The crustal and the upper mantle structure of southwestern Nigeria from inversion of teleseismic surface waves

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ABSTRACT

No detailed information has been provided on the shear-wave velocity structure of the crust and the upper mantle of Nigeria till-date. In this study, the depth distribution of seismic wave velocities over southwestern Nigeria was determined using teleseismic surface waves of different azimuths recorded by our 3-component broadband station between November 2009 and 2011. The group velocities of Rayleigh and Love waves with surface wave magnitude ≥ 6.0 in the period range of 16 – 100 s were inverted for plane-layered earth shear-velocity structure. The shear-wave velocity of the crust increases gradually from about 3.12 to 4.29 km/s. The Moho was found at the depth of 40 km. The upper mantle shear-velocity increases from about 4.37 to 4.5 km/s between the depths of 40 and 73 km and a low velocity layer between the depths of 73 km and 238 km with shear-wave velocity of 4.01 – 4.47 km/s. An average values for the crust and the upper mantle velocities have been assumed over southwestern Nigeria from seismic data of a single seismic station within this region, however, further studies using data from many stations when available in this area will help to improve on the result of this study.

Keywords: shear-wave velocity, group velocity, P velocity, Moho, teleseismic surface wave

1 INTRODUCTION

Seismic activities are not pronounced in Nigeria except for the few tremors recorded most especially in the southwestern part of the country [1],[2],[3]. Probably as a result of this relative seismic stability, there have not been seismological observatories with long-established tradition of data collection. But recently, due to the menace of earthquakes and the subsequent global attention given to it, the Federal government of Nigeria has established seismic stations in some part of the country managed by Centre for Geodesy and Geodynamics, Toro, Bauchi State. Also individual research institutions now have seismic stations. One of these is the seismic station in Obafemi Awolowo University, Ile-Ife, managed by the Department of Geology. With this evolving interest in earthquakes, it has afforded us an opportunity to carry out studies using these sets of data acquired over a period of time.

Epicentres and other seismic information on tremors that have been felt in Nigeria in past years have not been provided. This is majorly because there have not been functioning seismic stations within the country and even when seismic data are available, P wave velocity structure of the crust and upper mantle of Nigeria for locating local earthquakes is not known. This study intends to determine the shear-wave velocities structure for both the crust and part of the upper mantle in the southwestern part of Nigeria (Fig. 1) using surface waves from teleseismic events so as to be able to determine epicentres of local earthquakes on which other seismic information depends.

2 GEOLOGY OF THE STUDY AREA

The geology of the study area is made up of the Precambrian basement complex and the Cretaceous to Recent sedimentary rocks (Fig. 2).

The sedimentary rock of the study area partly constitutes the Dahomey Basin and the Niger Delta. Dahomey basin is a layered rock sequence which extends from Southern Ghana to the western flank of the Niger Delta [4],[5]. The sedimentary rocks consist of Abeokuta formation, the oldest of the formations, which overlies directly the basement rocks. Abeokuta formation consists of sands and clay and is Cretaceous in age. Ewekoro Formation which is Paleocene in age lies conformably on the Abeokuta Formation. It consists of limestone and shale member. The Ilaro Formation lies on top of the Ewekoro Formation. It is dated Eocene in age and has lithology consisting of sand and sandstone with clay fractions and shale. The Ilaro Formation is about 70 m thick and shows rapid lateral facies changes that characterize the formation. The coastal plain sand probably lies uncoformable upon Ilaro Formation. This stratigraphic unit is Pleistocene to Oligocene in

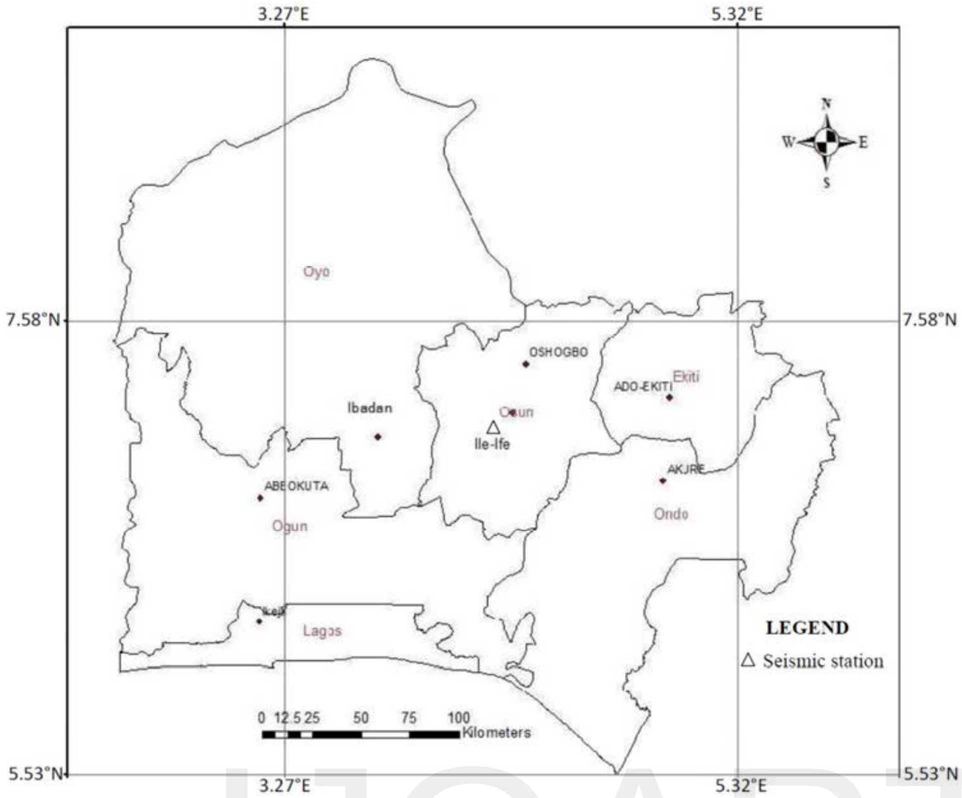


Fig. 1. Map of Southwestern Nigeria showing seismic station at Ile-Ife

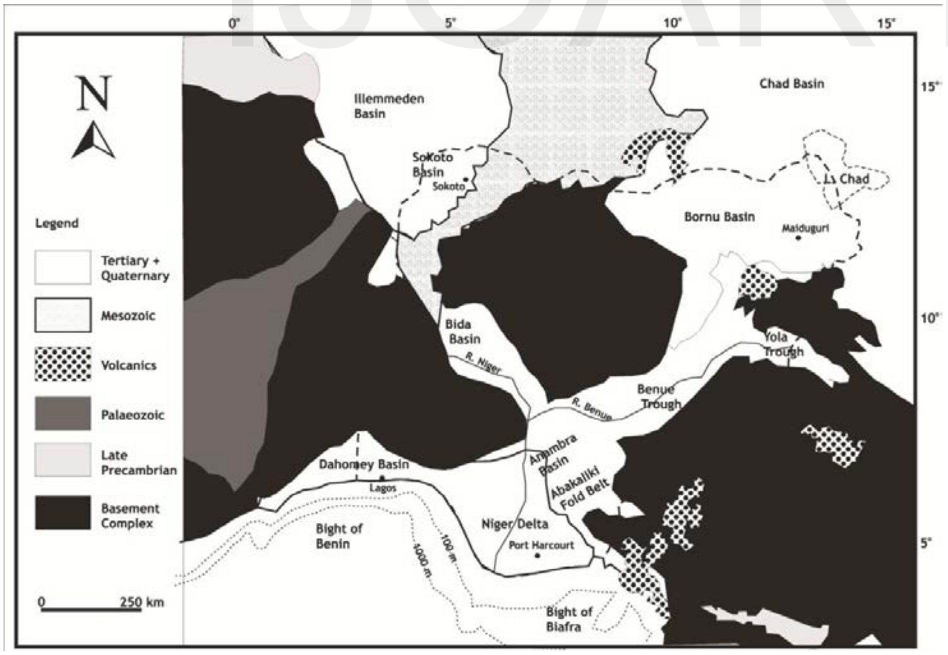


Fig. 2. Simplified geologic map of Nigeria and surrounding areas showing main drainage into the Gulf of Guinea [6].

age and it consists of poorly sorted, loosely consolidated sands, sandy clay bands with intercalation of clay lenses. Its thickness varies from place to place. Along the lower courses and around the mouth of rivers are recent alluvial deposit consisting of coarse, clayey unsorted sand and occasionally there are pebble beds. Recent deposits also include littoral and lagoon deposits n areas where land is opened to the coastal creeks, lagoons and the Atlantic Ocean [4]. The Niger Delta is situated in the Gulf of Guinea and extends throughout the Niger Delta Province as defined by [7]. southwestward, forming depobelts that represent the most active portion of the delta at each stage of its development [8]. These depobelts form one of the largest regressive deltas in the world with an area of some 300,000 km^2 [9], a sediment volume of 500,000 km^3 [10], and a sediment thickness of over 10 km in the basin depocenter [11]. The onshore portion of the Niger Delta Province is delineated by the geology of southern Nigeria and southwestern Cameroon. The northern boundary is the Benin flank – an east-northeast trending hinge line south of the West African basement massif. According to [12], the Niger Delta basin consists of three formations – Akata, Agbada and Benin Formations. Akata Formation is a marine sedimentary sequence dated between Eocene to Recent conformably overlay the basement. Agbada Formation which consists of alternating sandstones and shales of the delta-front dated Eocene to Pliocene overlay conformably on Akata Formation. Benin formation is the topmost unit of the Niger delta and is dated Oligocene to Recent. It consists of predominantly massive, highly porous, freshwater-bearing sandstones, with local thin shale interbeds which are considered to be of braided-stream origin [13].

The Precambrian crystalline basement complex of southwestern Nigeria is part of the basement complex of Nigeria [14]. According to [15], the Nigeria basement complex consists of migmatite-gneisses-quartzite complex; slightly migmatised to non-migmatised meta-sedimentary and meta-igneous rocks; charnockitic gabbroic and dioritic rock; members of the older granite suits; metamorphosed to unmetamorphosed calc-alkaline volcanic and hyperbysal rocks and unmetamorphosed dolerite, basic and syenite dykes. The basement of southwestern Nigeria lies within the western province of Pan-African belt. According to [16], most of its crustal rocks evolved by ensialic processes during the Kibaran Orogeny. However, [17] opined that the crustal rocks of southwestern Nigeria evolved by plate tectonic processes during the late Proterozoic which resulted from the crustal extension and continental rifting at the West African craton magin.

3 DATA SELECTION

The focus in this study is the surface waves part of seismogram with pronounced dispersion . The appearance of seismograms is distance dependent and partly dependent on the magnitude of the events. The further an earthquake travels, the more high frequency energy is filtered away and the signals appear to contain more low frequencies. At large distances, recording an earthquake requires a certain minimum magnitude and large events at teleseismic distance generate relatively more low frequency energy than small earthquakes. Since interest is on these low frequency (16 – 100 s) signals, only teleseismic events that met the selection criteria were used. More than 600 events were recorded between year 2009 and 2011 but ten teleseismic events from different azimuths to the receiver were finally used for the study. The first selection criterium was based on the size of the surface wave magnitude of the earthquakes. Only events with $M_s \geq 6.0$ were considered. Secondly, events with epicentral distance < 25° were not considered because they are typically small and poorly dispersed and also very distant events (> 105°) were as well neglected because of their multi-pathing effects. Thirdly, earthquake seismograms with low signal to noise ratio were avoided. Figure 3 shows the location of the station and the epicentres of the ten earthquakes. Table 1 gives the summary of the information on the events. Figure 4 shows two of these long-period surface waves.

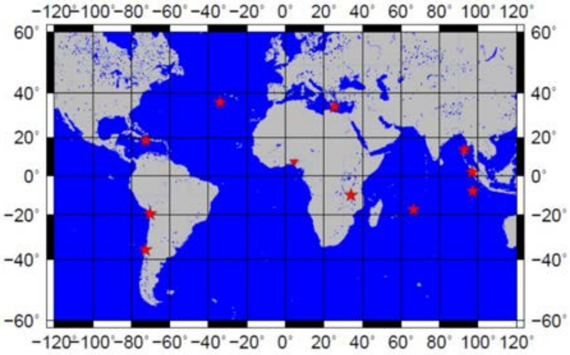


Fig. 3. Location of seismic station (triangle) in Obafemi Awolowo University (OAU) and earthquake epicenters (stars).

4 DATA PROCESSING

Analysis of the data was preceded with some basic processing tools. The first processing technique applied was the removal of the contributory effects of each element of the seismograph. In achieving this, the seismograms were deconvolved with the instrument response and the corrected seismograms were transformed to velocity seismogram in m/s. Secondly, The horizontal components of the deconvoled seismograms were rotated to obtain the radial component from N-S component and transverse component from E-W component (Fig. 5). Thirdly, the resulting waveforms were tapered, low-pass filtered and decimated to 0.25 sec.

5 GROUP VELOCITY DETERMINATION

Group velocity is the horizontal apparent velocity of surface wave and is the velocity at which a wave group visible on a seismogram travels [18]. The velocity of surface waves in layered media is a function of the frequency or period. Thus for an impulsive time function at the source, surface waves at distances are formed by trains of waves or group of waves [19]. The velocity of each group of waves is given as:

$$U = \frac{dw}{dk}, \tag{1}$$

Table 1. Information on earthquakes used for the study showing epicenters, Ms, depth and epicentral distance

S/N	ORIGIN TIME (GMT)	LATITUDE (°)	LONGITUDE (°)	Ms	DEPTH (Km)	DISTANCE TO STATION (km)
1	2009 07 01 09:30:11	34.1	25.4	6.3	30	3641
2	2009 09 02 07:55:01	-7.8	107.3	6.2	49	11528
3	2009 10 12 03:15:46	-17.2	66.6	6.1	10	7353
4	2009 11 04 18:41:44	36.1	-33.9	6	10	5022
5	2009 11 13 03:05:55	-19.4	-70.2	6.3	10	8713
6	2009 12 19 23:19:23	-9.9	34	6.1	47	3792
7	2010 01 12 21:53:09	18.4	-72.4	7.4	10	8380
8	2010 02 27 06:34:14	-35.9	-72.7	8.5	35	9362
9	2010 03 30 16:54:48	13.6	92.9	6.1	45	9646
10	2010 04 06 22:15:02	2.2	97	7.6	48	10257

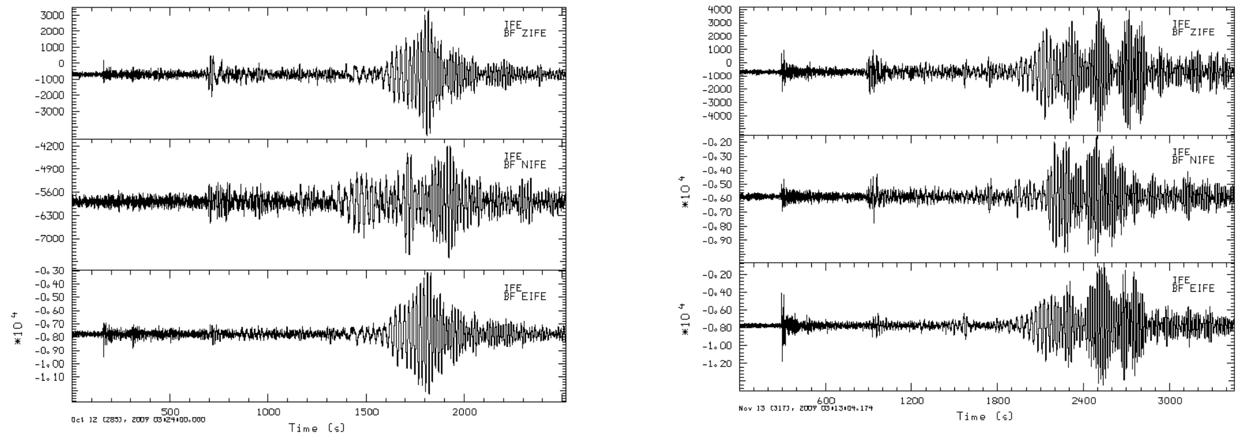


Fig. 4. Seismogram recorded on 3-component seismometer at Obafemi Awolowo University, Ile-Ife for the (left) Mauritius-Reunion region earthquake of 12 October, 2009. Epicentral distance for this event is 7353 km, (right) Northern Chile earthquake of 13 November, 2009. Epicentral distance for this event is 8713 km. ZIFE, NIFE and EIFE are respectively vertical, north-south and east-west components.

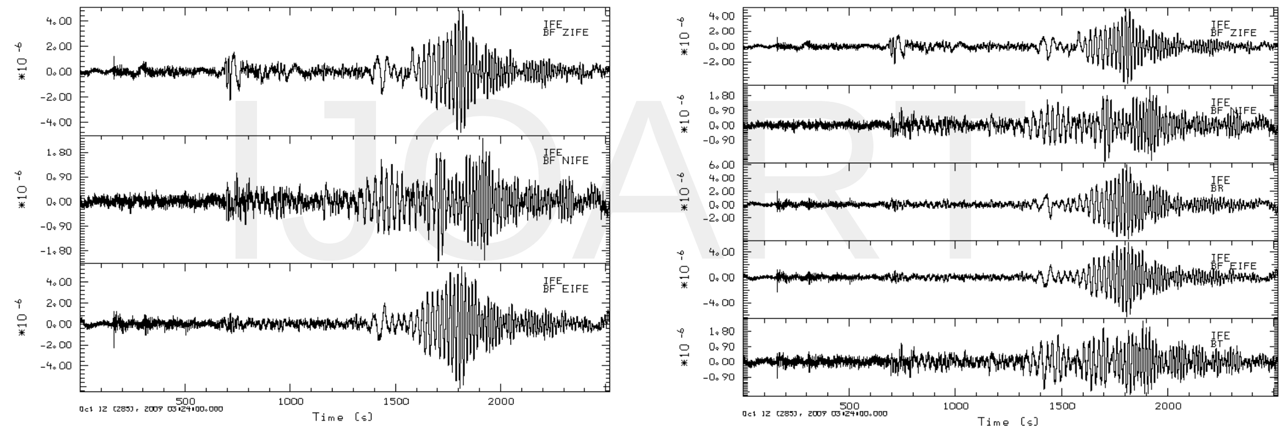


Fig. 5. Velocity Seismogram for the Mauritius-Reunion region earthquake of 12 October, 2009 (right) after removal of instrument response (left) after removal of instrument response showing radial and transverse components

where *w* is angular frequency and *k* is wave number. At a single station, the group velocity can be determined from the record of surface waves. If instrumental phase shift ϕ is corrected, according to [19], the phase Φ is given as:

$$\Phi = kx - wt + \phi \pm \pi/4 \qquad (2)$$

On taking the derivative with respect to *w*, and solving for *U*, equation (3) will be obtained.

$$U = \frac{x}{\frac{d\Phi}{dw} + \frac{d\phi}{dw} + t}. \qquad (3)$$

For a stationary phase dΦ/d*w* = 0 and $w = w_0$. Assuming that the initial phase does not depend on frequency, the group velocity for each instantaneous frequency w_0 is

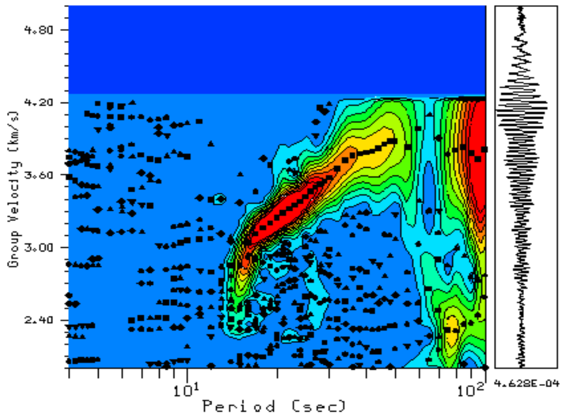
$$U(w_0) = \frac{x}{t(w_0)}. \qquad (4)$$

Equation 4 shows that group velocity $U(t_0)$ for each period can be determined by measuring time of arrivals from peak to peak and dividing epicentral distance by each arrival time. Fourier analysis of seismograms which involves the application of a band-pass filter centered on a frequency that takes various value can be used to isolate the wave groups at different frequencies or period [20].

The group velocities of this study were obtained using the multiple-filter method [21].The fundamental-mode of group velocities for both Rayleigh and Love waves were determined using interactive software *do_mft* developed by [22]. Figures 6 and 7 show the group velocity estimation for two seismograms.

6 SURFACE WAVE INVERSION

The group velocities of the fundamental mode of Rayleigh and Love waves were isolated from the different dispersion curves and their combined group velocities in the period range of 16 – 100 s were inverted separately for plane-layered shear- wave velocity structure of the crust and the upper mantle of southwestern Nigeria following the method described by [23] and [24]. Multiple flat-layered earth over a half-space earth model with constant S-wave and P-wave velocities was used. A total depth of 278 km was investigated. A linearized least-squares inversion program *surf96* [22] was used to carry out joint inversion of the group velocities for the Rayleigh and Love waves. In carrying out the inversion, we started with a velocity model in which the thickness of each earth layer was kept constant and S-wave velocities were allowed to vary. A total of 30 iterations for the inversion process were performed and a velocity model with highest percentage of fit was adopted. Figures 8 and 9 show the Share-wave velocity structure obtained from combined inversion of Rayleigh and Love waves group velocities for four events.



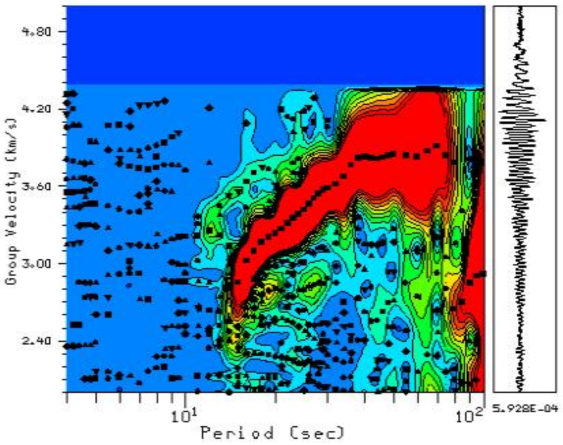


Fig. 6. Dispersion curve obtained from Multiple Filter Analysis of Tanzania event of 19 December, 2009 recorded at OAU (top) vertical component and (bottom) transverse component. The trace to the right is that obtained after band-pass filtering of the original signal using a Gaussian filter.

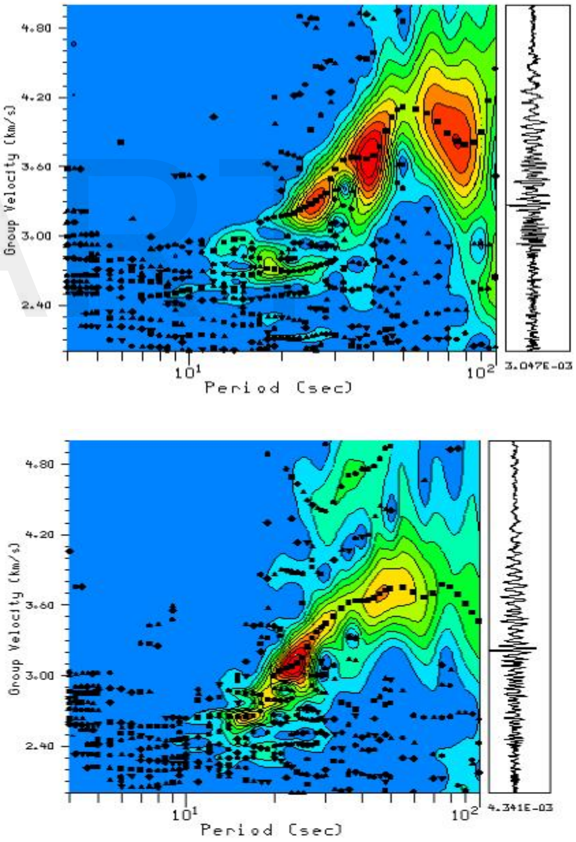


Fig. 7. Dispersion curve obtained from Multiple Filter Analysis of Crete, Greece event of 1 July, 2009 recorded at OAU (top) vertical component and (bottom) transverse component. The trace to the right is that obtained after band-pass filtering of the original signal using a Gaussian filter.

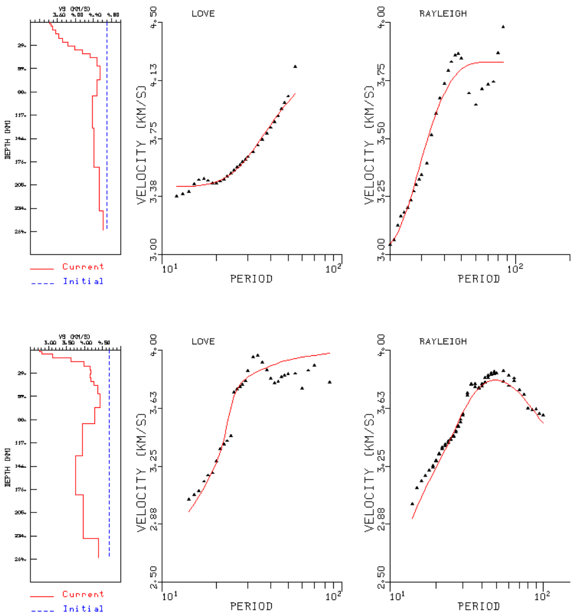


Fig. 9. Share-wave velocity structure (solid line) at OAU obtained from combined inversion of Rayleigh and Love wave group velocities of (top) Tanzania earthquake of 19th December, 2009, rms velocity perturbation = 0.00096 (bottom) Mauritius-Reunion earthquake of 12th October, 2009, rms velocity perturbation = 0.0014. Dispersion data are the indicated symbols and the solid curves are the predicted model.

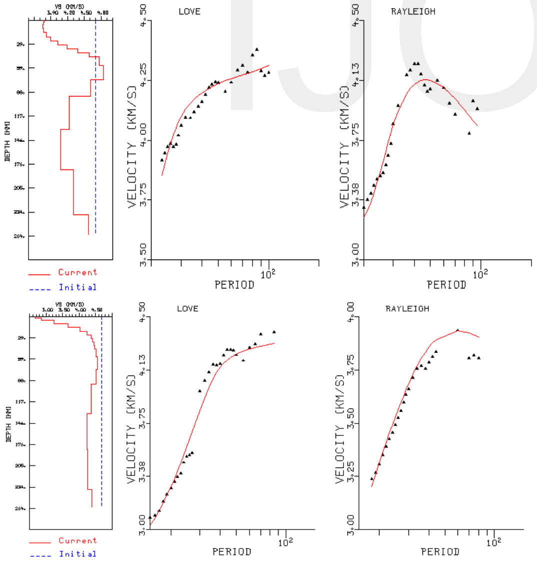


Fig. 10. Share-wave velocity structure (solid line) at OAU obtained from combined inversion of Rayleigh and Love wave group velocities of (top) Haiti earthquake of 12th January, 2010, rms velocity perturbation = 0.0018 (bottom) Northern Sumatra, Indonesia earthquake of 6th April, 2010, rms velocity perturbation = 0.0037. Dispersion data are the indicated symbols and the solid curves are the predicted model.

7 RESULTS AND DISCUSSIONS

The inversion of group velocity of surface waves presents a 1-D velocity-earth model over the seismic station. For the purpose of this study, the same velocity-earth model was used for the inversion of the group velocities of the surface waves from the 10 different earthquakes and a simple average of the velocities across each earth layer was used as a representative velocity for each earth layer. The reason for this is to minimise the effects of the path (continental, oceanic or both) of the seismic waves. The results of the group velocities inversion for the ten teleseismic events used for this study with their respective standard deviations for each earth layer are presented in Table 2.

The shear-wave velocity values for the 10 different models (Table 2) show that there is similar trend for the majority of the models for both velocity increment and decrement for all the earth layers. For example the first 12 layers, that is, down to the depth of 73 km, velocity increases and from this depth downward velocity decreases except for velocity models of earthquakes from Northern Chile and Central Chile where velocity started decreasing from the depth of 93 km and 40 km respectively. Considering the absolute velocity values of the different models, there are disparities in the velocity values for each layer of the earth for the models and this is as a result of the effects of the path of the seismic waves. Each wave travels to the seismic station through different paths crossing different geologic units with different mineralization of different velocity gradient. This account for why in this type of work, seismic data are usually collated from different azimuth preferably from all the sides of seismic station and an average model is used as a representative model for a region.

The precision of the results of these models when compared can be adjudged reasonable considering the fact the mean standard deviation is 0.2 km/s. The standard deviations for the majority of the earth layers are less than 0.2 km/s with the exception of the first three layers and the 15th and 16th layers which vary between 0.30 and 0.41 km/s and this implies that within the first 15 km of the crust there is a relatively high lateral heterogeneity of crustal composition and as we move down into the crust, lateral heterogeneity decreases. Also lateral heterogeneity is also well pronounced between the depth of 133 km and 238 km depth and this is in agreement with the concept that the upper mantle contains relatively high lateral heterogeneity which is primarily associated with temperature variations [18].

The average velocity model for the ten analyzed earthquake data is shown in Figure 11. It shows that the S-velocity increases from 3.12 to 4.52 km/s down to the depth of 73 km and from this depth,

Table 2. Results of Surface Wave Group Velocity Inversion

DEPTH (km)	S-WAVE VELOCITY (km/s)										
	AZORES ISLAND	CENTRAL CHILE	NORTHERN CHILE	CRETE GREECE	HAITI	ANDAMAN INDIA	JAWA INDONESIA	SUMATRA INDONESIA	MAURITIUS REUNION	TANZANIA	AVERAGE ±0.21
2	3.002	3.072	3.101	2.484	3.776	3.528	3.35	2.665	2.765	3.42	3.1163±0.41
5	2.886	2.997	2.947	2.549	3.762	3.607	3.316	2.864	2.807	3.449	3.1184±0.39
10	3.002	3.088	2.973	2.947	3.753	3.714	3.36	3.235	3.117	3.497	3.2686±0.30
15	3.446	3.462	3.345	3.406	3.772	3.757	3.567	3.672	3.626	3.553	3.5606±0.15
20	3.86	3.866	3.756	3.701	3.82	3.745	3.828	4.024	3.996	3.623	3.8219±0.12
25	4.109	4.165	4.048	3.883	3.901	3.751	4.067	4.248	4.155	3.716	4.0043±0.18
30	4.207	4.331	4.19	4.008	4.022	3.835	4.253	4.363	4.177	3.841	4.1227±0.19
35	4.225	4.393	4.222	4.105	4.183	4.002	4.385	4.415	4.165	3.991	4.2086±0.15
40	4.233	4.394	4.208	4.2	4.375	4.214	4.475	4.447	4.185	4.157	4.2888±0.11
45	4.273	4.367	4.208	4.305	4.577	4.421	4.53	4.483	4.256	4.324	4.3744±0.12
55	4.356	4.335	4.258	4.421	4.764	4.581	4.56	4.528	4.361	4.475	4.4639±0.15
73	4.468	4.301	4.404	4.504	4.841	4.613	4.551	4.571	4.439	4.555	4.5247±0.14
93	4.405	4.202	4.46	4.353	4.618	4.473	4.502	4.526	4.281	4.488	4.4308±0.12
133	4.095	3.972	4.216	3.93	4.22	4.276	4.46	4.379	3.936	4.374	4.1858±0.19
183	3.821	3.731	3.797	3.544	4.069	4.203	4.525	4.238	3.762	4.413	4.0103±0.33
238	4.027	3.889	3.864	3.739	4.3	4.315	4.644	4.256	3.957	4.536	4.1527±0.30
Below	4.46	4.327	4.41	4.281	4.569	4.51	4.72	4.393	4.386	4.624	4.468±0.14

S-velocity decreases to 4.01 km/s down to the depth of 183 km. From the depth of 183 km to 238 km depth, velocity increases to 4.47 km/s. Velocity increment between the first three layers is very small but from the third layer through the fifth layer, the increment in velocity is relatively high. From the fifth layer through the twelvefth layer, velocity increment reduced. For Moho determination, the shear-wave velocity crust-mantle transition is usually fixed at 4.2 – 4.4 km/s [25],[26],[27]. Applying this, the crust-mantle transition can therefore be said to occur at about 35 km or 40 km where there is an increase in velocity to 4.29 km/s and 4.37 km/s respectively. The velocity contrast between the two possible transition zones are approximately 0.08 and 0.085 km/s respectively which shows that at depth 40 km velocity contrast is higher. The Moho can therefore be said to exist at 40 km depth although judging from the model the Moho is poorly resolved. The crustal velocity ranges from 3.12 to 4.29 km/s and the velocity of part of the mantle investigated ranges from 4.37 to 4.5 km/s. Within the upper mantle there is a distinct low-velocity layer between the depth of 73 km and 238 km depth with shear-wave velocity of 4.01 – 4.47 km/s. This shows that there is low-velocity layer within the upper mantle of southwestern Nigeria which falls within the global low-velocity layer of the upper mantle [18].

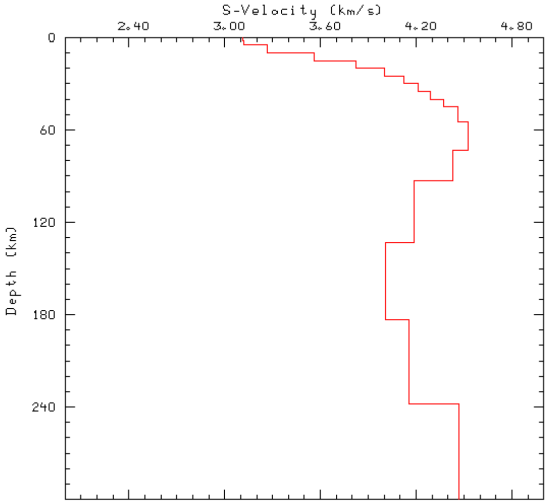


Fig. 11. Shear-wave velocity structure for southwestern Nigeria

8 CONCLUSION

The 1-D velocity-earth model of thickness 238 km was obtained for the investigated area in southwestern Nigeria. The crust is 40 km thick with velocity range of 3.12 to 4.29 km/s and the velocity of part of the mantle investigated ranges from 4.37 to 4.5 km/s. The mantle has a distinct low-velocity layer between the depth 73 km and 238 km depth with shear-wave velocity of 4.01 – 4.47 km/s. Considering the fact that over a region, the lateral variations in seismic velocities are negligible, this result has been considered as the shear-wave velocity model for southwestern Nigeria. This model can be used to locate earthquakes within and around Nigeria. The dataset for this study is however limited and it may not be able to minimise to a large extent the effects of seismic wave path. But because of the distribution of earthquakes used for this study, in almost all the sides of the seismic station, the result of the study can be considered reasonable. However, further studies using data from many earthquakes or seismic stations when available in this area will help to improve on the result of this study.

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