Gas leakage from palaeogene reservoir in Assam – a geophysical puzzle

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Reports of gas leakage started coming since the beginning of 2012 from different localities in the Deohal area near the oil township Duliajan, Assam (India). The source was located in a gas reservoir in the Palaeogene sediments (Barail group). Multi-component seismic reflection methods which were highly successful to locate gas bearing zones at depths, were not very effective to locate the same in the shallow subsurface. From different types of electrical surveys conducted, self-potential (SP) method showed the most promising result. Probable SP was sensitive to high electrokinetic potential difference between the leaking and non-leaking zones.

Keywords: Deohal, electrokinetic potential, gas leakage, palaeogene.

GAS leakage, unprecedented in the entire history of oil exploration spanning over 150 years in India, has been haunting Oil India Limited (OIL), the oldest oil company operating in the upper reach of the Brahmaputra valley in Assam (Figure 1 *a*). The leakage zone at present covers an area of $4.8 \times 1.2\ km^2$ and is located at Deohal tea estate, between Tinsukia and Duliajan, two major townships of upper Assam. The area is also between two westward flowing tributaries, the Burhi Dihing and the Dibru, of the Brahmaputra River (Figure 1 *b*). Interestingly, the first oil well in Asia was hand dug to a depth of 102 ft at Naharpung[1] in Assam by the British in 1866 barely 18.5 km away from Deohal. The area is surrounded by highly prolific oil fields and when gas reserves were identified in Deohal in 1975 (drilled in 1976) the well was kept in abeyance for future market. During the first decade of the 21st century, when the gas well was opened up again for exploitation, there was a blowout due to unmanageable high pressure. The well was destroyed in December 2011. Reports of gas leakage started coming from different localities at different distances from the well since the beginning of 2012. Since then the problem became more complex. Putting the area in its regional backdrop, we report the nature of problems developed due to gas leakage, the efforts made to understand the problem, uncertainties with seismic methods and the encouraging results obtained from the electrical methods of geophysical investigations.

Regionally, the Deohal gas field is located in the Upper Assam basin which is a typical example of convergent basin[2–4] as shown by continent scale modelling and analysis of geophysical data sets and seismic studies. This basin is sandwiched between two NE–SW trending frontal thrust belts: in the east by the Naga–Patkai Thrust (NPT) and in the west by the Himalayan Frontal Thrust (HFT) (Figure 1 *b*). The pattern of basin depth variation is usually explained by stronger subduction along the HFT and generation of larger accommodation space[5–7], for fluvial sediment deposition. The northern fringe is closed by the Mishmi Hills, which is in syntaxial relationship[8] with the NPT. The southern fringe is bound by the Mikir Hills which is supposedly the northern extension of Shillong massif[9]. The Naga thrust plays an important role in the distribution of the oil fields in the area as most of the hydrocarbon production in the area is either parallel to, or to the northwest of the Naga thrust. In the basin, mainly Cenozoic sediments are present[10], so it is not very old. A thick cover of alluvium is present on top of these Cenozoic formations. Sedimentation of the basin is controlled by the river Brahmaputra[11] which acts as a valley divider[12,13]. From geomorphic evidences, the role of active tectonics can be clearly recognized[14,15]. The area is replete with prominent impressions of palaeochannels. The course of the palaeochannels to the south of the study area is highly meandering, sometimes taking near right-angled turns and travelling additional paths[15], from their points of initiation in the valley to the points of confluence with the Brahmaputra River. A number of oxbow lakes are present. The nearby Naga thrust and its associated faults have a significant role in determining the tectono-geomorphic status of the area. Following the first-order tectono-geomorphic zonation of the area, the study area comes under upper central uplift[15].

OIL followed a systematic course of studies to understand the gas leakage problem. First, the areas from where gas leakages were reported (Figure 2) were marked on the map. Second, a few shallow wells were drilled to release gases continuously accumulating in the shallow subsurface. The targeted depths were 100 ft. There were gushing fountains of gas release (Figure 2 *b* and *c*) along with huge stacks of sands closely resembling the channel fill deposits (Figure 2 *d*). In the third stage, shallow reflection survey was conducted; initially using hammer as the energy source and then by using very low amount of explosives. Geophones (3C) were used to monitor both the P-waves and S-waves in anticipation that in the gas-bearing zones V_P/V_S ratio would show substantial variation compared to the non-gas bearing zones. In the fourth stage, a massive geochemical study was undertaken in a grid to monitor the amount of Propane gas. Though the results were positive, it was difficult to integrate all the data and generate a reliable model.

Compressed gas at great depths which come up by some means and spread along different porous and

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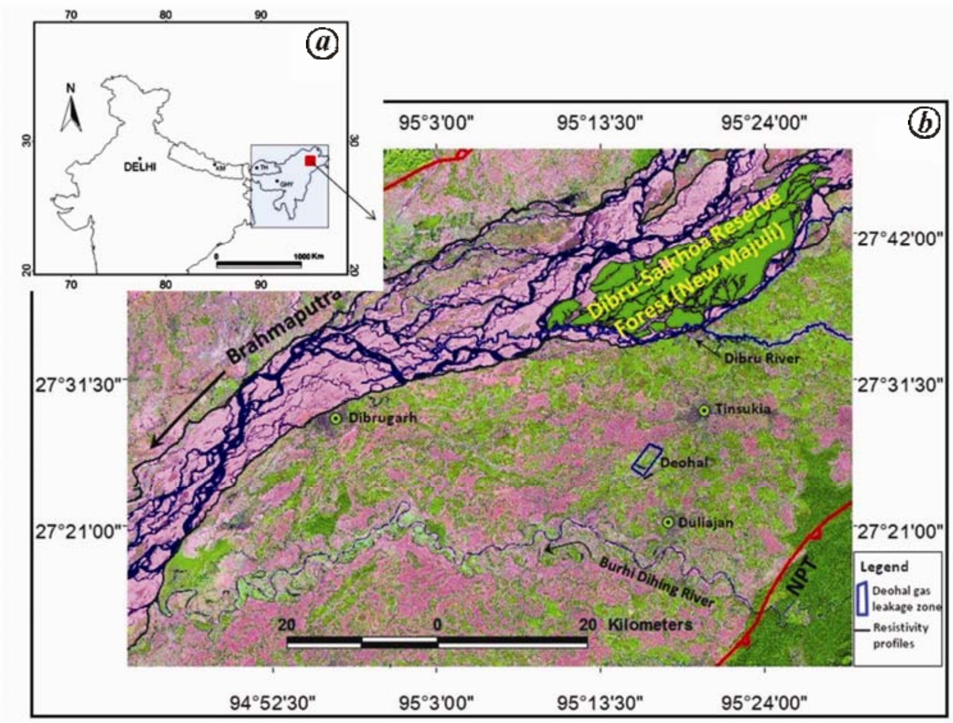

Figure 1. Deohal gas leakage zone in the Brahmaputra valley, Assam. ***a***, The place is located in the extreme NE region of India. ***b***, The gas leakage zone is shown on the IRS-P6-LISS-3 image. Naga Patkai Thrust (NPT) belt lies closer to the area. Distinct palaeochannel marks and the angularities shown by the meandering Burhi Dihing River show the tectonic controls on the fluvial dynamics.

Figure 2. Field photographs showing gas leakage in the Deohal area of upper Assam valley. ***a***, Continuous effervescence showing low pressure gas leakage through a waterlogged area. ***b***, High pressure gas leakage from a shallow well drilled and subsequently deviated through a nallah to avoid accidents. ***c***, Gushing flow of gas charged water through a shallow well drilled near No. 10 labour line of the Deohal tea garden. ***d***, Channel sand dumped at a shallow well drilled to release pressure from the shallow gas pockets and subsequently closed to avoid accidents.

permeable units of rocks, will cause expansion in volume usually proportional to the decreasing litho-static pressure (Figure 3). This causes activation of dormant fractures, fissures and faults. Gas coming out vertically is comparable to that with a high electrical resistivity vertical cylinder.

Three types of geoelectrical surveys[16] were conducted as a part of the pilot project to study the scope of applicability of these simple geophysical techniques.

Two lines, one of 1.2 km length passing through the maximum gas leakage zone and another with no gas leakage zone of identical length were surveyed (Figure 1 *b*). For the gas leakage zone, profiling was done with 50 and 20 m spacing of Wenner array as well as half-Schlumberger array with 20 m station interval. Besides these, six vertical electrical sounding (VES) were done at intervals of 250 m on the same 1.2 km long line with Schlumberger array (Figure 4 *b*). Additionally, near a shallow well from where gas gushed out with clean channel sands (Figure 2 *d*); four short profiles were taken with SP method (having 5 m station interval) (Figure 4 *c*).

Resistivity profiling data-sets despite positive indications (Figure 4 *a*) show that the overall magnitude of anomaly is much lower than anticipated. This might be due to two reasons: (a) data acquisition was during August and September. The moisture content of the soil was high, thereby, considerably lowering soil resistivity; (b) for continuously leaking gas, air is replaced by hydrocarbons; thus, causing only a small increase in resistivity.

Secondly, lateral correlation of the three-layered earth model generated from the interpretation of six numbers of the VES data show considerable thickening of the second layer above which vigorous gas leakage is reported (Figure 4 *b*). For interpreting the VES data, we used IPI2 Win (version 3.1.2c, 17.10.08, 1990–2008). Resistivity Sounding Interpretation software, developed in Moscow State University by A. A. Bobachev.

Thirdly, the SP data-sets suggest a clear zonation with lower values in the middle and higher values in the peripheral part of the study area. On an average, the lower SP values range from –20 to 15 mV. The higher SP values range from >15 to 50 mV. As the SP generation mechanisms are of various types, it is difficult to explain the SP

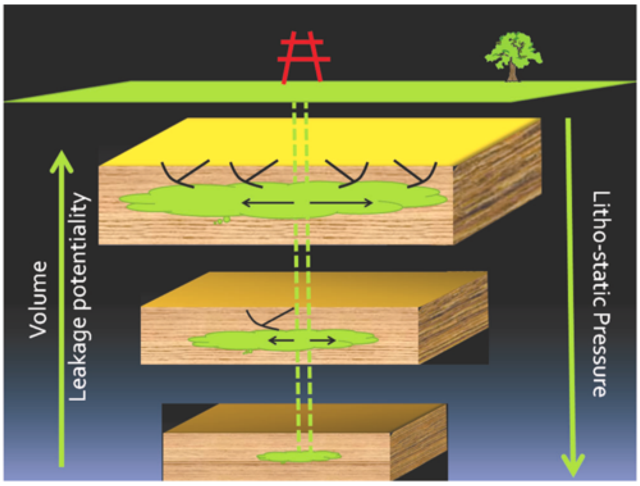

Figure 3. A cartoon showing how condensed gas at depths if leaks continuously, keeps on becoming larger in volume at different shallower horizons activating weaker zones and the horizontal spread of vulnerability also keeps on mounting simultaneously.

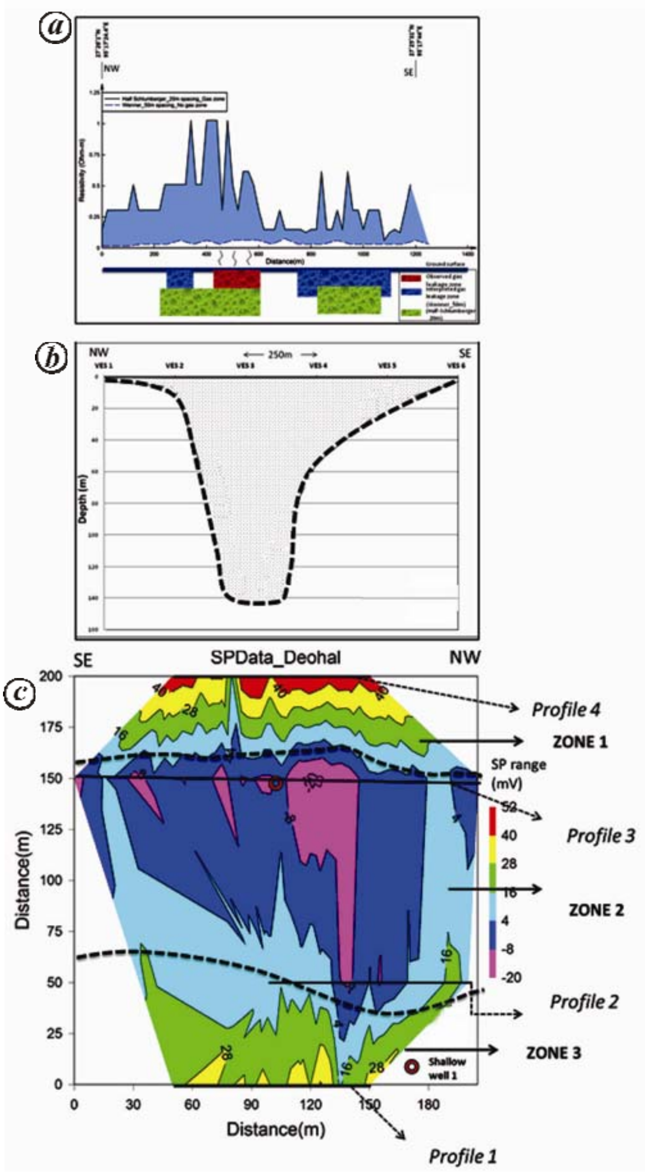

Figure 4. Findings of the electrical survey done in the gas leakage zone at Deohal in the upper Assam valley. ***a***, Profiling results show a fair degree of conformity between the lateral variation in apparent resistivity monitored by the Wenner and half-Schlumberger spreads identifying thereby the gas leaking zones. ***b***, Vertical electrical sounding (VES) done at six different points, when interpreted for a three-layered earth, shows highly variable thickness of the second layer. ***c***, Self potential (SP) survey result shows high negative anomaly over the gas leaking zones which fall within zone 2. This corridor can be distinctly separated from high positive SP anomaly zones having no information of gas leakage so far.

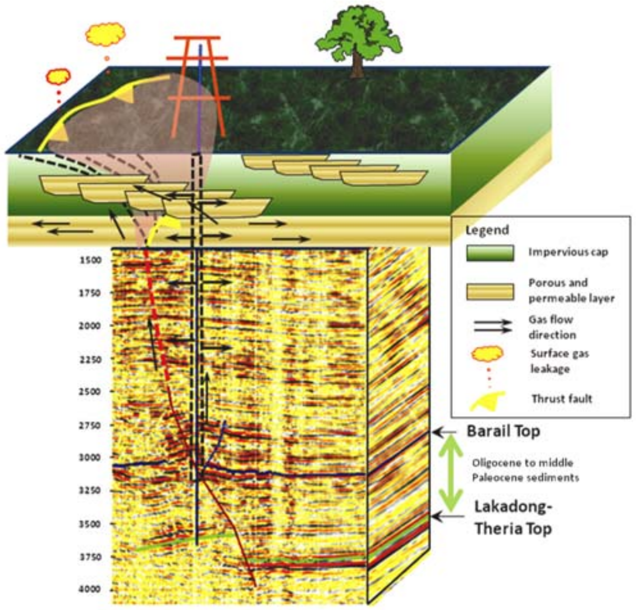

Figure 5. A composite model showing gas leakage taking place through the annulus of the well as well as certain cracked portion of the gas pipe and activated fault plain junction and subsequently follow different paths in the shallow subsurface. The gas reservoir is located within the Oligocene to middle Palaeocene sediments below the Two-Way-Travel-Time (TWTT) of 3100 msec. Seismic data suggests that the fault is blind but there is every possibility that it has activated and propagating upward but the magnitude of throw is not sufficient to be identified by seismic reflection method.

variability. However, the conformity of SP variability with physical surface observations suggests the possibility of linkage between gas leakage and electro-kinetic potential[16] (also known as streaming potential, E_k). Though for surface SP investigations, mineralization potential usually plays the key role; however, for a gas leakage, high electrical resistivity and low viscosity contributing to the sharp increase in E_k.

Our observations are summarized below.

(a) The surface topography of Deohal and adjacent neighbourhood shows that the area is replete with palaeochannel marks suggesting avulsive trend of the major tributary of the Brahmaputra, the Burhi Dihing river (amplitudes of the palaeo-meandering trend matches with the present Burhi Dihing River). Southward shift of the Burhi Dihing River is related to the neo-tectonic[15] activities of the area.

(b) As the area is very close to NPT belt, the influence of the thrusting in a converging basin margin is bound to create neo-thrust fronts which can sometimes be blind as corroborated by seismic data of the area (Figure 5).

(c) The shallow subsurface is not constituted of simple horizontal stratification. This is evident from the results of the VES data as well as the field evidences of the channel sands, gushing out with gas charged water from the shallow wells drilled in the study area.

(d) In the tectonically active areas, the cement bond insulating the gas well and the reservoir may erode considerably with time and the annulus can act as the conduit for the gas under high pressure to escape the reservoir and move upward.

(e) During upward movement, wherever the gas finds porous and permeable beds, it enters and the magnitude of entry is dictated by the formation pressure of the particular litho-unit, as well as the extent of dissolving capacity of the gas in the formation fluid. Shallower the porous and permeable units, greater is the possibility of the gas to escape as shown in Figure 3.

Based on the above observations, a concept model explaining the gas leakage has been prepared (Figure 5). The composite mechanism in the proposed model suggests that the gas reservoir located within the Palaeogene sediments below 3100 msec Two-Way-Travel-Time (TWTT) horizon leaks principally due to anthropogenic intervention, supplemented by neo-tectonic activities. If deeper high pressure gas reservoir gets connected with the shallower horizons, the problem attains a multi-layered dimension. Since the time when gas leaks is not known, the problem cannot be 'removed' and the right approach will be to 'manage' it in a better way and 'stabilize' the situation. This can be done by more precise assessment of leaking zones; mapping of shallow subsurface aquifer and identification of pressure build-up zones. To check the wastage of leaked gas; micro-level gas-pipe networking can be laid to tap the shallow subsurface gas pockets for domestic uses in the locality.

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Groundwater prospects in basaltic formations of Mangaon, Raigad district from electrical resistivity imaging technique

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A two-dimensional resistivity survey was conducted using the Wenner–Schlumberger configuration in the premises of Vijaya Gopal Gandhi Primary and Secondary Ashramshala, Utekhol in Mangaon, Maharashtra. Measurements of three profiles were studied with an aim to delineating the groundwater potential by studying the degree of weathering and fracturing in the weathered profile developed above the basement. The measured resistivity data were inverted using the RES2DINV software. Results from the 2D inverse models of resistivity variation with depth suggest the occurrence of potential aquifer mostly in weathered/fractured zones within the traps or below it. In addition, the resistivity models produced indicate the presence of saturated fracture zone that could be exploited for groundwater extraction. Vertical electrical sounding measurement using the Schlumberger arrangement was conducted at two locations, which substantiate the 2D model results.

Keywords: Aquifer, Deccan Traps, electrical resistivity imaging, Maharashtra.

GROUNDWATER, a natural and renewable resource, plays a crucial role in the socio-economic advancement of any region. The area under study is the hard rock terrain of Deccan Volcanic Province (DVP) in Maharashtra facing a major problem in terms of depletion of groundwater due to various reasons such as sporadic spatial and temporal distribution of precipitation. Thus it is pertinent to identify additional sources of groundwater for exploitation over the Deccan Traps covered region. The geophysical studies were carried out at the Vanavasi Kalyan Ashram, Vijaya Gopal Gandhi Primary and Secondary Ashramshala, Utekhol in Mangaon, Maharashtra. This residential school, which functions with the grant-in-aid from the Government of Maharashtra, is for the children of the local tribes as they are not able to take care of education of their children because of their nomadic and weak financial status. The school caters to about 450 students staying on a water-starved campus. Due to the inadequate supply of pipe-borne and surface water, it is essential to make alternate arrangement of water supply for the students. Attempts were made by other agencies in the past to drill bore wells in the campus, however, two bore wells failed to yield water and the third well yields less water but usually goes dry during summer.

Geophysical studies are regularly employed to assess the groundwater potential of an area. Though such studies provide a fast and cost-effective means to derive subsurface information, however at times, this is plagued with ambiguities and uncertainties in data interpretation[1]. The use of geophysical techniques for groundwater resource mapping has increased radically over the last couple of decades due to rapid strides in instrumentation and advanced numerical modelling solutions[2,3]. Although various geophysical methods exist, electrical resistivity is a widely used technique owing to its operational simplicity and effectiveness in areas with contrasting resistivity, such as between the weathered overburden and the bedrock[4].

One-dimensional (1D) vertical electrical soundings (VES) have been conventionally used to obtain a layered model of the subsurface and the depth to substratum. Nevertheless in many cases, the subsurface cannot judiciously be resolved into horizontal homogeneous layers with lateral resistivity variations as necessary for interpretation. In this study, two-dimensional (2D) electrical resistivity imaging (ERI) and VES surveys were carried out for assaying the depth and thickness of groundwater potential zones and to produce 2D resistivity models of the shallow subsurface in the basaltic hard rock formation within the premises of the school in Mangaon area. A

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