VELOCITY ANISOTROPY IN THE NIGER DELTA SEDIMENTS DERIVED FROM GEOPHYSICAL LOGS

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Abstract

An investigation of velocity anisotropy was carried out using density and dipole sonic logs comprising compressional and shear interval transit times, acquired between 2000 and 2002 in some well-spaced petroleum wells in the western part of the Niger Delta. The anisotropy was modeled by deriving stiffness constants at some depths in each well and relating them to the anisotropic parameters, ε, δ *and* γ*. The study shows that the Niger Delta sediments are clearly anisotropic; the values being higher in shales than in sands. Average P-wave anisotropy is concentrated between -3.5% and 5.7% while near-vertical P-wave anisotropy is concentrated between -3.5% and 4.9%. The localized S-wave anisotropy is higher and concentrates between -4.3% and 7.4%. Seismic velocities decrease and increase laterally and vertically, respectively, towards the coast. These variations are attributable to the lateral and vertical changes in the degrees of compaction coastward and reduction in porosity with depth. Three zones of steep, moderate and slow velocity gradients, respectively, have been identified in the study area. The velocities generally decrease SW towards the coastline and also towards the southern part of the delta. This decrease can be attributed to a decrease in sediment compaction and the presence of synsedimentary structures, clay diapirs and other structural features which become more pronounced coastward.*

***Keywords**: Intrinsic velocity anisotropy, Niger Delta, Thomsen's parameters, vertical transverse isotropy (VTI)*

Introduction

In seismology, a layer is anisotropic if seismic waves propagate through it at different velocities in different directions. Sedimentary rocks possess some degree of intrinsic velocity anisotropy (Jones and Wang, 1981, Venik and Nur, 1992, Johnston and Christenson, 1995, Jacobson and Johansen, 2000, Wang, 2002 and Liu, 2005) caused by the presence of shales or preferential orientation of clay minerals and fine layering of the sediments. Thus, when seismic waves propagate through a stack of earth layering, such as a sequence of sands and shales, they tend to propagate more quickly along the bedding than perpendicular to the layer boundaries. As a result, seismically derived velocities tend to be faster than vertical (well) velocities. If the amount of velocity anisotropy is not quantified and accounted for in seismic processing and imaging algorithms, subsurface images will be mispositioned in both depth and lateral location (Vestrum *et al.*, 1999; Isaac and Lawton, 1999 and Lawton *et al.*, 2001).

Alkhalifah and Tsvankin (1995) explored the feasibility of inversion of anisotropy parameters solely from surface seismic data by estimating η (eta) and $V_{nmol}(0)$. The drawback of this method is that it requires a layer with at least two apparent dips. Successful estimation of also depends on the degree of moveout from the hyperbola. Velocity anisotropy measurements have also been carried out in the laboratory on shales or clay-bearing samples (Jones and Wang, 1981; Tosaya, 1982; Banik, 1984, Vernik and Nur, 1992). Wang (2002) experimentally studied in detail the anisotropy of rocks from different oil fields in the world, and showed that intrinsic anisotropy in sediments vary from 6% to 33% for P-waves and 2% to 55% for S-waves, with shales generally having high anisotropy than sands and carbonates.

Alexandrov and Ryzhov (1961) calculated Thomsen's, $,\varepsilon, \delta$ *and* γ and parameters from a single-crystal elastic constants of sediments and obtained average value of 1.24%, -0.39% for δ and 6.12% for γ respectively. Katahara (1996) also used laboratory measurements to calculate an average P-wave anisotropy of 1.14%, near-vertical P-wave anisotropy of between -0.39% and 0.08% and between 1.75% and 2.49% for S-wave anisotropy. Laboratory measurements of velocity anisotropy are carried out under 'room dry' or 'vacuum dry' conditions, leaving unconstrained key parameters of in-situ conditions.

The aim of the study was to understand how seismic velocities vary laterally and vertically within the sediments, and obtain a trending of the velocities. In this study, an effort was made to directly compute velocity anisotropy at different depths within each of 11 well-spaced petroleum wells in the western Niger Delta from density and dipole sonic log data. We derived the five independent components of the elastic stiffness tensor with the assumption of vertical transverse isotropy, and then related them parameters to the Thomsen's anisotropic parameters.

Geology of the Study Area

The Niger delta is a sedimentary basin formed by the built out and up of sediments over a transitional crustal tract that was developed by rift faulting during the Precambrian with outlines controlled by deep seated faults associated with the rifting (Weber,1971). The delta started as separate depocentres in the BendeAmeki area, east of the delta and in the Anambra shelf, west of the delta in the midlate Eocene (Hospers, 1965). The two depocenters coalesced to form a single united Niger delta sedimentary basin in the late Miocene to date. The delta has a tripartite lithostrgraphic succession in which a regressive sequence is properly defined. The delta sequence is mainly a sequence of over pressurized marine clays (Akata Formation) overlain by a paralic sediment sequence (Agbada Formation), that is predominantly sandy and shaly at the top and bottom, respectively. These two formations were finally capped by continental gravels and sands (Benin Formation). Of these three formations, the Agbada Formation constitutes the main reservoir for hydrocarbon in the Niger delta (Short and Stauble, 1967).

The maximum thickness of the sediments may be of the order of 12,192m to the basement. The known thickness of the continental sands is variable but generally exceeds 6000ft 1,828.8m, while that of the paralic sequence is 3048m to 4572m at the center of the delta. The Akata Formation exceeds 1,219.2m (Merki, 1972). These sediments thicken progressively towards the continental shelf and accumulated rather fast resulting in faulting contemporaneous with deposition. The delta is characterized by synsedimentary faulting (growth faults) within the delta pile and lateral flowage of prodelta sediments (clay diapirs). There is evidence that only the Akata and Agbada Formations are so deformed by these structures, the Benin Formation being only slightly tilted regionally down (Weber, 1971)

Basic Data

The data used for this study include a set of density and dipole sonic logs comprising compressional and shear interval transit times, acquired between 2000 and 2002 in 11 well-spaced petroleum wells in the

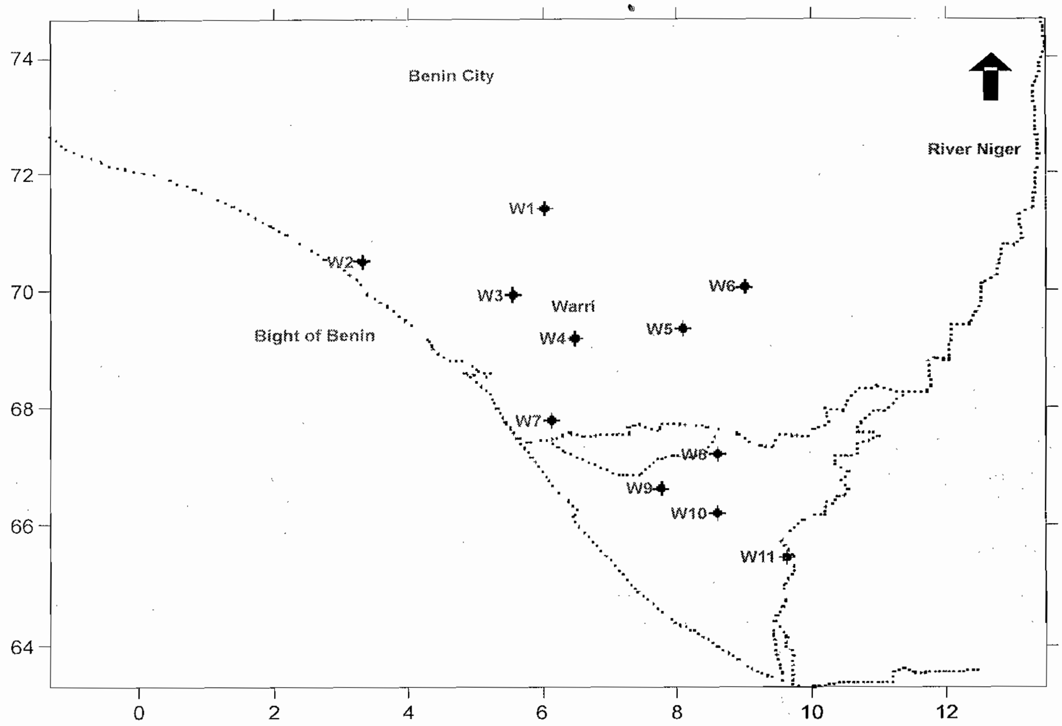


Fig.1: Map of the Western Niger Delta showing approximate well locations.

Niger Delta (Fig. 1).

The logs were rasterized, digitized at 0.15m sample rate, and resampled to have log digit at every 0.61m along the entire depth of each well. Using equations 1 and 2, the interval transit times were transformed into vertical P-wave and S-wave velocity, respectively, while Equation 3 was used to transform the density log to porosity log in each well.

$$v_p = \frac{1000000 * 0.305}{\Delta_{tp}} \tag{1}$$

$$v_s = \frac{1000000 * 0.305}{\Delta_{ts}} \tag{2}$$

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \tag{3}$$

where,

and Δ_{ts} are the interval transit times recorded by the compressional and shear sonic logs respectively.

ρ_{ma}= density of rock matrix, taken to be 2.65 g/cc.

ρ_b = formation bulk density recoded by density tool, and

P_f= density of fluid, taken to be 1.08 g/cc.

Velocity Anisotropy Modeling Procedure

The Niger Delta sediments are composed of a sequence of predominantly sand and shale layers. As a result, we assume that seismic anisotropy in the Niger Delta is transversely isotropic with vertical axis of symmetry (VTI). Velocity anisotropy in VTI media can be modeled by defining the parameters, ε, δ and γ which quantify the degree of anisotropy of compressional and shear waves (Cholah and Schmitt, 2003; Jones et al., 2003, Wang, 2002; Berrymann *et. al.*, 1999; Kabaili and Schmitt, 1995; Thomsen, 1986). These parameters are given by:

$$\varepsilon = \frac{c_{11} - c_{33}}{2c_{33}} \qquad (4)$$

$$\delta = \frac{(c_{13} + c_{44})^2 - (c_{33} - c_{44})^2}{2c_{33}(c_{33} - c_{44})} \qquad (5)$$

$$\gamma = \frac{c_{66} - c_{44}}{2c_{44}} \qquad (6)$$

where C_{11}, C_{13}, C_{33}, C_{44} and C_{66} are elastic stiffness tensors, and the parameters ε δ and γ denote P-wave anisotropy, near-vertical P-wave anisotropy and Shear-wave anisotropy respectively.

Following Backus (1962), Brittan *et al.* (1995), we define the parameters **M, R, S** and **T** in terms of the Lame parameters λ and μ, the volume fraction ϕ and the ratio θ of compressional and shear velocities in a medium, for a stack of two layers. The parameter **M** for a stack of two layers is governed by the porosity of the upper layer, and the shear moduli of each layer; R is influenced by the porosity of the upper layer, bulk and shear moduli of the layers; **S** is a dimensionless parameter which is influenced by porosity, Vs to Vp ratio and the shear moduli of the layers; and **T** is a parameter defined in terms of porosity and velocity ratio only. We relate these parameters to the stiffness constants as follows:

$$c_{11} = 4M - 4S + \frac{(1-2T)^2}{R} \qquad (7)$$

$$c_{13} = \frac{1-2T}{\mathrm{R}} \qquad (8)$$

$$c_{33} = \lambda + 2\mu \qquad (9)$$

$$c_{44} = \mu \qquad (10)$$

$$c_{66} = M \qquad (11)$$

where,

$$M = \phi\mu_1 + (1-\phi)\mu_2 \qquad (12)$$

$$R = \frac{\phi}{(\lambda_1 + 2\mu_1)} + \frac{(1-\phi)}{(\lambda_2 + 2\mu_2)} \qquad (13)$$

$$S = \phi\theta_1\mu_1 + (1-\phi)\theta_2\mu_2 \qquad (14)$$

$$T = \phi\theta_1 + (1-\phi)\theta_2 \qquad (15)$$

$$\theta = \left(\frac{vs}{vp}\right)^2 \qquad (16)$$

where λ denotes the Lame's constant and μ denotes the shear modulus of the medium, respectively, and ϕ is the porosity.

To become suitable for this study, we modified the above set of equations into the form:

$$c_{11}{}^{i} = 4c_{66}{}^{i} - 4\left[\phi^{i}\theta^{i}c_{44}{}^{i} + (1-\phi^{i})\theta^{i+1}c_{44}{}^{i+1}\right] + \frac{\left[1-2\left(\phi^{i}\theta^{i} + (1-\phi^{i})\theta^{i+1}\right)\right]^2}{\left[\frac{\phi^{i}}{c_{33}{}^{i}} + \frac{1-\phi^{i}}{c_{33}{}^{i+1}}\right]} \qquad (17)$$

$$c_{33}{}^{i} = \frac{1-2T^{i}}{R^{i}} \qquad (18)$$

$$c_{33}{}^{i} = \rho^{i}vp^{2i} \qquad (19)$$

$$c_{44}{}^{i} = \rho^{i}vs^{2i} \qquad (20)$$

$$c_{66}{}^{i} = \phi^{i}c_{44}{}^{i} + (1-\phi^{i})c_{44}{}^{i+1} \qquad (21)$$

with:

$$\phi^{i} = \left(\frac{vs^{i}}{vp^{i}}\right)^2, \quad \phi^{i+1} = \left(\frac{vs^{i+1}}{vp^{i+1}}\right)^2 \qquad (22)$$

where i and $i+1$ represent the present depth and the next depth level, respectively.

Using equn. 18-22, we derived stiffness constants at every 0.61m along hole for each well, and using equations 4- 6, we computed the anisotropy parameters at these depth levels.

Discussion of the Results

Based on the computed results, we investigated how seismic velocities vary vertically and laterally within the Niger Delta.

The variation of velocities with depth shows a generally moderately scattered trend of increasing seismic velocity. This is also confirmed by the dipole sonic logs. This increase may be due to compaction which also causes a general reduction in porosity with depth. Three distinct zones of high, moderate and low velocity gradient have been identified for the Niger Delta sediments (Fig. 2). The central part of the study area has a steep increase in velocity with depth, and this decreases SW towards the coastline and in the NS direction. P-wave velocity generally varies vertically from 2,100 m/s to 4,000 m/s in the central part, and from 2,400 m/s to about 3,500 m/s in the sediments further south of the study area. Sediments around the coastline in the south-western part of the area have a low P-wave velocity gradient; the velocity varies vertically from 2,300 m/s to 2,600 m/s in the upper part and from approximately 3,200 m/s to 3,900 m/s in the lower part.

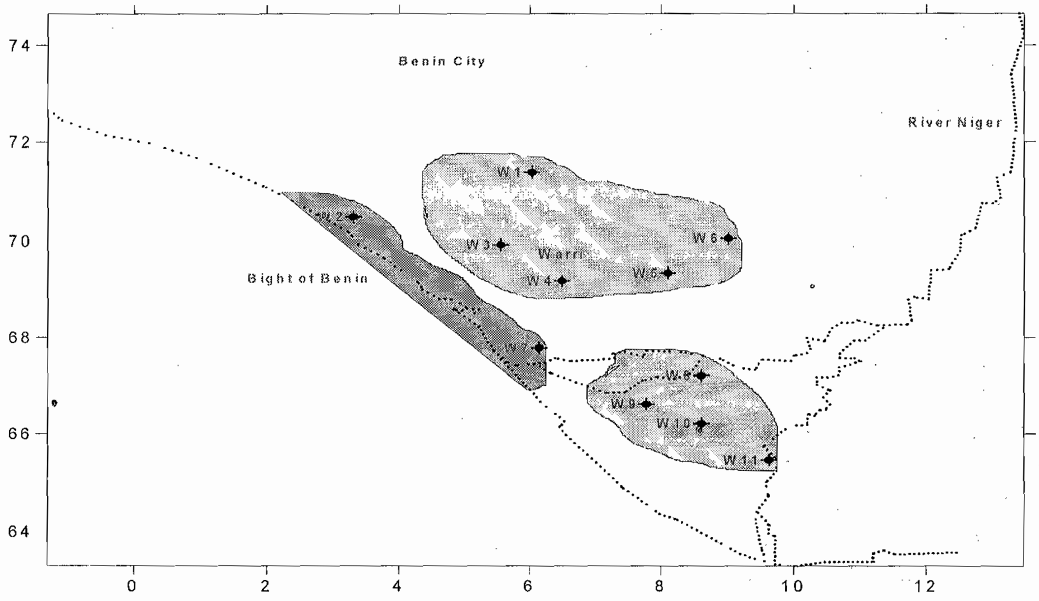
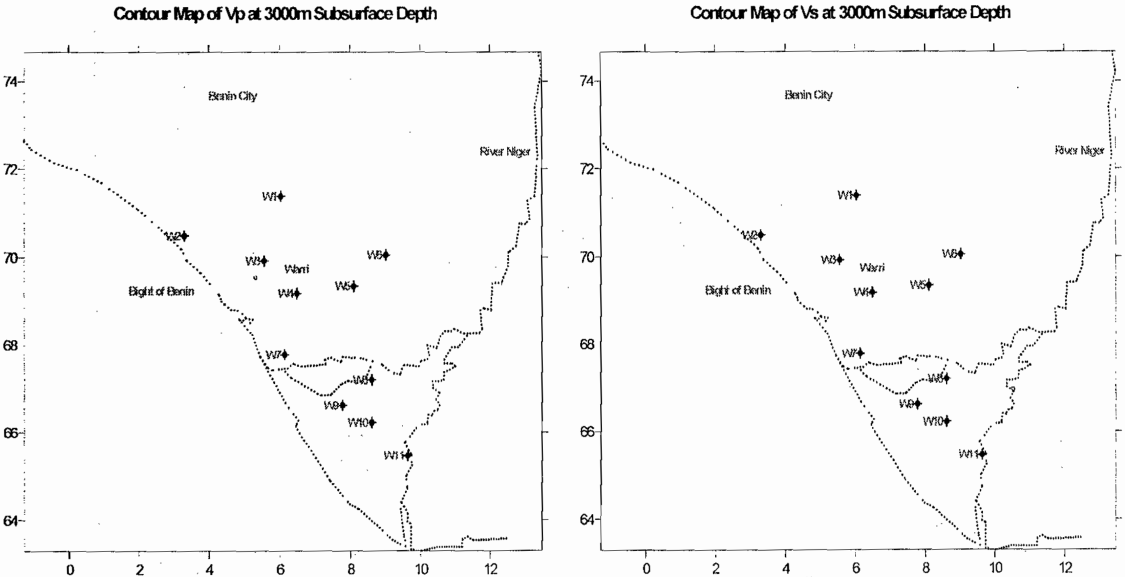


Fig.2: Velocity gradient map of the study area

The computed shear velocities are generally about 40% to 50% lower than the compressional velocities. These decreases may be due to the decrease in the degree of compaction and the pronounced presence of synsedimentary structures and clay diapirs in the sediments coastward.

We constructed velocity maps at subsurface depths of 2,000 m, 2,200 m, 2,500 m, 2,800 m, 3,000 m and 3,100 m to investigate the lateral variation in compressional and shear velocities at various depths in the Niger Delta. This interval is chosen for interpretation because majority of drilling and petroleum production activities in the study area are concentrated within this interval. Similar features were observed in all of the maps at the various depths. P-wave and S-wave velocity map at 3,000 m subsurface depth is shown in Fig. 3. The maps show a general NE-SW trend of decreasing seismic velocity within the delta. Seismic velocities are relatively high in the central part on the area, and decrease SW towards the seashore. This is however, in accordance with the trend of the Benue valley which is a continuation of the Niger delta offshore (Short and Stauble, 1967). The sediments of the delta thickens progressively in this trend with lateral and vertical variation in compaction and pronounced influence of synsedimentary structures (Growth faults) and clay diapirs towards the coast which affects seismic P-and S velocities.

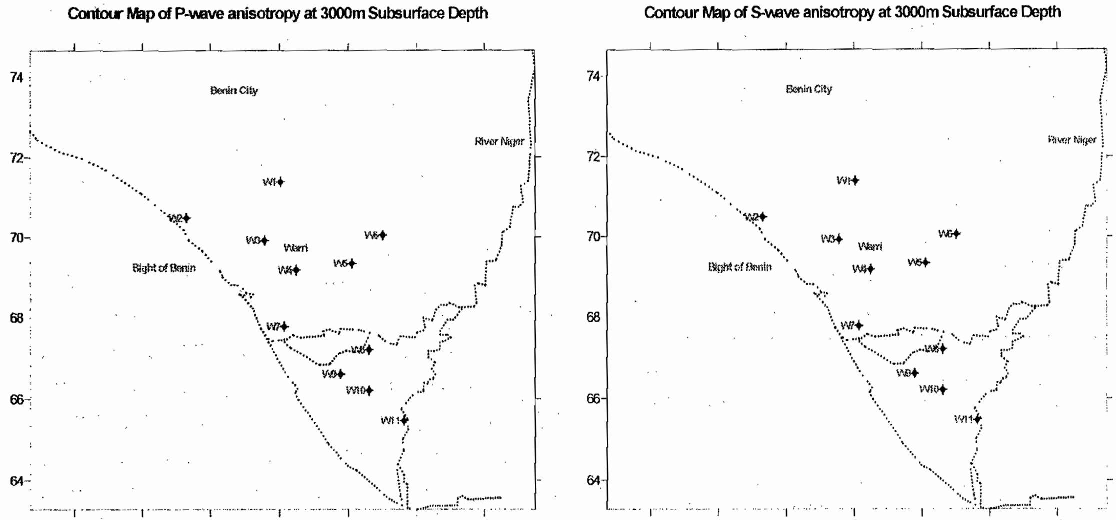
A summary of the P-wave and S-wave anisotropy computed at the above depths is given in Appendix 1. Average P-wave anisotropy (the Epsilon parameter) varies from -7.6% to 16.8% within this interval in the study area, but most of the P-wave anisotropy is concentrated between -3.5% and 5.7%. The near-vertical anisotropy ranges between -11.7% and 16%, with most of the anisotropy concentrating around -3.5% and 4.9%. The localized S-wave anisotropy is generally much larger, and varies between -12% and 13.2%, with most of the S-wave anisotropy concentrating at -4.3% and 7.4%. Investigation of the anisotropy parameters over the entire depth of each well shows that anisotropy is generally higher in shales than in sands. The higher anisotropy observed in the shales may be due to the preferred clay mineral orientation, growth faults, and clay diapiric structures associated with shale's at these depths.


Contour Map of Vp at 3000m Subsurface Depth

Contour Map of Vs at 3000m Subsurface Depth

Fig.3: Velocity map of the study area: (a) P-wave, (b) S-wave.

P-wave and S-wave anisotropy maps were also constructed at the above mentioned depths within the area. The maps also exhibit similar features at each depth. Figs. 4 show P-wave and S-wave anisotropy maps of the area.


Contour Map of P-wave anisotropy at 3000m Subsurface Depth

Contour Map of S-wave anisotropy at 3000m Subsurface Depth

Fig.4: Anisotropic velocity map of the study area, (a) P-wave; (b) S-wave

The observed trends in velocity and anisotropy are supported by the geology of the Niger Delta. Evamy *et al.*, 1978; Ejedawe, 1981, Doust and Omatsola, 1990, have identified the oil prolific belt of the Niger Delta. These areas have high thickness of sediments and also have the highest oil maturity per unit depth (Fig. 5). Shales constitute about ¾ of clastic basin fill and have intrinsic velocity anisotropy. The oil prolific areas correlate well with the trends of velocity and anisotropy observed in this study. Also, Weber (1987) indicates that the oil prolific areas coincide with a concentration of synsedimentary structures. These may also be responsible for the changes in the lateral velocity variation in the area, and this have a direct effect on velocity anisotropy.

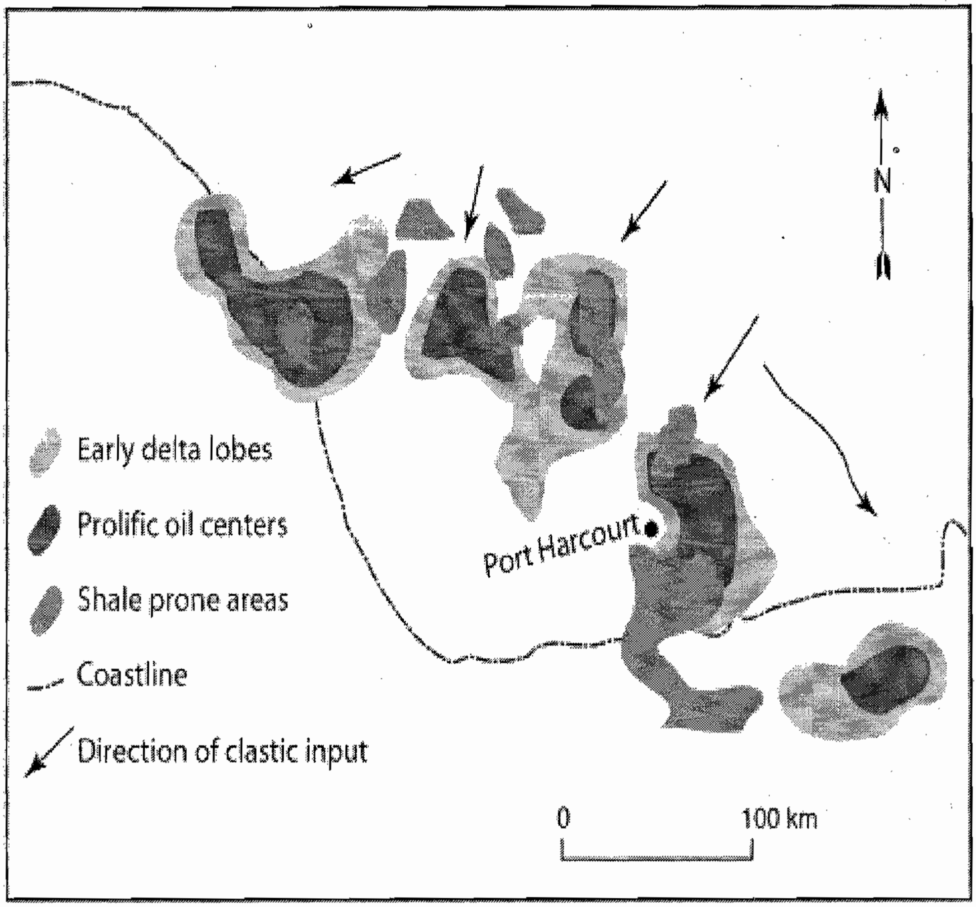


Fig. 5: Schematic showing the location lobes of the early Niger Delta prolific oil centers, and shale prone areas. Modified from Ejedawe (1981), and Reijers *et al.* (1997).

Conclusion

Using well log data alone, we have computed velocity anisotropy in the western Niger Delta. The computed anisotropy parameters are comparable to the values recorded so far for horizontally stratified sediments (Alexandrov and Ryzhov, 1961; Katahara, 1996; and Wang, 2002). The results show that the Niger Delta sediments are seismically anisotropic, the anisotropy ranging from weak to moderate. These are due to the preferred alignment of clay minerals, varying degrees of sediment compaction, presence of synsedimentary structures and clay diapers which are pronounced coastward in agreement with the tectonics of the delta as the continuation of the Benue trough offshore. There is therefore a need to account for the degree of the anisotropy in migration algorithms in the processing of data acquired in the Niger Delta basin.

References

Alexandrov, K.S. and Ryzhov, T.V. (1961): Elastic Properties of Rock-Forming Minerals, II. Layered silicates. Bulletin USSR Academy of Science, Geophysics Series 9, 1165-1168.

Alkhalifah, T. and Tsvankin, I. (1995): Velocity Analysis For Transversely Isotropic Media, Geophysics, 60, 1550-1566.

Backus, G.E. (1962): Long-Wave Elastic Anisotropy Produced by Horizontal Layering, Journal of Geophysical Research, 67, 4427-4440.

Banik, N.C. (1964): Velocity Anisotropy of Shales and Depth Estimation in the North Sea Basin, Geophysics, 49(9), 1411- 1420.

Berryman, J.G. Grechka, V.Y. and Berge, P.A. (1999): Analysis of Thomsen Parameters for Finely Layered VTI Media, Geophysical Prospecting, 47, 959-978.

Brittan, J., Warner, M. and Pratt, G. (1995): Anisotropic Parameters of Layered Media in Terms of 'Composite Elastic Properties, Geophysics, 60 (4), 1243-1248.

Cholah, P.Y. and Schmitt, R. (2003): Seismic Anisotropy of Shales, CSEG Recorder, Calgary, 39-43.

Doust, H. and Omatsola, E., (1990): Niger Delta, in, Edwards, J. D., and Santogrossi, P.A., eds., Divergent/Passive Margin Basins, AAPG Memoir 48: Tulsa, American Association of Petroleum Geologists, 239-248.

Ejedawe, J.E., (1981): Patterns of Incidence of Oil Reserves in Niger Delta Basin: American Association of Petroleum Geologists, 65, 1574-1585.

Evamy, B.D., Haremboure, J., Kamerling, P., Knaap, W.A., Molloy, F.A., and Rowlands, P.H. (1978): Hydrocarbon Habitat of Tertiary Niger Delta: American Association of Petroleum Geologists Bulletin, 62, 277-298.

Hospers, J. (1965): Gravity Field and Structure of the Niger Delta, Nigeria , West Africa, Geol. Soc. of Amer. Bulletin, 76, 407-422.

Isaac, J.H. and Lawton, D.C. (1999): Image Mispositioning Due to Dipping TI Media: A Physical Seismic Modeling Study, Geophysics, 64, 1230-1238.

Jacobsen, M. and Johansen, T.A. (2000): Anisotropic Approximation for Mudrocks: A Seismic Laboratory Study, Geophysics, 65, 1711-1725.

Johnston, J.J. and Christensen, N.I. (1995): Seismic Anisotropy of Shales, Journal of Geophysical Research, 100, (B4), 5991-6003.

Jones, I.F., Bridson, M.L. and Bernitsas, N. (2003): Anisotropic Ambiguities in TI Media, First Break, 21, 5.

Jones, L.E.A., and Wang, H.F. (1981): Ultrasonic Velocities in Cretaceous Shales from the Williamson Basin, Geophysics, 46, 288-297.

Katahara K.W. (1996): Clay Mineral Elastic Properties. 66th SEG

Meeting, Denver, USA, Expanded Abstracts, 691-1694.

Kebaili, A. and Schmitt, D.R., (1996): Velocity Anisotropy Observed in Wellbore Seismic Arrivals: Combined Effects of Intrinsic Properties and Layering, Geophysics, 61, (1), 12-20.

Lawton, D.C., Isaac, J.H., Vestrum, R.W. and Leslie, J.M. (2001): Slip-Slidin' Away Some Practical Implications of Velocity Anisotropy on Depth Imaging, The Leading Edge, 20, 70-73.

Merki, P. (1972): Structural Geology of the Cenozoic Niger Delta. African Geology, Ibadan Univ. Press, Ibadan, Nigeria, 635-646.

Reijer, T. J. A., Peters, S. W., and Nwajide, C.S.(1997): The Niger Delta Basin, in Selley, R. C., ed., Africa Basin-Sedimentary Basin of the world 3: Amsterdam, Elsevier Science, 157-172.

Short, K. C. and Stauble, A. J. (1967): Outline of Geology of Niger Delta. Bul. Amer. Ass. Petr. Geol. 54, (5), 761-779.

Thomsen, L., (1986): Weak Anisotropy, Geophysics, 51, 1954-1966.

Tosaya, ○C.A., (1982): Acoustic Identification and Detection of Abnormal Pore Pressures in Shale Lithologies, Submitted to Geophysics.

Vernik, L. and Nur, A., (1992): Ultrasonic Velocity and Anisotropy of Hydrocarbon Source Rocks; Geophysics 57, 727- 735.

Vestrum, R.W., D.C. Lawton and R. Schmid, (1999): Imaging Structures Below Dipping TI Media, Geophysics, 64, 1239-1246.

Wang, Z. (2002): Seismic Anisotropy in Sedimentary Rocks, Part 2, Laboratory Data, 67, 1423-1440.

Weber, K. J. (1971): Sedimentological aspects of oilfields in the Niger delta. Geol. en Mijnbouw, 50, 559-576.

Weber, K.J., (1987): Hydrocarbon Distribution Patterns in Nigerian Growth Fault Structures Controlled by Structural Style and Stratigraphy: Journal of Petroleum Science and Engineering, 1, 91-104.

Appendix: Summary of anisotropy parameters computed at depths.

Depth 2,000 m	P-anisotropy (%)	Near-vertical anisotropy (%)	S-anisotropy (%)
W 1	-1.4	-0.2	-2.2
W 3	-3.3	-11.7	5.2
W 3	0.7	1.7	-0.2
W 5	-0.7	-2.1	1
W 6	0	-0.2	1.5
W 8	3.1	4.1	2.3
W 10	-2.6	-8.1	3.5
W 11	16.8	16	13.2

Depth 2,200 m	P-anisotropy (%)	Near-vertical anisotropy (%)	S-anisotropy (%)
W 1	1.7	0.3	3.4
W 3	-1.6	-1.6	-1.1
W 4	1	1.8	0.2
W 5	-0.7	-2.1	1
W 6	-7.6	-4.5	-12
W 8	0.1	0.6	-0.3
W 9	4.6	4	3.8
W 10	0.8	1.6	-0.1
W 11	-1.9	-3.3	-0.2

Depth 2,500 m	P-anisotropy (%)	Near-vertical anisotropy (%)	S-anisotropy (%)
W 1	0.3	-0.1	0.7
W 3	-3.9	-6.9	-0.5
W 5	0.9	0.4	1.7
W 6	1.4	-0.3	2.5
W 8	-1.2	-1.3	-1
W 9	-1.9	-1.5	-1.9
W 10	1.5	3.2	-0.1
W 11	-0.2	1.1	-1

Depth 2,800 m	P-anisotropy (%)	Near-vertical anisotropy (%)	S-anisotropy (%)
W 1	-1.6	-1.2	-1.7
W 2	-0.8	0	-2
W 5	1.9	1	2.9
W 6	-0.9	2.4	-4
W 8	-0.2	0	-0.4
W 9	0.8	-0.7	2.1
W 10	0.2	-3.2	3.1
W 11	-0.9	3.8	-4.3

Depth 3,000 m	P-anisotropy (%)	Near-vertical anisotropy (%)	S-anisotropy (%)
W 1	-7.3	-7.3	-10.3
W 2	-0.6	-0.6	-0.8
W 4	1.6	1.6	0.7
W 6	-2.4	-2.4	-6.8
W 7	4.9	4.9	3.8
W 8	1.1	1.1	2.4
W 9	-0.5	-0.5	0.6
W 10	-3.5	-3.5	2.7
W 11	1.7	1.7	1

Depth 3,100 m	P-anisotropy (%)	Near-vertical anisotropy (%)	S-anisotropy (%)
W 1	0.5	0.5	0.5
W 2	0	-0.1	0.3
W 5	-4.6	-1.9	-5
W 6	3.1	2.1	4.2
W 7	-0.5	-1	0
W 8	5.7	3.8	7.4
W 9	0.5	-0.9	1.7
W 10	1.1	1.7	0.5
W 11	-4	-4.8	-2.6