per foot. The arithmetic sensitivity scale is used for the log. For interpretative purposes, root mean square velocity (V_{RMS}) was determined for each formation at each well using the transit times and thicknesses. These V_{RMS} values have been used to compare velocity across different wells for every individual formation as well as formations within a well. The gradual change of velocity with progressively deeper formations has also been considered. Comparisons were made with available formation temperature, pressure data and maps from the repositories of BOGMC.

5. Stratigraphy and formation velocity

The stratigraphic framework of Bengal basin was initially established by lithostratigraphic correlation to type sections in the Assam basin, northeastern India (Evans, 1964; Holtrop and Keizer, 1970; Khan and Muminullah, 1980). Seismostratigraphic correlations have subsequently refined the conventional stratigraphic framework for most parts of the Bengal basin, including the Sylhet trough (Hiller and Elahi, 1984).

The Paleogene sediments in the Bengal basin are exposed only in the northern margin of the Sylhet trough. These are also sporadically drilled in northwest, northeast, and southeast of the Bengal basin. The Paleocene and Eocene strata consist of (1) the Paleocene–Eocene Tura Sandstone Formation (also known as Cherra Formation), (2) the middle Eocene Sylhet Limestone, and (3) the overlying upper Eocene mostly marine Kopili Shale (40–90 m-thick; Reimann, 1993). The Oligocene strata, informally referred to as the Barail Group, are exposed along the northern fringe of the Sylhet trough near the Dauki Fault area. The Barail equivalent rocks, the Bogra Formation (Khan and Muminullah, 1980), in the Platform area are less than 200 m thick

The Miocene Surma Group has traditionally been divided into two units; the lower Bhuban and the upper Boka Bil formations (Holtrop and Keizer, 1970; Khan and Muminullah, 1980; Hiller and Elahi, 1984; Uddin and Lundberg, 2004) which extend throughout the Bengal basin. Beginning in the early Miocene, large volumes of orogenic sediment were funneled into the basin from the northeast, building a major Mio-Pliocene delta complex (Uddin and Lundberg, 1999), while a lesser influx of sediment from the northwest formed several smaller deltas (Alam et al., 2003). Miocene sedimentation was in fluvial, deltaic, and open-shelf environments in shallower areas, and in submarine fans in deeper parts of the basin (Alam et al., 2003). The upper and middle part of the Bhuban Formation was deposited in a near-shore depositional regime (Reimann, 1993), whereas the lower part is considered as shallow-to-deep marine, exposing turbidite sequences (Alam et al., 2003). The Boka Bil Formation was deposited in shallow-marine-to-marine setting; the top portion of the formation is composed of shaly sequence, and was designated as the Upper Marine Shale by Holtrop and Keizer (1970).

Deposition of the Bhuban and Boka Bil formations were followed by mainly fluvial deposition of the Mio-Pliocene Tipam Sandstone (Johnson and Nur Alam, 1991). In the eastern part of the Bengal basin, major subsidence led to deposition of fluviatile and deltaic sandstones and conglomerates in the Plio-Pleistocene, forming the Dupi Tila Sandstone and Dihing Formation (Hiller and Elahi, 1984).

In the Titas-11 well, sonic and lithologic logs between depths from about 915 to 3080 m were available for this study. This depth range encountered two formations, namely, Boka Bil and Bhuban (BAPEX Core lab, 1996).

Table 1
Stratigraphic table showing lithology, velocity and formational depth ranges of the strata drilled at the Titas-11 well (BAPEX Corelab Report, 1996)

Formation	Lithological description	Depth range (m)	Average velocity (m/s)	Velocity range (m/s)
Tipam Sandstone (Upper Miocene to Pliocene)	Medium- to coarse-grained sandstones with calcareous cement interbedded with microcrystalline limestone. Also minor mudstones that are hard to friable, with occasional siltstone	+539 to 842	Data not available	–
Boka Bil (Middle to upper Miocene)	Siltstones are firm, hard to soft, thinly laminated; mudstones are hard, blocky, and rarely laminated	842 to 1445	2630	2117–3278
Bhuban (lower to middle Miocene)	Mudstones are firm, grading to and interlaminated with siltstones. Sandstones are loose, disaggregated, fine to medium grained, sub-angular and micaceous	1445 to 3189+	3480	2722–4355

Wavy line indicates an unconformity surface.

Table 2
Stratigraphic table showing lithology, velocity and formational depth ranges of the strata drilled at the Bakhrabad-9 well (BAPEX Corelab Report, 1996)

Formation	Lithological description	Depth range (m)	Average velocity (m/s)	Velocity range (m/s)
Tipam Sandstone (Upper Miocene to Pliocene)	Medium- and fine-grained sandstones which are angular to sub-angular with occasional lithoclasts, commonly micaceous and argillaceous. Mudstones are firm to hard, fissile, non-calcareous hydrophilic and sometimes blocky	Near surface to 800	Data not available	–
Boka Bil (Middle to upper Miocene)	Soft to firm, micro-micaceous siltstone grading to mudstone. Sandstone as above but more abundantly micaceous and with laminations of sandstone and siltstone	800–1890	2820	2292–3350
Bhuban (Lower to middle Miocene)	Mudstones are accompanied by very fine-to-fine-grained sandstones with laminations of mudstone and silt	1890 to 3038+	3750	3143–4690

Wavy line indicates an unconformity surface.

Stratigraphic subdivision of Titas-11 well along with their average velocities is given in Table 1.

Likewise in the Bakhrabad-9 well, sonic and master logs were available from a depth range of about 915–3050 m. Two distinguishable formations are identified in Bakhrabad (BAPEX Core lab, 1996; Table 2).

For the Rashidpur-4 well, sonic and master logs were available from a depth range between 915 and 2866 m. The stratigraphic units in this depth range are the Tipam, Boka Bil and Bhuban formations (BAPEX Core lab, 1996). Stratigraphic subdivisions from the Rashidpur-4 well along with their average velocities are given in Table 3.

The Sitakund-1 well in the Chittagong folded belts was chosen for this study where geophysical logging was done back in April 1986. A total depth of about 1400 m (2600–4000 m) was available during the logging. This coverage is low compared to the wells of other three structures. Although the logged portion has not been further subdivided, data from BAPEX Corelab (1996) suggest that this portion may belong to the lower to middle Miocene

Table 3
Stratigraphic table showing lithology, velocity and formational depth ranges of the strata drilled at the Rashidpur-4 well (BAPEX Corelab Report, 1996)

Formation	Lithological description	Depth range (m)	Average velocity (m/s)	Velocity range (m/s)
Tipam Sandstone (Upper Miocene to Pliocene)	Fine-grained sandstones which are angular to sub-angular with occasional lithoclasts, commonly micaceous and argillaceous. Mudstones are firm to hard and fissile, often containing micas	From surface to 1127	2630	2400–3049
Boka Bil (Middle to upper Miocene)	Loosely to moderately consolidated, medium to very fine-grained, angular to sub-rounded, calcareous to locally argillaceous cemented sandstone. Soft, blocky, sub fissile, moderately calcareous shale. Interbeds of loosely consolidated, argillaceous to moderately calcareous sandstone	1127 to 1968(?)	3430	1993–5081
Bhuban (Lower to middle Miocene)	Grey to white, hard, fine to very fine- grained, locally calcareous sandstone with intercalation of shale and siltstone	1986(?) to 2868+	3843	3111–4550

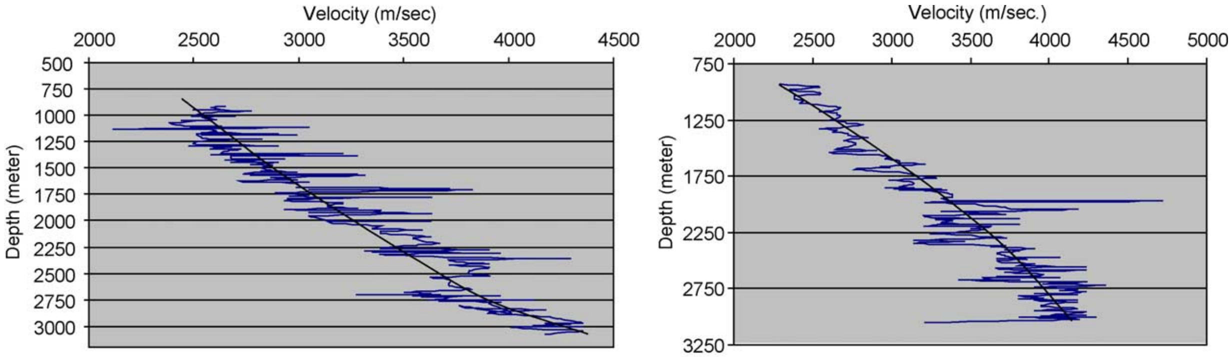
Wavy line indicates an unconformity surface.

Bhuban Formation. Detailed velocity analysis is not possible for the Sitakund-1 well with such limited data; this well has been included only to compare the calculated velocity of this structure with those of other three structures with the fact that the other three wells are gas-producing but the Sitakund-1 did not have any extractable hydrocarbon.

6. Interpretation of velocity data

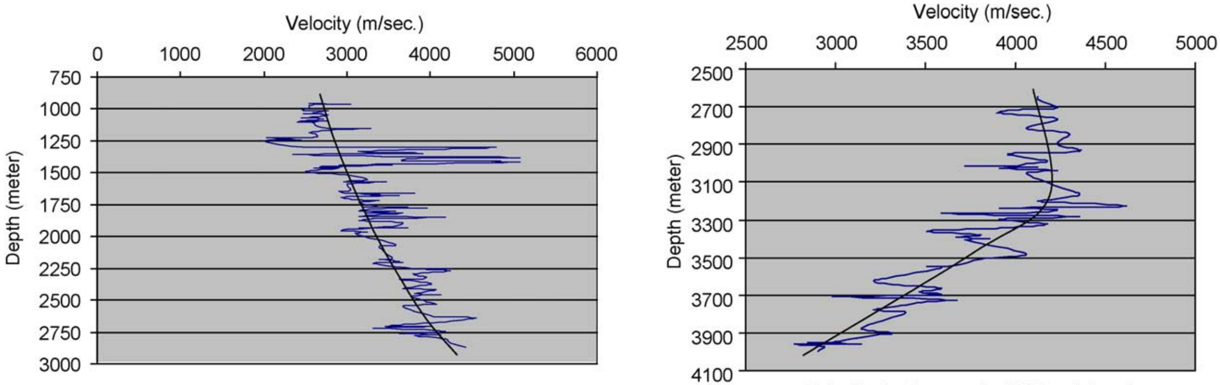
Sonic logs available for this study encounter three formations in Rashidpur structure (Table 3), two formations in Titas and Bakhrabad structures (Tables 1 and 2) and one formation (?) for the Sitakund structure. The amount of variation in velocity is 32% from Miocene to Pliocene stratigraphic units in Titas and Bakhrabad structure, whereas 21% in Rashidpur structure. Average velocities of the Miocene Boka Bil and Bhuban formations are, respectively, 2630 and 3480 m/s at the Titas structure; 2820 and 3750 m/s at Bakhrabad; and 3430 and 3843 m/s at the Rashidpur structure. According to velocity–depth distribution (Fig. 2), the Titas-11, Bakhrabad-9 and Rashidpur-4 wells show a gradual increase of velocity with depth, reflecting a normal trend of velocity increment due to increasing compaction. This is resulting from the fact that the Tipam Sandstone is relatively thin and shallowly buried. This is also because of the variations in compaction, porosity and lithological parameters of the stratigraphic units. The Tipam Sandstone is composed of medium to fine grained massive sandstones with some shale and siltstone, whereas the Boka Bil and Bhuban formations are composed of alternation of sandstone, mudstone and some siltstone. However, from velocity data of the four wells used in this study, no sharp velocity contrast at the formation boundaries can be observed for all the four wells. Intraformational velocity fluctuations are related to lithological and porosity variations within the formation, and the presence of gas-bearing zones. Presence of hydrocarbon in an interval has also a significant effect on velocity. Gas-bearing zones in the Boka Bil and Bhuban formations in three wells show lower velocity relative to the average formation velocity by as much as 3–7%. In the Sitakund structure, however, the velocity–depth distribution shows a short interval of initial increase followed by a decrease in velocity with increasing depth (Fig. 2), indicating the probable presence of overpressured and undercompacted shale in the depth range of about 3000–4000 m.

Lithology log indicates that the Sitakund-1 well is mainly composed of a thick mass of shale with some sandstones and siltstones. This thick shale apparently does not provide effective porosity and permeability to accumulate significant hydrocarbons. Moreover, the presence of such an interval increases the possibility of undercompaction and reduces the density of shale. This will ultimately produce



Velocity-deph curve for Titas-11 well

Velocity-depth curve for Bakhrabad-9 well



Velocity-depth curve for Rashidpur-4 well

Velocity-depth curve for Sitakund-1 well

Fig. 2. Velocity–depth curves in four studied wells. Note that unlike the other three wells, a decrease in sonic velocity with depth has been observed in Sitakund-1 well.

a reverse velocity–depth situation, which is in fact justified by the velocity–depth curve of the Sitakund-1 well, in which velocity decreases with increasing depth, progressively at a relatively constant rate within the depth range of about 3000–4000 m (Fig. 2).

7. Overpressure in sitakund

Occurrence of overpressure has frequently been reported in several exploratory wells in Bangladesh (Khan and Husain, 1980; Uddin, 1987). One overpressured zone in the Sitakund structure occurs at a depth of 1100 m and the other zone starts around 1600 m (Ahmed, 1985). Fig. 3 shows a relatively high temperature gradient (4 °C/100 m) in the proximity of the more compressed and uplifted eastern fold belt where all of the study wells are located. Many of the petroleum producing wells in Bangladesh are located along this temperature gradient adjacent to the fold belt (Khan, 1991). On the other hand, the rapidly subsiding Sylhet trough shows a low temperature gradient (<2.22 °C/100 m) toward the center of the basin. Geothermal information from the northwest Platform area show a temperature gradient of 2.85 °C/100 m, which tends to increase towards the northwest, as basement rocks shallow towards the same directions (to as close to the surface as 136 m).

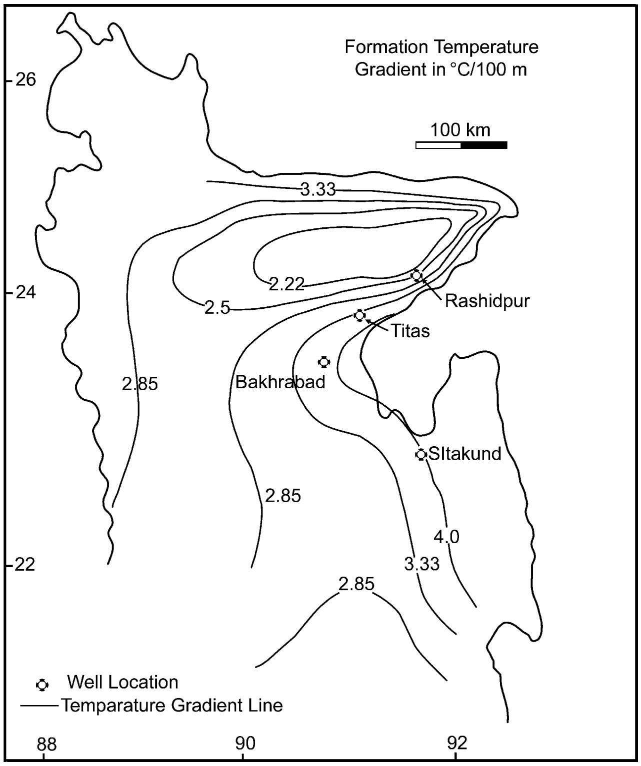


Fig. 3. Formation temperature gradient in Bangladesh. All the wells analyzed for this work are from a belt with relatively higher temperature gradient (After Anwar and Husain, 1980).

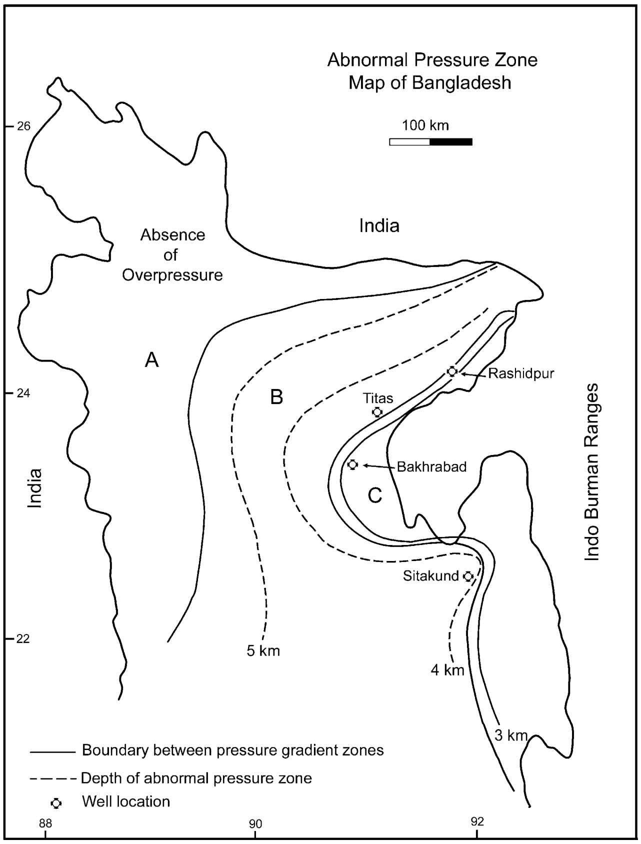


Fig. 4. Distribution of overpressure zone in Bangladesh. Zone A: normally pressured, Zone B: abnormal pressure at depth of 3000–6000 m, and Zone C: abnormal pressure at depth of 1000–3000 m. Note that overpressure at Sitakund-1 well should not be expected above 4 km depth according to the regional trend of the occurrence of overpressure (after Matin et al., 1986). However, an anomaly of this trend has been observed in the Sitakund structure (overpressure at 1100 m).

Fig. 4 shows the distribution of depths of abnormal pressure zones, which corresponds closely with the pattern of geothermal gradients presented in Fig. 3. These data show that abnormal pressure occurs at relatively shallower depth in the more compressed and uplifted strata of the eastern fold belt of the Bengal basin.

On the basis of distributions of pressure and temperature, three zones have been separated: Zone A: where there is no abnormal pressure, temperature gradient is <2.5 °C/100 m; Zone B: abnormal pressure occurs at a depth from 3 to 6 km, temperature gradient is 2.5° to 3.33 °C/100 m; Zone C: abnormal pressure occurs at depth from 1 to 3 km, temperature gradient is >3.33 °C/100 m. The four wells analyzed in this study are located within or in the vicinity of Zone C of Fig. 4. Table 4 shows the depth of overpressured zones in studied wells in Bangladesh.

The Sitakund structure is located close to the eastern margin of Zone B (corresponding to a 4 km depth of overpressured strata; Fig. 4); however, sonic, resistivity and chloride ion concentration data show the presence of overpressured strata at a much shallower depth (1100 m; Ahmed, 1985). The Platform area at the northwestern

Table 4
Depth to the top of overpressured zone in the four studied wells (from Ahmed, 1985 and BOGMC)

Tectonic framework	Well	Top of overpressure zone (m)
Eastern fold belt	Rashidpur-4	3680
	Titas-11	4140
	Bakhrabad-9	1100
	Sitakund-1	3100

Bengal basin is a region where sediment thickness is very shallow, is floored by continental crust, and is far from the zone of structural convergence (Fig. 1). These facts and the subsurface data obtained from the data center of BOGMC suggest that structures in the Platform and the Hinge zone are devoid of overpressured strata. The studied structures in the eastern folded belt however show overpressure zones (Fig. 4). The Indo-Burman ranges are in close proximity to this area and east–west shortening has been active since the late Oligocene (Brunnschweiller, 1966). Considering the structural patterns and tectonic relationship with overpressure, it is evident that the development of overpressures is closely related to the intensity of folding and variations in depth to the top of the Bhuban Formation. The Sitakund structure experienced greater uplift than the other three structures studied, and the depth to the top of the Bhuban Formation is therefore at a shallower depth here. Consequently, the overpressured zone is also shallower at Sitakund-1 than at the other three wells.

8. Geological controls of overpressure in the Sitakund anticline

Many sedimentary basins throughout the world exhibit some degree of non-hydrostatic fluid pressure, particularly overpressure (Hunt, 1990; Fertl et al., 1994; Neuzil, 1995; McPherson and Garven, 1999; Xie et al., 2001). The multivariate aspect of geological environment, the uniqueness of every field situation, and most importantly the requirement for establishing a ‘normal’ fluid pressure profile are necessary to establish in order to identify high or abnormal pressure (Bradley, 1975). Normal hydrostatic pressure is a product of depth, gravitational factor and water density. A seal is required for the development of abnormal formation pressure without which fluid pressures would equalize to hydrostatic pressure. Formation of high pressure in the Sitakund structure at shallow depth may be controlled by two factors (Ahmed, 1985; Uddin, 1987): (i) overall structural regimes:overpressures are present within the folded flank areas and (ii) lithology:overpressures are preferentially developed in an over-thickened shale with alternating sandstone.

Consideration of the above two points and the overall geological setting suggest three possible explanations for the development of overpressures in the Bengal basin strata: rapid burial and incomplete dewatering of fine grained sediments (McPherson and Garven, 1999), diagenesis of clay minerals (Colton-Bradly, 1987), and tectonic compression associated with the Indo-Burman Ranges to the east. The east–west tectonic shortening has resulted in tectonic compaction that is opposed to the vertical overburden stresses. Such tectonic compression might be responsible for developing highly compacted shale at very shallow depth, which could act as permanent barrier just above an under compacted shale interval developing overpressure. Overburden stress alone cannot cause abnormally high pressures at such a shallow depth (Bradley, 1975). Furthermore, such stresses cannot explain most of the loss of porosity actually measured in rocks as their depths increase.

Smectite (often called montmorillonite) is an important expandable clay found in sedimentary basins (Colton-Bradly, 1987). Smectite is progressively converted into illite during burial, in the process producing transitional ‘mixed-layer’ clays. The smectite–illite conversion, as discussed by Burst (1969) and Powers (1967), is the main diagenetic change in clay minerals that generates free pore water. Powers’ (1967) theory was that the interlayer water is denser than the pore water, which would result in an increase in fluid pressure as the interlayer water expands during the clay-transformation process. This hypothesis is still supported by others (Osborne and Swarbrick, 1997).There is however, no current consensus on this point, and an alternate scenario is proposed which does not require a difference in fluid density between interlayer water and pore water (Plumley, 1980). Colton-Bradly (1987) calculated clay transformation from the viewpoint of thermodynamic consideration and found that in highly overpressured rock (‘effective stress’ approaching zero), smectite is stable in two or three water-layer complexes at temperature of less than 200 °C, but becomes unstable under conditions of high effective stress. In condition of high effective stress, one water layer is expelled at less than 60 °C; loss of the second layer occurs at 67–81°C, and collapse of the last layer requires a temperature of 172–192 °C (Colton--Bradly, 1987). According to Burst (1969), dehydration occurs at an average temperature of 105 °C. The onset of overpressure in three of the four studied wells is below 3100 m (Table 4) and the temperature at this depth in those wells is around 100 °C (Table 5), which is consistent with the temperature cited by Burst (1969) as the average dehydration temperature of these clay minerals.

In contrast to the other three wells, overpressured strata at Sitakund-1 were first detected at around 1100 m (Fig. 5). At this depth, the temperature recorded (62 °C) is not optimal for the development of overpressure by clay diagenesis (Burst, 1969; Bethke, 1986). A possible explanation is that the Sitakund anticline has developed adjacent to an orogenic belt, similar to the situation in the California Coast Range, where tectonism plays a major role in developing overpressure (Berry, 1973). This may have

Table 5
Temperatures and temperature gradients at four wells analyzed (Ahmed, 1985)

Well	Temperature (°C) at depth				Temperature gradient (°C/100 m) at depth		
	1000 m	2000 m	3000 m	4000 m	1000–2000 m	2000–3000 m	3000–4000 m
Titas	50	68	90	119	1.8	2.2	2.9
Bakhrabad	60	80	103	131	2.0	2.3	2.8
Rashidpur	42	58	–	–	1.6	–	–
Sitakund	60	80	103	–	2.0	2.3	–

exacerbated high fluid pressures produced by probable rapid deposition of the strata that have been folded into the Sitakund anticline (Khan et al., 2002), similar to the situation in the US Gulf Coast where rapid subsidence and sedimentation play a major role in developing overpressure (Dickinson, 1953; Bethke, 1986). Thus sharp uplift and concomitant erosional unroofing might bring the overpressured strata close to the surface at Sitakund.

Strata of the Sitakund anticline contain abundant shaly intervals, and intense folding may have added to development of high fluid pressures. Sitakund lies in the western margin of the folded flank, where east–west shortening produced broad, flat structures like the Semutang, Patiya, and Jaldi structures located in the Chittagong hill tracts (east of Sitakund; Fig. 6). The Sitakund anticline is a large-amplitude, complex and faulted structure in which the core rocks have experienced significant uplift along an east-dipping thrust fault developed at the western flank of the anticline. The anticline is marked by a relative gravity high flanked by gravity minima (Fig. 6). A gravity maximum (greater than −10 mgal) in the axial region of the Sitakund anticline may be attributed to the anomalously shallow occurrence of deeper, well-compacted strata (Bhuban Formation) compared to younger sediments in the adjacent rim synclines. Relative gravity lows are observed in the Patiya and Jaldi anticlines (−30 to −20 mgal), suggesting that these anticlines have lower elevation and are less deformed than the Sitakund structure (Fig. 6). The anticlines of this region of the eastern fold belt developed as buckle folds over a regional detachment during the initial stage of shortening (Sikder and Alam, 2003). Sharp uplift of the Sitakund structure has been suggested to have

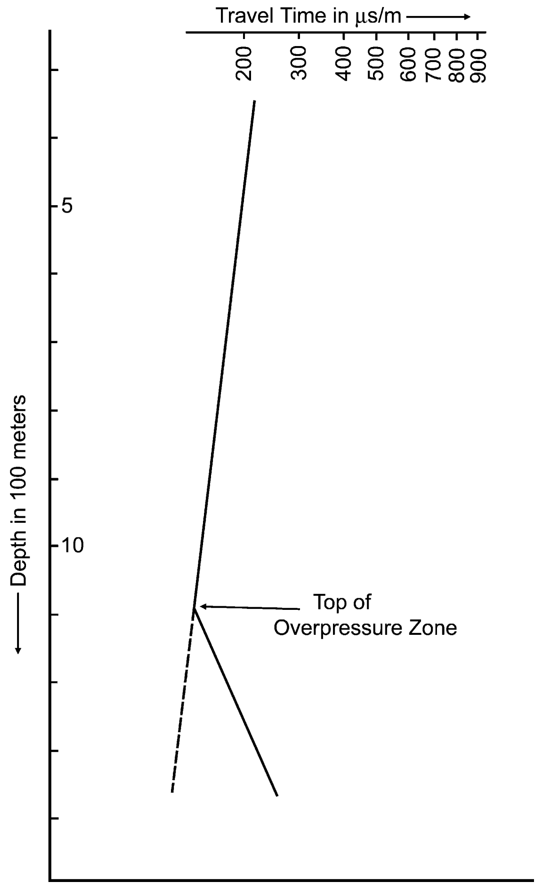


Fig. 5. Sonic velocity data showing top of overpressure zone (at 1100 m depth) in the Sitakund structure (data from check shot, BOGMC).

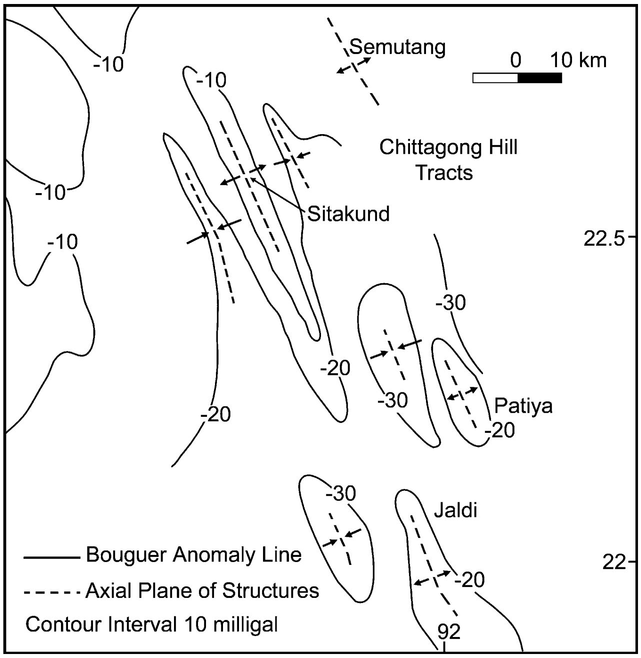


Fig. 6. Bouguer anomaly pattern at Sitakund anticline and adjacent structures. Note that the Sitakund anticline shows a relatively higher gravity value than other anticlines (after Ali and Raghava, 1985).

caused by Shale diapirism (Hoque, 1982; Kononov et al., 1983). Shale flowage in the Sitakund structure reflects occurrence of thick deep-water marine shale deposited in distal portions of prograding Miocene and Oligocene deltas (Hoque, 1982). Development of the Sitakund structure can be divided into pre-faulting and a post-faulting stage (post-Dupi Tila). Faulting brought the eastern flank over the western flank of the Sitakund anticline, initiated by overthrusting from the east; uplift of the crestal region was accentuated by shale diapirism. This combination produced a high and narrow anticline (Fig. 6). Folding was intensified in the hanging wall of the fault due to fault propagation, and the thrust acted as a buttress to fold development by limiting the internal flexural slip (Mitra, 1990; Sikder and Alam, 2003).

A series of landmark papers by research teams at the Shell Petroleum Company, like Dickinson (1953), Hubbert and Rubey (1959), and Hottman and Johnson (1965), established that the primary cause of abnormally high fluid pressures is the compaction of shale during progressive burial. Their ideas have popularly been accepted. Overpressure in the US Gulf Coast is thought to be due to disequilibrium compaction during very rapid sedimentation in the Pleistocene and Holocene (Dickinson, 1953; Rochon, 1967; Jones, 1969), resulting in part from the dehydration of smectite to illite. The depth of onset of this mineral transformation coincides with the overpressured zones (Schmidt, 1973; Freed and Peacor, 1989).

In contrast, fluid overpressure in strata of the California Coast Ranges has been attributed principally to tectonic compression (Berry, 1973). This phenomenon corresponds closely to the situation observed in the Sitakund structure of the southeastern Bengal basin. The Sacramento basin of northern California is located in a transpressional tectonic setting similar to that of the eastern Bengal basin (Alam et al., 2003). Overpressure in the Sacramento basin is observed over a regional scale in an area where sedimentary compaction, geochemical diagenesis and aquathermal pressuring have been considered less dominant over tectonic compression (McPherson and Garven, 1999). Factors that favor generation of overpressure by burial processes over tectonic compaction include, high sedimentation rates, extremely low permeability of confining units, and very high compressibility distribution (McPherson and Garven, 1999). An inverse illitization trend has been reported at Sitakund, which suggests that clay diagenesis is not responsible for development of overpressure at Sitakund (Sikder and Alam, 2003). We infer for the Sitakund structure, tectonic compression has been the dominant factor for overpressure generation. In contrast, for the other three structures penetrated by wells analyzed in our study, sedimentary compaction with subsequent clay diagenesis is the most plausible cause for the high fluid overpressures developed west of the advancing deformation front of the eastern fold belt.

9. Conclusions

Formation velocity data of the four wells analyzed in this study reveal the following observations of the Neogene strata of the eastern Bengal basin:

1. Apparently no sharp velocity contrast at the formation boundaries in any of the studied wells can be seen from sonic log.
2. Fluctuations in intraformational velocity are strongly related to lithological variations, porosity distribution and compaction.
3. Presence of hydrocarbon in an interval has a significant effect on velocity. Gas-bearing zones in the Miocene strata in three wells show 3–7% lower than the average formation velocity in these wells.
4. Velocity–depth distributions at the Titas-11, Bakhrabad-9 and Rashidpur-4 wells show a gradual increase of velocity with depth, reflecting normal trend of velocity increment with depth and compaction.
5. Velocity–depth distribution at the Sitakund structure shows a short interval of initial increase in velocity, followed by a constant decrease with depth, indicating the presence of overpressured and undercompacted shale in the depth range from 3000 to 4000 m.

Overpressure in the Sitakund structure may have been caused by a combination of factors, including strong horizontal deviatoric regional stresses and uplift produced by fault propagation folding and concomitant shale diapirism. Compressive stresses associated with the Indo-Burmese plate convergence to the east are inferred to have contributed the most for the formation of overpressure.

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