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Seismological Research at Georg-von-Neumayer Base, Antarctica. Part II: The Analysis of Travel Time Residuals

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Summary: The analysis of teleseismic travel time residuals is one of the classical methods in seismology by which often basic models of the structure and the physical properties of the earth's crust and the upper mantle beneath the receiver station can be derived. The purpose of this work was to detect possible anomalous structures of the deeper earth beneath the Georg-von-Neumayer base (GvN). For a comparative analysis data of other seismogical stations in the Queen Maud Land area were incorporated, namley Sanae (SNA), Novolazarevskaya (NVL) and also Syowa (SYO). For the computation of relative travel time residuals, which are less contaminated by errors, data of station Amundsen-Scott (SPA) were used. Because the data of all stations are characterized by a very unequal azimuthal distribution and also a large scattering, appropriate methods for a suitable data reduction had to be developed. Two different methods with equivalent results are presented. At the stations GvN, SNA and NVL it can be shown that the azimuthal variation of the residuals is very similar to each other. This means that there are principal similarities of the deeper earth beneath these stations. Especially from results for the stations GvN and NVL a marked velocity-anisotropy in the upper mantle must be concluded, which might probably be brought in connection with the break-up of Gondwana. Furthermore, the general and relatively great delays at these stations indicate a low velocity zone within the upper mantle below Queen Maud Land. There are some indications that this result can be correlated with a marked, widely spaced negative anomaly of the magnetic field (satellite data). Another common result, the marked delays at easterly azimuths at the stations GvN, SNA and NVL, cannot unambigously be explained. For the station SYO the results also cannot be interpreted without any doubts. The residual variation at the station SPA at the South Pole allows the conclusion that the residuals may partly be influenced by an anomalous structure below the Transantarctic Mountains.

Zusammenfassung: Die Analyse teleseismischer Laufzeit-Residuen ist eine der klassischen Methoden in der Seismologie, mit der häufig grundlegende Modelle über die Struktur und die physikalischen Eigenschaften von Erdkruste und oberem Erdmantel unter einer Empfängerstation abgeleitet werden können. Ziel dieser Arbeit war, evtl. anomale Strukturen des tieferen Untergrundes unter der Georg-von-Neumayer Station (GvN) zu erfassen. Für eine vergleichende Analyse wurden zusätzlich Daten anderer seismologischer Stationen im Bereich von Queen Maud Land mit einbezogen, nämlich Sanae (SNA), Novolazarevskaya (NVL) und auch Syowa (SYO). Für die Berechnung von weniger fehlerbehafteten relativen Laufzeit-Residuen wurden Daten der Station Amundsen-Scott (SPA) herangezogen. Da an allen Stationen die Daten eine sehr ungleiche azimutale Verteilung, bzw. auch sehr starke Streuung aufweisen, mußten geeignete Methoden zur Datenreduktion gefunden werden. Es werden zwei Verfahren beschrieben, die äquivalente Ergebnisse liefern. Für die Stationen GvN, SNA und NVL kann eine sehr ähnliche azimutale Variation der Residuen konstatiert werden, was auf prinzipiell übereinstimmende Eigenschaften des tieferen Untergrundes unter diesen Stationen schließen läßt. Insbesondere muß aus den Ergebnissen für die Stationen GvN und NVL eine ausgeprägte Geschwindigkeits-Anisotropie im oberen Mantel gefolgert werden, die vermutlich mit dem Zerfall von Gondwanaland in Verbindung zu bringen ist. Des weiteren deuten die generellen, relativ großen Verspätungen an diesen Stationen auf eine Zone erniedrigter seismischer Geschwindigkeiten im oberen Mantel unterhalb von Queen Maud Land hin. Es gibt Anzeichen, daß dies evtl. mit einer entsprechend großräumigen negativen Magnetfeld-Anomalie (Satelliten-Daten) in diesem Gebiet zu korrelieren sein kann. Ein weiteres Ergebnis, die ausgeprägten Verspätungen an den Stationen GvN, SNA und NVL bei östlichen Azimuten, kann nicht eindeutig interpretiert werden. Für die Station SYO sind die Ergebnisse ebenfalls nicht gesichert zu interpretieren. Die Residuen-Variation an der Station SPA am Südpol läßt den Schluß zu, daß diese noch durch eine anomale Struktur unter dem Transantarktischen Gebirge beeinflußt werden können.

INTRODUCTION

The analysis of teleseismic travel time residuals is one of the most classical and widely applied methods in seismological research to detect anomalous structural or physical features within the earth's crust or upper mantle. Therefore as well as for its relatively low computing requirements this method was chosen for evaluating the first earthquake recordings at Georg-von-Neumayer base (GvN) from 1982 to 1984, in order to get an idea, whether there are any characteristic differences in the physical nature of the earth below GvN compared to a suitable global reference model. Additionally data from three other bases, Sanae (SNA), Novolazarevskaya (NVL) and Syowa (SYO), also situated near the continental margin to the East from GvN, and data from the Amundsen-Scott base (SPA) at the South Pole were available and could be incorporated in the calculations (Figs. 1 and 2). This provided the opportunity to eliminate or reduce several error influences in the residual calculation and to study possible common or distinctly different features in the traveltime residuals at these seismological stations.

THE METHOD

Travel time residuals are defined as the difference between actually measured travel times of the seismic waves from the earthquake source to the recording site and the theoretical travel times, which should be expected according to an appropriate global earth reference model. Positive residuals therefore represent a late arrival of the seismic waves at the recording site, negative residuals signal an early arrival, as compared to the reference earth. If there is a distinct deviation of the mean travel time residual from zero or if there is a systematic variation of the residuals dependent upon the azimuth of the approaching wavefronts, one must assume that this is caused by a special anomaly within the deeper earth below the recording site.

In practice theoretical travel times are calculated by interpolation of a suitable set of travel time tables, which contain the reference travel times for different epicentral distances and source depths. This implies that travel time residuals are as correct as the travel time tables are, which were used for calculating them. Since the necessary information about hypocentre and origin

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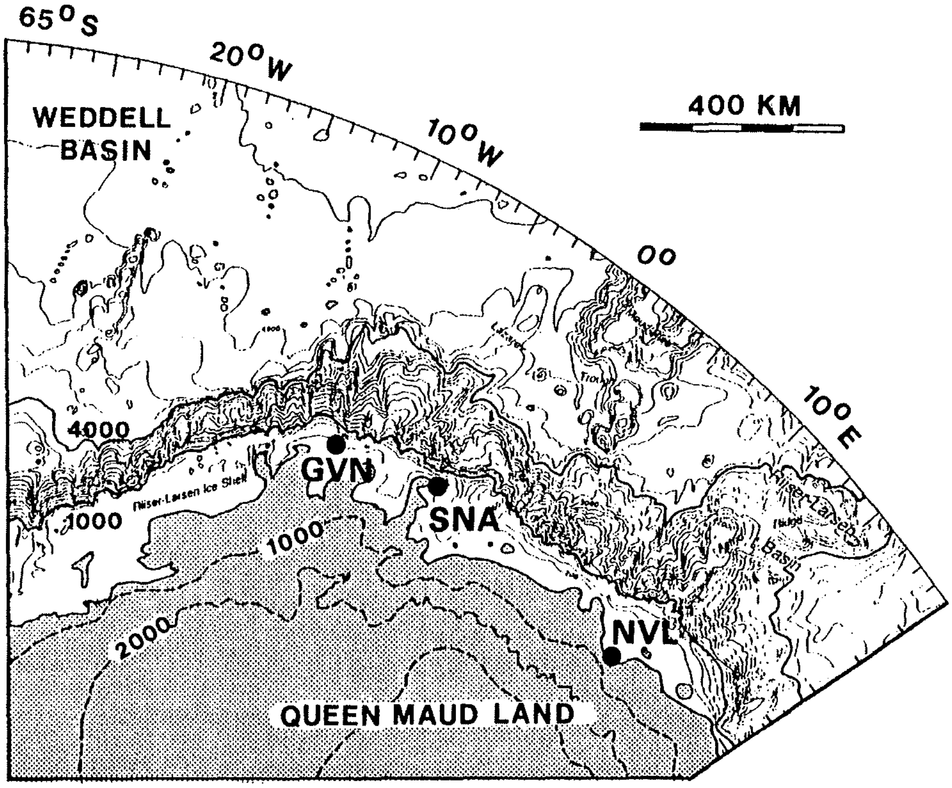


Fig. 1: Sketchmap showing the positions of the stations GVN, SNA and NVL near the continental margin of Queen Maud Land. Seismological data of these stations were used for the analysis of travel time residuals.

Abb. 1: Kartenskizze über die Lage der Stationen GVN, SNA und NVL bezüglich des Kontinentalrandes von Queen Maud Land. Seismologische Daten dieser Stationen bildeten die Grundlage der Residuenanalyse.

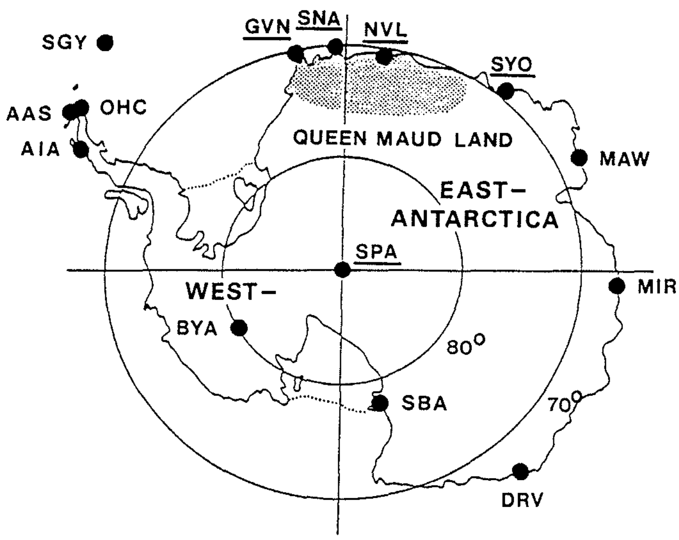


Fig. 2: Seismological stations in Antarctica, which were permanently operating in 1983. Data from these stations which are underlined were incorporated in the residual analysis reported here. Hatched area denotes Queen Maud Land.

Abb. 2: Seismologische Stationen in der Antarktis, die 1983 ganzjährig in Betrieb waren. Daten der Stationen mit unterstrichener Stationskennung sind in der hier vorgestellten Residuenanalyse einbezogen. Der schraffierte Bereich kennzeichnet Queen Maud Land.

time of the recorded earthquakes were taken from the ISC bulletins (ISC, INTERNATIONAL SEISMOLOGICAL CENTRE), which uses for the earthquake localization procedure the Jeffreys-Bullen tables (JB), these tables were also used here. The JB-tables have been the standard for seismological research for almost more than 50 years. Therefore the JB-tables can be regarded as sufficiently accurate in describing the travel times of the reference earth.

Because most of the earthquakes occuring worldwide have their origins in regions with very pronounced anomalies of the seismic velocities (e.g. earthquakes along the descending lithospheric slab at subduction zones), travel time residuals are also mostly more or less contaminated by the influence of these anomalous source structures. This disadvantage of the absolute residuals, however, can be eliminated for the most part by normalizing the residuals in relation to a nearby reference station, yielding the so called relative residuals. With this process, e.g. subtracting the residual at the reference station from the corresponding residual at the station of interest, also errors both in localization and origin time of the earthquakes are greatly reduced. The possible structural model of the deeper earth below the recording site resulting from these residuals must then be related to the deeper earth at the reference station.

Another approach to get a significant residual signal that will be only caused by a particular structure below the recording site is to reduce the influence of contaminated residuals by an appropriate data reduction. This will be discussed more detailed in a later section.

With a dense distribution of recording stations, completely covering the area over a seismic anomaly, it is possible to develop a relatively detailed model of this anomalous structure, e.g. by means of seismic tomography. Contrary to this, dealing just with data of single and more or less isolated stations, one must realize that this will imply only limited conclusions about the structure of the deeper earth. Nevertheless, a lot of investigations just dealing with travel time residuals from isolated stations showed that the analysis of these data in most cases will lead to a quite well-founded idea about the principal physical structures and properties of the deeper earth below these stations. Especially the analysis of the variation of residuals dependent upon the azimuth can give some decisive hints for possible extended anomalous structures or large scaled areas with different physical properties within the earth's crust or upper mantle.

A very reliable method for this objective is to approximate the residuals' variation with azimuth by simple trigonometric functions, e.g. to approximate an obvious azimuth-variation of residuals by sine- and cosine-functions with the azimuth Φ as independent variable. The functional relation between residuals and azimuth, established by this procedure, may reveal the principal character of the seismic anomaly within the deeper earth.

For the analysis of the travel time residuals reported here the following function was used for the least squares approximation of the residuals:

$$F(\Phi) = A_0 + \underbrace{A_1 \, COS\,(\Phi - \Phi_1)}_{1^{st}\text{ azimuthal term}} + \underbrace{A_2 \, COS\,(2[\Phi - \Phi_2])}_{2^{nd}\text{ azimuthal term}}$$

Φ = azimuth of the incoming seismic waves
Φ_1 = „slow direction" of the 1st azimuthal term
Φ_2 = „slow direction" of the 2nd azimuthal term

In this function the term A_0 represents the mean or average station residual. The reference azimuths Φ_1 and Φ_2 of the two azimuth-dependent terms represent the so called „slow directions", which are the azimuths along which the largest positive residual is being observed. For the second azimuthal term there is of course another „slow direction", namely $\Phi_2 + 180°$.

If statistical significance of the azimuthal terms can be established, they can be related to certain structural or physical properties of the deeper earth, which may cause this specific azimuthal variation of residuals. Possible interpretations of the azimuthal terms are:

- The azimuthal independent constant A_0 represents the mean station residual and can essentially be explained by a deviation of the mean seismic velocity distribution with depth compared to the reference model. For example, a thickened earth´s crust or the deep reaching root of a mountain belt may cause a significant positive station residual.

- The first azimuthal term with the coefficient A_1 and the slow direction Φ_1 generally is interpreted as the effect of a non-horizontal discontinuity or anomaly of the seismic velocity, e.g. an inclined boundary between the earth´s crust and the upper mantle („dipping MOHO"), a feature which may be expected in the transition zone between two completely different tectonic provinces. A theoretical example for this is shown in Figure 3. The Φ_1 in this case exactly corresponds with the azimuth of the dip-direction. The coefficient A_1 is a measure for the dip-angle as well as for the velocity-contrast across the dipping boundary.

- For the second azimuthal term more direct explanations are possible. An elongated upwelling of a zone with lower seismic velocities, for example below a graben-like structure, may cause a pronounced COS (2Φ) variation of the residuals. Another cause for an observed significant second azimuthal term can be a pronounced anisotropy of the seismic velocities in the earth´s crust or elsewhere in the upper mantle along the seismic wave path. A number of recent investigations showed that most of the earth's upper mantle is evidently seismically anisotropic; for a quite detailed listing for example it is referred to CRAMPIN et al. (1984).

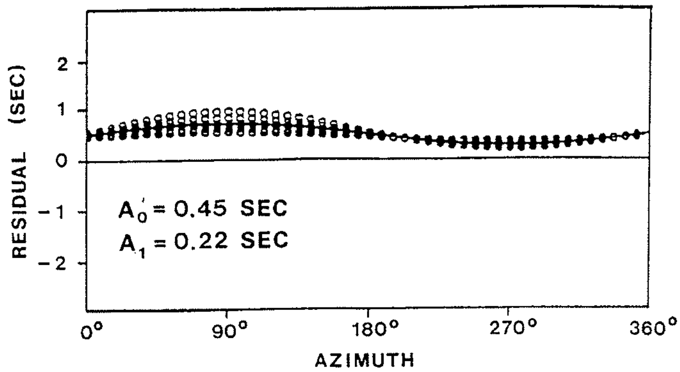


Fig. 3: COS (Φ) - approximation of theoretical travel time residuals resulting from a modified model of the earth's crust. The crust is assumed to be 10 km thicker compared to the Jeffreys-Bullen reference earth model and the crust-mantle boundary layer (MOHO) is downdipping to the East with an angle of incidence of 15°. Different angles of emergence for arriving rays are the reason for the slight scattering in the data.

Abb. 3: COS (Φ)-Approximation von theoretischen Laufzeitresiduen für ein modifiziertes Modell der Erdkruste. Es wurde im Vergleich zum Jeffreys-Bullen Referenz-Erdmodell eine um 10 km dickere Kruste angenommen. Die Grenzfläche zwischen Erdkruste und Erdmantel (MOHO) taucht unter einem Inzidenzwinkel von 15° nach Osten hin ab. Unterschiedlich angenommene Auftauchwinkel für die ankommenden Wellen sind die Ursache für die geringe Streuung der errechneten Modell-Residuen.

The objective of the residual analysis, reported here in this paper, was mainly to examine whether one can observe an azimuthal residual variation at these Antarctic stations. Of special interest was, whether and how the derived particular azimuthal terms can be related to the bases´ position near the transitions between different tectonic regions, e.g., the nearby transition between East and West Antarctica for the station SPA and the ocean-continent transition for the four other stations.

THE DATA

The residual analysis is based, as far as GvN is concerned, on the recordings of the years 1982 to 1984 (analogous and digital PCM-network recordings). Within this period a total number of more than 1000 earthquakes were recorded (ECKSTALLER 1988). This amount of data is large enough to guarantee the necessary statistical significance. Included in these data are also PKP-phase onset-readings, which are only of limited value for residual anlysis as PKP travel time table values are less exact.

Therefore PKP-phase recordings were not included in the analysis of absolute residuals. Since these possible errors are greatly reduced by dealing with relative residuals, PKP-phase readings were allowed in the analysis of relative residuals.

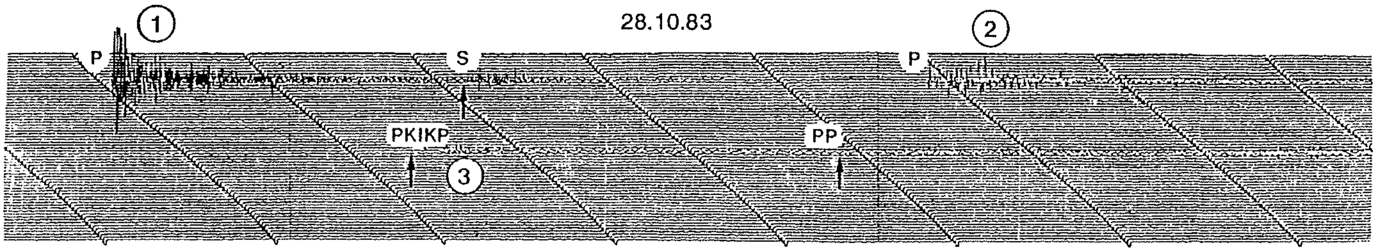
Source parameters (source location, source depth and origin time) were taken from the ISC-bulletins. The calculation of the theoretical travel times for P-phases (epicentral-distance up to 102°) was carried out using the JB-tables, as mentioned above. Travel times for PKP phases are based on the Herrin-tables, which are more appropriate for this case than those of Jeffreys-Bullen tables.

To avoid the influence of just regional velocity anomalies, e.g. errors caused by possible anomalous structures in the upper mantle relatively close to the recording site, where the ray paths are completely restricted to „nearby“ epicentres, residuals for epicentral distances of less than 20° were excluded. Therefore the residual analysis presented here is solely based on true teleseismic events.

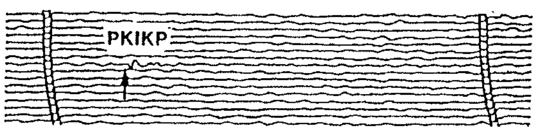
For all the earthquakes recorded at GvN, onset readings at the other four stations, if these events were also recorded there, have equally been taken from the ISC-bulletins. Additional data for SYOWA base were available through the JARE DATA REPORTS 1984-1986.

Apart from the aspect to study whether there are significant differences in azimuthal residual variation between the coastal bases and a base on the continental shield, data from the Amundsen-Scott base at the South Pole were especially included for calculating relative residuals. For the latter the great distance of more than 2000 km between this reference station SPA and the other, more coastal bases is somewhat unusual. Normally the distances to a reference station are less than 1000 km, typically in the range of just a few 100 km. Some error considerations, however, showed that the mean error in calculating relative residuals due to errors in the earthquakes' source location should typically not exceed more than ±0.3-0.4 sec, although the stations' distances are unusually great.

Figures 4 and 5 show some typical seismograms recorded at GvN. As mentioned already in WÜSTER et al. (1992), earthquake monitoring at GvN is adversely affected by an increased ground noise level and an unfavourable signal-noise ratio due to GvN's position on the floating Ekström Ice Shelf. This handicap, however, is partly compensated by the extended seismic network, especially by the two 3-component remote stations

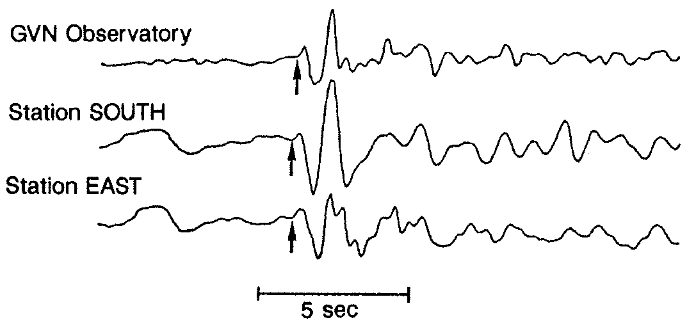


1	South Sandwich Islands	60.28° S	24.94° W	33 km	mb = 5.1	Delta = 12.3°
2	Kermadec Islands	31.42° S	179.52° W	10 km	mb = 5.5	Delta = 78.1°
3	Eastern Idaho	44.10° N	113.81° W	10 km	mb = 6.1	Delta = 135.9°



strip chart monitoring record

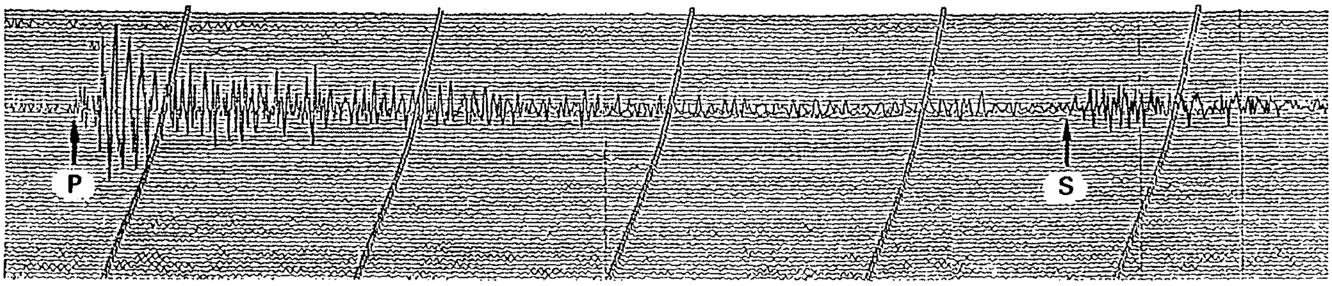
05.05.82 Nevada Test Site
37.14° N 116.01° W 0 km
mb = 5.7 Delta = 130.35°



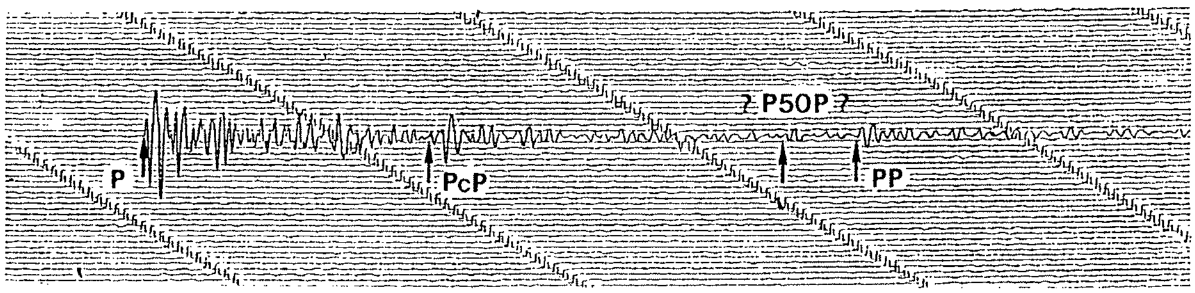
digital PCM-recording with GVN's network

Fig. 4: Some examples of seismograms recorded at GVN. The onset in the recording of a nuclear test explosion at the Nevada Test Site is scarcely to determine on the monitoring strip chart recorder due to very low amplitudes. However, on the playback of the network´s digital PCM-recording, the first break can be determined quite exactly due to the high signal coherence.

Abb. 4: Einige Registrierbeispiele von Seismogrammen, die an GVN aufgenommen wurden. Der Ersteinsatz in der Registrierung einer Kernexplosion im Nevada Test-Gelände ist auf der Monitor-Aufzeichnung aufgrund der sehr geringen Amplituden kaum zu bestimmen. In der Abspielung der digitalen PCM-Registrierung der Netzwerk-Stationen kann der Ersteinsatz wegen der hohen Signalkohärenz jedoch noch exakt festgelegt werden.



Palmer Peninsula 13.12.82 63.15° S 61.00° W 3 km mb = 5.7 Delta = 21.28°



North of Macquarie Island 23.05.84 51.88° S 161.08° E 10 km mb = 5.8 Delta = 57.58°

Fig. 5: Earthquakes occuring in the South Sandwich Islands area and near the Antarctic Peninsula (above) are the few events, where more or less pronounced S-waves can be observed at GVN. The seismogram of an event near the Macquarie Island (below) exhibits distinct reflections at the earth's core-mantle boundary (PcP) and at the free surface (PP). There is no indication for a possible precursor „P50P", which might be generated by a reflection at the base of the crust about 50 km below the PP-reflection point. This reflection point should be situated below the Transantarctic Mountains.

Abb. 5: Erdbeben im Bereich der Süd-Sandwich-Inseln und nahe der Antarktischen Halbinsel (oben) sind die wenigen Ereignisse, bei denen an GVN teils noch ausgeprägte S-Wellen-Einsätze beobachtet werden können. Das Seismogramm eines Bebens im Bereich der Macquarie Insel (unten) zeigt deutliche Reflexionen an der Kern-Mantel-Grenze (PcP) und an der freien Oberfläche (PP). Für einen möglichen Vorläufer „P50P", der durch eine Reflexion an der Unterseite der Erdkruste in etwa 50 km Tiefe unterhalb des PP-Reflexionspunktes entstehen könnte, gibt es keine Hinweise. Der Reflexionspunkt sollte unterhalb des Transantarktischen Gebirges liegen.

installed on grounded ice in the last years (on Søraasen Ice Rise since 1986, on Halfvar Ridge since 1989. The signal-coherence in most recordings is great enough to determine the onset times unambigously even for very small amplitudes (Fig. 4, the recording of a nuclear test at the Nevada Test Site).

An important requirement for the analysis of azimuthal residual variation is a uniform azimuthal distribution of recorded events. This essential condition is unfortunately not fulfilled at all these bases. On the contrary from Figure 6 one can see that the azimuthal distribution of observed earthquakes is very irregular. About 80% of the recorded earthquakes at GvN are concentrated on the subduction zones in the New Hebrides area, the Fidji-Tonga-Kermadec island arc, off and below the mountain belt of the Andes and the South Sandwich island arc. All these earthquake zones cover only a very limited azimuth range of not more than about 10° at all stations (Figs. 6 and 7). Additionally, earthquakes in these regions have widely varying focus depths up to 600 - 700 km. These imply that an essential part of residuals for these areas may be contaminated to a great extent by anomalous source structures depending on the depth of focus. Different lengths of the ray paths in these anomalous source structures, predominatly within the down-dipping, cold and therefore fast lithospheric slabs, may and actually do result in a great residual scattering (Figure 7). Therefore an appropriate data reduction is an essential requirement for residual analyses.

DATA REDUCTION

For a conclusive residual analysis possibly faulty or even evidently wrong residuals must be excluded in an appropriate manner. Different approaches can be taken to solve this task, according to the different sources of errors mentioned above, e.g. errors due to anomalous source structures, incorrect source parameters (hypocentre coordinates and origin time) or improper onset readings. An appropriate data reduction should also ensure the wanted fairly exact uniformity in azimuthal coverage.

Figure 7 shows the absolute residuals of recorded P-phases at the stations GvN and SPA. Remarkable is the unusually large scattering of the data compared to data published by many other authors. This is to a great part caused by the fact that localizations of earthquakes in the southern hemisphere, especially in the southern pacific area (e.g. data from the Fidji-Tonga-Kermadec area at about 190° azimuth) are more inaccurate than in most

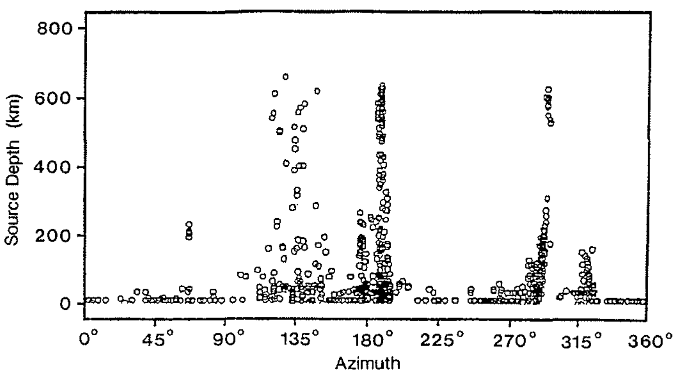


Fig. 6: The source depths of earthquakes recorded at GVN, plotted in relation to the corresponding azimuths. This picture shows that the azimuthal distribution of recorded events is distinctly non-uniform and predominantly characterized by earthquakes occuring in subduction zones. Between four marked „peaks“ or „clusters“ with varying depth extensions can easily be distinguished, corresponding to different source regions: Azimuth 180° = New Hebrides area; Azimuth 190° = Fiji-Tonga-Kermadec island arc; Azimuth 290° = Andes mountain belt; Azimuth 320° = South Sandwich Islands area. The deep focus earthquakes at about 135° azimuth are events from the Western Pacific area, predominantly the Japan Sea and the Philippine Islands.

Abb. 6: Die Herdtiefen von an GVN beobachteten Erdbeben, dargestellt in Abhängigkeit von den zugehörigen Azimuten. Das Bild zeigt, daß die azimutale Verteilung der registrierten Ereignisse äußerst ungleichmäßig ist und vorwiegend bestimmt ist von Beben in Subduktions-Gebieten. Es können vier markante „Cluster“ mit unterschiedlicher Tiefenerstreckung unterschieden werden, die folgenden Bebenregionen zuzuordnen sind: Azimuth 180° = Neue Hebriden, Azimuth 190° = Fidschi-Tonga-Kermadec Inselbogen, Azimuth 290° = Andengürtel, Azimuth 320° = Süd-Sandwich-Inseln. Die Tiefherdbeben bei einem Azimut von ca. 135° sind Beben aus dem Randbereich des westlichen Pazifik, vorwiegend aus der Japan-See und den Philippinen.

other regions. One of the main reasons for this is the relatively wide-meshed network of seismological stations in these regions which will result in greater localization errors. To eliminate such evident dropouts a certain tolerance level was established (±3 sec and ±5 sec, resp.).

Furthermore one can learn from Figure 7 that there are great differences between the mean values of the two closely adjacent residual clusters at about 180° and 190° azimuth, e.g. between the mean residuals concerning earthquakes in the New Hebrides area and in the Fidji-Tonga-Kermadec region. This is true for both GvN and SPA. Therefore, this effect cannot be related to a special anomalous structure of the deeper earth below these stations, especially because this discrepancy can also be clearly observed at the remaining three stations not included in this figure. Consequentely the reason for this discrepancy must be explained by different velocity anomalies in the particular source regions, e.g. different dip-angles or depth-extensions of the down dipping lithospheric slabs. Different ray paths from the earthquake foci to the different observing stations within such lithospheric slabs additionally have a crucial impact on the travel time residuals. This can be demonstrated quite impressively with data obtained from earthquakes in the Tonga area. Figure 8 shows the azimuthal dependence of travel time residuals to be expected for a theoretical velocity model of the „Tonga slab“ derived by SLEEP (1973). The corresponding observed mean residuals for earthquakes in this region are lying almost exactly on this theoretical curve for all stations; in this case the

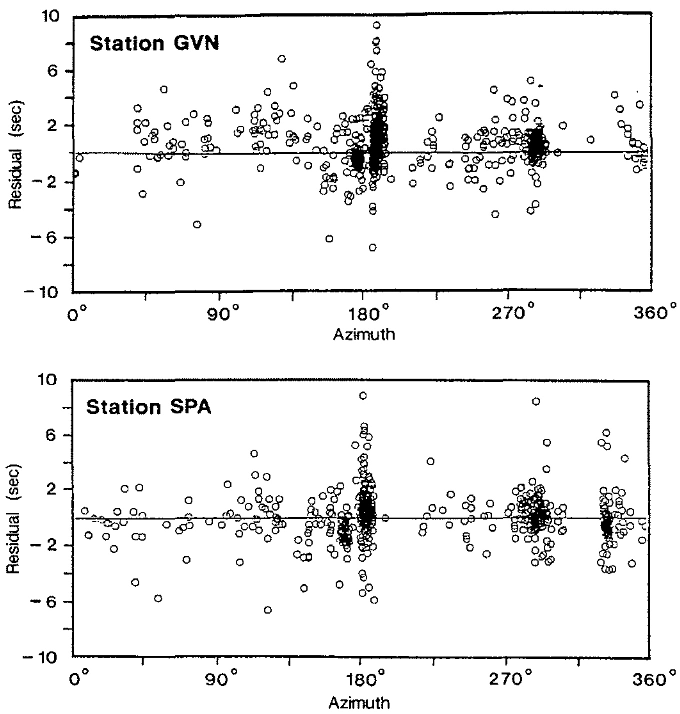


Fig. 7: Absolute travel time residuals for the stations GVN and SPA. Apart from the unusually large scattering in the data and the extreme data concentration within only small azimuthal windows, it is striking that there is a marked discrepancy between the mean residual values of the two closely adjacent residual „clusters“ at 180° and 190° azimuth, respectively (residuals for events in the New Hebrides area and the Fiji-Tonga-Kermadec area, resp.). This discrepancy can be observed at all considered stations.

Abb. 7: Absolute Laufzeitresiduen für die Stationen GVN und SPA. Abgesehen von der ungewöhnlich großen Streuung und der extremen Datenkonzentration innerhalb nur sehr begrenzter Azimutintervalle ist der deutliche Unterschied der mittleren Residuen der zwei eng benachbarten Residuen-„Cluster“ bei 180° und 190° Azimut besonders auffällig (Residuen von Ereignissen in den Neuen Hebriden, bzw. dem Gebiet Fidschi-Tonga-Kermadec). Diese Diskrepanz ist an allen betrachteten Stationen festzustellen.

azimuth is not the back-azimuth but the azimuth from the center of the source region to the different recording sites. For completeness it should be mentioned that the mean values of these clusters were only corrected by the mean station residuals to reduce the effect of a possible station-based anomaly.

In order to keep out such evidently „slab-contamined“ residuals and besides this restriction to maintain a sufficient azimuthal coverage only deep focus earthquakes within these clusters were used for analysis. The idea for doing so was that in the case of deep focus events the ray paths within the anomalous structures are confined to a very limited range. The seismic waves will soon reach the depths at which lateral velocity deviations vanish at all or are at least less distinct. The justification for this assumption can be seen in Figure 9, which depicts the depth-dependance of the Fidji-Tonga-Kermadec residuals at GvN. With increasing depth there is a linear trend to decreasing residual values, almost tending to the mean station residual. Additionally the scattering of the data is remarkable decreased.

Another method for data reduction is to divide the full azimuth

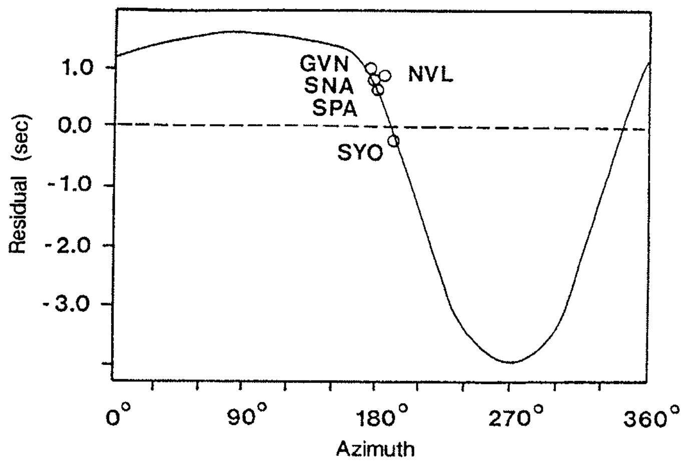


Fig. 8: Theoretical travel time residuals for a velocity model of the subduction zone in the Tonga Islands region (downdipping lithospheric plate of the „Tonga Slab", after SLEEP 1973). The mean residual values for events from this region, only corrected for real station based residual effects (mean station residual), coincide almost exactly with the theoretical values for all stations. This shows quite clearly the impact of lithospheric slab effects in the source region on the travel time residuals and how strongly these may be contaminated by pure source effects.

Abb. 8: Theoretische Laufzeitresiduen für ein Modell der Subduktions-Zone im Bereich der Tonga-Inseln (abtauchende Lithosphäre des „Tonga Slab's", nach SLEEP 1973). Die mittleren Residuen von Ereignissen aus dieser Region, lediglich korrigiert im Hinblick auf wirklich stationsseitige Effekte (mittleres Stations-Residuum) decken sich nahezu vollständig mit den theoretischen Werten an allen Stationen. Dies demonstriert deutlich den gewichtigen Einfluß lithosphärischer Platteneffekte auf die Berechnung von Laufzeitresiduen und wie stark diese durch herdseitige Einflüsse kontaminiert werden können.

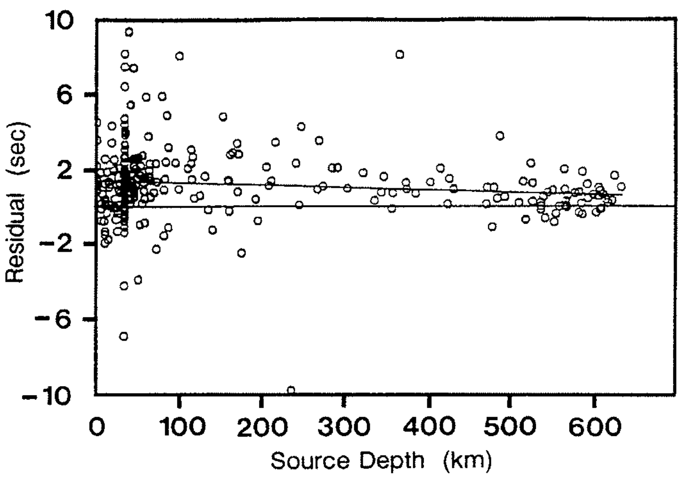


Fig. 9: Absolute travel time residuals for events in the Fiji-Tonga-Kermadec region dependent on the the source depth. With increasing source depth one can observe a remarkable decrease in the scattering of the data and also a linear trend to decreasing residual values, almost tending to the mean station residual. These are indications that source influences on the wave propagation are greatly reduced for deeper earthquakes and thus the corresponding residuals are less contaminated by source effects.

Abb. 9: Absolute Laufzeitresiduen für Ereignisse in der Region Fidschi-Tonga-Kermadec in Abhängigkeit von der Herdtiefe. Mit zunehmender Herdtiefe ist eine deutliche Abnahme der Datenstreuung zu beobachten sowie ein linearer Trend hin zu abnehmenden Werten. Zudem nähern sich die Residuen immer mehr dem mittleren Stations-Residuum. Dies sind Hinweise, daß herdseitige Einflüsse auf die Wellenausbreitung bei tieferen Erdbeben schon weitgehend reduziert sind und so die resultierenden Residuen dadurch weniger kontaminiert sind.

range in separate azimuth-intervalls and consequently taking only the mean values within these intervalls in the residual analysis. This was done by defining 20° wide azimuth-windows. The influence of large clusters with probably contaminated residuals is thereby greatly reduced, while at the same time a uniform azimuthal coverage can easily be achieved. In addition the quality of the data can be taken into some account by using the inverse of the residual variance within the azimuth-intervals as weighting coefficient for the azimuthal approximation.

Both methods for data reduction were applied and the results of the corresponding analyses are almost exactly equivalent. With the latter method there also are almost no differences depending on the definition of the interval-boundaries, provided that the azimuthal distribution of residuals is free of large gaps in the data.

RESULTS

The characteristic feature of the azimuthal (absolute) residual variation at each station is already delineated in Figure 10. In this figure only the mean values within single azimuth intervals related to the mean station residual are depicted. Though the scattering is only partly suppressed by smoothing averages, this figure already shows that the azimuthal residual variation at the stations GvN, SNA and NVL is quite similar.

Related to the mean station residuals there are distinct delays for northeasterly and easterly azimuths. A more or less abrupt change can be observed to the Southeast, at least at GvN and NVL. Contrary to this the arrival times are too early in the azimuth-interval approximately from the Southeast to the Northwest. The mean residual also is almost of the same value und represents a general mean delay of about half a second.

The residual variation at the station SYO shows, apart from the negative mean value, a somehow similar behaviour compared to that described for the stations above. Marked earlier arrivals, however, are only limited to westerly directions, while other azimuths generally display too late arrivals.

A less pronounced dependence of the residuals upon the azimuth can be stated for the station SPA. Too early arrivals, although not very distinct, are more or less restricted to azimuths indicating that region where the seismic waves are passing the continental shield area. Contrary to this, most of the relative delays are bound to ray paths crossing the deeper earth below West Antarctica and the Transantarctic Mountains.

The special feature of the residuals at SPA is thus characteristic for a station on and nearby the margin of the continental Antarctic shield. Some aspects of these first results are thus consistent with many other investigations about residuals and travel times in old continental shields and platforms. These tectonic regions are generally characterized by a thicker lithosphere and higher seismic velocities in the upper mantle, which imply a faster wave propagation, thereby resulting in

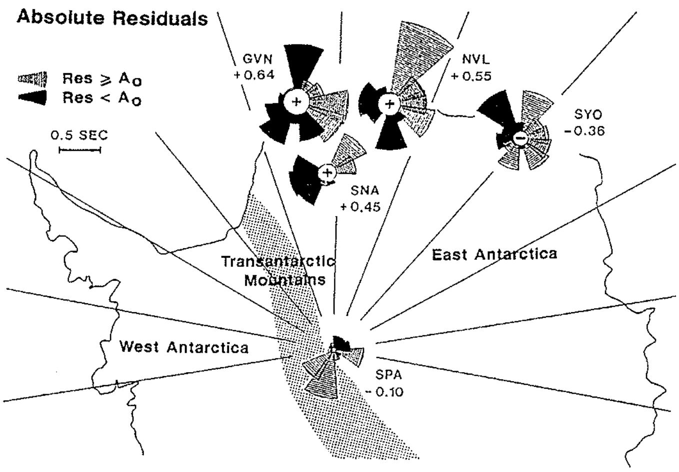


Fig. 10: The azimuthal variation of absolute travel time residuals of the considered stations, represented as residual roses. Plotted are the mean residual values of overlapping 30° wide azimuth windows (smoothed averages) if there are at least five residual values within these windows. The rose bars are related to the mean station residual or the constant A_0, resp., which is given below the stations' abbreviation.

Abb. 10: Die azimutale Variation der absoluten Laufzeitresiduen an den untersuchten Stationen, dargestellt als Residuen-Rosetten. Eingezeichnet sind die Residuen-Mittelwerte von überlappenden 30° weiten Azimutintervallen (gleitendes Mittel), sofern sie mehr als fünf Werte enthalten. Die Rosettenwerte sind auf das mittlere Stationsresiduum, bzw. den A_0-Wert bezogen, der unterhalb der Stationskennung angegeben ist.

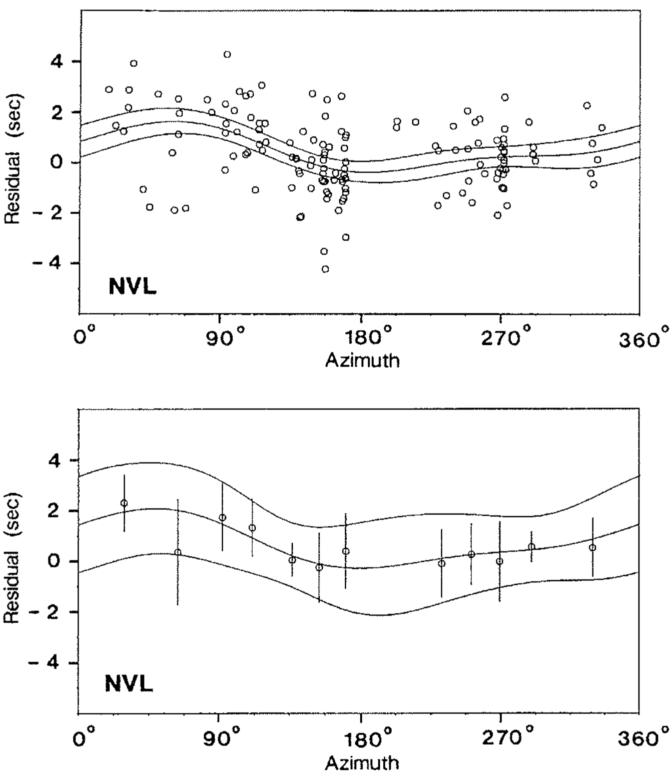


Fig. 11: Azimuthal approximation of absolute travel time residuals of the station GVN with both the COS (Φ)- and COS (2Φ)-term, obtained with different methods of data reduction.
Top: Data reduction done by considering only these events with the deepest source depths within the predominant residual clusters. Results: A_0 = 0.63 ±0.10 sec;
COS(Φ)-term: A_1 = 0.45 ±0.19 sec, Φ_1 = 67° ±24°,
COS(2Φ)-term: A_2 = 0.50 ±0.20 sec, Φ_2 = 110° ±11°
Bottom: Data reduction by taking only the mean values of the residuals within 20° wide azimuth windows. The window means were weighted proportional to the corresponding variance within the window. Results: A_0 = 0.57 ±0.18 sec;
COS(Φ)-term: A_1 = 0.38 ±0.25 sec, Φ_1 = 81° ±40°,
COS(2Φ)-term: A_2 = 0.42 ±0.35 sec, Φ_2 = 115° ±20°

Abb. 11: Azimutale Approximation der absoluten Laufzeitresiduen der Station GVN durch die COS(Φ)- und COS(2Φ)-Terme mit unterschiedlichen Methoden der Datenreduktion.
Oben: Datenreduktion erreicht durch ausschließliche Verwendung der Beben innerhalb der Residuen-„Cluster", die die größten Herdtiefen aufweisen. Ergebnisse: A_0 = 0.63 ±0.10 sec; COS(Φ)-term: A_1 = 0.45 ±0.19 sec, Φ_1 = 67° ± 24°, COS(2Φ)-term: A_2 = 0.50 ±0.20 sec, Φ_2 = 110° ±11°
Unten: Datenreduktion durchgeführt durch Mittelung innerhalb von 20° breiten Azimutintervallen. Die Mittelwerte sind umgekehrt proportional zur Varianz der Daten innerhalb der Intervalle gewichtet. Ergebnisse: A_0 = 0.57 ±0.18 sec;
COS(Φ)-term: A_1 = 0.38 ±0.25 sec, Φ_1 = 81° ±40°,
COS(2Φ)-term: A_2 = 0.42 ±0.35 sec, Φ_2 = 115° ±20°

negative travel time residuals. On the other side the relative delays connected with rays emerging at azimuths pointing to West Antarctica and the Transantarctic Mountains possibly indicate the influence of a regional low velocity anomaly below West Antarctica. As East and West Antarctica are tectonically and from their history of origins quite different, this characteristic feature of the residuals at SPA may be quite plausible. One may even imagine that a deep reaching velocity anomaly below the Transantarctic Mountains may be somehow responsible for the observed delays.

Nevertheless, since the azimuthal residual variation at the station SPA is not so pronounced, it is thoroughly justified to refer to this station as a reference for calculating relative residuals.

Figures 11 to 14 show representative for the remaining stations the azimuthal approximation of the absolute and relative residuals at the stations GvN and NVL, including both the first and the second azimuthal term. Generally at all stations there is quite an excellent agreement between the results obtained with different methods of data reduction. The differences between the approximation using selected single residuals and the approximation using the averages within certain azimuth windows are almost negligible. Statistical tests, i.e. Fisher-tests for the „goodness of fit" and the statistical certainty of each azimuthal term, resp., generally turn out positively for the first azimuthal term (except for the station SNA, due to less data). The second azimuthal term, however, can be prooved to be statistically significant only for the residuals of the stations GvN and NVL. The pronounced similarity of the residual variation at the station SNA compared to the results for the stations GvN and NVL suggests that the second azimuthal term must also be used in describing the residual variation at this station. The general correspondence in the azimuthal features of the residuals at these three stations can also be stated by simple correlation calculations. Thus the three neighbouring stations GvN, SNA and NVL can be characterized by almost the same residual variation.

Figures 15 and 16 show the resulting coefficients and phase values for the azimuthal approximation of both absolute and relative travel time residuals at the four coastal stations GvN, SNA, NVL and SYO. From these figures two substantial characteristics can be deduced:

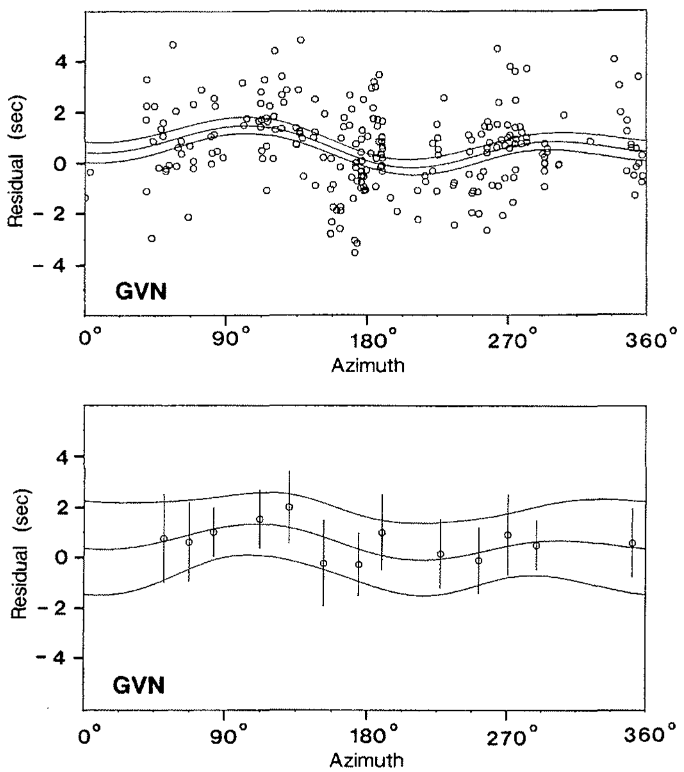


Fig. 12: Azimuthal approximation of absolute travel time residuals of the station NVL with both the COS (Φ)- and COS (2Φ)-term, obtained with different methods of data reduction.
Top: Data reduction done by considering only these events with the deepest source depths within the predominant residual clusters. Results: $A_0 = 0.49 \pm 0.14$ sec;
COS(Φ)-term: $A_1 = 0.83 \pm 0.28$ sec, $\Phi_1 = 43° \pm 18°$,
COS(2Φ)-term: $A_2 = 0.36 \pm 0.27$ sec, $\Phi_2 = 71° \pm 19°$
Bottom: Data reduction done by taking only the mean values of the residuals within 20° wide azimuth windows. The window means were weighted proportional to the corresponding variance within the window. Results: $A_0 = 0.76 \pm 0.17$ sec;
COS(Φ)-term: $A_1 = 1.05 \pm 0.32$ sec, $\Phi_1 = 35° \pm 16°$,
COS(2Φ)-term: $A_2 = 0.35 \pm 0.31$ sec, $\Phi_2 = 60° \pm 21°$

Abb. 12: Azimutale Approximation der absoluten Laufzeitresiduen der Station NVL durch die COS(Φ)- und COS(2Φ)-Terme mit unterschiedlichen Methoden der Datenreduktion.
Oben: Datenreduktion erreicht durch ausschließliche Verwendung der Beben innerhalb der Residuen-„Cluster", die die größten Herdtiefen aufweisen. Ergebnisse: $A_0 = 0.49 \pm 0.14$ sec; COS(Φ)-term: $A_1 = 0.83 \pm 0.28$ sec, $\Phi_1 = 43° \pm 18°$, COS(2Φ)-term: $A_2 = 0.36 \pm 0.27$ sec, $\Phi_2 = 71° \pm 19°$
Unten: Datenreduktion durchgeführt durch Mittelung innerhalb von 20° breiten Azimutintervallen. Die Mittelwerte sind umgekehrt proportional zur Varianz der Daten innerhalb der Intervalle gewichtet. Ergebnisse: $A_0 = 0.76 \pm 0.17$ sec;
COS(Φ)-term: $A_1 = 1.05 \pm 0.32$ sec, $\Phi_1 = 35° \pm 16°$,
COS(2Φ)-term: $A_2 = 0.35 \pm 0.31$ sec, $\Phi_2 = 60° \pm 21°$

1) The slow directions of the first azimuthal term are pointing almost uniformly into easterly directions for all stations. This effect, although already quite distinct concerning absolute residuals, can be seen much more clearly in the case of relative residuals. The amplitudes of the COS(Φ)-term all are of comparable size.

2) Both slow directions of the second azimuthal term, even if this term (slightly) fails to meet the statistical significance in the results for SNA and SYO, exhibit a distinct orientation almost parallel to the coast line or continental margin.

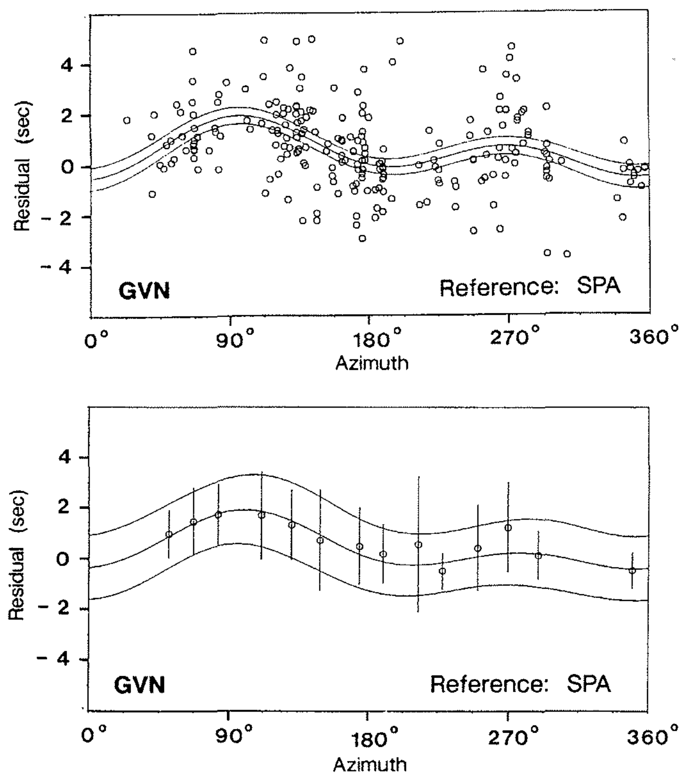


Fig. 13: Azimuthal approximation of relative travel time residuals of the station GVN with both the COS (Φ)- and COS (2Φ)-term, obtained with different methods of data reduction (reference station SPA).
Top: Data reduction by consideration of only events with deepest source depths within the predominant residual clusters. Results: $A_0 = 0.52 \pm 0.11$ sec;
COS(Φ)-term: $A_1 = 0.67 \pm 0.20$ sec, $\Phi_1 = 113° \pm 18°$,
COS(2Φ)-term: $A_2 = 0.80 \pm 0.17$ sec, $\Phi_2 = 93° \pm 6°$
Bottom: Data reduction by taking only mean values of residuals within 20° wide azimuth windows. The window means were weighted proportional to the corresponding variance within the window. Results: $A_0 = 0.46 \pm 0.10$ sec;
COS(Φ)-term: $A_1 = 0.85 \pm 0.17$ sec, $\Phi_1 = 105° \pm 11°$,
COS (2Φ)-term: $A_2 = 0.64 \pm 0.17$ sec, $\Phi_2 = 100° \pm 8°$

Abb. 13: Azimutale Approximation der relativen Laufzeitresiduen der Station GVN durch die COS(Φ)- und COS(2Φ)-Terme mit unterschiedlichen Methoden der Datenreduktion (Referenzstation SPA).
Oben: Datenreduktion erreicht durch ausschließliche Verwendung der Beben innerhalb der Residuen-„Cluster", die die größten Herdtiefen aufweisen. Ergebnisse $A_0 = 0.52 \pm 0.11$ sec; COS(Φ)-term: $A_1 = 0.67 \pm 0.20$ sec, $\Phi_1 = 113° \pm 18°$, COS (2Φ)-term: $A_2 = 0.80 \pm 0.17$ sec, $\Phi_2 = 93° \pm 6°$
Unten: Datenreduktion durchgeführt durch Mittelung innerhalb von 20° breiten Azimutintervallen. Die Mittelwerte sind umgekehrt proportional zur Varianz der Daten innerhalb der Intervalle gewichtet. Ergebnisse: $A_0 = 0.46 \pm 0.10$ sec;
COS(Φ)-term: $A_1 = 0.85 \pm 0.17$ sec, $\Phi_1 = 105° \pm 11°$,
COS (2Φ)-term: $A_2 = 0.64 \pm 0.17$ sec, $\Phi_2 = 100° \pm 8°$

These results show that even across great distances, at least along the continental margin of Queen Maud Land, special major tectonic features or characteristic physical properties of the deeper earth are characterizing this region and therefore must determine the observed azimuthal residual variations.

INTERPRETATION

From the results of this analysis alone it is not possible to deduce a realistic model of the deeper earth. Additional information about characteristic geological and tectonic features must

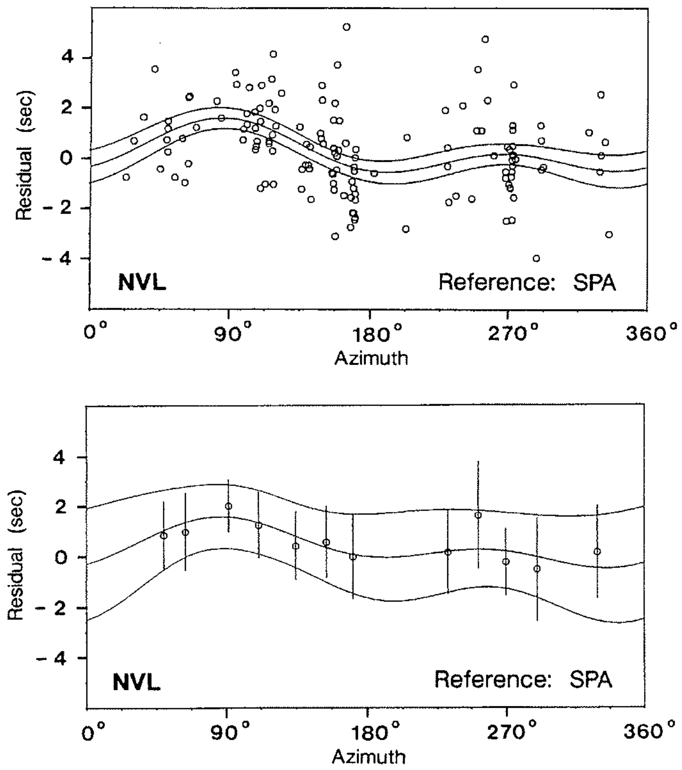


Fig. 14: Azimuthal approximation of relative travel time residuals of the station NVL with both the COS (Φ)- and COS (2Φ)-term, obtained with different methods of data reduction (reference station SPA).
Top: Data reduction by consideration of events with the deepest source depths within the predominant residual clusters. Results: $A_0 = 0.23 \pm 0.17$ sec;
COS(Φ)-term: $A_1 = 0.72 \pm 0.22$ sec, $\Phi_1 = 83° \pm 23°$,
COS(2Φ)-term: $A_2 = 0.66 \pm 0.24$ sec, $\Phi_2 = 86° \pm 11°$
Below: Data reduction by taking only mean values of residuals within 20° wide azimuth windows. The window means were weighted proportional to the corresponding variance within the window. Results: $A_0 = 0.37 \pm 0.22$ sec;
COS(Φ)-term: $A_1 = 0.71 \pm 0.28$ sec, $\Phi_1 = 102° \pm 28°$,
COS(2Φ)-term: $A_2 = 0.55 \pm 0.35$ sec, $\Phi_2 = 82° \pm 16°$

Abb. 14: Azimutale Approximation der relativen Laufzeitresiduen der Station NVL durch die COS(Φ)- und COS(2Φ)-Terme mit unterschiedlichen Methoden der Datenreduktion (Referenzstation SPA).
Oben: Datenreduktion erreicht durch ausschließliche Verwendung der Beben innerhalb der Residuen-„Cluster", die die größten Herdtiefen aufweisen. Ergebnisse: $A_0 = 0.23 \pm 0.17$ sec; COS(Φ)-term: $A_1 = 0.72 \pm 0.22$ sec, $\Phi_1 = 83° \pm 23°$, COS(2Φ)-term: $A_2 = 0.66 \pm 0.24$ sec, $\Phi_2 = 86° \pm 11°$
Unten: Datenreduktion durchgeführt durch Mittelung innerhalb von 20° breiten Azimutintervallen. Die Mittelwerte sind umgekehrt proportional zur Varianz der Daten innerhalb der Intervalle gewichtet. Ergebnisse: $A_0 = 0.37 \pm 0.22$ sec;
COS(Φ)-term: $A_1 = 0.71 \pm 0.28$ sec, $\Phi_1 = 102° \pm 28°$·
COS(2Φ)-term: $A_2 = 0.55 \pm 0.35$ sec, $\Phi_2 = 82° \pm 16°$

be included to restrain the model. As the number of geophysical and geological investigations, covering this region of interest, is limited, this demand cannot be fulfilled. Nevertheless, some of the results obtained by this analysis can be explained quite satisfactorily.

- From dispersion analysis of surface waves and other investigations, like combined analysis of travel times and short-period amplitude data or gravity measurements one should expect at the station SPA a crustal thickness of at least some 40 km to about 50 km (for example DEWART & TOKSÖZ 1965, MCMECHAN 1981, GROUSHINSKY & SAZHINA 1982). The higher value of about 50 km for the crustal thickness at the South Pole seems to be more reliable. This is much thicker compared to the reference earth model. Therefore one should also expect a delay in the travel times and thus a positive absolute mean station residual. Contrary to this we observe a negative mean station residual of -0.10 sec at SPA. Referring to the model of Jeffreys and Bullen, this effect can be explained by a slightly higher seismic average-velocity of about 6.4 km/sec compared to 6.0 km/sec in the JB-model. Similar mean velocities within the crust were also found by deep seismic sounding experiments near the bases NVL and SYO (KOGAN 1972, IKAMI et al. 1983).

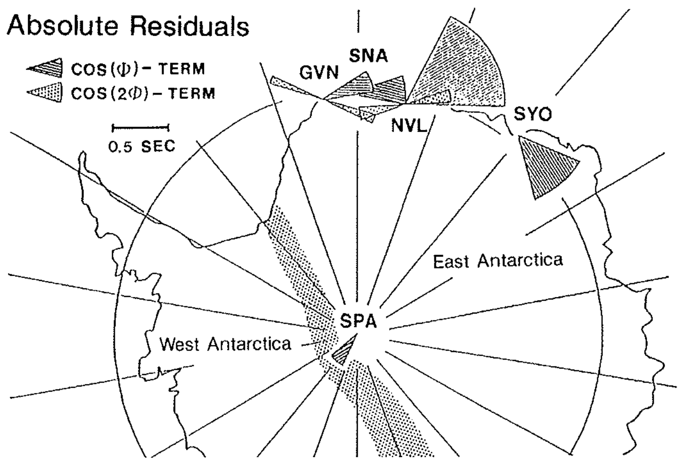


Fig. 15: The „slow directions" of the COS (Φ)- and COS (2Φ)-terms from the approximation of absolute travel time residuals for all considered stations. The results for the stations SNA and SPA, however, did not reach the desired level of statistical significance of 90 %, but failed only slightly. The error interval comprises the standard deviation ±Δ (Φ) for the calculated directions.

Abb. 15: Die „langsamen Richtungen" der COS(Φ)- und COS(2Φ)-Terme aus der Approximation der absoluten Laufzeitresiduen für alle untersuchten Stationen. Die Ergebnisse für die Stationen SNA und SPA erreichten zwar nicht die geforderte statistische Sicherheit von 90 %, verfehlten diese Signifikanzschwelle jedoch nur knapp. Das Fehlerintervall bezieht sich auf die Standardabweichung von ±Δ (Φ) für die errechneten Richtungen.

- At the stations GvN, SNA and NVL the comparable values of the positive mean station residuals of about +0.50 sec are too large to be explained by just a single crustal effect. They can only be interpreted in a plausible manner by postulating a low velocity layer somewhere in the upper mantle. The position of these stations near the continental margin may lead to believe that this low velocity layer could represent a somehow more oceanic type of lithosphere. A possible model, for example, could be composed of a 100 km thick lithospheric layer within an otherwise normal earth, which is characterized by a seismic velocity reduced from normally about 8.0 km/sec down to 7.5 km/sec.

Some indirect indication of the possible existence of such a low velocity layer may be deduced from anomalies of the earth's magnetic field detected by the MAGSAT satellite (RITZWOLLER & BENTLEY 1983). Over the central part of Neuschwabenland there is a distinct negative, large scale anomaly (Fig. 17). A possible interpretation of this minimum

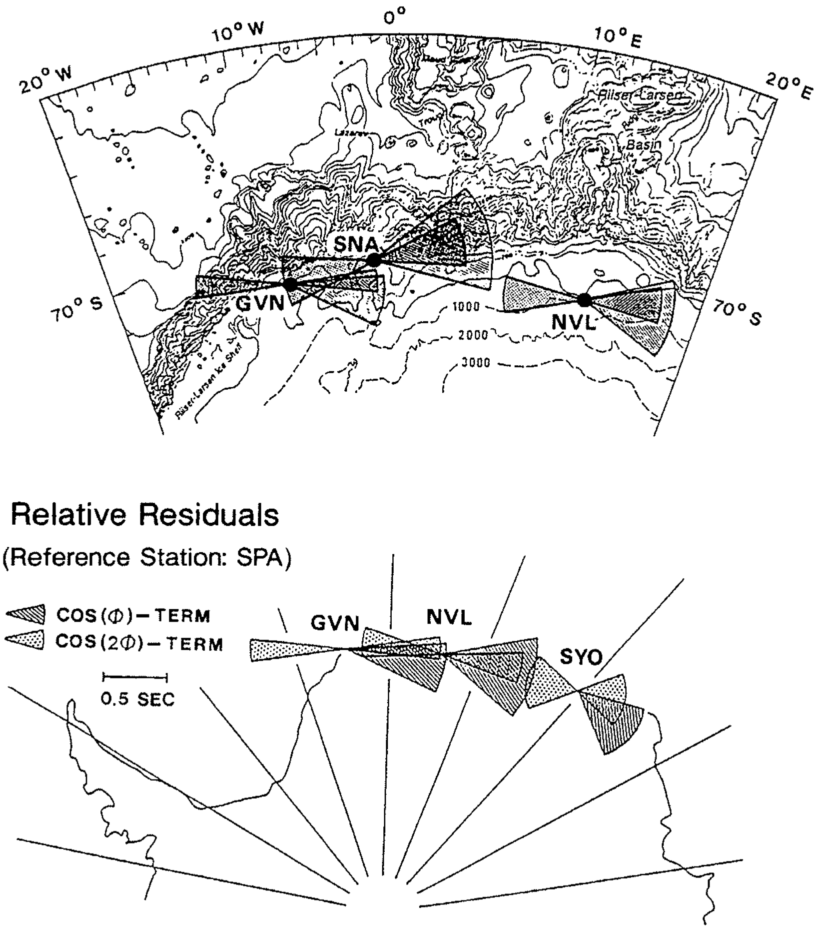


Fig. 16: The „slow directions" of the COS (Φ)- and COS (2Φ)-terms from the approximation of relative travel time residuals at the coastal stations GVN, SNA, NVL and SYO within the corresponding standard deviation ±Δ (Φ). Even if at the stations SNA and SYO the COS (2Φ)-term failed slightly to prove statistically significant at a confidence level of 90 %, the orientations of the „slow directions" of both first and second azimuthal term exhibit an almost similar behavior at all these coastal stations. The „slow directions" of the COS (Φ)-term generally point almost parallel to the coast to easterly directions. The almost exact coast parallel orientation of the both „slow directions" of the COS (2Φ)-term is also clearly visible. Compared to the results with absolute residuals (Fig. 15) the latter effect is distinctly more pronounced with relative residuals.

Abb. 16: Die „langsamen Richtungen" der COS(Φ)- und COS(2Φ)-Terme aus der Approximation der relativen Laufzeitresiduen an den küstennahen Stationen GVN, SNA, NVL und SYO mit den entsprechenden Standardabweichungen ±Δ (Φ). Auch wenn für die Stationen SNA und SYO die geforderte statistische Sicherheit von 90 % für den COS(2Φ)-Term nicht ganz erreicht wurde, so zeigen die „langsamen Richtungen" der beiden azimutalen Terme dennoch an allen Stationen das gleiche Verhalten. Die „langsamen Richtungen" des COS(Φ)-Terms zeigen generell nahezu küstenparallel in östliche Richtung. Die nahezu völlig küstenparallele Orientierung der beiden „langsamen Richtungen" des COS(2Φ)-Terms ist ebenfalls deutlich zu erkennen. Verglichen mit den Ergebnissen für die absoluten Residuen (Abb. 15) ist dieser Effekt bei den relativen Residuen deutlich ausgeprägter.

is a regionally elevated level of the Curie-isotherm and thus higher temperatures within the earth, which could be responsible for lower seismic velocities. But up to this day there are only limited experiences in the interpratation of such magnetic data.

- The general easterly orientation of the slow directions of the first azimuthal term cannot be explained unambiguously. Normally one would expect an orientation more or less perpendicular to the coastal line or continental margin, i.e. perpendicular to the striking direction of the main tectonic features. Either the specific tectonic situation at these bases is very complicated or the easterly orientations may also be seen in relation to the already mentioned MAGSAT-anomaly, at least for the stations GvN, SNA and NVL.

- The marked alignment of the second azimuthal term's slow directions, almost exactly parallel to the coast, cannot be interpreted just as a local effect. Although the necessary statistical significance for this term cannot be stated with these data for the stations SNA and SYO, there are some reasonable arguments that for this case this term should also be allowed for the residuals' approximation. This effect must be considered as typical for the passive continental margin of East Antarctica. The most simple and also plausible explanation for this coast-parallel orientation is that this effect is caused by a marked velocity anisotropy in the upper mantle. Recent investigations in other comparable regions in the world support this argument (e.g. DZIEWONSKI & ANDERSON 1983, DRUMMOND 1985). The fact that the approximation of GvN's residuals leads to different results for different angles of incidence is a further indirect indication for this interpration. Residuals corresponding to comparatively low angles of incidence (30° - 50°) can only be approximated properly with the COS(2Φ)-term. Contrary to this the COS(Φ)-term is entirely sufficient for steeper angles of incidence. Although this can only be stated exactly with data from GvN, the same effect appears in outlines also with the data from the station NVL.

It is generally accepted that the reason for a marked velocity anisotropy of the upper mantle is a preferred orientation of olivine and pyroxene crystals, the main constituents of the upper mantle´s petrology. The reorientation of the minerals may either be caused directly by viscoplastic flow processes within the earth's mantle or also by syntectonic recrystallization under uniaxial stress conditions. Within the last years investigators found quite a number of indications that the mantle's velocity anisotropy must be directly coupled with predominant flow processes in the deeper earth and the principal axes of the tectonic stress regime. The fast direction of the seismic velocities should thereby in general coincide with the predominant direction of flow and the orientation of maximal tectonic extension, respectively.

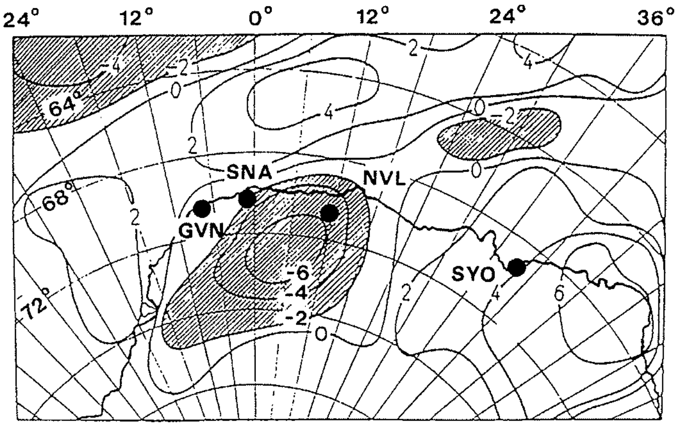


Fig. 17: MAGSAT anomaly of the Earth's magnetic field intensity over the central part of Queen Maud Land (contouring interval 2 nT, flying altitude 470 km). A direct relation between this negative anomaly and the supposed low-velocity layer in the Earth´s mantle must still be speculative.

Abb. 17: MAGSAT-Anomalie der Totalintensität des Erdmagnetfeldes über d zentralen Teil von Queen Maud Land (Kontur-Intervall 2 nT, Flughöhe 470 kn Eine direkte Beziehung zwischen dieser negativen Anomalie und der anzunehmenden Niedergeschwindigkeits-Zone im Erdmantel muß weiterhin spekulati bleiben.

It is difficult to give a satisfying explanation for the age of the anisotropy. But there are some indications that the beginning of the anisotropy's generation may coincide with the starting separation between Africa and Antarctica and the major tectonic activities following this event in the Jurassic. The anisotropy of the seismic velocities may therefore be seen as a „frozen in memory" of the palaeo-movements during the time of the beginning desintegration of Gondwanaland.

CONCLUSIONS

The travel time analysis reported in this paper is a further contribution to the „jigsaw puzzle" of the interdiscplinary exploration of Antarctica's deeper earth and its geological history, especially of East Antarctica's Queen Maud Land. Many questions about the structure and physical properties of the earth's crust and upper mantle in this region still remain unanswered and even more new problems appeared. Is there really a distinct low velocity layer under Queen Maud Land as it can be postulated from the residual analysis, what is its nature and extension in depth and lateral directions? Which layer is predominantly characterized by a marked velocity anisotropy and how great is the coefficient of anisotropy? These are only some of the new questions which emerged by this travel time analysis.

But with these new experiences seismological investigations at GvN can be directed forward to these new problems and some efforts have already been undertaken. The expansion of the seismic network in 1986 and 1989, providing greater baselines, should give us the opportunity to study slowness and azimuth anomalies. Supplemented with further mobile recording stations, operating for some time at different locations, data from this network can be used for tomographic modelling. New long-period seismometers, installed at the grounded ice at Søraasen Ice Rise and Halfvar Ridge, will enable us to calculate crustal transfer functions and thus to get a more detailed picture of the deeper earth. Additionally, observations of the expected shear-wave-splitting at these stations can give us more information about the anisotropic layer.

Thus, travel time analysis with data from GvN was just the beginning of seismological work to investigate the structural features below this station. Future seismological observations at GvN therefore will be a valuable contribution to develop a more detailed model of the deeper earth in this area.

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