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The Compressional to Shear Wave Velocity Ratio of the Crust and the Uppermost Mantle of Nigeria

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Abstract: ***The compressional to shear wave velocity ratio (Vp/Vs) of the crust and the uppermost mantle of Nigeria have been determined using data on four local earthquakes recorded by Nigerian Network of Seismographic Stations (NNSS) between 2009 and 2016. We used the Wadati diagram to compute the Vp/Vs values. The time of first arrivals of P-wave and S-wave mainly P_gS_g, $P_n$and S_n were obtained and the time difference between the P- and S-waves time arrivals were computed. A graph of S-P time difference against the absolute P-wave arrival times for each earthquake was ploted. The Vp/Vs values were computed from the slope of line of best fit of the graph determined using least square method. The Vp/Vs values derived from the four earthquakes are 1.756, 1.755, 1.760 and 1.758. The average of the different velocity ratios is 1.76 and this is considered to be the Vp/Vs ratio of the crust and the uppermost mantle of Nigeria. The result obtained however is subject to review with more seismic stations and local earthquakes within the region.***

Keywords: *Vp/Vs*values, P-wave, S-wave, first arrivals,local earthquakes

1. Introduction

The compressional to shear wave velocity ratio (*Vp/Vs*) is an important parameter in seismology. In exploiration seismology, *Vp/Vs*is used in seismic amplitude versus offset analysis, reservoir fluids characterisation and as lithology indicator (Robert, 1982 andHamada, 2004).*Vs/Vp* ratio is an essential parameter used in the determination of epicenters of local earthquakes and very useful in velocity modelling and prediction (Lee, 2003).In hydrogeology, high *Vp/Vs* values are associated with highly fractured and water-saturated rocks while low values *Vp/Vs* are expected where microcracks within the subsurface is closing under increasing confining pressure (Finotello *et al*, 2011). In volcanic regions, low Vp, low Vsand high *Vp/Vs* often indicate partial melting. *Vp/Vs* is also very sensitive to the silica content of volcanic rocks (Christensen, 1996). On a general note, the velocity ratio usually depends on porosity, degree of consolidation, silica content, clay content, differential pressure, pore geometry, partial melting and other factors.

Over the past years, not much progress have been made on understding the velocity of seismic waves in the Nigerian crust and the uppermantle. This is as a result of unavailability of earthquake data that can be used to carry out studies on the physical properties of the interior of the earth. Earthquake seismic data made availlable from 2009 by NNSS and coupled with the occurrence of low magnitude earthquakes in Nigeria, have awaken the interest of geoscientists in the country to study the physcical properties of the earth interior. Also Nigerian students at undergraduate and postgradute levels have begun research in earthquake seismology. Some notable research on the physical properties of the earth interior in Nigeria using earthquake data, are Yakubu *et al* (2012), Isogun *et al* (2013), Akpan *etal* (2016) and Afegbua and Ezomo (2016).

In this study, we carried out an estimation of the *Vp/Vs* ratio of the crust and the uppermost mantle using earthquake data on some local earthquakes from seismic stations located across Nigeria. The result of the study will enable earthquake scientists to determine epicenters of local earthquakes within and around the country accurately with minimal errors and carry out seismic data analysis involving *Vp/Vs* ratio.

2. Geology and Tectonic Setting of Nigeria

The Nigerian geology is almost equally divided between the Crystalline Basement and Cretaceous to Quaternary sediments and volcanics (Fig. 1). The basement complex is divided into two provinces – Westernand the Eastern provinces (Ajibade *et al*., 1979). The Western province is west of longitude 8º, characterized by N-S to NNE-SSW trending schist belts separated from one another by migmatite, gneiss and granites. The schist belts are interpreted differently as small ocean basins (Ajibade and Wright, 1989), in filled rift structures or synclinal remnants of an extensive supra-crustal cover (Ball, 1980). According to Danbatta (2008),the Schist are divided as Older metasedimentary found in SW Nigeria and Younger Metasedimentary found in NW Nigeria. The Eastern province is almost east of longitude 8º and is more nearly NE-SW. The trend changes to ENE-WSW towards Cameroun (Haruna, 2017). The Eastern province is made up of migmatite, gneiss and Pan-African granitoids (Older granites) intruded by the Younger granites of the Jos Plateau. Few occurrences of schist are recorded in Madagali (Hawal Massif), Toungo and Gayam (Adamawa Massif) and Oban Massif in Southeast Nigeria. The Cretaceous to Recent sediments are preserved in structurally controlled basins: Benue, Bida, Chad, Dahomey, Niger-Delta and Illumeden (Sokoto).

The Cretaceous marked the beginning of sedimentation following the development of early rifts that was initiated in early Jurassic. Marine transgression marked by the growth of transcontinental seas and epirogenic movements resulted in the formation and infilling of the many basins flanking the basement high (Haruna, 2017). Periodic sedimentation continued through the Tertiary and Quaternary.

The Precambrian Basement Complex of Nigeria is polycyclic in nature (Ajibade and Fitches, 1988) and has undergone four major Orogenic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2700Ma), Eburnean (2000Ma), Kibaran (1100Ma) and Pan-African(600Ma). The first three cycles are characterized by intense deformation and Isoclinal folding accompanied by regional metamorphism which was further followed by extensive migmatization. The PanAfrican deformation was accompanied by regional metamorphism, migmatization and extensive granitization and gneissification.

Following the E-W collision of West African Craton westward moving plate created N-S to NE-SW trending structures parallel to the edge of the West African Craton (Oluyide,1988; Egesi and Ukaegbu, 2010). The effect of these movements is reflected as highly deformed series of multidirectional orientations found in folds, lineaments and faults in the entire Nigerian basement complex which extend to Northern Cameroun (McCurry, 1976; Toteu *et al*., 1990). The latter also observed that N-S and NE-SW structures are presumably associated with the Pan-African Orogeny, pre Pan- African structures are oriented differently to these structures in the basement. Thus, veins and intrusions that are oriented NW-SE may be pre Pan-African. Another feature of the basement complex tectonics is the wide spread occurrences of fractures and are identified as lineaments as silicified sheared rocks and zones, which form as dykes and ridges, also straight channeled streams which exploit the weak zones of the earth. The principal fracture directions in the basement are the N-S, NNE-SSW; NE-SW, NNW-SSE and NW-SE. The N-S fractures are easily identified as prominent scarp surfaces and depressions and assume to control the major N-S following streams.

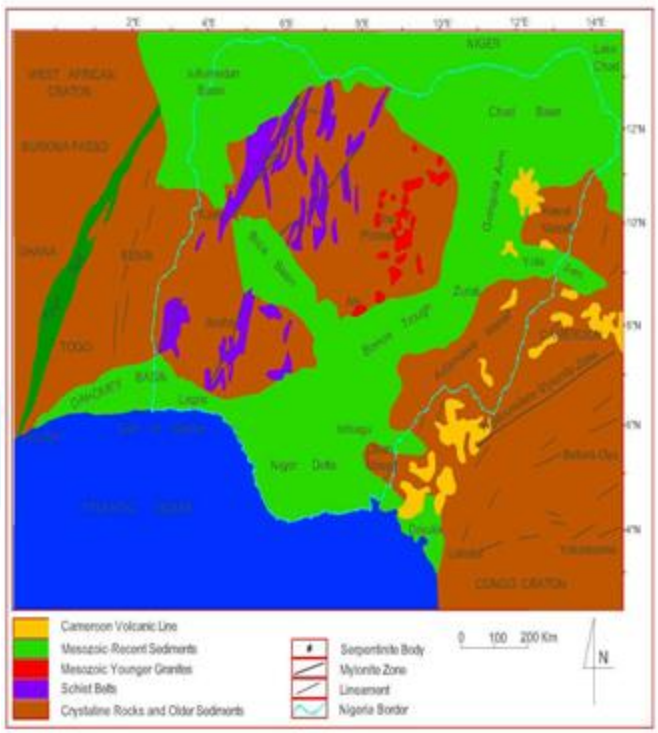

Figure 1. Geologic map of Nigeria and the adjoining areas (After Haruna, 2017).

3. Theory

Considering a seismic wave traveling from the source to a receiver. The travel times of P-wave and S-wave are given as

$$t_p = t_0 + {}^{d}/_{v_p} \quad (1)$$

$$t_s = t_0 + {}^{d}/_{v_s} \quad (2)$$

Where t_p and t_s are the P- and S- arrival times respectively in seconds, $t_o$is the origin time, d is the epicentral distance for surface source or hypocentral distance for deeper source, $v_p$andv_s are the P- and S- wave velocities respectively. Subtracting (1) from (2), we have

$$t_s - t_p = \frac{d}{v_s} - \frac{d}{v_p} \quad (3)$$

$$= \frac{dv_p - dv_s}{v_s v_p} \quad (4)$$

$$t_s - t_p = \frac{dv_p}{v_s v_p} - \frac{dv_s}{v_s v_p} \quad (5)$$

$$= \frac{v_p}{v_s} t_p - t_p \quad (6)$$

$$t_s - t_p = \left(\frac{v_p}{v_s} - 1\right) t_p \quad (7)$$

A plot of t_s-t_p against absolute t_p using local or rigional earthquake data gives a straight line graph (Wadati diagram) where the *Vp/Vs* ratio can be determined as

$$\frac{v_p}{v_s} = m + 1 \quad (8)$$

where *m* is the slope of the line of best fit.

4. Data and Methodology

The data for this study were obtained from the records of NNSS (Fig. 2). The NNSS comprises of 7 sesimic stations located in south west, south east, north west, north central and north east of Nigeria operated from 2009 till date. Data on four earthquakes that occurred 11th September 2009, 11th and 12th September, 2016 (Fig. 3, Fig. 4 and Fig.5) in Nigeria were used for the study. The three existing seismic stations in 2009 recorded the 11th September 2009 and four seismic stations recorded the three earthquakes of 11th and 12th September, 2016.

The time of first arrivals of P-wave and S-wave mainly P_g and S_g(direct crustal phases of S and P) or $P_n$and S_n(head waves critically refracted at the Moho discontinuity or waves diving as body waves in the uppermost part of the upper mantle) depending on the epicentral distance of the events, were obtained and the time difference between the P and S time arrivals were computed. A graph of S-P time difference against the absolute P-wave arrival times for each earthquake at each seismic station was plotted.. The line of best fit of the graph was determined using least square method and its slope was also calculated. The coefficient of determination, R^2, of the datasets from the line of best fit was calculated to have idea of the numbers of the data points that fall within the results of the line formed by the regression equation. The *Vp/Vs* ratio was then calculated using (8). The regional *Vp/Vs* ratio was calculated as the average of the *Vp/Vs* ratios obtained for all the four earthquakes.

In picking the first arrivals of the P- ans S- waves for all the seismic stations, their travel times were plotted to identify which of the arrival times waspoorly picked.

Figure 2: Map of Nigeria showing locations of Seismic stations (red triangle) and some cities (green circle).

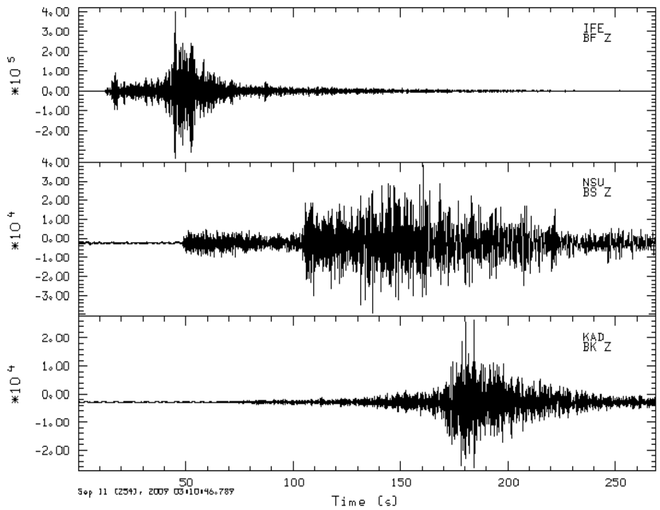

Figure 3: Seismogram of 11 September, 2009 earthquake in southwest Nigeria.

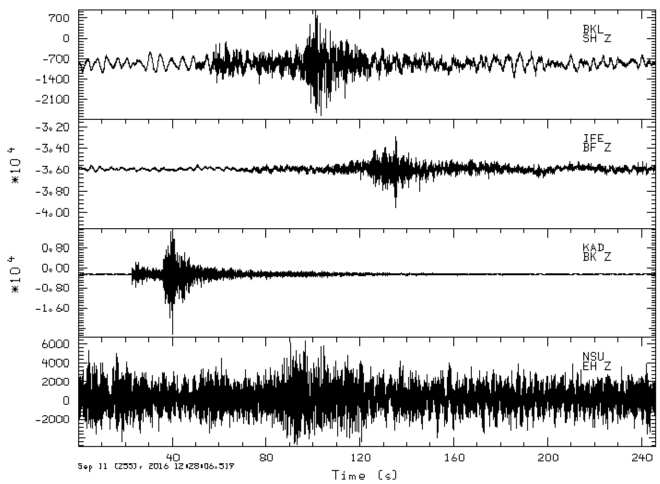

Figure 4: Seismogram of 11 September, 2016 earthquake in Kwoi, Kaduna State, norththwest Nigeria showing the vertical components.

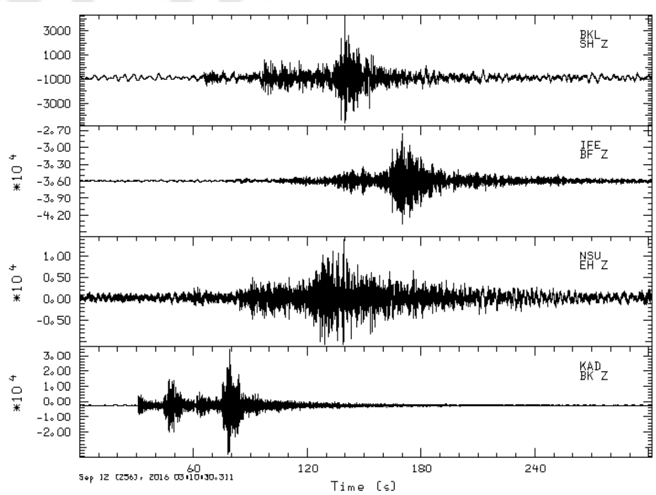

Figure 5: Seismogram of two earthquakes in Kwoi, Kaduna State, norththwest Nigeria on 12th September, 2016

5. Results and Discussion

The P- and S-waves first arrival times are shown in Table 1, Table 2, Table3and Table 4 and their respective plots are shown in Fig.6, Fig. 7, Fig. 8 and Fig.9.

Table 1: P- and S-Wave Arrival Times of 11 September, 2006Earthquake in Southwestern Nigeria

Station Code	P-Wave First Arrival Time (HRMM SEC)	S-Wave First Arrival Time(HRMM SEC)
IFE	310 58.95	311 26.80
NSU	311 35.13	312 30.57
KAD	311 55.12	313 5.43

Table 2: P- and S-Wave Arrival Times of 11 September, 2016 Earthquake in Kwoi, Northeastern Nigeria

Station Code	P-Wave First Arrival Time(HRMM SEC)	S-Wave First Arrival Time (HRMM SEC)
KAD	1228 29.23	1228 42.35
NSU	1228 50.83	1229 20.40
BKL	1228 58.05	1229 33.08
IFE	1229 11.51	1229 56.56

Table 3: P- and S-Wave Arrival Times of 12 September, 2016 Earthquake in Kwoi, Northeastern Nigeria

Station Code	P-Wave First Arrival Time (HRMM SEC)	S-Wave First Arrival Time (HRMM SEC)
KAD	311 0.85	311 14.62
NSU	311 22.38	311 54.65
BKL	311 28.62	312 5.26
IFE	311 44.14	312 30.61

Table 4: P- and S-Wave Arrival Times of 12 September, 2016 Earthquake in Kwoi, Northeastern Nigeria

Station Code	P-Wave First Arrival Time (HRMM SEC)	S-Wave First Arrival Time (HRMM SEC)
KAD	311 31.75	311 45.21
NSU	311 54.25	312 24.25
BKL	312 0.78	312 35.86
IFE	312 14.65	313 0.71

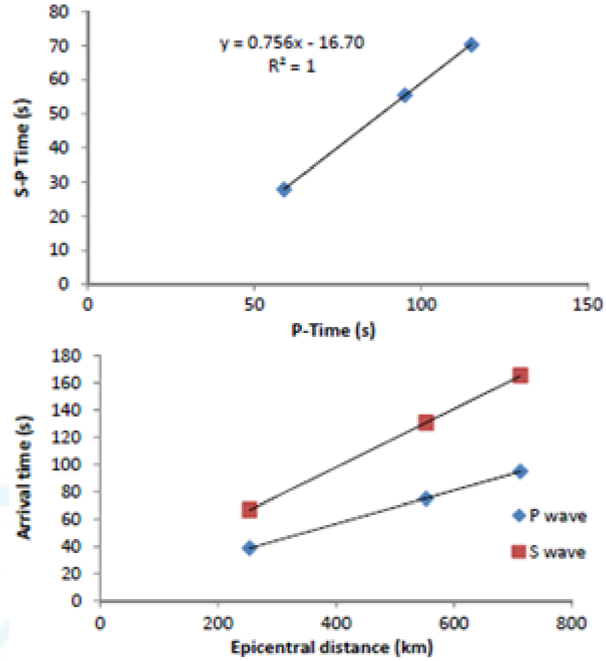

Figure 6. Plots of waves arrival times analysis of 11 September, 2009 earthquake in Southwestern Nigeria.Wadati diagram (above) and Travel time (below).

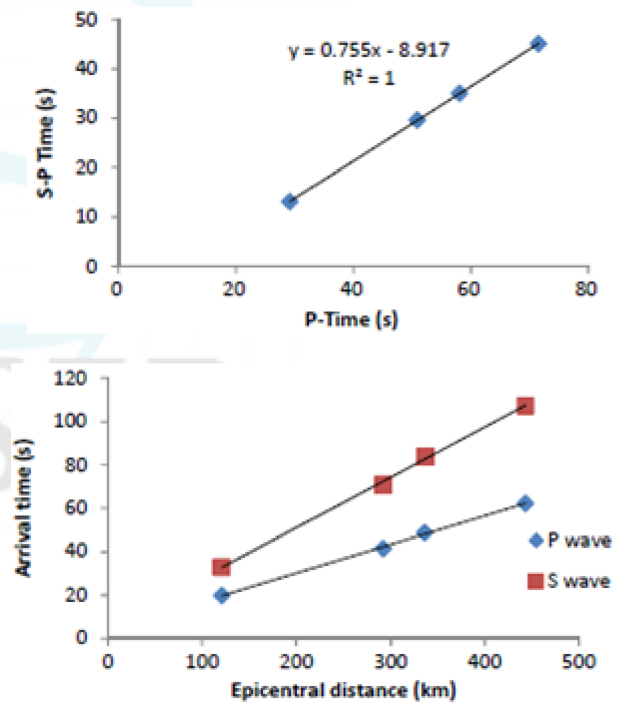

Figure 7: Plots of waves arrival times analysis of 11 September, 2016 earthquake in Kwoi, Kaduna State, Northwestern Nigeria.Wadati diagram (above) and Travel time (below).

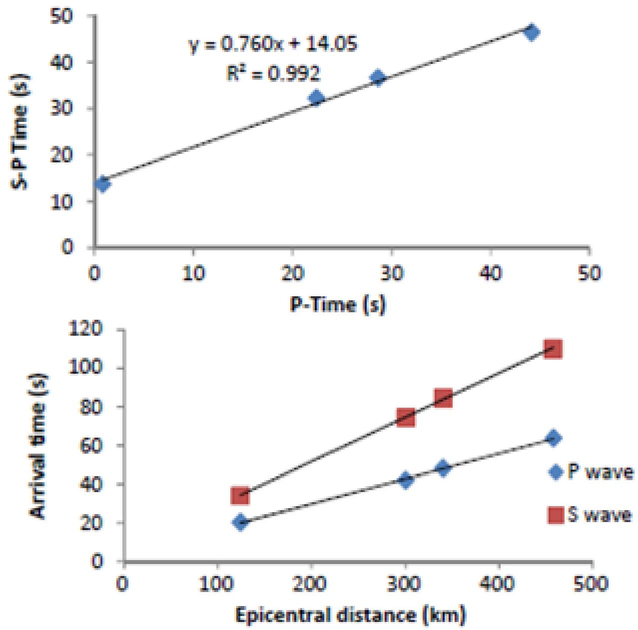

Figure 8: Plots of P- and S-waves arrival times analysis of 12 September, 2016 earthquake in Kwoi, Kaduna State, Northwestern Nigeria. Wadati diagram (above) and Travel time (below).

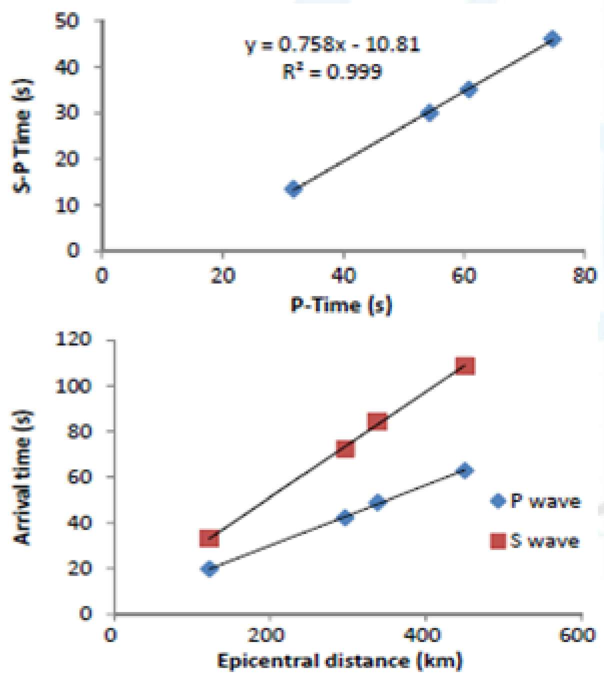

Figure 9: Plots of P- and S- waves arrival times analysis of 12 September, 2016 earthquake in Kwoi, Kaduna State, Northwestern Nigeria. Wadati diagram(above)and Travel time (below)

The slopes of line of best fit from Fig. 6, Fig. 7, Fig. 8 and Fig. 9 are respectively 0.756, 0.755, 0.760 and 7.58. The *Vp/Vs* ratio derived from the earthquakes 11 September, 2009, 11 September, 2016 and the two earthquakes of 12 September, 2016 are respectively 1.756, 1.755, 1.760 and 1.758. The R^2 of the line of best fit for the four graphs are 1, 1, 0.992 and 0.999 respectively and these show that the regression lines perfectly represent the sets of data points and therefore the slopes of the plots are reliable. The difference in the *Vp/Vs* ratios shows the anisotropic properties of the earth medium through which the seismic waves pass.

The average of the four velocity ratios is 1.76 and is taken to be the *Vp/Vs* ratio for the crust and the uppermost mantle of Nigeria. According to Stewart*et al* (1997) the average *Vp/Vs* value is the transit-time weighted sum of interval velocity ratios of a layered medium. Therefore 1.76 is the weighted average of velocity ratios (*Vp/Vs*)for seismic waves traveling from the uppermost mantle through the different layers of Nigerian crust. Akpan *et al* (2013) had earlier estimated the *Vp/Vs* ratio to be 7.2 using data from 11 September, 2009 earthquake only but this study used data from four local earthquakes and as such the *Vp/Vs* ratio of 1.76 is an improvement on the earlier value.

According to Finotello (2011), typical *Vp/Vs* values for different lithologies are on average ≈ 1.70 for felsic rocks (i.e granite), ≈1.76 for intermidiate rocks (i.e diorites) and ≈1.84 for mafic rocks (i.e basalt). The *Vp/Vs* value of 1.76shows that bulk Nigerian crustal and the uppermost mantle lithologies on the average are of intermidiate rocks which implies that the crustal compositions have not been significantly changed by mafic magmatism. The *Vp/Vs* ratio of 1.76 compares to the average *Vp/Vs* ratio of 1.75 for Pan African crust in East Africa that has not been affected by Cenozoic rifting, obtained by Dugba *et al* (2005).

6. Conclusion

The *Vp/Vs* value for the Nigerian crust and the uppermost mantle has been estimated to be 1.76 using data on four local earthquakes from Nigerian Network of Seismographic Stations. This value can be used in determining the epicenters of local earthquakes in Nigeria and estimating *Vp* or *Vs* in crustal or upper mantle velocity structure. However, this result can be refined further with more seismic stations and local earthquakes within and around Nigeriato minimise likely errors in the *Vp/Vs* value.

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