Velocity anisotropy and trend in Niger Delta, Nigeria

Emmanuel Aniwetalu1 · Emmanuel Anakwuba1 · Juliet Ilechukwu1

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Abstract
In geophysical data interpretation, matching the vertical velocity direction from seismic data with borehole-derived velocities is a challenging task because seismic-derived velocities are faster than borehole recorded velocities. This geophysical phenomenon is caused by velocity anisotropy. In this study, we used an empirical approach to estimate the degree of velocity anisotropy in the study area. The results showed that the delta anisotropy in sandstone beds varies from −2.5% to 7.2% while most of them concentrate between 3.2% and 6.1%. The epsilon ranges between -6.4% and 9.3% while many of them concentrate between 3.2% and 7.2%. The gamma varies from −6.3% to 7.3% while most of them concentrate between 1.2% and 5%. At shale beds, delta anisotropy varies from −11.2% to 11.1% but most of them concentrate between 4.3% and 10.5%. The epsilon varies from −7.2% to 14.5% while most of them concentrate between 4.5% and 10.5%. The gamma varies from 6.4% to 8.2% while majority of them concentrate between 2% and 5.3%. The results indicate that the study area is weakly to moderately anisotropic with shale beds having higher anisotropy values than sandstone beds. This probably results from preferential alignment of clay mineral orientations which also affect in situ velocity propagation. Three distinct velocity gradients (low, moderate and very high) were identified in the study area. These velocities vary erratically but showed northeast–southwest increase in velocities. Thus, the need to derive correction factors for individual wells for improved exploration success.

Keywords Anisotropy · Velocity · Delta · Epsilon · Gamma

Background to the study
The term anisotropy can be defined as the dependent of seismic velocity upon an angle or a variation of physical properties that are dependent on the direction of its measurement (Thomsen 1986). Anisotropy can also be considered as an anomaly caused by directional variations which must be removed or corrected. Although, in quantitative reservoir study, it can be exploited to improve interpretation especially in vertical fracture characterization. However, in seismic processing, it is important to consider the effects of anisotropy in processing flow. But in most cases, this important stage in reservoir interpretation is often ignored on the assumption that elastic medium is isotropic while in reality, it is anisotropic (Thomsen 1988 and Jones et al. 2003). Sedimentary rocks are fundamentally anisotropic and the most common velocity anisotropy is transverse isotropy also known as polar anisotropy, where the velocity is constant on the surface of a cone about some axis, known as the axis of symmetry (Jones et al. 2003; Alkhalifah and Tsvankin (1995). In other words, the velocity is azimuthally invariant but only varies as a function of angle from the symmetry axis. This is of different types and includes vertical transverse isotropy (VTI), horizontal traverse isotropy (HTI) and tilted traverse isotropy (TTI). Niger delta geological setting is favored by vertical transverse isotropy (VTI) probably due to the sequential sand-shale layering.

Thomsen (1986) introduced three major constants considered as effective parameters for measuring anisotropy especially for vertical transverse isotropy (VTI). They are known as near vertical anisotropy or delta (δ), P-wave anisotropy or epsilon (Ɛ) and S-wave anisotropy or gamma (γ). Among these, near vertical anisotropy does not involve the horizontal velocity at all in its definition and thus the most critical measure of anisotropy. The P-wave anisotropy controls the normal move out of the compressional wave arrivals especially in a horizontally layered sequence. It is an influential
shallower than their true depths in the subsurface. This mis-
structural depths interpreted from surface seismic would be
(well) recorded velocities and the resultant effect is that the
derived velocities are faster and often higher than borehole
area.

measures that could improve exploration success in the study
the study is to use an empirical method to quantify velocity
anisotropy in the area is ignored. Therefore, the focus of
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positioning of the depth may lead to unimaginable errors
(Whiteman 1982). The Niger Delta basin is framed on the
entire hydrocarbon production at present-day Nigeria
because of its major geological features that account for
carbon exploitations in the basin have been on the increase
apex of the Gulf of Guinea. For the past 50 years, hydro-
density and gamma ray logs and 2006 processed vintage
set of dipole sonic log (compressional and shear wave logs),
the data used in this study include suite of well logs with
of the ISAKO PSDM seismic data. The seismic data were
 acquire in 2006 using short offset (3000 m cable length)
set of dipole sonic log (compressional and shear wave logs),
the number of depositional environment and morphological
units such as coastal flats, ancient/modern sea, river and
lagoonal beaches, sand bars/flats, flood plains, seasonally
flooded depressions, swamps, backswamps, abandoned and
modern river/creek channels have been recognized in the
basin but the study area cut across active and abandoned
coastal beaches, saltwater mangrove swamps and Freshwater
swamps, backswamps, deltaic plain, alluvium and meander
belt. These areas remained the seat of onshore hydrocarbon
exploration in Niger Delta.

paramater for seismic wave travelling close to the vertical
transverse isotropy (VTI) which has a hexagonal symmetry
and fine layering where individual particles are preferentially
aligned. But near vertical and S-wave anisotropy represents
the percentage difference between the vertical and horizon-
tal P-wave velocities and polarized shear wave respectively.
Tsvankin et al. (1994) proposed a technique of inverting
anisotropic non-hyperbolic normal move out equation for
the estimation of these anisotropic parameters. They con-
cluded that the determination of delta anisotropy (δ) which
has short offset move out is relatively easy while P-wave
anisotropy (E) which carries long offset move out informa-
tion needs a measure of horizontal velocity which is diffi-
cult to measure. Toldi (1999) highlighted the importance of
near vertical anisotropy in processes like depth imaging and
stated that it must be measured with the aid of well control to
give integrity in the interpretation. But generally, estimation
of anisotropic parameters in VTI is dependent on the hori-
zontal layered media where seismic waves tend to propagate
at different velocities in different direction. The variations
in the velocities are dependent on the various sequences of
lithologies and seismic velocities tend to travel more quickly
along the bedding planes than perpendicular to the layered
boundaries (Thomsen 1986; Jakobsen and Johansen 2000;
Hudson 1981; Johansen et al. 2004; Rudd et al. 2003, and
Kaushik 2009).

This geophysical phenomenon is the reason why seismic-
derived velocities are faster and often higher than borehole
(well) recorded velocities and the resultant effect is that the
structural depths interpreted from surface seismic would be
shallower than their true depths in the subsurface. This mis-
positioning of the depth may lead to unimaginable errors
during data interpretation if the knowledge of the velocity
anisotropy in the area is ignored. Therefore, the focus of
the study is to use an empirical method to quantify velocity
anisotropy, velocity trend and also recommend appropriate
measures that could improve exploration success in the study
area.

Geologic framework of the study area

The study area is located in Isako Field in the south-western
parts of Niger Delta (Fig. 1). The Niger Delta basin ranks
among the world’s most prolific province of hydrocarbon
and also known as the world’s largest Tertiary Delta System.
It is situated on the West African Continental Margin at the
apex of the Gulf of Guinea. For the past 50 years, hydro-
carbon exploitations in the basin have been on the increase
because of its major geological features that account for
the entire hydrocarbon production at present-day Nigeria
(Whiteman 1982). The Niger Delta basin is framed on the
northwest by subsurface continuation of the West African
Shield known as the Benin Flank while the eastern edge of
the basin coincides with Calabar Flank and to the south of
the Oban Massif.

However, during continental break-up, the basin formed
the site of a triple junction which was fed by river Benue,
Niger and Cross rivers. This drained more than $10^5$ km$^2$
of continental lowland Savanna with different deposi-
tional environments and geomorphic units. Reijers (1997)
classified lithostratigraphic units of the Niger Delta Basin
into three major subdivisions; an Upper Delta Top Facies;
a Middle Delta Front Lithofacies; and a Lower Pro-Delta
Lithofacies. According to Short and Stauble (1967), these
correspond, respectively, with the loose continental sands of
the Benin Formation (Oligocene-Recent), Paralic Agbada
Formation (Eocene-Recent) and the under compacted shales
of the Akata Formation (Paleocene-Recent) respectfully. The
Delta-Top Benin Formation which overlies the Delta-Front
Agbada Formation consists of continental sands and gravel
while the composition of its subsurface reflects the present-
day Quaternary land and swamp outcrops. Agbada Forma-
tion is major petroleum bearing unit which represents the
seat of petroleum explorations and exploitations in Niger
Delta. This is because most prolific reservoirs are embed-
ded in the intercalated sand-shale sequence of the Forma-
tion. The Formation consists of shoreface, channel sands and
alternation of sands and shales which represent the current
beach ridges (Reijers 2011). The Akata formation composed
mainly of turbidities and continental slope channel fills such
as marine shales, with sandy and silty beds. However, vari-
ous types of depositional environment and morphological
units such as coastal flats, ancient/modern sea, river and
lagoonal beaches, sand bars/flats, flood plains, seasonally
flooded depressions, swamps, backswamps, abandoned and
modern river/creek channels have been recognized in the
basin but the study area cut across active and abandoned
coastal beaches, saltwater mangrove swamps and Freshwater
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exploration in Niger Delta.

Materials and methods

The data used in this study include suite of well logs with
set of dipole sonic log (compressional and shear wave logs),
density and gamma ray logs and 2006 processed vintage
of the ISAKO PSDM seismic data. The seismic data were
acquired in 2006 using short offset (3000 m cable length)
and processing was carried out on the data to address shal-
low channels and velocity variation, amidst attenuating
steeply dipping long period multiples that were somewhat
retained in the data.
Velocity anisotropy modeling

In vertical traverse isotropic (VTI) media, anisotropy can be modeled by defining the following parameters namely $\varepsilon$ (p-wave anisotropy), $\delta$ (near vertical anisotropy) and $\gamma$ (shear wave anisotropy).

Let consider an expression given by Hudson (2000) for the effective stiffness tensor in cracked media for long wave-length seismic waves

$$C_{ijkl} = C^0_{ijkl} + C^1_{ijkl} + C^2_{ijkl}$$

where $C^1_{ijkl}$, $C^2_{ijkl}$ and $C^0_{ijkl}$ denote the first-order, the second-order perturbation of the isotropic elastic constants, and uncracked medium, respectively. Using crack density and the lame constant, the first-order and second-order perturbations can be computed. Interestingly, one can also find an expression for an anisotropic medium for a set of cracks through the effective stiffness tensor which are often expressed in two indices notations given as.

Stiffness tensor for an isotropic medium

$$C^0_{ijkh} = \begin{pmatrix} \lambda + 2\mu & \lambda & \lambda & \lambda + 2\mu \\ \lambda & \lambda + 2\mu & \lambda & \lambda + 2\mu \\ \lambda & \lambda & \lambda + 2\mu & \lambda + 2\mu \\ \lambda & \lambda & \lambda & \lambda + 2\mu \end{pmatrix}$$

where $\lambda$ and $\mu$ are Lambda Rho and Mu Rho respectively. And,

Stiffness tensor for a transverse isotropic medium with vertical axis of symmetry.
These elastic stiffness tensors define an elastic medium and also control the pattern of wave travel through it. For instance, in earth model (Fig. 2), wave travels more quickly along the layers than across the layer boundaries. The vertically travelling waves across the boundaries are said to be out of plane. This could be out of plane compressional modulus ($C_{33}$) or out of plane shear modulus ($C_{44}$). The horizontally travelling waves are said to be in plane which could also be in-plane compressional modulus ($C_{11}$) or in-plane shear modulus ($C_{66}$). $C_{13}$ is an important constant that controls the shape of these wave surfaces (Sayers 1994; Berryman et al. 1999).

These parameters ($C_{11}$, $C_{13}$, $C_{33}$, $C_{44}$, $C_{66}$) are referred to as five independent components of elastic stiffness tensors and they can be expressed as follows:

\[
C_{11} = 4M - 4S + \frac{(1 - 2T)^2}{R} \tag{4}
\]

\[
C_{13} = \frac{1 - 2T}{R} \tag{5}
\]

\[
C_{33} = \lambda + 2\mu \tag{6}
\]

\[
C_{44} = \mu \tag{7}
\]

\[
C_{66} = M \tag{8}
\]

Where,

\[ M = \Phi \mu_1 + (1 - \Phi) \mu_2 \]

\[
R = \frac{\Phi}{\lambda_1 + 2\mu_1} + \frac{(1 - \Phi)}{(\lambda_2 + 2\mu_2)} \tag{9}
\]

\[
S = \Phi \theta_1 \mu_1 + (1 - \Phi) \theta_1 \mu_2 \tag{10}
\]

\[
T = \Phi \theta_1 + (1 - \Phi) \theta_2 \tag{11}
\]

\[
\theta = \frac{V_S}{V_P} \tag{12}
\]

\[ \lambda \text{ and } \mu \text{ are the first and second Lame parameters, respectively, } \Phi \text{ is the porosity while } \Theta \text{ is the phase angle.} \]

Following Ogagarue (2007), we define the parameters $M$, $R$, $S$ and $T$ in terms of the Lame parameters $\lambda$ and $\mu$, the volume fraction $\Phi$ the ratio of compressional and shear wave velocities in a medium for a stack of two layers. The parameter $M$ is for a stack of two layers that are controlled by the porosity of the upper and shear moduli of each layer; $R$ is governed by the porosity of the upper layer, bulk and shear moduli of the layers; $S$ is a dimensionless parameter which is influenced by porosity, $V_s$ to $V_p$ ratio and the shear moduli of the layers while $T$ is defined in terms of porosity and velocity ratio only.

For the above sets of the equations to become suitable for this study, they were modified into these forms.

\[
C_{33} = p^i V_P^{2i} \tag{13}
\]

\[
C_{44} = p^i V_S^{2i} \tag{14}
\]

\[
C_{13} = \frac{1 - 2T}{R} \tag{15}
\]

\[
C_{66} = \Phi C_{44} + (1 - \Phi) C_{44} + 1 \tag{16}
\]

\[ C_{11} = C_{66}^i - 4\Phi^i \theta^i C_{44}^i + (1 - \Phi^i) \theta^{i+1} C_{44}^{i+1} (1 - 2T)^2 \tag{17}
\]

Where $T = \Phi \theta_1 + (1 - \Phi) \theta_2$ and $R = \frac{\Phi}{C_{33}^i} + \frac{1 - \Phi}{C_{53}^i}$

$p$, $V_P$, $V_S$, $\Phi$, $i$, $i$ + lare the density, compressional velocity, shear wave velocity, porosity, present depth and next depth interval, respectively.

Using Eqs. 9, 10, 11, 12, 13, the five elastic stiffness tensors for a transverse isotropic medium with vertical axis of symmetry can be deduced.

Fig. 2 Modes of wave propagation in elastic earth model.
However, to quantify the degree of velocity anisotropy present in the sediments, the following relations were used.

\[
\varepsilon = \frac{C_{11} - C_{33}}{2C_{33}}
\]  \hspace{1cm} (14)

\[
\delta = \frac{(C_{13} - C_{44})^2 - (C_{13} - C_{44})^2}{2C_{33}(C_{13} - C_{44})}
\]  \hspace{1cm} (15)

\[
\gamma = \frac{C_{66} - C_{44}}{2C_{44}}
\]  \hspace{1cm} (16)

Where parameter \(\varepsilon\) is epsilon (P-wave anisotropy), \(\delta\) is delta (near vertical anisotropy) and \(\gamma\) is gamma (S-wave anisotropy). According to Tsvankin, (1997), the near vertical anisotropy \(\delta\) defines the second derivative of the P-wave phase velocity function at vertical incidence and he showed that for weak anisotropy, \(\delta\) can be approximated as follows:

\[
\delta = \frac{(C_{13} - 2C_{44} - C_{33})}{C_{33}}
\]  \hspace{1cm} (17)

Data transformation and estimation

The interval transit times were transformed to vertical P-wave and S-wave velocities in feet/second (ft/s) using Eq. 18 and 19, respectively. Density logs were transformed to porosity (\(\Phi\)) values using Eq. 20.

\[
\Delta t_p = \frac{V_p}{0.305}
\]  \hspace{1cm} (18)

\[
\Delta t_s = \frac{V_s}{0.305}
\]  \hspace{1cm} (19)

\[
\rho_b = \frac{\Phi(p_{ma} - \rho_f)}{p_{ma}}
\]  \hspace{1cm} (20)

Where \(\Delta t_p\) and \(\Delta t_s\) are the interval transit time recorded by compressional log and shear sonic log, respectively. \(p_{ma}\) is the density of rock matrix, taken to be 2.65g/cc (2,650kg/m³), \(\rho_b\) is the formation bulk density recorded by density tool, and \(\rho_f\) is density of fluid, taken to be 1.08g/cc (1,080 kg/m³). The average rock density in the sandstones from exploration wells is about 2.66 g/cm³ while that of shale...
is assumed to be 2.65 g/cm³. The fluid density determined using electrical resistivity log depends on whether the well encountered water or hydrocarbons.

As shown in Fig.3, gamma ray, density, compressional and shear wave velocity values can be directly estimated from well logs at any chosen interval. For instance, at depth interval of 5870ft and 5873ft (next sample interval), the gamma ray (API), density (g/cc), P-wave (ft/s) and S-wave (ft/s) readings were directly estimated from the well logs (Fig.3). Similar parameters were also estimated at 6050ft depth interval (Fig.4). The extracted P-wave and S-wave values in feet/second were transformed to meter/second using Eq. 18 and 19, respectively. The

![Density value at 6050ft = 2.25 g/cc](image)

![Gamma Ray value at 6050ft = 75API](image)

![P-Wave value at 6050ft = 10,500ft/s](image)

![S-Wave value at 6050ft = 5000ft/s](image)

Fig.4 Direct estimation of well log values at 6050ft depth interval

| Well log parameters | Well Log Values 1570ft (Sandstone bed) | Well Log Values 1573ft (Sandstone bed) | Well Log Values 1560ft (Shale bed) |
|---------------------|----------------------------------------|----------------------------------------|-----------------------------------|
| Gamma ray           | 45 API                                  | 37.5 API                                | 75API                             |
| DT (Compressional log) | 95 000ft/s (2898m/s)                    | 8,750ft/s (2,669 m/s)                  | 10,500ft/s (3203 m/s)             |
| DT (Shear wave log) | 4000ft/s (1220 m/s)                     | 3625 ft/s (1,106 m/s)                  | 5000 ft/s (1525 m/s)              |
| Rhob (Density)      | 2.2 g/cc (28.66%)                       | 2.25 g/cc (25.47%)                     | 2.25 g/cc (25.47%)                |

Table 2 The computed density, gamma ray, velocities, elastic stiffness tensors and anisotropic parameters at 5870ft sand 5873ft

| Depth | Den | GR | Poro | Vp | Va | Cu | Cl3 | C33 | C44 | Qs | delta | epsilon | Gamma |
|-------|-----|----|------|----|----|----|-----|-----|-----|----|-------|----------|-------|
| 5870  | 2.20| 45 | 0.286| 2898| 1220 | 22.7| 13.4| 18.47| 3.27| 3.04| 0.115| −0.003| −0.012 |
| 5873  | 2.25| 37 | 0.254| 2668| 1,105| 23.14| 12.5| 15.67| 2.75| 5.33| 0.016| 0.238   | 0.46   |
| 6050  | 2.25| 75 | 0.254| 3203| 1525 | 23.21| 13.20| 17.22| 3.10| 6.22| 0.15 | 0.22    | 0.24   |
density values were transformed into standard porosity values using Eq. 20.

The log readings at depth interval of 5870ft, 5873ft, and 6050ft and their corresponding conversions are shown in table 1 while their equivalent elastic stiffness tensors and anisotropic parameters are shown in table 2.

However, with density, gamma ray, compressional and shear wave velocities from well logs already known, five independent elastic stiffness tensors can be calculated using Eqs. (9, 10, 11, 12, 13) while epsilon, delta and gamma anisotropy can also computed at different depth intervals using Eqs. 14, 15 and 16 respectfully.

Method of velocity depth modeling and trend analysis

In subsurface velocity modeling, we used seismic volume and well log data to set up a typical 3D velocity model in depth domain using Pro4D tool of Hampson-Russell Software (HRS). The aim was to produce 3D seismic velocity depth model of the subsurface measured in feet per seconds (ft/s) where velocity depth maps at various depth intervals can be extracted with interpolation guided by well logs. The well logs data were imported through well log Explorer tool of HRS and the amplitude unit and name of the corresponding log types were defined. The well log depth domain range starts from 449 to 9996 ft with sample interval of 0.5ft while seismic volume displayed range from 0-6000 ms (two-way time) with sample interval of 8 ms. However, to create subsurface velocity depth profile that could show the subtle lateral velocity variation, we build 3D velocity model using seismic volume and the control wells or amplitude source. The available wells to be included in the model were selected. The grid geometry needed for accessing the model traces within the display and the processing window was defined. We chose the amplitude unit (ft/s) for P-wave or S-wave and name of the logs for building the corresponding log type. The domain type (depth) and range of the output model were specified. The horizons in depth domain were created from the top and model geometry was defined. However, using model trace filtering option, we apply a blocked trace by taking the average within the horizon layer and fully processed 3D velocity depth model which showed subsurface velocity variations was created (Fig. 5).

Therefore, we created velocity depth profile at various depth intervals by producing the slices of velocity depth

![Fig. 5 P-wave velocity depth Model](image-url)
maps from the 3D velocity depth model. The velocity depth maps revealed velocity variation at different depth intervals. But to obtain the subsurface velocity trend, we produced the Isopach maps that reflect the thickness of the deposited beds created at different horizons by subtracting the lower surface (base) from the upper layer (top) because velocity increase or decrease is strongly dependent on thickness variation of the sediments. This has offered a solution for an improved exploration and development problems associated with the velocity depth imaging and positioning of a wide range of subsurface geological structures.

Table 3  Velocity anisotropy at selected depths of sandstone layers

| Sample wells | Depth (Ft) (MD) | Near vertical anisotropy (δ)% | P-wave anisotropy (ε)% | Shear wave anisotropy (γ)% | Depth (Ft) (MD) | Near Vertical anisotropy (δ)% | P-wave Anisotropy (ε)% | Shear wave anisotropy (γ)% |
|--------------|----------------|-------------------------------|------------------------|---------------------------|----------------|-------------------------------|------------------------|---------------------------|
| Isako-1      | 5855           | −1.20                         | 2.40                   | −4.20                     | 5870          | 4.11                          | 7.30                   | 2.42                      |
| Isako-2      | 5839           | −2.5                          | 3.3                    | 3.2                       | 5860          | −2.0                          | −1.3                   | 1.2                       |
| Isako-3      | 5980           | 4.3                           | 5.1                    | −4.0                      | 6031          | 4.0                           | 5.0                    | 3.0                       |
| Isako-4      | 5843           | 3.2                           | 4.3                    | 5.2                       | 5891          | 3.2                           | 5.3                    | −4.2                      |
| Isako-5      | 6000           | 6.3                           | 7.2                    | 4.0                       | 6046          | 4.2                           | 2.3                    | 2.0                       |
| Isako-6      | 5849           | 0.00                          | 0.0                    | 2.0                       | 5870          | 5.1                           | −1.6                   | 1.2                       |
| Isako-7      | 5848           | 4.2                           | −1.2                   | 3.0                       | 5869          | 6.1                           | 7.3                    | 7.3                       |
| Isako-8      | 6001           | −3.2                          | 6.2                    | 2.6                       | 6040          | 5.3                           | −6.4                   | 4.1                       |
| Isako-9      | 5858           | 6.3                           | 8.4                    | 5.0                       | 5906          | 5.1                           | −4.1                   | −6.3                      |
| Isako-10     | 6300           | −2.1                          | 3.6                    | 2.4                       | 5921          | 0.0                           | 0.0                    | 0.0                       |
| Isako-11     | 5855           | 6.1                           | −5.2                   | 5.3                       | 5879          | 5.12                          | 4.1                    | 2.2                       |
| Isako-12     | 5854           | 7.2                           | 9.3                    | 5.3                       | 5881          | 4.7                           | 7.4                    | 3.2                       |

Table 4  Velocity anisotropy at selected depths of shale layers

| Sample wells | Depth (Ft) (MD) | Near vertical anisotropy (δ)% | P-wave anisotropy (ε)% | Shear wave anisotropy (γ)% | Depth (Ft) (MD) | Near Vertical anisotropy (δ)% | P-wave Anisotropy (ε)% | Shear wave anisotropy (γ)% |
|--------------|----------------|-------------------------------|------------------------|---------------------------|----------------|-------------------------------|------------------------|---------------------------|
| Isako-1      | 5966           | 8.3                           | 7.2                    | 6.4                       | 5970          | 9.20                          | 7.00                   | 5.00                      |
| Isako-2      | 6051           | −7.3                          | 6.4                    | 7.2                       | 6081          | 6.5                           | 10.4                   | 5.4                       |
| Isako-3      | 5766           | 5.5                           | 10.2                   | 4.1                       | 5805          | 4.3                           | −4.2                   | −6.5                      |
| Isako-4      | 5700           | −11.2                         | 9.34                   | 4.3                       | 5712          | 3.3                           | 4.3                    | −2.2                      |
| Isako-5      | 5972           | 7.20                          | 13.7                   | 5.5                       | 5841          | 4.5                           | 6.1                    | 5.3                       |
| Isako-6      | 6063           | 11.1                          | 12.2                   | 7.3                       | 5990          | 10.5                          | 12.7                   | 6.42                      |
| Isako-7      | 5778           | 8.2                           | 6.2                    | 5.5                       | 6090          | 7.2                           | 14.2                   | 4.2                       |
| Isako-8      | 5706           | −4.3                          | −7.2                   | 3.7                       | 5820          | 6.4                           | 4.2                    | 4.1                       |
| Isako-9      | 5978           | 8.0                           | 5.5                    | −6.4                      | 5718          | 7.3                           | 6.4                    | 4.2                       |
| Isako-10     | 6072           | −5.2                          | 6.6                    | −4.2                      | 5841          | 3.5                           | 3.1                    | 2.3                       |
| Isako-11     | 5790           | 8.0                           | 5.6                    | 8.2                       | 5993          | 5.2                           | −3.7                   | 6.5                       |
| Isako-12     | 5712           | 5.6                           | 7.0                    | −6.3                      | 6099          | 5.6                           | 8.9                    | 5.5                       |

Table 5  Average velocity anisotropy in sand and shale layers in western Niger Delta

| Anisotropy parameters | Sandstone layers | Shale Layers |
|-----------------------|------------------|--------------|
| Near vertical anisotropy | −2.5% to 7.2% | −11.2% to 11.1% |
| P-wave anisotropy | −6.4% to 9.3% | −7.2% to 14.5% |
| S-wave anisotropy | −6.3% to 7.3% | 6.4% to 8.2% |
Results and discussions

At sandstone beds, average near vertical anisotropy (delta) varies from −2.5% to 7.2%. The P-wave anisotropy (epsilon) values range between -6.4% and 9.3% while the localized S-wave anisotropy (gamma) varies from −6.3% to 7.3% (Table 5). However, most of the near vertical and P-wave anisotropy concentrate within the range of 3.2% to 6.1% and 3.2% to 7.2% respectfully while S-wave anisotropy (γ) concentrates between 1.2% and 5%. The results of computed anisotropic parameters from sandstone beds at different depths are expressed in percentage as shown in Table 3. However, at the shale beds, average near vertical anisotropy varies from -11.2% to 11.1%. The P-wave anisotropy varies from -7.2% to 14.5% while the Localized S-wave anisotropy varies from 6.4% to 8.2%. But generally, the percentage of near vertical and P-wave anisotropy have its major peaks between 4.3% to 10.5% and 4.5% to 10.5% respectfully while the S-wave anisotropy range between 2% to 5.3%. The computed anisotropic parameters from shale beds at different depths are expressed in percentage in Table 4 while the average velocity anisotropy in both sand and shale beds are shown in Table 5.

Careful study of the above results revealed varying velocity anisotropy values in the two major rock types in the study area. Shale beds showed higher velocity anisotropy values than sandstone beds but generally the velocity anisotropy in the study area is moderately to weakly anisotropic. This suggests that the study area is intrinsically anisotropic with shale beds having relatively high velocity anisotropy values than sandstone beds. However, shale accounts for about 60–70% in every stratigraphic column and often referred to as clay rich sedimentary rocks. Clay minerals are the abundant kind of all shale that the rate of velocity propagation in the subsurface depends on sediment thickness. Although, several factors such as compaction, synsedimentary structures like growth faults and clay diapers may also have. 

Affected velocity and anisotropy in different scales in the study area. Sediment compaction is often accompanied with increase in velocity, decrease in sediment anisotropy and porosity with depth. The depth range where such mechanical compaction is more pronounced, very weak near vertical anisotropy is often recorded. But in areas where there are slow sediment compaction, synsedimentary structures and clay diapers, velocity inversion usually occurs. This explains why velocity sometimes do not follow normal trend of increase in velocity with depth as evident in some velocity maps of the study area. But generally, velocity increases with depth because as sediments are deposited, the underlying sediment become more compacted which often lead to the expulsion of pore fluids from the pore spaces. The continuous deposition and compaction of the sediments result to normal compaction trend with a decrease in porosity and anisotropy.
Conclusions

In this study, an empirical approach was used to derive the elastic stiffness tensors and estimate the degree of velocity anisotropy present in the sediment. The range of the anisotropic values shows that the study area is weakly to moderately anisotropic with percentage of anisotropy values higher in shale beds than sandstone beds. The higher anisotropy observed in shale may be attributed to plate-like structure of clay minerals which are often elongated and preferential aligned in shale domain while in sandstone beds, biotubations, non-flaky and silt minerals are common and these reduce grain alignment thus making them less anisotropic. However, the results showed that sediment anisotropy in the study area is significant and thus, could pose a very serious exploration risks arising from depth mispositioning between well logs and seismic data if it is ignored. Thus, it becomes important to derived anisotropy correction factor so as to establish a good trend for individual wells before seismic to well ties. This is
**Fig. 7** The Isopach map of HD3 Horizon in depth domain

**Fig. 8** The Isopach map between HD2 version2 and HD2
hoped to improve reservoir interpretation and thus maximize hydrocarbon productions.

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Declarations

Conflict of interest The authors declared that they have conflict of interest.

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