CSIRO PUBLISHING www.publish.csiro.au/journals/eg Copublished paper, please cite all three:
Exploration Geophysics, 2011, **42**, 50–57; *Butsuri-Tansa*, 2011, **64**, 50–57; *Jigu-Mulli-wa-Mulli-Tamsa*, 2011, **14**, 50–57

Overpressure prediction of the Efomeh field using synthetic data, onshore Niger Delta, Nigeria

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Abstract. For effective and accurate prediction of overpressure in the Efomeh field, located in the Niger delta basin of Nigeria, integrated seismic and borehole analyses were undertaken. Normal and abnormal pore pressure zones were delineated based on the principle of normal and deviation from normal velocity trends. The transition between the two trends signifies the top of overpressure. The overpressure tops were picked at regular intervals from seismic data using interval velocities obtained by applying Dix's approximation. The accuracy of the predicted overpressure zone was confirmed from the sonic velocity data of the Efomeh 01 well. The variation to the depth of overpressure between the predicted and observed values was less than 10 m at the Efomeh 01 well location, with confidence of over 99 per cent. The depth map generated shows that the depth distribution to the top of the overpressure zone of the Efomeh field falls within the sub-sea depth range of 2655 ± 2 m (2550 ms) to 3720 ± 2 m (2900 ms). This depth conforms to thick marine shales using the Efomeh 01 composite log. The lower part of the Agbada Formation within the Efomeh field is overpressured and the depth of the top of the overpressure does not follow any time-stratigraphic boundary across the field. Prediction of the top of the overpressure zone within the Efomeh field for potential wells that will total depth beyond 2440 m sub-sea is very important for safer drilling practice as well as the prevention of lost circulation.

Key Words: Efomeh, Niger Delta, overpressure prediction, seismic, synthetic, velocity.

Introduction

When the pressure of a formation fluid exceeds the normal pressure at a given depth, overpressure results. Overpressure is a global phenomenon because it is present in all the basins of the world and is common in rocks of all ages. It occurs at all depths but is especially common at depths below 3000 m (Martinsen, 1994). The concept of overpressure prediction has its roots in the work of Terzaghi, a soil scientist dating back to 1930s. Pennebaker, Hottman and Johnson were the earlier researchers that started the involvement of a geoscientist in pore pressure prediction in their published papers in the 1960s (Bruce, 2002; Sayers et al., 2006). Since then, various authors from different backgrounds have been involved in the development of modern day pore pressure prediction.

For safe and economic drilling, the prior information about the formation pressure is a prerequisite. When overpressure formations are perforated without this knowledge, an uncontrollable influx of fluid from the formation into the borehole could result, with the possibility of blowouts accompanied by fire. There is therefore an essential need for these zones to be identified before drilling, in order to prevent the loss of lives, equipment, wells and the expenditure for remedial solutions. Dutta (2002*a*) stated that 80% of the budget made available for predrilling predictions (about US $1.28 million per well) is always used in dealing with problems associated with shallow water-flow hazards in deep water. If these regions were not identified and all the necessary measures taken into consideration before drilling, it could cost more or result in blowouts which may cause environmental catastrophe. There is also a need to monitor the pore pressure while drilling to avoid environmental disaster such as that recently experienced off the Coast of Louisiana (Gulf of Mexico) where a blowout resulted in the loss of a rig (most modern type) and 11 oil rig workers, and spewed ~4.9 million barrels of crude oil into the Gulf of Mexico. Millions of dollars will be spent for both remediation purposes and the inevitable ensuing lawsuits from different interest groups (LaPorte, 2010; Mufson, 2010; Wikipedia, 2010).

This highlights the need for proper overpressure prediction program before spudding, when, compared to normally pressured sediments at the same depth, abnormally pressured sediments exhibit the following physical properties (Pennebaker, 1968; Dutta, 2002*a*): (1) higher porosities, (2) higher temperatures, (3) lower formation water salinity in sands, (4) lower bulk densities, (5) lower shale resistivities, and (6) lower interval velocity (from seismic data).

Fluid movement within the subsurface is hindered both vertically and horizontally, and various authors have proposed possible mechanisms influencing overpressure. Non-equilibrum compaction as discussed by Rubey and Hubbert (1959), is the primary cause of abnormal pressure in sedimentary basins. It occurs when high-porosity clay is deposited at a rate greater than it can de-water and compact under gravity. Overburden weight increases as a result of increasing sedimentation, and fluid pressure. Burial history of the sediments and the hydraulic communication with neighbouring sand formations are the

 10.1071/EG09040 0812-3985/11/010050

dominant factors (Osborne and Swarbrick, 1997; Dutta, 2002*a*; Wolinsky and Pratson, 2007; Osinowo et al., 2007). Other possible mechanisms are: aquathermal pressuring (Barker, 1972; Bowers, 2002); organic matter transformation (Barker, 1990; Martinsen, 1994); the transformation of smectite to illite (Dutta, 1997, 2002*a*; Mouchet and Mitchell, 1989) and tectonic compression (Rubey and Hubbert, 1959; Fertl, 1976).

Using well known rock physics and seismic principles in seismic detection, Dutta (2002*b*) put forward that only non-equilibrum compaction and transformation of smectite to illite are the two mechanisms that can be detected relatively easily compared to the remaining mechanisms. This study shows the relevance of 3-D seismic data in robust overpressure prediction in the absence of borehole data.

Prediction and detection of overpressure

Geophysical methods are the only means of obtaining subsurface information other than drilling. Good and properly processed seismic data can provide copious hints for detecting abnormally pressured zones and structural information as well. Overpressure zones can also be predicted using the regional geology; this requires a large quantity of data using statistical analyses. Maps are generated and abnormal pressure regions are mapped out, however, new data will be required for making local prediction in the course of exploring a particular basin. Lithology correlation across two or more wells could also be utilised to predict overpressure formations (Mouchet and Mitchell, 1989).

Indicated and measured pressures are the two methods of detecting overpressure in the subsurface. The indicated pressure is derived from geothermal gradients, analysis of logs (sonic, resistivity, conductivity and density), drilling penetration rate, mud weight and so on, and are mostly limited to interpreting pressures in shales. The latter are direct measurements of subsurface pressures that can be obtained from analysis of diverse pressure–time tests (drill stem test, repeat formation tester, formation multi-tester, modular dynamic tester) that are commonly performed on wells (Martinsen, 1994).

During burial, when fluid cannot escape, they support the overburden and prevent compaction of the sediments. The greater the fluid pressure, the lower the compaction and the higher the porosity. Various logging data such as acoustic travel time, bulk density and formation resistivities can be used to estimate porosity, thus the degree of compaction can be ascertained.

The sonic logging is a porosity log that measures the sound wave transit time per foot in a vertical direction in the vicinity of the borehole. Modern sonic logs are borehole compensated devices; these devices reduce errors due to tilt of the sonic tool as well as the spurious effects of borehole size variations. Interval transit time (Δt) is the reciprocal of the longitudinal sonic velocity in the formation.

Numerous empirical relationships between interval velocity and root mean square velocity, porosity (or bulk density), velocity (or transit time) and pore pressure of a given rock type have been documented in the literature. Some of the commonly used relations are stated below.

Relationship of interval velocity and root mean square velocity

The Dix (1955) equation is the most commonly used to estimate interval velocities from the root mean square velocity and this is stated as below:

$$V_n^2 = \left[\frac{(V_{Lrms}^2 \times T_L - V_{Urms}^2 \times T_U)}{T_L - T_U}\right], \quad (1)$$

where: V_n = interval velocity, T_L = travel time to the lower interface, T_U = travel time to the upper interface, V_L = root mean square velocity to the lower interface, and V_U = root mean square velocity to the upper interface.

Relationship of velocity and porosity

The two commonly used relationships (equations 2 and 3) for sonic logs are:

1. The Pickett-type equation (Pickett, 1963):

$$\Delta t = B_0 + C_0\phi, \quad (2)$$

where Δt is the sonic interval transit time (usually expressed in microseconds per foot), ϕ is the porosity, B_0 and C_0 are lithology-dependent constants.

2. The Gardner et al. (1974) equation:

$$\rho_b = d' V^{e'}, \quad (3)$$

where ρ_b is the bulk density, V is interval velocity and d' and e' are lithology-dependent constants.

Relationship of pore pressure and seismic velocity

Pore pressure could be predicted from elastic wave velocity using the relationship developed by Pennebaker 1968 (assuming elastic wave velocity is a function only of the vertical effective stress σ) and is defined by:

$$\sigma = s - p \quad (4)$$

where p is pore pressure and S is the total vertical stress.

The pore pressure can be predicted from equation 4 if the vertical component of the total stress S is known and the seismic velocity has been determined, given the relation between the seismic interval velocity and the vertical differential stress:

$$\mathrm{S}(z) = \mathrm{g}\int_0^z \rho(z)dz, \quad (5)$$

where g is the acceleration due to gravity, and $\rho(z)$ is the density at depth z below the surface.

The determination of effective stress that accounts for both undercompaction and fluid expansion through definition of the unloading curve was proposed by Bowers (1995). The method is based on the fact that during compaction (loading) a velocity increase occurs. During the unloading process, the effective stress is reduced due to fluid expansion. Fluid expansion zones are characterised as zones of reversal in velocity trend.

For normally pressured sediments, the relation between the effective stress and velocity as suggested by Bowers is:

$$V = V_0 + A\sigma^B, \quad (6)$$

where V_0 is the velocity of unconsolidated fluid-saturated sediments, A and B are the variation in velocity with increasing effective stress, this could be derived from offset well data.

The effective stress can be determined from the following equation:

$$\sigma = \left[\frac{(V - V_0)}{A}\right]^{\frac{1}{B}}. \quad (7)$$

The pore pressure can then be calculated from equation 4.

Geology of the study area

The Efomeh field is located in the western part of the Niger Delta sedimentary basin of Nigeria (Figure 1). The field is fairly well developed with four wells drilled, from which one well penetrates the overpressure zone while the rest terminate within normal compaction zone. Figure 2 is the base map of the Efomeh field showing the well locations and some of the stacking velocity points. The figure exhibits a typical example of structure, stratigraphy and geopressure development observed in many onshore fields of the basin. The three Formations present are the Benin Formation (made up of massive sands and gravels) which unconformably overlies the Agbada Formation and the basal Akata Formation. The Agbada Formation is comprised of alternating sands and shale of various proportions. The Akata Formation is made up of mainly marine shales and where associated sandstone units are generally lowstand turbidite fans deposited in a deep marine setting (Short and Stauble, 1967; Weber and Daukoro, 1975; Reijers et al., 1997). Velocity survey data in Pliocene and Miocene at the four wells and 85 seismic data points were used.

Materials and method of study

Four well logs (comprised of gamma ray and sonic), checkshot and stacking velocity (3-D) data were used for delineating the top of under compacted and overpressure zones from the normal compaction zone. The data were then assembled in the form of velocity-depth profiles for further analysis.

Well data (sonic logs) were used to identify the upper boundary of the under compacted zone. The boundary was defined by an abrupt increase in sonic travel time and this was associated with the withholding of pore water in the under compacted shale. A total of four velocity-depth plots were generated, all the four wells exhibiting a similar trend within the normal compaction zone. Three of the wells terminate within this zone. The wells were fairly evenly distributed over the entire field as seen on the base map (see Figure 2) thus all the data were given equal priority.

The depth to the top boundary of the overpressure zone was delineated using stacking velocity data from the 3D-seismic data. Velocity-depth profiles were generated at a distance of between 50 and 100 m along the seismic line.

The interval velocities estimated were plotted against the sub-sea depth using Microsoft Excel. The top of the overpressure zone is defined by a sharp drop in seismic velocities and the velocity profiles show two linear trends. The map showing the top of the overpressure zone of the field was generated using time, while the depth equivalent was contoured using the conversion of checkshot data available for the field.

For lithology identification, gamma ray logs were adopted, since the lithology of the Niger Delta consists of sequences of sand and shale.

Results and discussion

The depth to the top of overpressure zone in the Efomeh field was delineated using interval velocity data generated from seismic data in compliment with borehole information (gamma ray, sonic and resistivity logs) in this research work. The overpressure tops in time and depth were established at different location points, based on the principle of normal velocity trends and departure from it, signifying the abnormal velocity trends. The interface between the normal velocity and low velocity layer is the top of overpressure.

Fig. 1. Map of the Niger Delta, Nigeria, showing the Efomeh field.

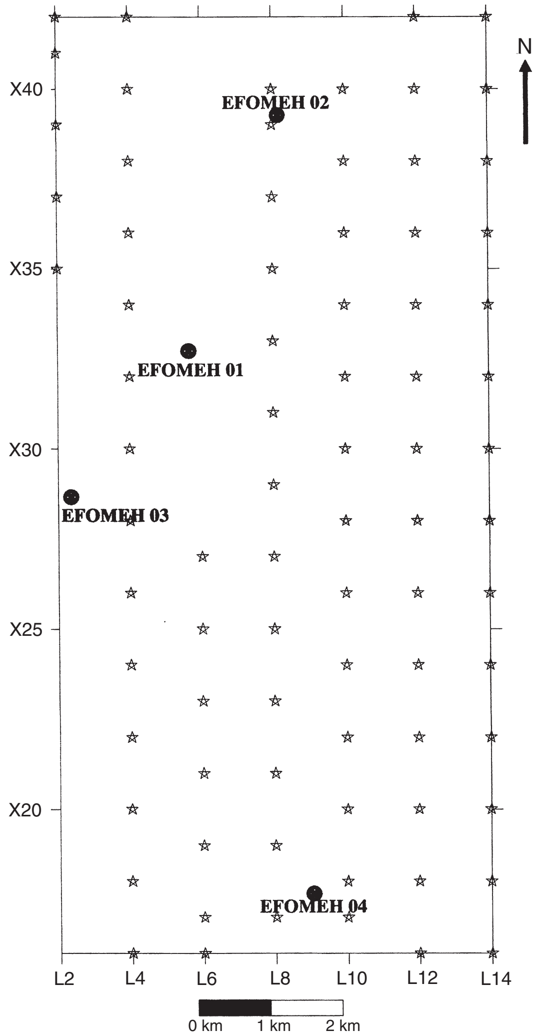

Fig. 2. The base map of the Efomeh field showing the well and some stacking velocity locations.

Trend curves

Velocity-depth curves from seismic data

Two distinct trends were obtained in all curves; normal trend (positive gradient) and the reverse from the normal trend (negative gradient). For the normal velocity trends, the rate of change of velocity increases with depth. The interface between the normal and the abnormal velocity trend signifies the top of overpressure and this varies significantly in the study area. The shallowest depth value of 2527 ± 2 m was obtained on line 10 shot point 23 (L10 X 23) while the deepest part was observed on line 14 shot point 16 (L14 X 16) with depth value 3750 ± 2 m.

Two different trends were also observed within the abnormal velocity trend:

1. Decreased velocity with depth and
2. Constant velocity with depth. Figures 3*a* and 3*b* are some of the profiles obtained in the Efomeh field where the first trend is the normal velocity profile while the second trend is the abnormal velocity profile.

Efomeh 01 velocity-depth profile

Two discrete trends similar to the one obtained in stacking velocity data were also observed in all the velocity-depth profiles generated, the normal velocity trend and deviation from normal. The gradual increase of velocity with depth is due to an increase in compaction to a depth of 2961 ± 2 m as shown in Figure 4. Further increase in depth leads to reduction of velocity within the abnormal velocity zone. The interface between the normal and abnormal velocity curve at depth 2961 ± 2 m signifies the top of the under compacted zone which conforms to the top of a thick mass of shale on the Efomeh 01 well. The lithology log shows that the Efomeh 01 well is comprised of alternating shale and sandstones. The presence of this thick mass shale interval (towards the base) increases the likelihood of undercompaction and reduces the density of shale. This will eventually result in a reverse

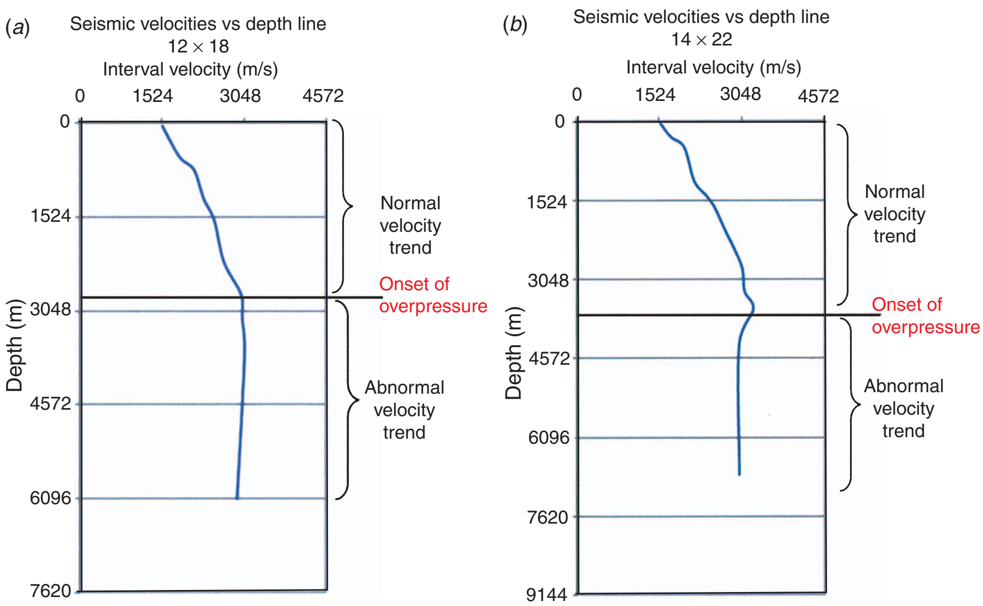

Fig. 3. (*a*) Velocity versus depth profile: gradual decrease in velocity with depth in the overpressure zone. (*b*) Velocity versus depth profile: relatively constant velocity with depth in the overpressure zone.

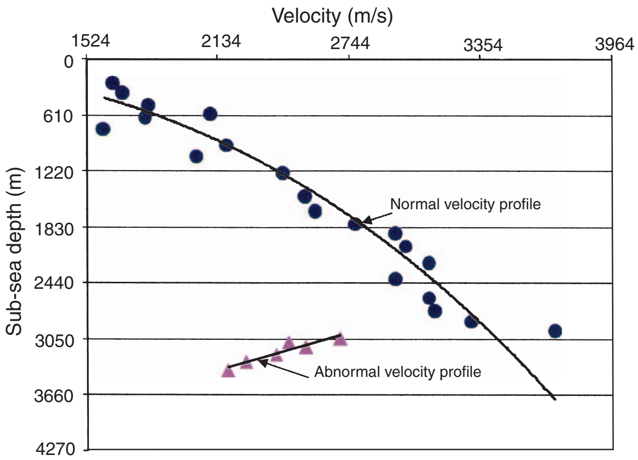

Fig. 4. Plot of velocity versus depth of the Efomeh 01 well.

velocity-depth trend within the depth range of ~2961 ± 2 to 3440 m (depth to the base of the well). Table 1 shows the lithologic percentage of the Efomeh 01 well.

Table 1. Lithologic percentage of Efomeh 01 well.

Interval (m)	Lithology (%)	
	Sandstone	Mud/Shale
304–609	90	10
609–914	86	14
914–1219	95	5
1219–1524	95	5
1524–1829	90	10
1829–2134	80	20
2134–2438	50	50
2438–2743	55	45
2743–3048	25	75
3048–3353	5	95
3353–3440	2	98

Depth and time maps

The top of the overpressure zone was predicted using surface seismic data collected at location points as shown on the base map of the Efomeh field. It shows variation in depth, with the shallowest depth to the top of overpressure zone obtained at the Southern part of the study area forming a closure labelled A1 in Figure 5*b* with contour value –2655 m and the equivalent time

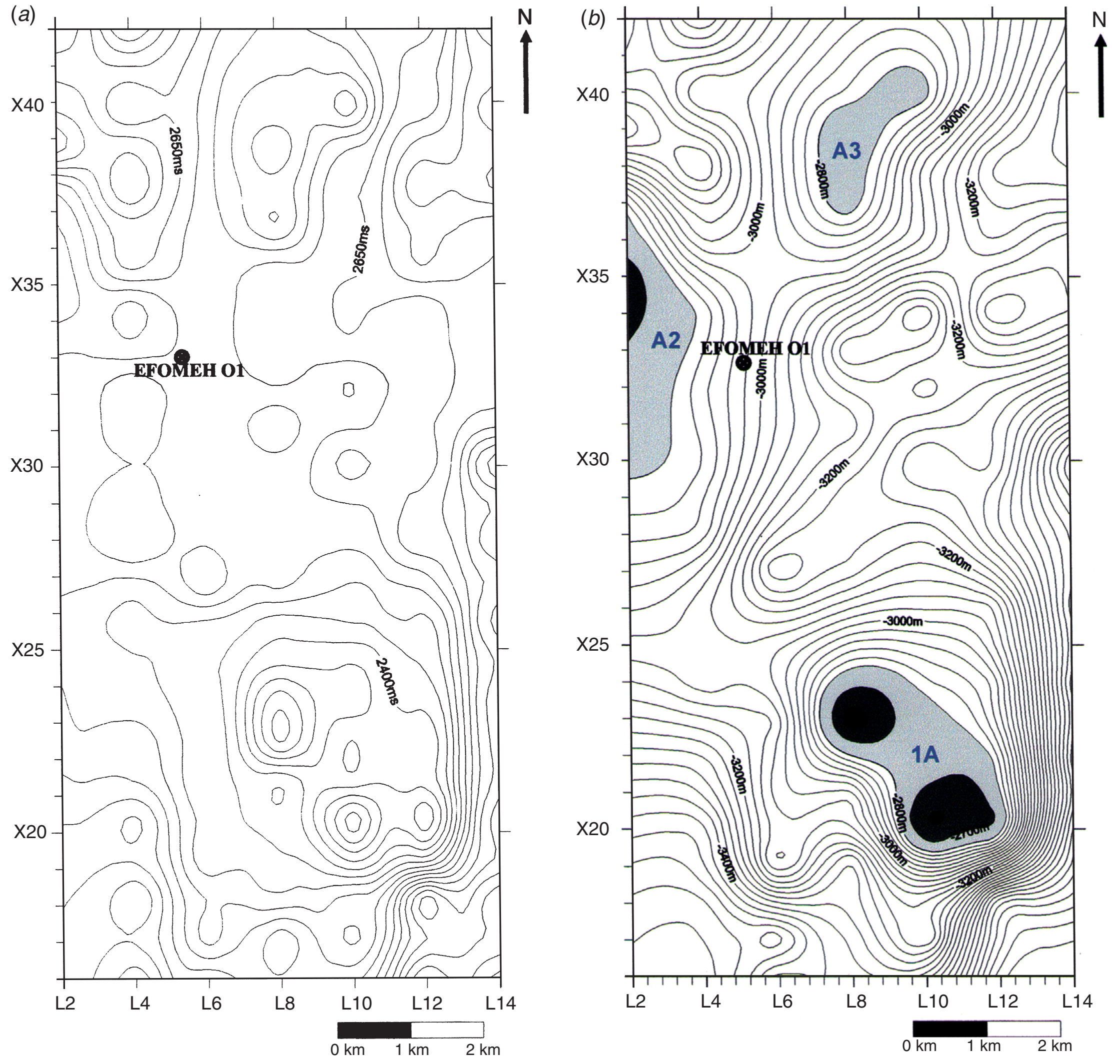

Fig. 5. (*a*) Efomeh field: time map of the top of the overpressure zone. (*b*) Efomeh field: the depth map of the top of the overpressure zone.

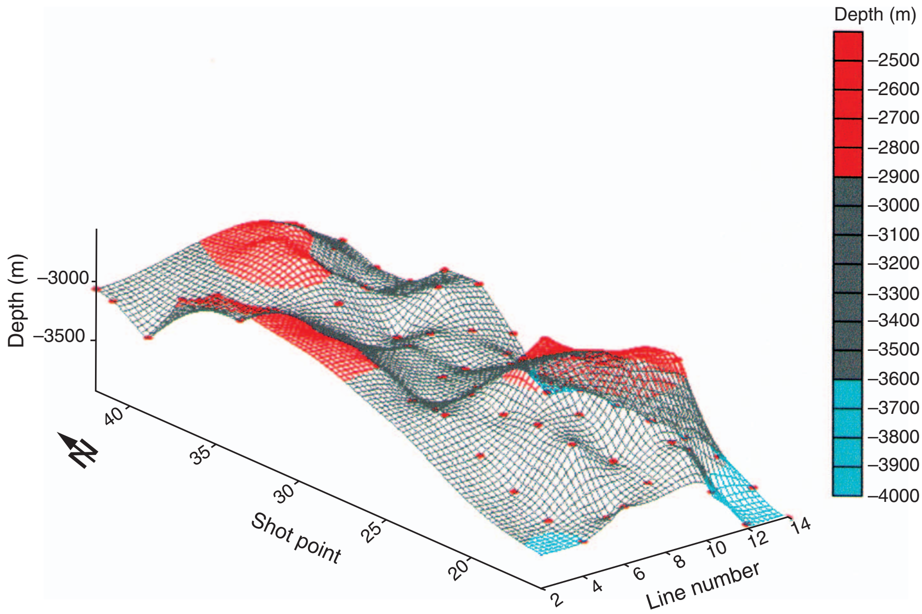

Fig. 6. Efomeh field: the depth web of the top of the overpressure zone.

of 2550 ms on the time map (Figure 5*a*). Other shallow depths are labelled A2 and A3 on the depth map. The depth to the overpressure zone at the Efomeh 01 well location is –2955 m (Figure 5*b*).

The deepest depth to the top of overpressure zone was observed at the Eastern part of the mapped area with a contour value of –3720 m (2900 ms). This shows that the top of overpressure varies from one location to another in the study area, and this does not follow a regular pattern.

The predicted top of overpressure using well processed 3D seismic data at the Efomeh 01 location point is 2955 $\pm$ 2 m and the observed value using the sonic log is estimated at 2961 $\pm$ 2 m. This shows a difference of less than 10 m and the correlation coefficient of between 0.9973 and 0.9986 in the Efomeh field, which is indicative of a confidence of over 99 percent in the prediction of the overpressure.

A contour interval of 50 ms and 40 m was adopted on the overpressure time and depth maps respectively. Figure 6 is the depth web of the top of overpressure zone in Efomeh field, it gives the 3-D pictorial view of the study area, and the 'highs' (red) indicate a shallow depth of the overpressure zone, that is, overpressure will be encountered earlier, while the 'lows' (light blue) indicate relatively deeper depth to the overpressure zone.

Conclusions

Accurate prediction of overpressure zone is vital in hydrocarbon exploration and is especially important when you are drilling beyond the 2440 $\pm$ 2 m sub-sea in the Efomeh field of the Niger Delta complex. The delineation of depth to the top of the under compacted zone of the Efomeh field was undertaken using sonic log, while surface seismic data was used to determine the depth to the top of overpressure zone. The top of the under compacted zone is defined as an increase in sonic travel time and this is observed at a depth of 2961 $\pm$ 2 m sub-sea. The lower part of the Agbada Formation within the Efomeh field is over pressured. This was established by departure from normal velocity trend. The top of the overpressure zone varies within the field and negative gradients are associated with this phenomenon. The difference between the top of under compacted zone observed using the Efomeh 01 well, and the top of overpressure zone predicted at the Efomeh 01 well location (2955 $\pm$ 2 m) using well processed seismic data, was estimated to be less than 10 m in the Efomeh field. Hence, in the absence of log data, well processed seismic data can predict the top of the overpressure zone, thereby reducing the effect of blowouts and other hazards associated with the drilling into overpressure without proper programs.

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Manuscript received 10 September 2009; accepted 17 November 2010.

数値シミュレーションによる異常高圧層の予測
ー　ナイジェリアのニジェール川三角州、Efomeh フィールドの例

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要　旨：　ニジェールデルタ盆地の Efomer ガス・油田の異常高圧を効率よく、正確に予測するために地震探査と孔井探査を統合して解析した。地層圧力の正常な部位と異常な部位を、速度トレンドからの相違に基づいて同定した。これらの間の遷移部分が、異常高圧層の上端を表す。Dix 方程式を使って、過剰地層圧力部の上端を、地震探査の測線上で等間隔に推定した。

この異常高圧層上端の予測精度を Efomeh 01 号井の音波検層による音波速度で確認した。Efomeh 01 号井での過剰地層圧力部の上端の予測深度と実際の深度との相違は 99%以上の信頼度で 10m 以内であった。ここで得られた深度図には 2655 ± 2 m (2550 ms) から 3720 ± 2 m (2900 ms)までの範囲で異常高圧層上端の深さが示されている。この深度は Efomeh 01 号井の総合検層図の海成性頁岩の厚さと一致する。Efomeh ガス・油田の Agbada 層の一部は異常高圧層で、そこでは異常高圧層の上端の深さは時系列層序の境界とは一致しない。

Efomeh ガス・油田の掘削候補地点での海面下 2440m を越える深度では、異常高圧層の上端の予測は掘削作業の安全と循環泥水の逸水などの掘削障害を避けるために大変重要である。

キーワード：Efomeh，ニジェール川三角州，異常高圧層予測，地震探査，数値シミュレーション，地震波速度

합성탄성파 기록을 이용한 나이지리아의 나이저 삼각주 해안 에포메(Efomeh) 지역의 이상고압 예측

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요 약： 나이지리아의 나이저 삼각주 분지에 위치한 에포메 지역의 이상고압을 효과적이고 정확하게 예측하기 위해 탄성파 및 시추공 자료를 종합적으로 해석하였다. 정상 공극압 영역과 및 이상 공극압 영역을 평균 및 편차의 원리를 기초로 하여 평균속도 경향성으로부터 도시하였다. 두 경향성 사이의 전이는 이상고압영역의 상부경계면을 나타낸다. Dix 근사식에 의해 구해진 구간속도를 이용하여 탄성파자료로부터 이상고압 영역의 상부경계면을 일정한 간격에서 발췌하였다. 예측된 이상고압 영역의 정확도는 에포메(Efomeh)01 시추공의 음파검층 자료를 통해 확인되었다. 이상고압 심도의 예측값과 관측값 사이의 편차는 에포메(Efomeh)01 시추공에서는 10m 이하 이며, 99퍼센트 이상의 신뢰도를 갖는다. 이렇게 생성된 심도 단면도는 에포메 지역 이상고압 영역의 상부 경계면이 해수면 아래 2655 ± 2 m (2550 ms) to 3720 ± 2 m (2900 ms)사이에 분포하고 있음을 보여준다. 이 심도는 에포메01 시추공의 지층평가를 이용하면, 두꺼운 해양성 셰일층에 해당한다. 에포메 지역 내의 아그바다층(Agbada Formation)의 하부는 과도한 압력을 받고 있으며, 이상고압의 상부 심도는 조사 지역에 걸쳐 항상 층서경계와 부합되는 것은 아니다. 에포메 지역에 향후 설치할 심도 2440 m 이상 시추공들에서의 이상고압 영역 상부 경계면 예측은 순환손실의 방지와 보다 안전한 시추를 위해 매우 중요한 정보이다.

주요어：에포메，나이저 삼각주，이상고압 예측，탄성파탐사，합성탄성파，탄성파속도