IC/95/351

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MIRAMARE – TRIESTE
October 1995

ABSTRACT

The non–linear inversion technique known as hedgehog is utilized to define the average crustal structure of North and North–Eastern Ethiopia. To accomplish the task a two dimensional frequency–time analysis is performed to obtain Rayleigh wave group velocity dispersion curves. Six earthquakes recorded by the broad-band digital seismograph installed at the Geophysical Observatory of Addis Ababa University are utilized. The crustal structure between the Gulf of Tadjura (western Gulf of Aden) and Addis Ababa crossing southern Afar (path I) can be approximated by a total thickness of about 22 km with average S–wave velocity in the range 2.3 - 3.9 km/s. The crust–mantle transition is poorly developed at greater depths and the shear wave velocity ranges from 4.0 km/s to 4.3 km/s. If the effect of the plateau part is taken into account the average total crustal thickness is found to be less than 18 km and the average S–wave velocity varies in the range 2.4 - 3.9 km/s. The low shear wave velocity under the Afar crust is consistent with the result of other geophysical studies. For path II, which passes through the border of the Western Ethiopian plateau, the average crustal structure is found to be approximated by a thickness of about 40 km and average S–wave velocity between 3.0 km/s and 3.9 km/s. The crust overlies a lithospheric mantle with a shear wave velocity in the range 4.1 - 4.4 km/s.

1. INTRODUCTION

The geological history of Ethiopia and its neighbouring countries indicates that in early Tertiary it became the site of intense magmatic and tectonic activity that has continued to the present day. From early Tertiary until the end of the Eocene period extensive vertical uplift took place with the eventual splitting of the crust into three rift systems - the Red sea, the Gulf of Aden and the Ethiopian Rift (Gass 1970) which are closely connected with (Fig. 1) in a structural and kinematic way (e.g. Mohr 1967; Mohr 1970a,b; McKenzie et al. 1970; Gass 1975; Bonatti 1987; Makris and Ginzburg 1987; Bohannon et al. 1989). These three rift systems meet in the Afar triple junction which is a unique geophysical and geological province. This junction is one of the two areas in the world (the other being Iceland) where crustal spreading, dike injections and the formation of new lithospheric plate material can be observed by geologists (Barberi and Varet 1975, 1977; Berhe 1986). Based on a small-scale plate tectonics model, Barberi and Varet (1975, 1977) proposed within Afar the existence of spreading centres connected by transform faults. This, in turn, led to the identification of several micro plates which move relative to each other. On the other hand, Berhe (1986) argued that the Afar depression and its neighbouring regions are experiencing an extensional tectonics due to spreading and dike injection. According to this idea one may expect the presence of normal faults as the only manifestations for the mode of deformation in Afar. In general, the unresolved issue as to which tectonic model can better explain the Afar tectonics indicates the complexity of the area. Furthermore, it indicates the extent to which the crust-mantle system in the region is complex and deformed due to relative motion of plates in the region. In this respect, the Afar depression is probably the best suited area for studying the different stages of development from a true continental rift (East African rift) to a juvenile oceanic trough (Red Sea, Gulf of Aden).

To infer crustal velocities Searle (1975) used dispersion of surface waves along a path crossing the southern part of the Afar depression and concluded that the crustal thickness is about 20 km.

Using deep seismic soundings data (Berckhemer et al. 1975) and gravity data (Makris et al. 1975) the crustal structure of the Afar depression has been studied along several profiles (especially along the central and northern part of Afar). Berckhemer et al. (1975) proposed that the crust below the Ethiopian plateau has a thickness of about 38 km and overlies a mantle of normal seismic velocity, a typical shield structure. They also proposed that in Afar the depth to the top of the anomalous mantle (P-wave velocity ranging from 7.3 km/s to 7.6 km/s) varies from 16 km (northern Afar) to 26 km (southern Afar) and estimated the thickness of the anomalous mantle layer to be in the range from 15 km to 40 km. Makris et al. (1975) proposed that the crustal thickness of Afar is in the range from 14 km to 22 km and that of the Ethiopian plateau (western and eastern plateau) is in the range from 30 km to 42 km.

From travel times of some earthquakes located in the Gulf of Aden and the Red Sea and recorded at the WWSSN (World Wide Seismological Station Network) station at Addis Ababa (AAE) Searle and Gouin (1971) obtained a Pn-wave velocity of 7.95 km/s and a Sn-wave velocity of about 4.3 km/s for waves propagating through Afar. Furthermore, from the 1969 Serdo earthquakes in central Afar, Dakin et al. (1971) obtained, a P-wave velocity of 7.4 km/s at the base of the crust in western Afar.

From near earthquakes travel time observations Searle and Gouin (1971) gave an upper limit of 48 km for the crustal thickness below Addis Ababa (on the western Ethiopian plateau). The crustal spectral transfer ratio was determined for Addis Ababa from long period teleseismic P-waves by Bonjer et al. (1970) and associated with a crustal model of 38 km thickness. The upper layer is 24 km thick with average P-wave velocity of 6.0 km/s, the lower layer is 14 km thick with 6.9 km/s for P-wave and the mantle top P-wave velocity is 8.2 km/s .

2. DATA SOURCE AND ANALYSIS

In March 1993 the Seismological station (AAE) at the Geophysical Observatory of Addis Ababa University upgraded its recording capability by installing a broad-band three component digital seismograph system equipped with a Guralp CMG-3T seismometer and Nanometrics data acquisition system. The system sampling rate is 40 samples per second. Since the installation of the seismograph system quite a large number of local and teleseismic events have been digitally recorded at AAE. However, for most of the local earthquakes recorded by the station it was not possible to get origin time and epicentral location accurate enough for the purpose of this study. Thus, we selected those events which were large enough to be recorded by other WWSSN stations outside Ethiopia and consequently their hypocentral parameters determined. Tab. I gives the hypocentral parameters of the six earthquakes selected for this study. The parameters given in the table are taken from Earthquake Data Report (EDR) bulletin published by the United States Geological Survey. Fig. 2 gives the location of epicentres of the events studied here and the paths to the AAE station, while Fig. 3 shows sample vertical component seismic records for some of the events (events 2 and 5 in Tab. I).

The paths between the epicentres and AAE station are divided into two groups (paths I and II, see also Fig. 2). Path I is sampled by the seismic waves generated by earthquakes occurred in the Gulf of Tadjura (western Gulf of Aden) and propagating through the southern part of the Afar depression. For this profile about 70% of the path lies in the rift (Afar depression). Similarly, path II is followed by seismic waves originated from the northern part of Afar depression. About 90% of the propagation path is through the western Ethiopian plateau.

In this study Rayleigh waves, recorded on vertical component broad-band digital seismograms, are utilized. Data are corrected for the instrument response and resampled with a 1s step.

The two-dimensional frequency time analysis (FTAN) (Dziewonski et al., 1969; Levshin et al., 1972) followed by phase equalization technique is employed to enhance the fundamental mode Rayleigh wave (see also Herrmann and Russell, 1990). During the data processing, band pass filtering and windowing are utilized. A detailed description of the method is given in Levshin et al. (1992).

Figures 4 and 5 show the dispersion curves obtained by performing FTAN analysis for events number 5 (path I) and number 2 (path II), respectively.

3. INVERSION FOR SHEAR WAVE VELOCITY STRUCTURE

The dispersion curves are mainly sensitive to shear wave velocity variations and this feature can therefore be used to find the S-wave velocity distribution with depth through an inversion scheme. To accomplish the task the non-linear hedgehog inversion procedure as developed by Kelis-Borok and Yanovskaja (1967), Valyus (1972) and Valyus et al. (1973) is utilized. A detailed description of the method, with the discussion of the appropriate parametrization of a plane layered Earth model, is given by Panza (1981).

To start the inversion process an initial model, characterised by shear and compressional wave velocities and density of the different layers, must be defined. The starting model must reflect a general subsurface picture of the region under consideration. Accordingly a model proposed by Searle (1975) for path I and the AFRIC model (Gumper and Pomeroy 1970) for path II are chosen as starting models.

Density values in each layer are determined from the corresponding shear wave velocities using the Nafe-Drake curve (e.g. Talwani et al. 1959). Furthermore, the compressional wave velocity needed in the input is computed by taking the Poisson's ratio equal to 0.25. All earthquakes studied here are regional earthquakes with the longest epicentral distance around 630 km (see Tab. I). For such an epicentral distance and the period range considered here (see Figs. 4 and 5) the difference in group velocities between a flat layered and spherical earth models is negligible (see Bolt and Dorman 1961; Brune and Dorman 1963). Thus no correction for the effect of earth flattening is performed.

Once the starting model is defined the goal of the inversion is to determine the depth of the crust-mantle boundary and to retrieve the lithospheric mantle shear wave velocity. For both paths I and II, we fix the thickness of the uppermost sedimentary layer equal to 3 km while we let variable its S-wave velocity parameter (P1). Below this depth we use a linear velocity gradient modelled with 6 thin layers of equal thickness. Therefore the deeper crustal structure is described with three variable parameters (P2, P3, P4): P2 represented the thickness of the layers, P3 the velocity gradient and P4 the shear wave velocity below the sediments. Finally the shear wave velocity of the upper mantle is allowed to vary up to a depth of 70 km (P5 and P6).

The inversion of the group velocities of path II is performed in a similar manner; in this case the parameter P6 represents the thickness of the layer under the crustal gradient and not its velocity. The range of the parameters and their incremental steps are shown in Tab. IIa for path I and in Tab. IIb for path II.

For each period the variance of the group velocities along similar paths is used as single point error. The models, for which the root mean square (RMS) is less than or equal to 0.055 km/s and the single point error is less than or equal to the values given in Tab. IIIa,b are considered acceptable.

Accepted models for the shear wave velocities are given in Figs. 6 and 7 for path I (AFAR) and path II (ERITREA). The comparison of the observed dispersion curves (dashed lines, representing the range of variability of the group velocity) with the theoretical ones, computed from the solutions shown in Figs. 6 and 7, is given in Figures 8 and 9 for path I (AFAR) and path II (ERITREA).

4. DISCUSSION AND CONCLUSION

Figure 6 shows the shear wave velocity structures as obtained for path I (AFAR). The crust has a total thickness ranging between 18 km to 22 km and the lithospheric mantle has a low shear wave velocity ranging from 4.0 to 4.3 km/s, even if in the inversion we have explored also normal mantle shear-wave velocity values (> 4.3 km/s).

To correct for the effect of the plateau, AFRIC model as given by Gumper and Pomeroy (1970) was employed. The observed Rayleigh wave group velocities along with the corrections needed to remove the effect of 175 km of plateau path are given in Tab. VI. The same parametrization applied for path I (AFAR) is used to invert the group velocities corrected for the effect of the plateau. The inverted shear wave velocity structures, AFARC, for path I, after correction for the effect of the plateau part are shown in Figure 10. The total crust can be approximated by shear wave velocities ranging between 2.4 Km/s to 3.9 Km/s. The lithospheric mantle shear wave velocity varies in the range 4.0 - 4.3 km/s. The comparison of the observed (group velocity variability ranges in the experimental data represented by dashed lines) and theoretical dispersion curves is shown in Figure 11. The total thickness to the top of the lithospheric mantle is less than 20 km and is smaller than the one obtained for the total path between the recording station and the epicentre (uncorrected case).

In general, our results are in quite good agreement with those of Searle (1975), both results indicating the presence of a low shear wave velocity (the presence of anomalous mantle) beneath the Afar crust.

Along several profiles (mainly in central and northern part of Afar depression) deep seismic soundings and gravity surveys have been conducted (Berckhemer et al. 1975; Makris et al. 1975; Makris and Ginzburg 1987), and they all show the presence of a low shear-wave velocity (anomalous mantle) beneath the Afar crust.

The crust for path II can be approximated by a total thickness greater than 40 km, with a shear wave velocity ranging between 3.0 km/s to 3.9 km/s. The lithospheric mantle shear-wave velocity varies in the range from 4.1 to 4.4 km/s lower than the typical one for stable continents and Precambrian shields (Panza,1980a; Henkel et al., 1990). The crustal thickness is comparable with the 38 km proposed by Berckhemer et al. (1975) for the western Ethiopian plateau and it is thinner than the 48 km crustal thickness proposed by Searle and Gouin (1971). A layer by layer comparison of the results obtained here with the model of Berckhemer et al. (1975), shows that the significant difference between the two results is mostly limited to the top (both for thickness and shear wave velocity) crustal layers. This difference can be due either to the poor resolving power of the used data set with respect to the uppermost part of the model or to the different locations of the sampled areas.

As a general conclusion we may observe that the surface feature marking the edge of the western plateau seems to extend almost vertically at depth. This is a quite different feature with respect to the Central European rift system, where the rift boundaries seem to be not so sharp (Ahorner 1970; Panza et al. 1980b; Panza 1984).

5. ACKNOWLEDGEMENTS

This work has been carried out at the Istituto di Geodesia e Geofisica (IGG), Universiá di Trieste, Italy. Fekadu Kebede and Tilahun Mammo thank the *Swedish Agency for Research* Co-operation with developing countries (SAREC) that through the International Centre for Theoretical Physics (ICTP) supported their work in Trieste. We would like to express our personal gratitude to all staff members of IGG for their help and co-operation during our stay. This research work is carried out as a contribution to the activities of the ILP Task Group II.4 (3DMET).

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TABLE CAPTIONS

Table I. Hypocenter parameters for the six earthquakes used in this study.

Table II. Range of the parameters and their incremental steps used in the inversion, a) for the path I (AFAR), and b) for the path II (ERITREA).

Table III. Single point error in the observation determined by the variance in the group velocity measurements; a) for the path I (AFAR), and b) for the path II (ERITREA).

Table IV. Obseved group velocities and corresponding correction needed to remove the effect of the western Ethiopian plateau.

No.	Date	Lat. (N)	Long. (E)	mb	Ms	Dist. (km)
1	02/05/1993	14.470	40.093	4.7	3.7	622.7
2	02/05/1993	14.573	39.993	4.7	4.3	631.4
3	04/05/1993	14.560	39.864	4.4	-	627.2
4	05/05/1993	14.371	40.148	4.7	4.4	613.4
5	11/04/1994	11.826	42.805	5.5	4.7	540.9
6	24/04/1994	11.600	43.089	5.2	4.7	553.3

Tab. I

Parameter	Minimum	Maximum	Step
P1	2.199 (km/s)	2.701 (km/s)	0.100 (km/s)
P2	1.900 (km)	7.016 (km)	0.500 (km)
P3	0.007	0.098	0.005
P4	2.859 (km/s)	3.561 (km/s)	0.100 (km/s)
P5	3.999 (km/s)	4.501 (km/s)	0.100 (km/s)
P6	3.999 (km/s)	4.501 (km/s)	0.100 (km/s)

Tab. IIa

Parameter	Minimum	Maximum	Step
P1	2.739 (km/s)	3.441 (km/s)	0.100 (km/s)
P2	1.400 (km)	6.016 (km)	0.500 (km)
P3	0.002	0.032	0.002
P4	2.759 (km/s)	3.661 (km/s)	0.100 (km/s)
P5	4.099 (km/s)	4.701 (km/s)	0.100 (km/s)
P6	2.900 (km)	21.10 (km)	3.000 (km)

Tab. IIb

Period (s)	Group velocity (km/s)	Single point error (km/s)
40.0	3.390	0.100
20.0	3.139	0.095
13.3	2.945	0.080
10.0	2.809	0.075
8.00	2.655	0.070
6.66	2.579	0.055
5.71	2.529	0.040
5.00	2.489	0.030

Tab. IIIa

Period (s)	Group velocity (km/s)	Single point error (km/s)
40.0	3.159	0.100
30.0	3.090	0.080
20.0	3.000	0.060
10.0	2.904	0.050
9.00	2.897	0.040
7.00	2.889	0.030
5.00	2.886	0.020

Tab. IIIb

Group velocity (km/s)	Correction(km/s)
3.39	-0.113
3.14	+0.097
2.95	-0.031
2.81	-0.111
2.66	-0.159
2.58	-0.176
2.53	-0.185
2.49	-0.193

Tab. IV

FIGURE CAPTIONS

Fig. 1. Major structural elements in and around Afar depression. MER, and DJI denote the main Ethiopian rift system (part of the northern part of the East African rift system) and Djibouti, respectively. Heavy lines in the Red Sea and the Gulf of Aden show the axial troughs. Lines indicate major faults in the region. The broken line in the southern Red Sea indicates the proposed transform fault connecting northern Afar to the axial trough of the Red Sea (Barberi and Varet, 1975; 1977).

Fig. 2. Map showing major tectonic provinces in Afar and neighbouring regions. Solid star and solid circle indicate the earthquake epicenter and the AAE seismic station, respectively. Roman numbers I and II are intended to indicate propagation paths.

Fig. 3. Display of vertical component seismograms for some of the events studied here as recorded by the broad-band seismograph system at the AAE station: a) for event 2 in Tab. I; b) for event 5 in Tab. I.

Fig. 4. Display of the two-dimensional Frequency Time Analysis (FTAN) for event 5 in Tab. I.

Fig. 5. Display of the two-dimensional Frequency Time analysis for event 2 in Tab. I.

Fig. 6. Accepted shear wave velocity structures for path I (southern Afar) without correction for the effect of the plateau part.

Fig. 7. Accepted shear wave velocity structures for path II as obtained in this study.

Fig. 8. Comparison of the observed dispersion curves for path I (dashed lines represent the variability range of the observations), not corrected for the effect of the plateau part, with the theoretical dispersion curves obtained from the crustal structures, solution of the inversion, shown in Fig. 6.

Fig. 9. Comparison of the observed dispersion curves for path II (dashed lines represent the variability range of the observations) and the corresponding theoretical dispersion curve as obtained from the crustal structures, solution of the inversion, shown in Fig. 7.

Fig. 10. Accepted shear wave velocity structures for path I as obtained in this study after correcting for the effect of the plateau part.

Fig. 11. Comparison of the observed dispersion curve for path I, corrected for the effect of the plateau part (dashed lines represent variability range of the observations), with the corresponding theoretical dispersion curves obtained from the crustal structures, solution of the inversion, shown in Fig. 10.

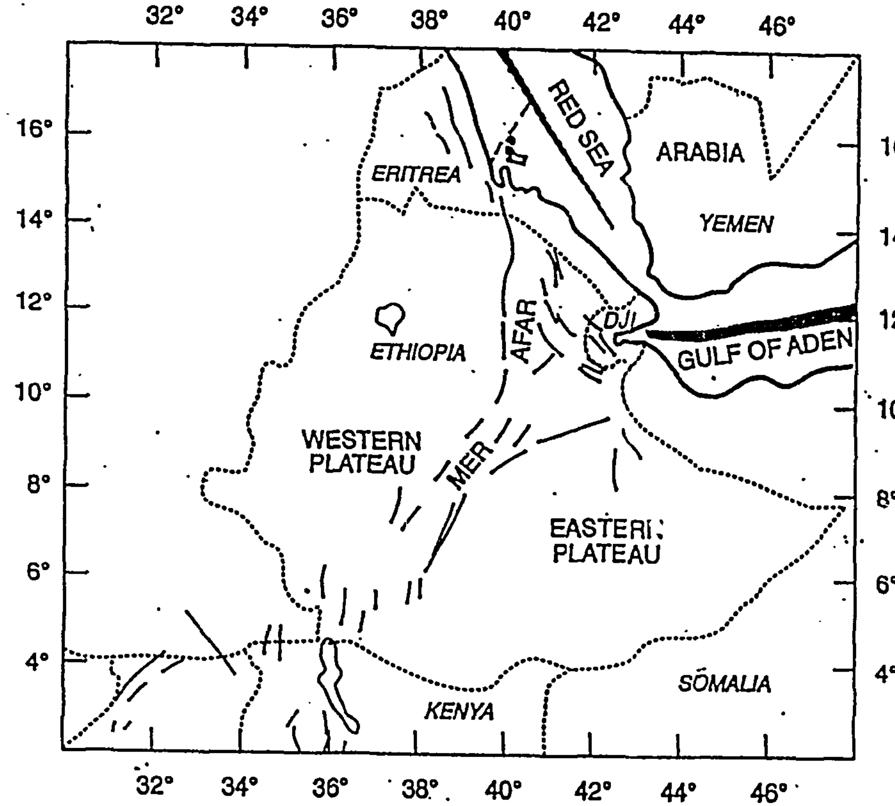
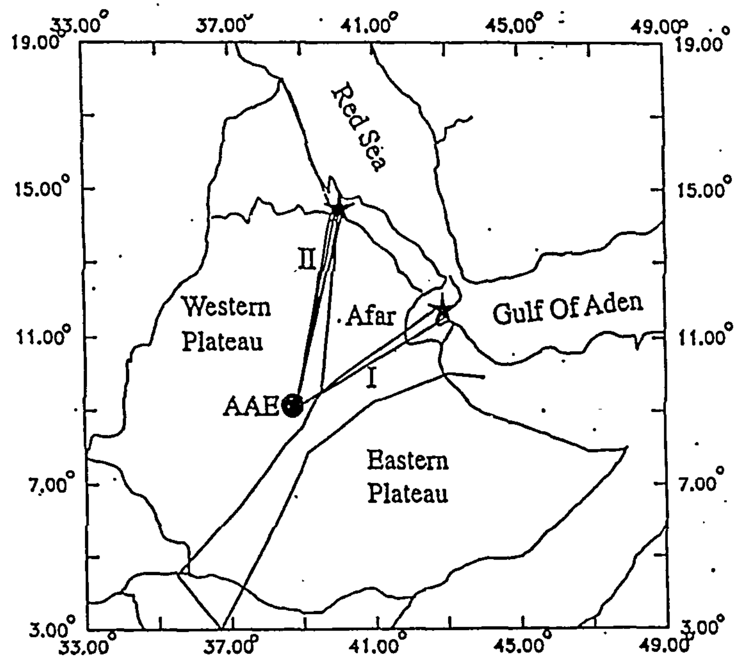


Fig.1


Red Sea
Western Plateau
Afar
Gulf Of Aden
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II
I
33.00°
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7.00°
3.00°

Fig.2

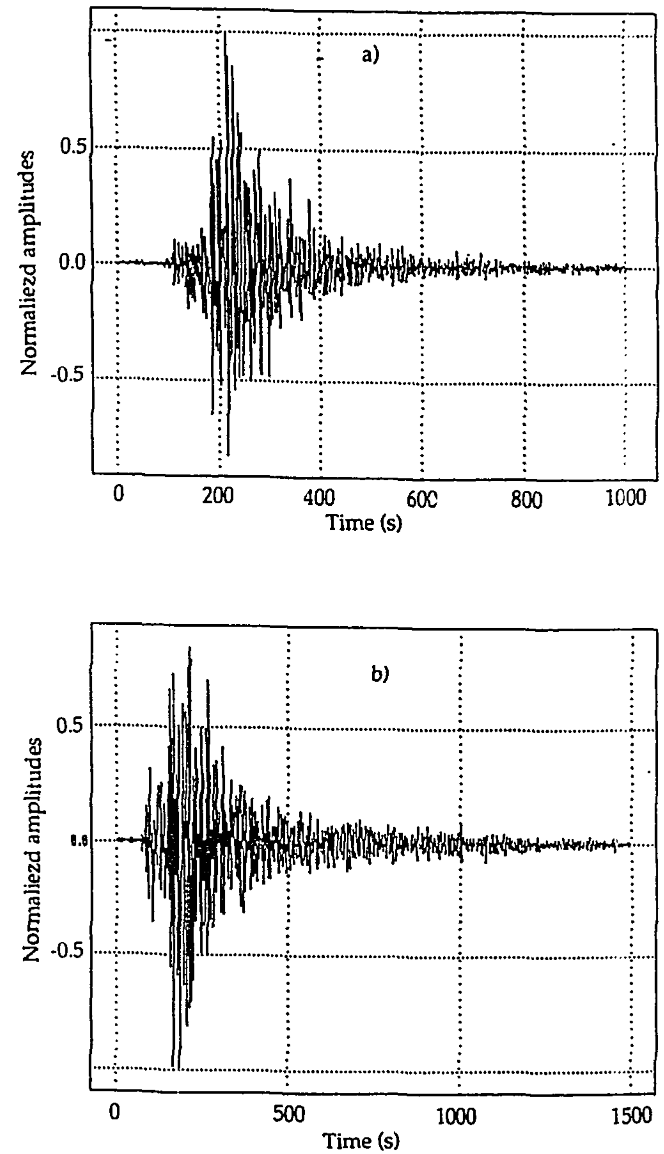

a)
b)
Normaliezd amplitudes
Time (s)
0.5
0.0
-0.5
0
200
400
600
800
1000
500
1000
1500

Fig.3

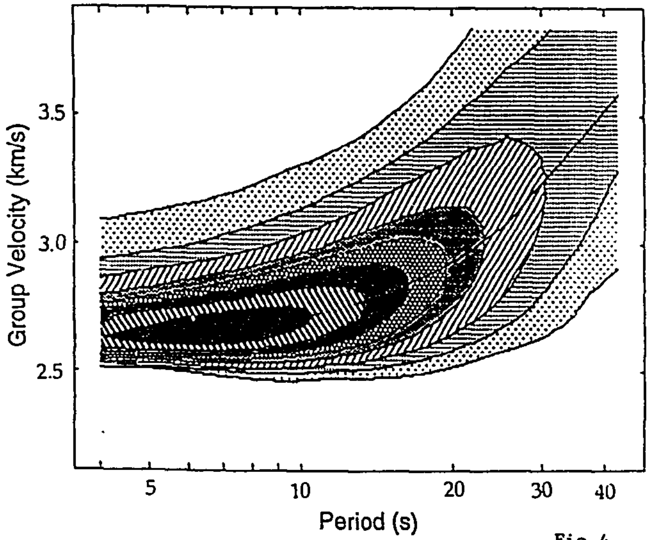


Fig.4

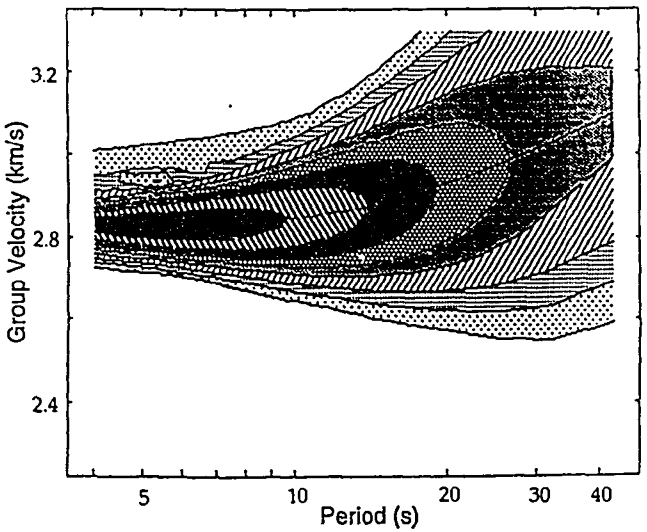


Fig.5

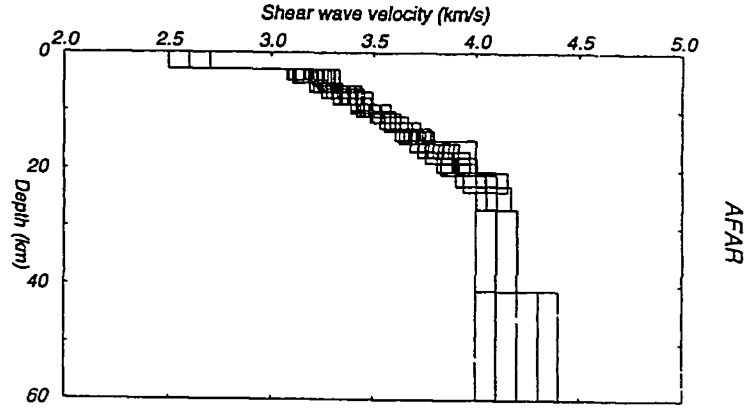
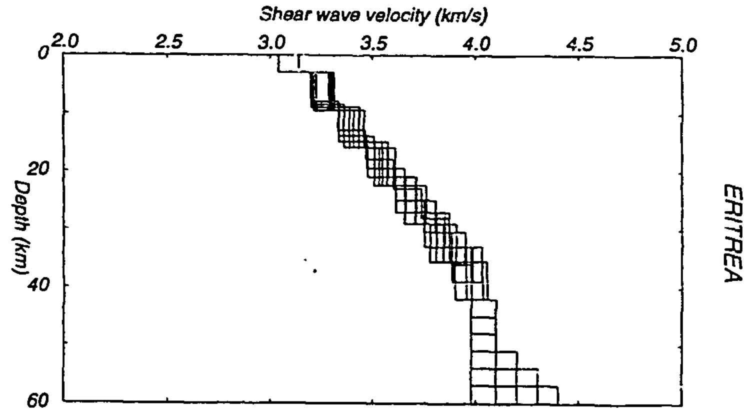


Fig.6



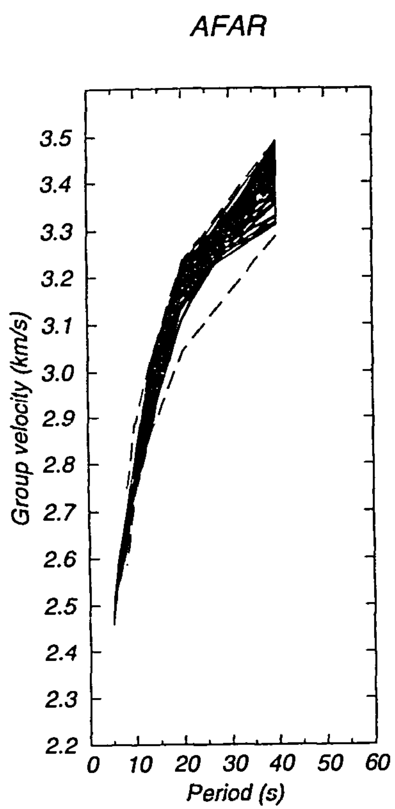


Fig.8

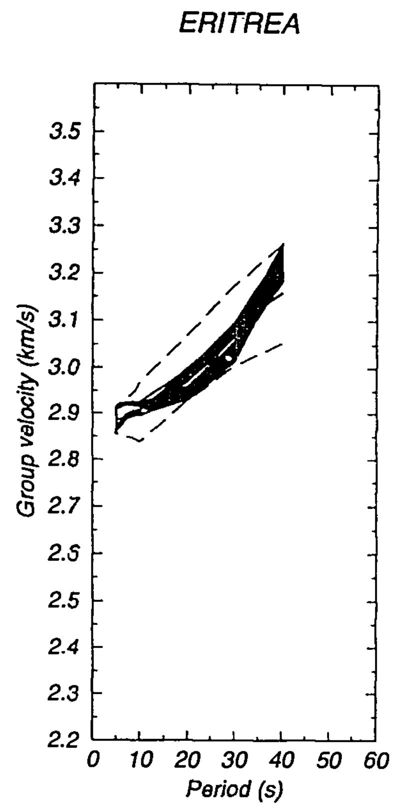


Fig.9

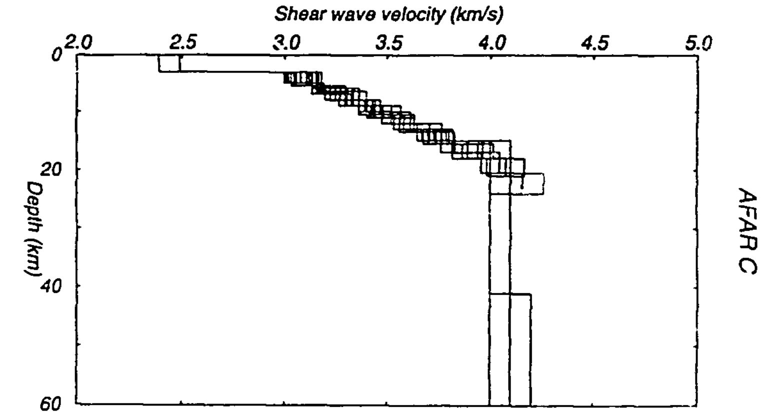


Fig.10

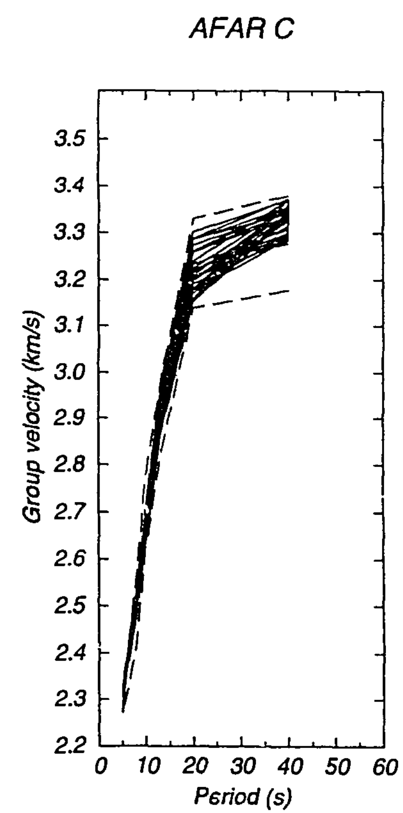


Fig.11