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Crustal structure of the East African Rift System from spectral response ratios of long-period body waves[1])

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Summary: Crustal response ratios within the East African Rift System are determined by spectral analysis of long-period body waves from two Hindu Kush earthquakes observed at the stations Addis Ababa, Nairobi and Lwiro. These experimental data are compared with theoretical response ratios of crustal models previously used in this region. A number of them must be rejected.

The travel time through the crust at LWI (Eastern Congo) is found to be shorter than at NAI (Kenya) and AAE (Ethiopia). From the derived crustal travel time, we can split up the travel time anomaly given by the 1968 Tables into a part associated with the crustal and another part associated with upper mantle structure. The existence of an intermediate high-speed layer in the lower crust is concordant with the experimental crustal response ratios.

An estimate of crustal structure in the East African Rift System and differences of the crust at the three stations are discussed. Instead of truncated transfer ratios, the signal dependent truncated response ratios are used which are in a wide range insensitive to the dominant period of the incident signal.

Zusammenfassung: Krusten-Antwort-Quotienten werden für das Ostafrikanische Riftsystem durch Spektralanalyse der langperiodischen Raumwellen von zwei Hindukusch-Erdbeben bestimmt, die an den Stationen Addis Abeba, Nairobi und Lwiro aufgezeichnet worden sind. Diese experimentellen Daten werden mit den theoretischen Antwort-Quotienten der Krusten-Modelle, die bisher in diesem Gebiet verwendet worden sind, verglichen. Einige sind zu verwerfen.

Die Laufzeit durch die Kruste bei LWI (Östl. Kongo) ist kürzer als bei NAI (Kenia) und AAE (Äthiopien). Aus der abgeleiteten Krusten-Durchlaufzeit kann die den 1968-Tabellen zu entnehmende Laufzeitanomalie in zwei Teile aufgespalten und der Krusten- bzw. Oberen-Mantel-Struktur zugeordnet werden. Die Existenz einer Zwischenschicht mit hoher Geschwindigkeit im unteren Teil der Kruste ist in Übereinstimmung mit den experimentellen Krusten-Antwort-Quotienten.

Die für das Ostafrikanische Riftsystem abgeschätzte Krustenstruktur und Unterschiede der Kruste unter den drei Stationen werden diskutiert. Statt zeitbegrenzter Übertragungsquotienten werden die signalabhängigen, zeitbegrenzten Antwort-Quotienten benutzt, die in einem weiten Bereich unabhängig von der dominierenden Periode des einfallenden Signales sind.

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The crustal structure of the East African Rift System has been investigated with crustal response ratios of long-period body waves. The most important results are:

An estimate of the average travel time through the crust for *P*- and *S*-waves is 6.6 and 10.7 sec, respectively, for a *P*-wave incident under 30° at the crust-mantle boundary.

The travel time through the crust at Lwiro (LWI), Eastern Congo, is shorter than at Nairobi (NAI), Kenya, and Addis Ababa (AAE), Ethiopia.

From the derived crustal travel time, we can split up the travel time anomaly given by HERRIN and TAGGART [1968] into a part associated with the crustal and another part associated with the upper mantle structure.

The existence of an intermediate high-speed layer in the lower crust is concordant with the experimental crustal response ratios.

The area under investigation is shown in Figure 1. The three stations LWI, NAI, AAE embrace the East African Rift System. LWI is located in the Western Rift, NAI in the Eastern Rift and AAE in the northern part of the Great Rift Valley. In this area, a number of crustal models have been established by other seismic methods. The consistency of these models with the experimentally determined crustal response ratios will be discussed.

Incorporating all available information on crustal structure, we have constructed new models by matching observed and computed response ratios. Implications of the present study on the crust and upper mantle structure in the East African Rift System will be pointed out at the end of the paper.

Crustal Response Ratio

The method of crustal investigations by spectral transfer ratios of long-period body waves, proposed and first applied by PHINNEY [1964], has since been used by several authors [HANNON 1964; FERNANDEZ 1965; LEBLANC 1967; BONJER, FUCHS 1969] as an additional source of information on crustal structure. The method is based on the comparison of experimentally derived and theoretically computed long-period spectral transfer ratios.

We have to comment briefly on the notion of the theoretical response ratio which is a generalization of the transfer ratio (a detailed discussion is in preparation). For some reason, one may be forced to use such short time windows that a non-negligible part of reverberating energy falls outside the window.

Then the truncated transfer ratio is no longer independent of the source signal [LEBLANC 1966]. However, it can be shown by numerical experiments that, although signal-dependent, the ratio is relatively insensitive to small variations of the dominant period of the incident signal. For this signal-dependent truncated transfer ratio, we prefer the term "truncated spectral response ratio". For brevity, we shall use the short form "response ratio" throughout this paper. It is our experience that a rough estimate of the source signal as viewed through the recording instrument is sufficient. In this study, we use a signal with a dominant period of 10 sec.

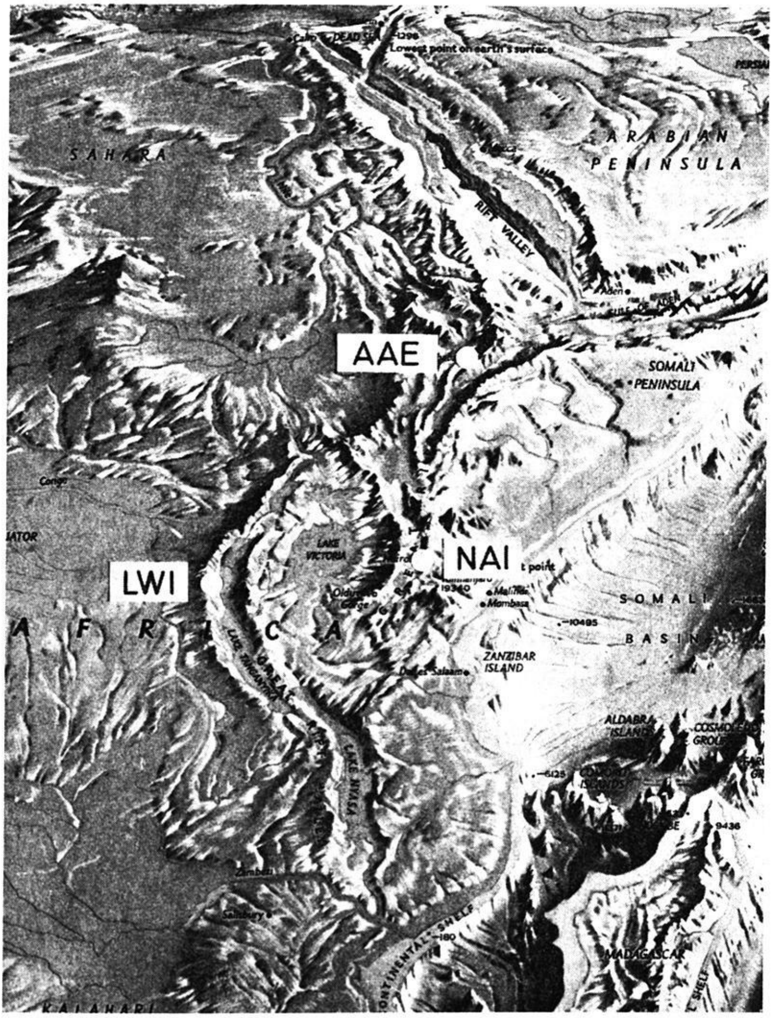

Fig. 1: Location of the three long-period stations AAE (Addis Ababa), NAI (Nairobi), and LWI (Lwiro) in the East African Rift System.

The basis for the application of the THOMSON-HASKELL matrix method—which is needed for the computation of the theoretical ratios — may be violated to a certain extent within the area under investigation. However, for the present, we assume that within a 40 sec window the secondary waves generated by the deviation from the horizontally layered crust are negligible compared to the reverberations caused by vertical interference.

Experimental Data

For our study, we have used the recordings of two deep focus Hindu Kush earthquakes as listed in Table 1. The recordings of the vertical component at the three stations LWI, NAI and AAE are shown in Figure 2. In addition, the horizontal

Table 1: Deep Focus Hindu Kush Earthquakes

Date	T_0	Long.	Lat.	Depth	Mag.
28 january 1964	14:09:17.1	70.° 9 E	36.° 5 N	207 km	6.1
06 june 1966	7:46:16.2	71.° 2 E	36.° 3 N	225 km	6.3

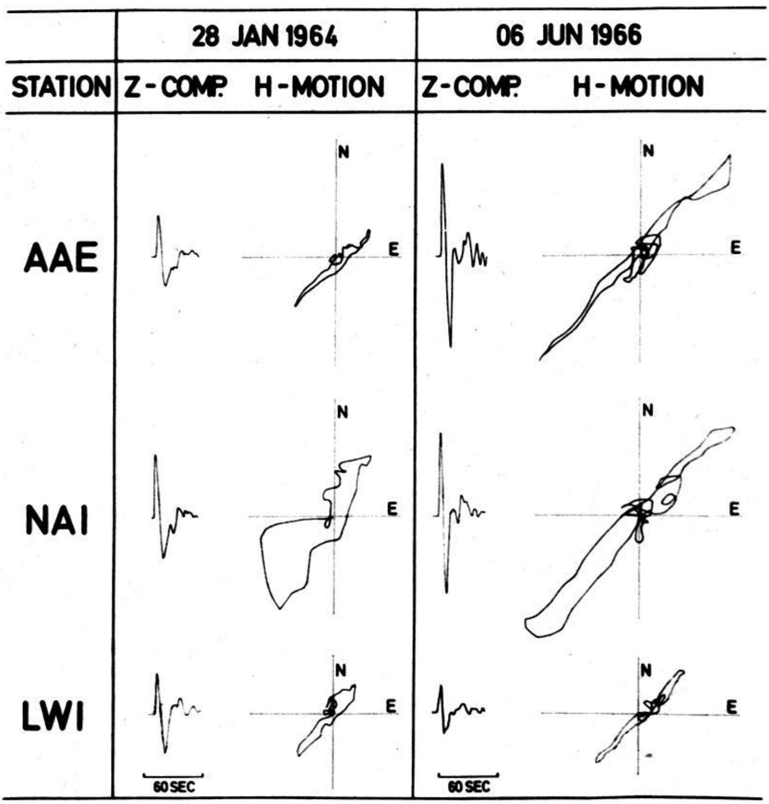

Fig. 2: Vertical components and horizontal motions recorded by the long-period instruments at the three stations AAE, NAI and LWI from two deep focus Hindu Kush earthquakes.

motion is displayed within the 40 sec hamming window. This time window had to be applied to exclude unexplained phases with different polarisation. Within this window, the horizontal motion is almost linearly polarized. Long-period noise at NAI does not affect the reproducibility of the ratios in the frequency range of interest.

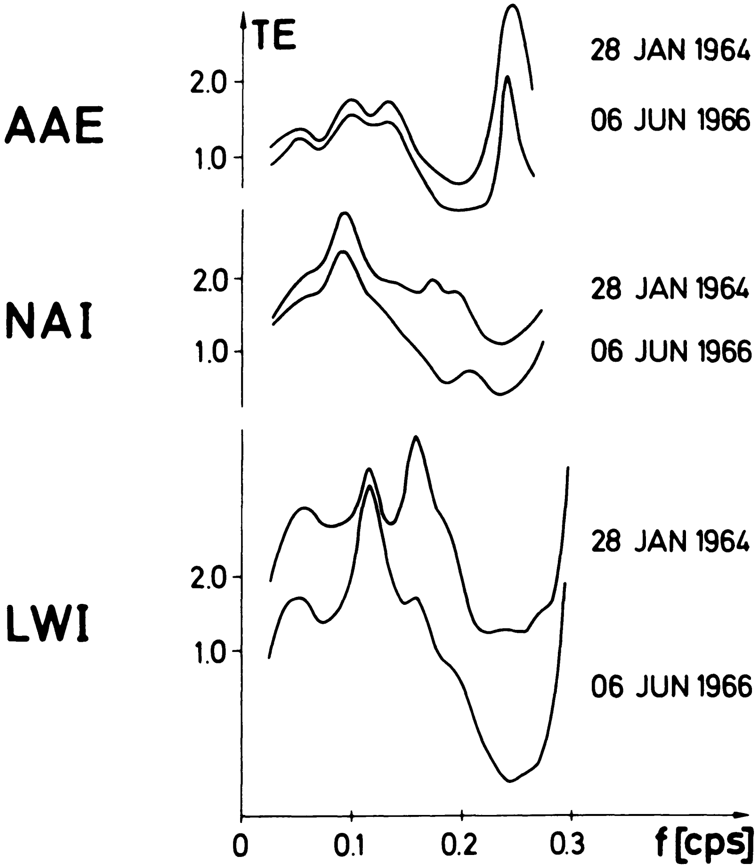

Fig. 3: Experimental "truncated spectral response ratios" of the two deep focus Hindu Kush earthquakes at AAE, NAI and LWI.

In Figure 3, we present the experimental response ratios TE for the two events at the three stations. For clarity, we have displaced the two sets of data. The reproducibility is remarkable. Furthermore, it should be noted that compared to AAE and NAI the spectral peaks at LWI are significantly shifted to higher frequencies indicating a shorter travel time through the crust at LWI than at the two other stations.

Inversion of Experimental Response Ratios

It is our first objective to obtain an estimate of crustal models concordant with the experimental response ratios. In Figure 4, we compare the experimental data with the theoretical response ratios of crustal models applied to this area by several authors.

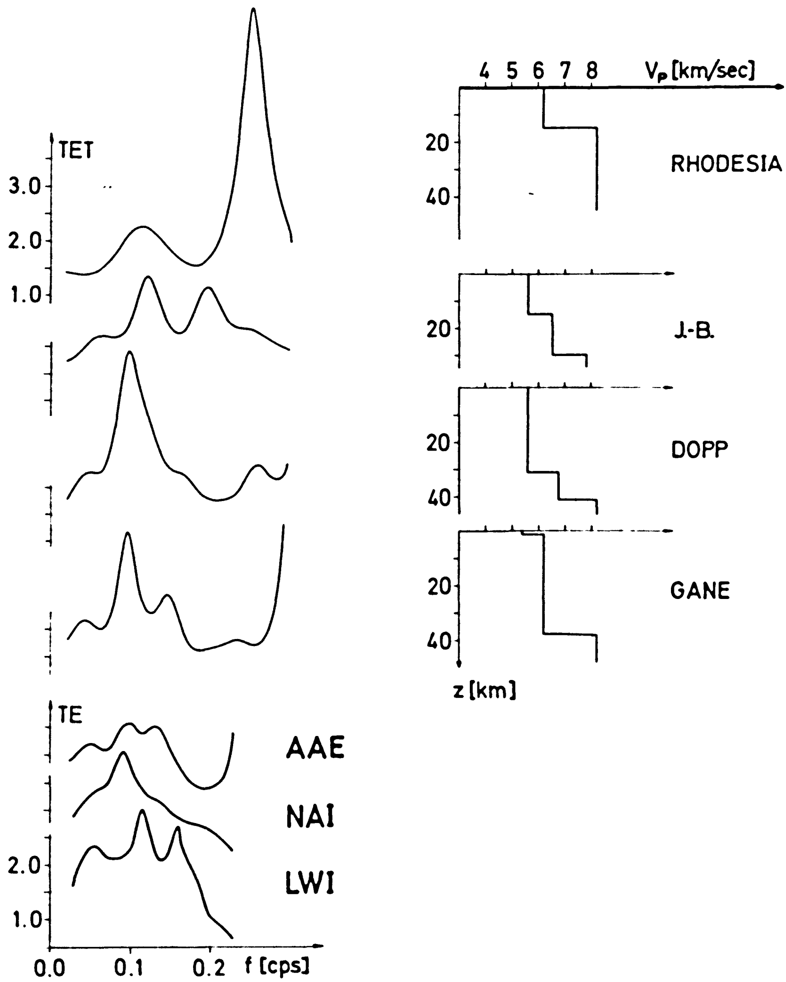

Fig. 4: Comparison of experimental response ratios TE at AAE, NAI and LWI with the theoretical response ratios TET of crustal models previously applied to the area under investigation by several authors. Only model GANE [1956] is acceptable for further computations.

The spectral peaks of the model RHODESIA [see WOHLENBERG 1967, p. 20] are severely shifted to higher frequencies compared to the experimental response ratios. This indicates that the travel time through the thin crustal model RHODESIA is too small. This model has to be rejected for the area under investigation.

In the second model, J.-B. [JEFFREYS, BULLEN 1948] the spectral peaks are again significantly shifted to higher frequencies. This shift is caused by the small crustal travel time. The model J.-B. cannot be accepted for this area.

The spectral peaks of the third model DOPP [1964] are within the range of the corresponding observed peaks. Nevertheless, on the basis of results obtained in explosion seismology, we do not consider a model with a P-velocity of 5.6 km/sec to a depth of 33 km as realistic.

In the last model GANE [GANE et al. 1956], the theoretical ratios almost match the observed ratios. This is practically a one-layer model with an acceptable average velocity of a normal continental crust. We shall adopt this model as a basis for the construction of crustal models whose theoretical response ratios are in better agreement with the observed ratios.

For the determination of the thickness of a one-layer crust FERNANDEZ [1965, 1967] proposed the use of master curves. This method is not applicable if a non-negligible part of the reverberating energy falls outside the time window. Instead, we shall use a catalogue of theoretical response ratios TET depicted in the middle part of Figure 5.

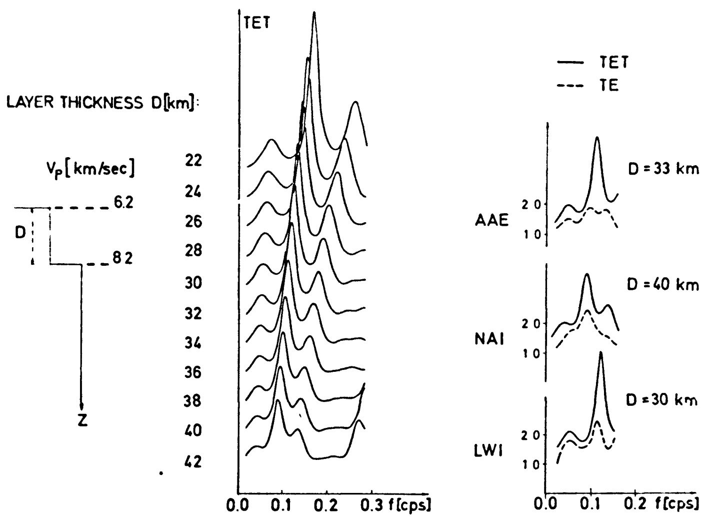

Fig. 5: Theoretical response ratios TET of a one-layer crustal model with variable thickness D. In the right part, the averaged experimental ratios TE (dashed line) are compared with the theoretical ratios TET (solid line) selected from the catalogue in the middle of the figure.

The corresponding one-layer crust is shown on the left. The *P*-velocity in the crust is 6.2, in the mantle 8.2 km/sec, and the angle of incidence at the crust-mantle boundary is 30°. The crustal thickness *D* is varied from 22 to 42 km. In the right part, the dashed lines are the averaged experimental ratios TE. The best fitting theoretical ratios (solid lines) are taken from the catalogue of response ratios. The thickness *D* for the one-layer crustal model is 33 km at AAE, 40 km at NAI, and 30 km at LWI.

The crustal models require further refinement for two reasons. First, a closer inspection of Figure 5 shows that the positions of theoretical and experimental peaks have only been fitted in the mean. Numerous attempts to fit all peaks individually failed since in the case of a one-layer crust the positions of the individual peaks of the response ratios cannot be changed independently from each other. Therefore, the experimental data require at least one more degree of freedom of the crustal models.— Secondly, there is a number of reports on the observation of intermediate velocities between 6.7 and 7.6 km/sec in rift structures in all parts of the world [WILLMORE, HALES and GANE 1952; HALES and SACKS 1958; DRAKE and GIRDLER 1964; DOPP 1964; LE PICHON, HOUTZ, DRAKE, and NAFE 1965; TALWANI, LE PICHON, and EWING 1965; ANSORGE, EMTER, FUCHS, LAUER, MUELLER, and PETERSCHMITT 1969; BLUNDELL, GRIFFITHS, KING, KHAN et. al. 1969].

For these two reasons, a high-speed intermediate layer has been introduced at the base of the three crustal models. Figure 6 demonstrates the improvement in the fit of the individual peaks of the theoretical and experimental ratios. At the bottom of the figure, the experimental response ratios for the three stations AAE, NAI, and

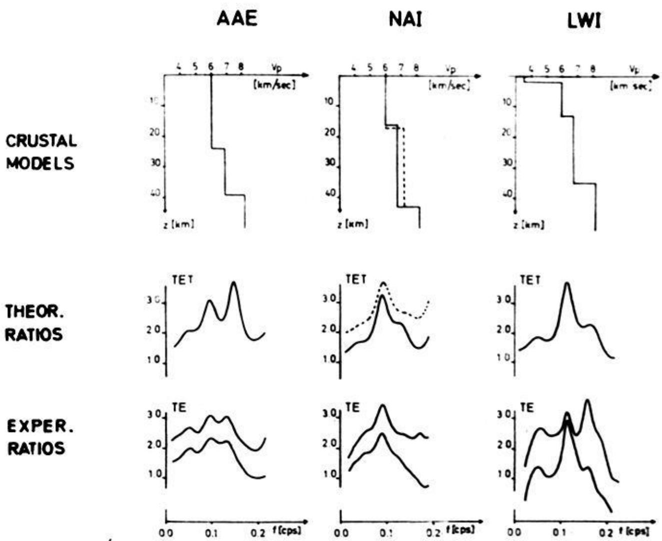

Fig. 6: Comparison of experimental TE and theoretical response ratios TET of the multi-layered crustal models derived for the three stations AAE, NAI and LWI.

LWI are depicted. In the middle part, the theoretical response ratios and in the top part the corresponding crustal models are displayed. In this type of crust, the top of the intermediate layer is found at a depth of 24 km in AAE, 16 or 17 km in NAI, and 12 km in LWI with an accuracy of about 2 km.

As travel times through the crustal models for a *P*-wave incident at 30° at the crust-mantle boundary, we find $t_p = 6.7$ sec in AAE, $t_p = 7.2$ sec in NAI, and $t_p = 6.0$ sec in LWI. Averaging these crustal travel times in the region of the East African Rift System, we obtain $t_p = 6.6$ sec. This corresponds to 10.7 sec *S*-travel time.

The difference in crustal travel times at AAE and LWI amounts to +0.7 sec. Comparing this result with the difference of +1.9 sec taken from the regional variations in *P* travel times [Herrin and Taggart 1968] at AAE and LWI, the remaining difference of 1.2 sec has to be attributed to the mantle. It must be concluded that the delay of *P*-waves in the mantle near AAE is larger than near LWI indicating the presence of more material with a lower velocity in the mantle below AAE as compared to LWI.

Molnar and Oliver [1969] arrived at a similar conclusion from the observed absence of S_n phases for paths crossing the northern part of the Great Rift Valley.

The difference in travel time through the crust under NAI and LWI is +1.2 sec. This delay at NAI is partly caused by the thicker intermediate layer compared to LWI.

Sowerbutts [1969] postulated the presence of more lowdensity material in the Eastern Rift near NAI than in the Western Rift near LWI. The resultant density deficit may be related to the crustal travel time delay derived from the present crustal response study.

Conclusions

Information on crustal structure in the East African Rift System has been obtained by the inversion of experimentally determined spectral response ratios of long-period body waves from two deep focus Hindu Kush earthquakes. The derived crustal models permit a number of important conclusions:

The average travel time through the crust for *P*- and *S*-waves can be estimated at 6.6 and 10.7 sec respectively, if a *P*-wave is incident under 30° at the crust-mantle boundary.

The difference in *P*-travel time through the crust is 0.7 sec at AAE and LWI, 1.2 sec at NAI and LWI.

The corresponding difference of travel time anomaly between AAE and LWI taken from the 1968 tables is 1.9 sec. The additional delay of +1.2 sec must be associated with the presence of more material of lower velocity under AAE than under LWI.

The existence of an intermediate high-speed layer in the lower crust is concordant with the experimental crustal response ratios.

The truncated spectral response ratios used in this study are a generalization of the well-known transfer ratios. The new method will be discussed in more detail in a future paper.

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