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Structure and Origin of the Earth's Crust in the Weddell Sea Embayment (beneath the Front of the Filchner and Ronne Ice Shelves) from Deep Seismic Sounding data

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Summary: Over-ice Deep Seismic Soundings (refraction and reflection seismic experiments) were carried out during three seasons across the Filchner and Ronne Ice Shelves using arrays of ground geophones and explosive charges. Seismic arrivals were received from boundaries in the crust and upper mantle. Ray-trace modelling shows that the crustal section has different characteristics along the seismic line. Normal or moderately stretched continental crust is observed on the flanks of the section with some evidence of igneous underplating and mafic intrusions beneath the East Antarctic margin, whereas the central part exhibits anomalous features. In this area, an up to 15 km thick, presumably Late Mesozoic-Cenozoic layer overlies an 8-10 km thick medium-velocity (5.5-5.6 km/s) layer interpreted as metamorphosed Paleozoic deposits which, in turn, rest directly on the lower "mafic" crust characterized by velocities of 6.9-7.5 km/s. According to suggested interpretation the entire thickness of the sedimentary basin strata is as much as 20-22 km. Two models are proposed to explain the anomalous crustal structure of the studied region. The first model suggests that the lower, high-velocity layer is a strongly stretched continental crust, contaminated by mafic (mantle-derived) rocks which was developed in the settings of Late Neoproterozoic rifting and Paleozoic to Mesozoic back-arc basin. The second model considers the lower crustal layer as a sligtly stretched Neoproterozoic or Early to mid-Palaeozoic relict oceanic crust which either was retained after the transformation of the Antarctic segment of the Gondwana margin from a rifted to a subducted one or originated due to sea-floor spreading in a back-arc setting.

Zusammenfassung: Tiefenseismische Messungen (refraktions- und reflexionsseismische Experimente) wurden auf dem Eis während drei Saisons über den Filchner- und Ronne-Eisschelfen mit Geophon-Arrays und Explosionsladungen durchgeführt. Seismische Einsätze sind von Diskontinuitäten der Kruste und des oberen Mantels empfangen worden. Modellierung im Strahlenverfahren zeigt, dass die Krustensektion verschiedene Charakteristika entlang der seismischen Linie aufweist. Normal oder moderat gedehnte kontinentale Kruste wird an den Flanken mit Nachweis von magmatischem "underplatin" und mafischen Intrusionen unterhalb des ostantarktischen Kontinentalrandes beobachtet, während der zentrale Abschnitt anomale Strukturen beinhaltet. In diesem Gebiet liegt eine bis zu 15 km mächtige, vermutlich spät-mesozoische Schicht über einer 8-10 km mächtigen Schicht mittlerer Geschwindigkeit (5.5-5.6 km/s), die als metamorphisierte paläozoische Ablagerung interpretiert wird. Diese wiederum liegt direkt auf der unteren „mafischen" Kruste, die mit Geschwindigkeiten von 6.9-7.3 km/s beschrieben ist. Nach dieser vorgeschlagenen Interpretation beträgt die gesamte Mächtigkeit des Sedimentbeckens ca. 20-22 km. Zwei Modelle werden vorgeschlagen, die die anomale Krustenstruktur der untersuchten Region erklären. Das erste Modell lässt vermuten, dass die untere Schicht hoher Geschwindigkeit eine stark gedehnte kontinentale Kruste ist, die mit mafischen (vom Mantel abgeleiteten) Gesteinen kontaminiert wurde und die sich im Zuge des späten neo-proterozoischen "rifting" und des paläozoischen bis mesozoischen "back-arc" Beckens entwickelte. Das zweite Modell betrachtet die untere Krustenschicht als ein leicht gedehntes neoproterozoisches oder früh- zu mittel-paläozoisches Relikt ozeanischer Kruste, das entweder nach der Transformation des antarktischen Segmentes des Gondwana-Kontinentalrandes von einem "rifted" zu einem subduzierten Kontinentalrand erhalten wurde, oder das aufgrund einer Meeresbodenspreizung in einer "back-arc"-Umgebung entstand.

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INTRODUCTION

This study is based on Deep Seismic Sounding (DSS) refraction and reflection data collected by the Soviet Antarctic Expedition (SAE) in the course of three field seasons (1979/1980, 1982/1983, 1983/1984) along the front of the Filchner and Ronne Ice Shelves. Previous magnetic and gravity surveys suggested a vast sedimentary basin beneath the Weddell Sea Embayment (WSE), i.e. the area of the southern Weddell Sea shelf and Filchner-Ronne Ice Shelves, with a thickness of nonmagnetic and low-density cover of between 10-15 km (MASOLOV 1980, KADMINA et al. 1983). The DSS investigations were aimed at examining the crustal structure, the nature and origin of this basin and to define the history of its development. Up to the present, only a preliminary 2-D crustal section, based mostly on manual depth calculations from time-distance curves, has been published (KUDRYAVTSEV et al. 1987, 1994). This work represents the results of advanced and more detailed reprocessing of the full DSS data set and an interpretation of the modelled section in the light of current knowledge of the structure and composition of the Earth's crust and plate tectonic relations.

Regional Geology and Existing Crustal Models

The WSE is bounded by geologically different crustal terrains which include the following units: a Mesozoic magmatic arc of the Antarctic Peninsula with thick arc to back-arc basin sequencnces on its eastern side; a Late Proterozoic (about 1.1 Ga) basement block of the Haag Nunataks; a 13 km thick Palaeozoic sedimentary succession of the Ellsworth Mountains and neighbouring nunataks folded during Gondwanian (Permian-Triassic) orogeny and intruded by Middle Jurassic granites; Late Precambrian to Palaeozoic sequences of the Pensacola Mountains also folded by Gondwanian orogeny and intruded by a large Lower Jurassic (180 Ma) gabbroic pluton (Dufek Intrusion); part of the East Antarctic craton with Precambrian basement overlain in places by Palaeozoic deposits of the Beacon Supergroup and intruded by Jurassic (172-182 Ma) tholeitic magmatic rocks; and the oceanic basin of the deep-water Weddell Sea with the Late Mesozoic-Cenozoic sea-floor spreading crust (Fig. 1).

The crustal structure of the WSE itself is still poorly studied and understood. First information on this region was obtained from magnetic data, collected by PMGRE during airborne

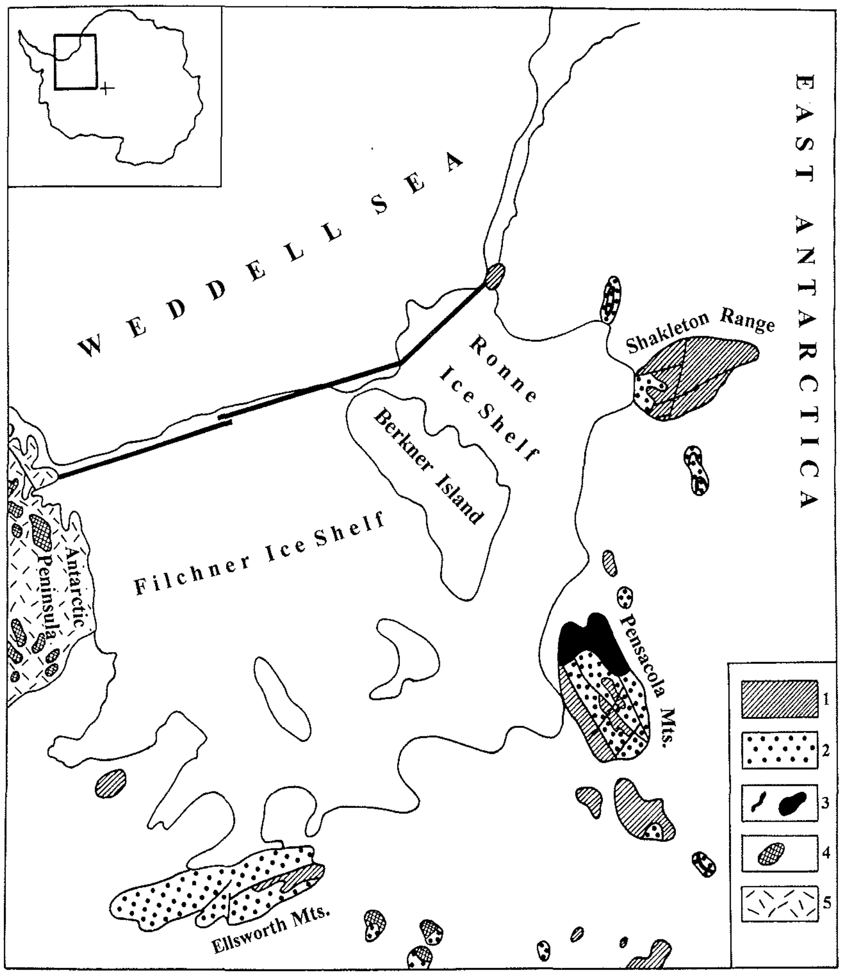


Fig. 1: Simplified geological map of the WSE region (modified from RAVICH & GRIKUROV 1976). 1 = Precambrian crystalline basement; 2 = Paleozoic sedimentary succession; 3 = Middle Jurassic mafic intrusions; 4 = Late Jurassic felsic (anorogenic) intrusions of the Ellsworth Mountains region and Early Cretaceous intermediate (subduction related) intrusions of the Antarctic Peninsula; 5 = Middle Jurassic to Early Cretaceous back-arc sedimentary sequence. Thick line is DSS profile discussed in this paper.

Abb: 1: Vereinfachte geologische Karte der WSE-Region (modifiziert nach RAVICH & GRIKUROV 1976). 1 = präkambrisches kristallines Basement; 2 = paläozoische Sedimentabfolge; 3 = mittel-jurassische mafische Intrusionen; 4 = spät-jurassische felsische (anorogene) Intrusionen der Region um die Ellsworth Mountains und früh-kretazische intermediäre (subduktions-bezogene) Intrusionen der Antarktischen Halbinsel; 5 = mittel-jurassische bis früh-kretazische "back-arc" Sedimentsequenzen. Die dicke Linie ist das DSS-Profil, welches im Text diskutiert wird.

surveys in 1970s (MASOLOV 1980, GOLYNSKY et al. 2000). A quantitative interpretation of these data showed that the causative magnetic bodies occurred 10-15 km below sea level suggesting the existence of thick nonmagnetic sedimentary cover (MASOLOV 1980, KADMINA et al. 1983). The DSS data confirmed this assumption and helped delineate a general framework of the earth's crust along the transect (KUDRYAVTSEV et al. 1987). It has been found that an up to 15 km thick laminated crustal layer with velocities of 4.0-4.8 km/s rests on the 8-10 km and 10-12 km thick layers which are characterized by predominant velocities of 5.4-5.7 km/s and 7.0-7.5 km/s, respectively (KUDRYAVTSEV et al. 1987). These three layers were interpreted, from the top down, as a sedimentary basin infill, folded basement and "basalt" crust. A total crustal thickness has been estimated between 30 and 35 km. GRIKUROV et al. (1991) regarded the 5.4-5.7 km/s layer as a mostly supracrustal (metamorphosed) Early to Middle Palaeozoic complex similar to that in the Pensacola and Ellsworth Mountains. Such an interpretation implied that the basin was filled by almost 25 km of sediments resting directly on the lower crust with velocities 7.0-7.5 km/s. To explain the extraordinary crustal section, the authors assumed a phase of strong stretching in Late Palaeozoic to Early Mesozoic time along transcrustal low-angle detachment faults, which resulted in an uplift of the lower crust into shallow level (GRIKUROV et al. 1991).

Refraction seismic experiments conducted by the Alfred Wegener Institute (AWI) in the front of the Ronne Ice Shelf (between 50 °W and 56 °W) showed crustal characteristics similar to those of the SAE section. However, AWI's investigations revealed in the north-western half of the section a 5-6 km thick unit characterized by an average velocity of 6.5 km/s (not found in Russian data) resting between the units with velocities 5.4-5.7 km/s and 7.1-7.5 km/s (HÜBSCHER et al. 1996). All these velocities were interpreted to belong in crystalline basement of the continental nature. Based on the obtained depth-velocity model the authors concluded that the WSE is a block of highly stretched (by a factor between 1.5 and 3.0) and igneously underplated continental crust with a 10-13 km thick sedimentary cover.

ACQUISITION TECHNIQUES AND PROCESSING

In every season similar methods and techniques were used during the three-year DSS experiment to acquire the refraction and reflection seismic data along the three individual profiles (a total of 800 km in length) crossing the area from 45 °W to 47 °W (1979/1980), from 47 °W to 56 °W (1982/1983) and from 56 °W to 62 °W (1983/1984; Fig. 2). A total of 20 marine and over-ice shotpoints with TNT explosives were fired with 20-60 km (occasionally up to 100 km) spacing (Fig. 2). The marine shotpoints represented linear groups at a water depth of 40-50 m. Each group consisted of up to 6 discrete charges positioned at 12-15 m intervals. The overall weight of explosives in single shotpoints ranged up to 1440 kg. Over-ice shotpoints were tested in different modifications to achieve the

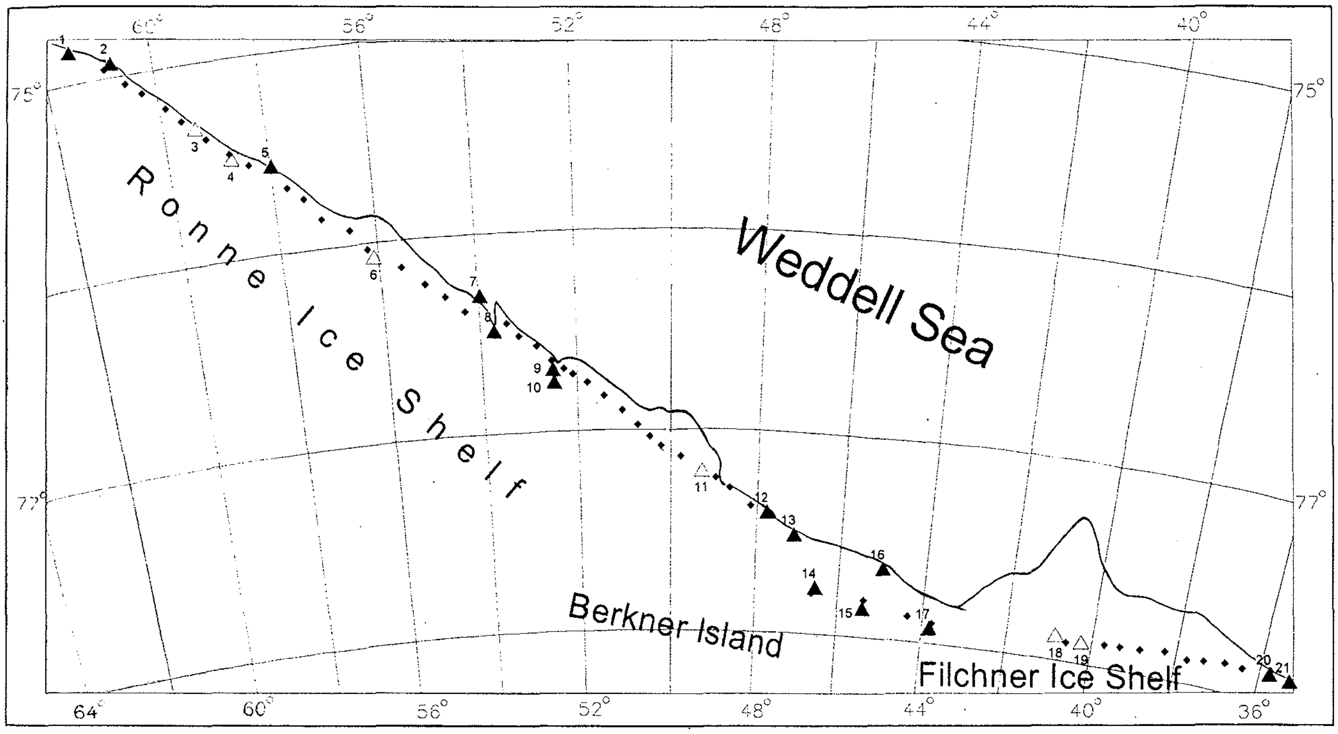


Fig. 2: Location of shotpoints and observation points along the DSS line. Black triangles are marine shotpoints, open triangles are over-ice shotpoints (shotpoints are numbered consistently from west to east); small rhombs are recording stations.

Abb 2: Lage der Schusspunkte und Beoachtungspunkte entlang des DSS-Profils. Schwarze Dreiecke sind marine Schusspunkte, offene Dreiecke sind Schusspunkte auf dem Eis (Schusspunkte sind durchgehend von Westen nach Osten nummeriert); kleine Rhomben sind die Registrierstationen.

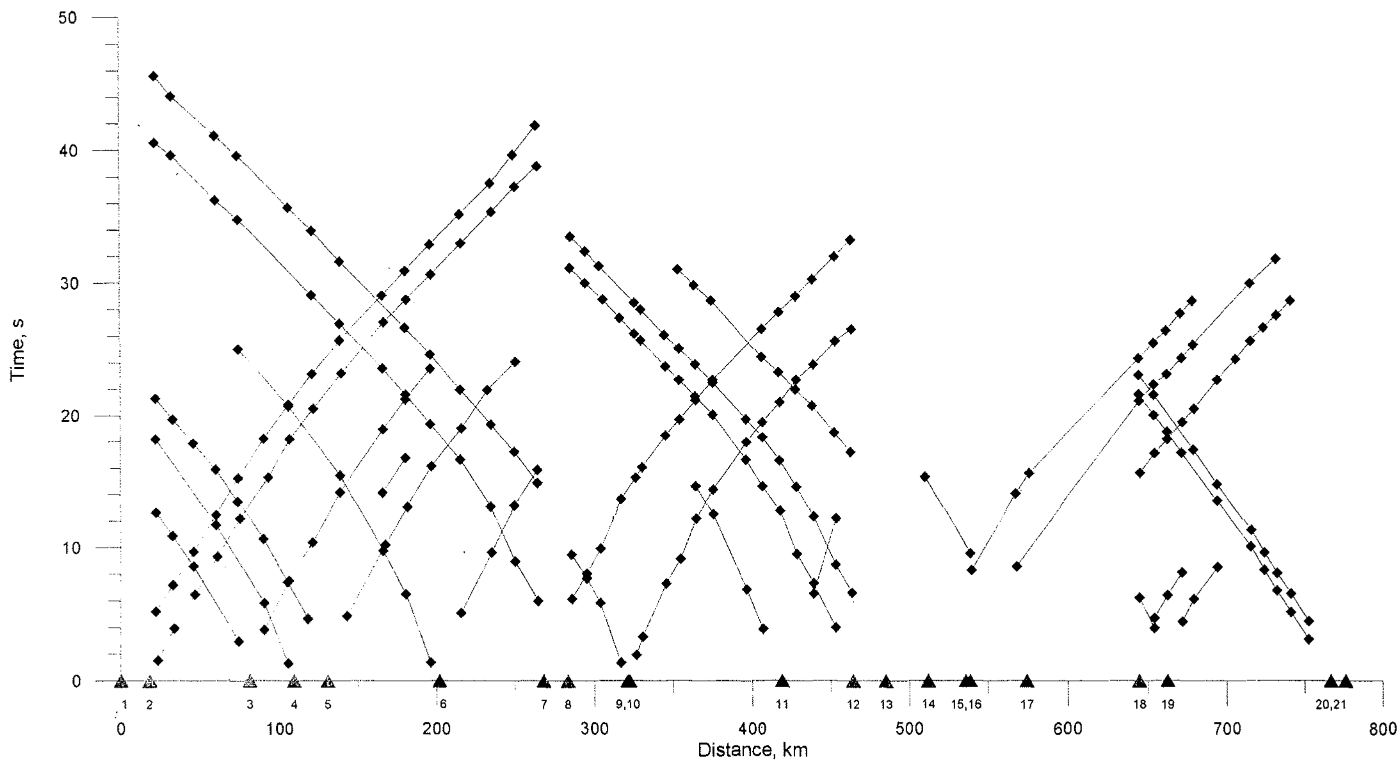


Fig. 3: Integrated time-distance plot for refraction and reflection wave arrivals which were identified and used for ray-tracing modelling. Triangles are shotpoints; rhombs are actual observations.

Abb. 3: Integrierter Zeit-Distanz-Diagramm für Refraktions- und Reflexionswelleneinsätze, die identifiziert und für das Modellieren mit dem Strahlenverfahren genutzt werden konnten. Dreiecke sind Schusspunkte; Rhomben sind die eigentlichen Beobachtungen.

best generation of compressional waves. It has been found experimentally that charges arranged in the vertices and centres of two hexagons with one common side were the most efficient. Explosives were embedded in 3.5 m deep dug-holes and averaged about 1400 kg. In this paper, shotpoints were numbered sequentialy from west to east for more convenient description.

The signals were recorded by 1 km long, 6-channel linear arrays with 200 m interval between sensor groups. Each group consisted of eight 5 Hz geophones. A total of 50 receiver points (recording stations) were deployed along the DSS profile. Receiver space intervals changed from season to season (from east to west) and averaged 17 km (7-25 km) during the first season, 10 km (5-14 km) during the second season and 15 km (10-20) during the last season (Fig. 2). Seismic arrivals were received at maximum distances between 125-250 km for marine explosive charges and between 40-125 km for over-ice explosive charges (Fig. 3). The „Tranzit" satellite system was used to position both shot and observation points. All operations during the DSS experiment were supported by a small airplane (AN-2) and a helicopter (Mi-8). Two seasonal bases, Druzhnaya-1 and Druzhnaya-2, were used for field operations.

All DSS data were originally obtained in analogue form, but were subsequently digitized. A band-pass filter (5-15 Hz), gain control and horizontal stacking of 6 channels were applied to improve the signal-to-nois ratio (Fig. 4). Travel-time branches were plotted using a reduction velocity of 8.0 km/s to provide more compact presentation (Fig. 4).

Mainly first arrivals of refracted waves and some intensive well-correlated reflections from deep interfaces observed in

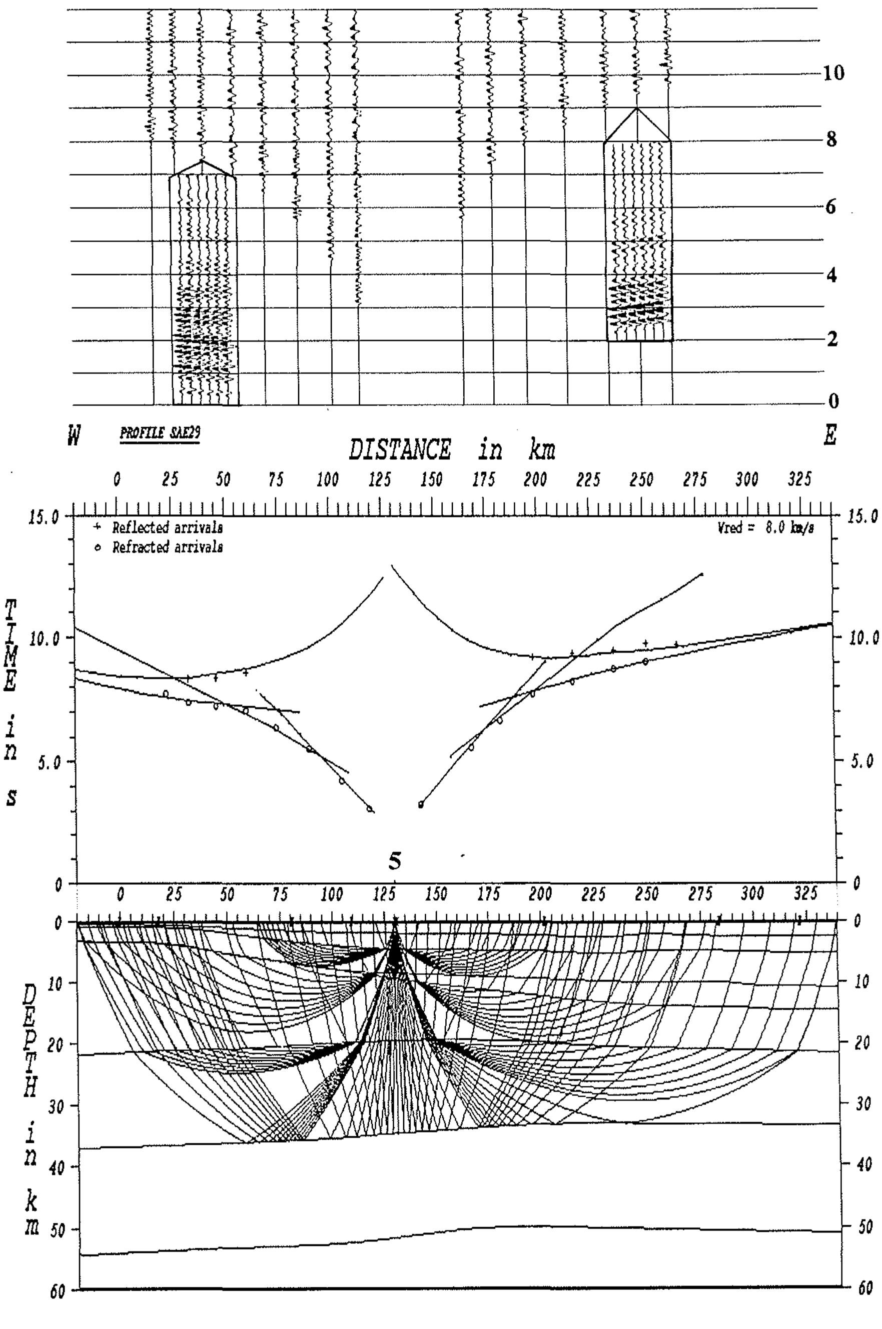
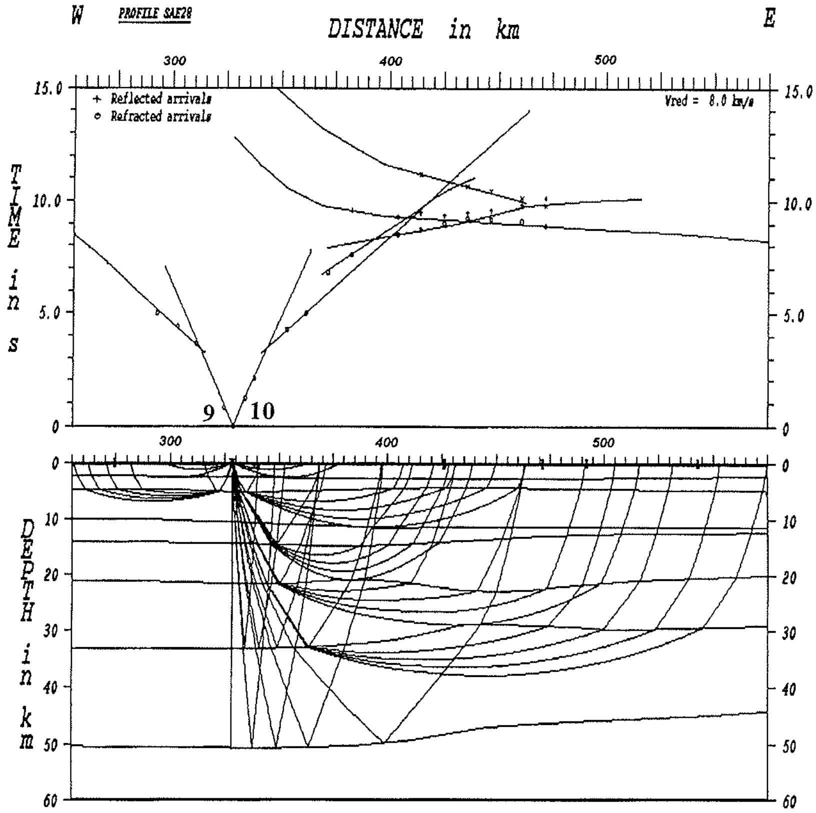


Fig. 4: Two-dimensional ray-tracing models for different parts of the DSS profile with examples of computed ray-paths and travel time branches for refracted (circles) and reflected (crocces) arrivals. The models for shotpoint 5 are accompanied by examples of DSS record (the traces are digitized and stacked arrivals of 6-channel records; insets are original analogue records of two seismic stations).

Abb: 4: Zweidimensionale Strahlenmodelle für verschiedene Abschnitte des DSS-Profils mit Beispielen von berechneten Strahlenwegen und Laufzeitkurven für refraktierte (Kreise) und reflektierte (Kreuze) Einsätze. Die Modelle für Schusspunkt 5 sind begleitet von Beispielen mit DSS-Aufnahmen (die Spuren sind digitalisierte und gestapelte Einsätze von 6-Kanal-Aufnahmen; die Einlagen enthalten analoge Originalaufnahmen von zwei seismischen Stationen).



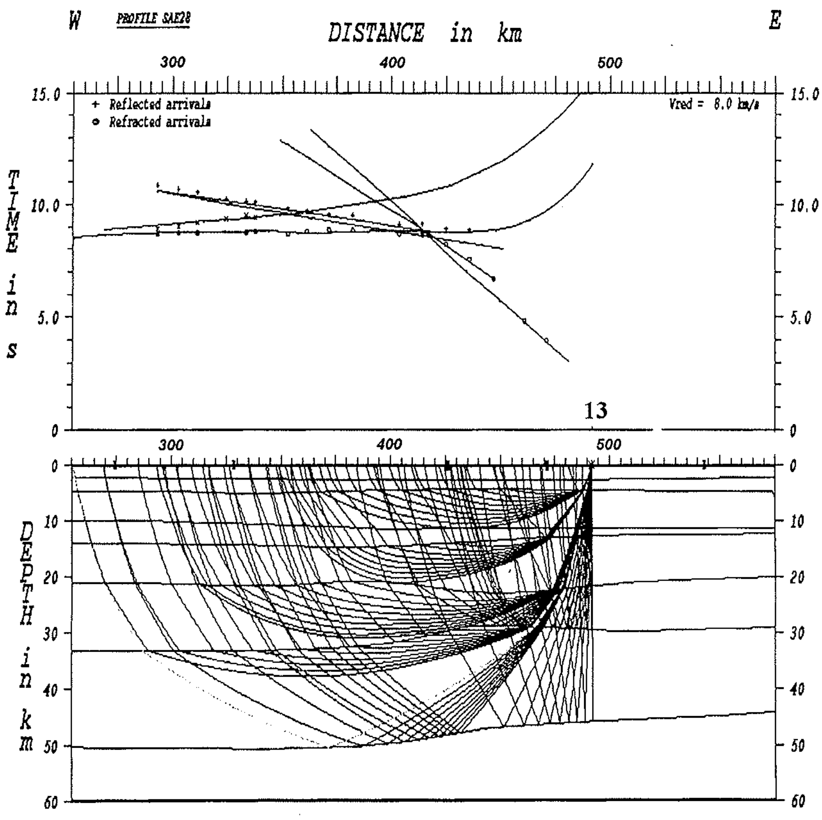


Fig. 4: (Continuation)

Abb: 4: (Fortsetzung)

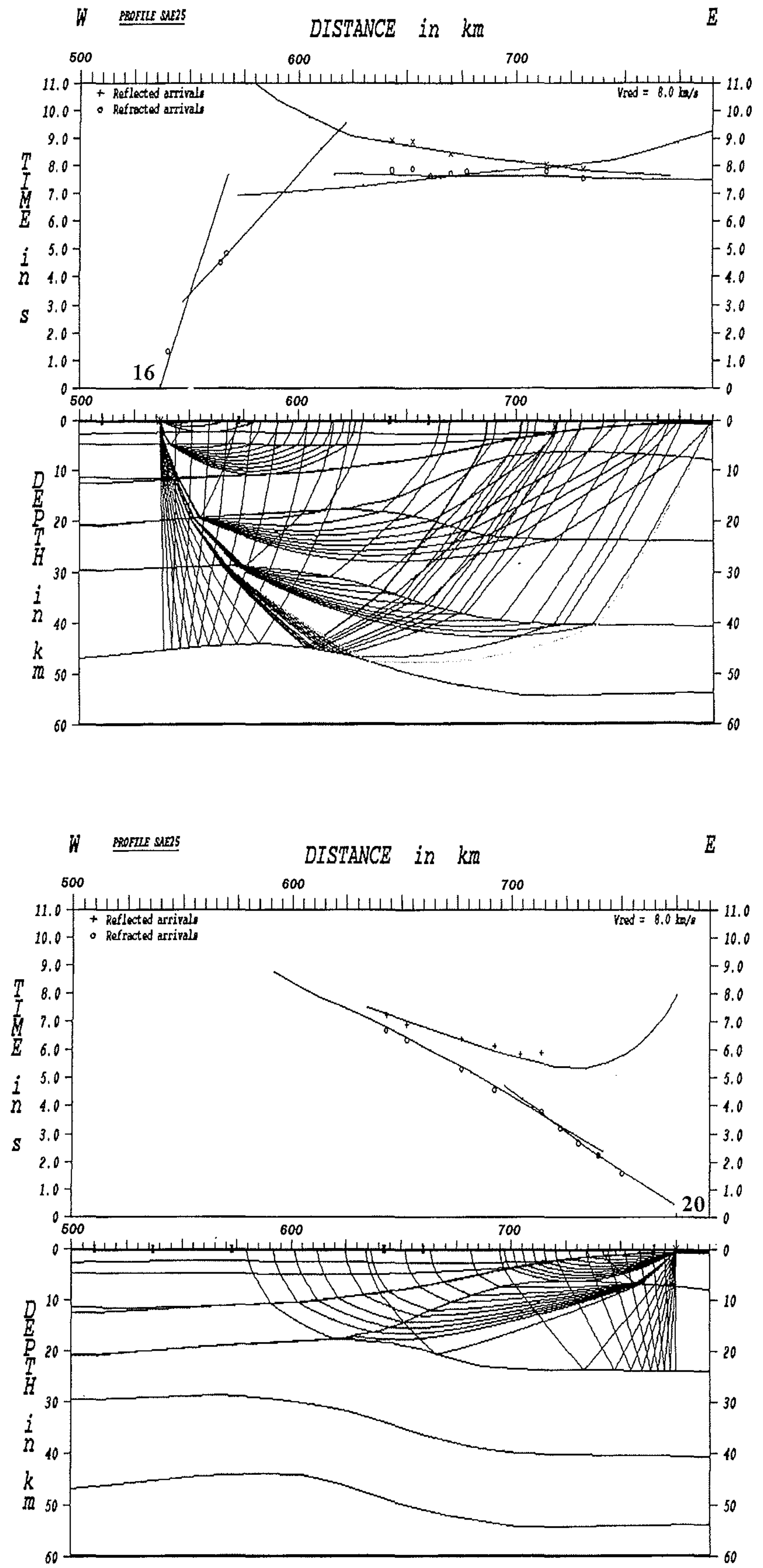


Fig. 4: (Continuation)

Abb: 4: (Fortsetzung)

secondary events were identified and included in the modelling process. Forward modelling by means of ray tracing was carried out at VNIIOkeangeologia with the use of the RAY86 program from CERVENY et al. (1977) which was modified at AWI into an interactive software to enable more convenient modelling (FECHNER 1994).

SEISMIC MODEL

The intervals between observation points are rather large for accurate correlation of seismic sygnals and crustal modelling. However, the integrated data with direct and reversed observations (time-distance plots) and the 6-channel records (providing the control of a slope of traveltime branches) enable us to distinguish adequately the principal crustal interfaces and velocity characteristics.

The results of the ray-tracing are demonstrated in Figure 5, which shows a combined 2-D crustal section along the DSS line. The Moho discontinuity provides clear refraction and reflection arrivals and is underlain by typical upper mantle velocities of 8.0-8.2 km/s. The thickness of the crust changes along the transect. Minimum values of approximately 30 km are modelled beneath the front of Berkner Island. From there the crust thickens rapidly, up to 40 km, toward the east below the Filchner Ice Shelf, and gradually toward the west to be as much as 37-38 km on the margin of the Antarctic Peninsula (Fig. 5).

Three major crustal layers and several interlayer units more inherent in the upper part of the section were identified within the crust. All of them are mainly characterized by persistent groups of velocities with small vertical gradients ranging between 0.01 s^{-1} and 0.03 s^{-1}, depending on thickness. The model also shows horizontal velocity gradients: minor (0.3-0.4 km/s per length of profile) in the upper part of crustal section and greater (up to 1.0 km/s per length of profile) in the lower crust (Fig. 5).

The upper layer constitutes a giant basin which reaches a maximum thickness of up to 15 km in the central part of the transect (between shotpoints 4 and 17) and wedges out on the margins of the East Antarctic Craton and the Antarctic Peninsula (Fig. 5). In most cases, a large offset between shotpoints and nearest observation points decreases the resolution

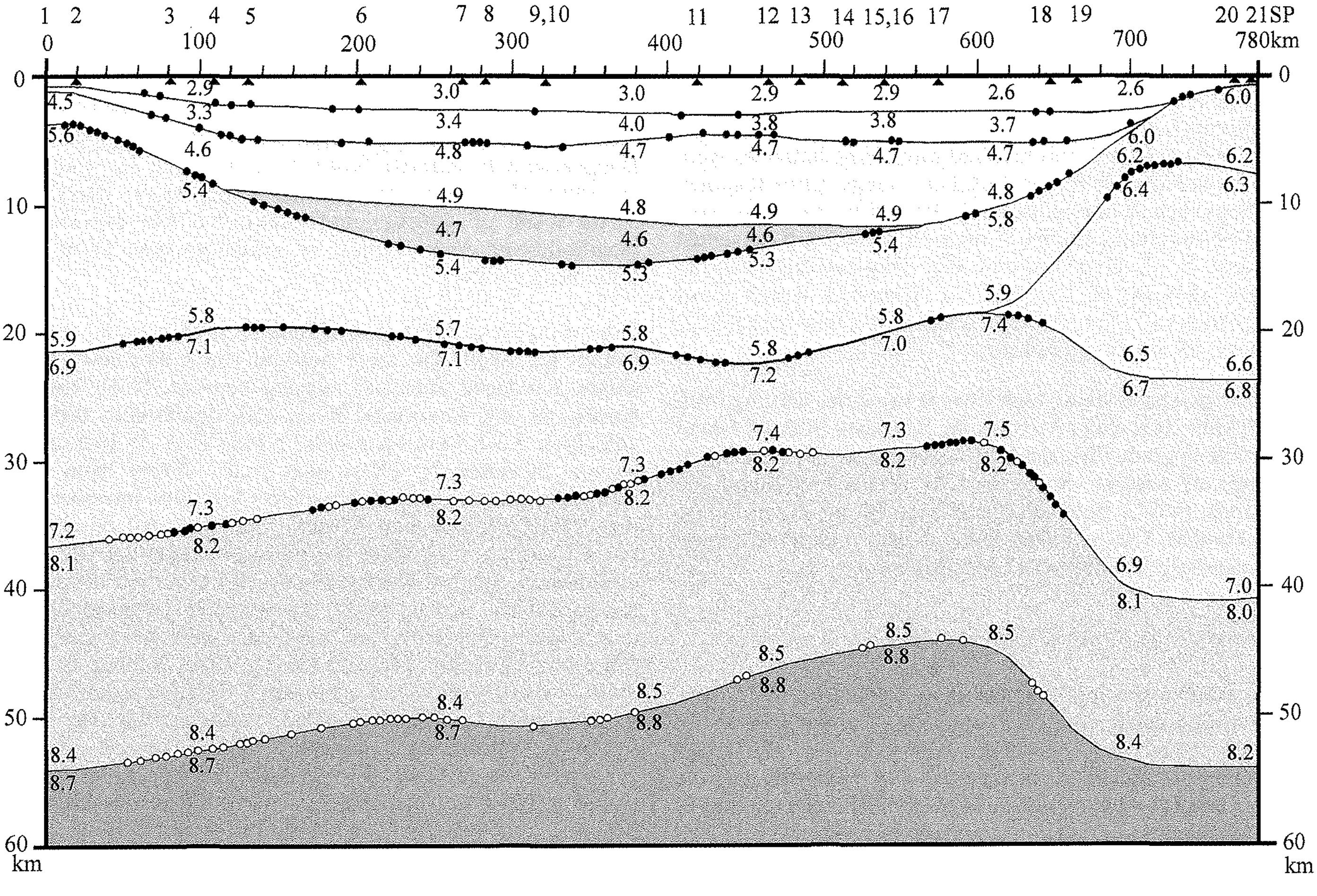


Fig. 5: Combined crustal (ray-tracing) model along the front of the Filchner and Ronne Ice Shelves computed from DSS data (totally 25 shotpoints and more than 50 observation points were used for modelling). Triangles are shotpoints; nubmbers on the section are modelled velocities. Black and open circles show fragments of refracting and reflecting crustal interfaces (respectively) corresponding to real discrete observations.

Abb. 5: Kombiniertes Krustenmodell (Strahlenverfahren) entlang der Filchner- und Ronne-Eisschelffronten, berechnet aus DSS-Daten (insgesamt 25 Schusspunkte und mehr als 50 Beobachtungspunkte wurden für das Modellieren benutzt). Dreiecke sind Schusspunkte; Nummern auf der Sektion beschreiben modellierte Geschwindigkeiten. Schwarze und offene Kreise zeigen die entsprechenden Fragmente der refraktierten und reflektierten Krustenübergänge, entsprechend der realen Beobachtungen.

of the shallow part of the section. Earliest refraction arrivals were received from an interface at a depth of 2.5-3.0 km which tops the unit with velocities of 3.3-4.0 km/s. The overlying (uppermost) unit was not resolved by the seismic experiment, and velocities of 2.6-3.0 km/s presented in the model are speculative. Reliable refraction arrivals were obtained from the top of up to 8 km thick unit with velocities between 4.6 and 4.9 km/s, which occurs close to the sea floor in the westernmost part of the section (Fig. 5). A 4.6-4.7 km/s low-velocity unit is believed to exist at the base of the upper crust layer as indicated by the offset of the wave phase, which is clearly observed on the traveltime plots between shotpoints 5 and 14 (Fig. 4, shotpoints 10 and 13).

The underlying mid-crustal layer can be subdivided laterally in two segments with clear differences in velocity values. Beneath the Filchner Ice Shelf, this layer includes a 4-8 km thick unit with velocities of about 6.0 km/s which is underlain by an up to 17 km thick, 6.4-6.5 km/s unit pinching out westward. At the eastern end of the DSS profile, the upper unit rises to shallow level, close to the sea bottom. Beneath Berkner Island and the Ronne Ice Shelf, the mid-crustal layer shows velocities between 5.2 and 5.5 km/s extending for about 550 km. The thickness of this layer varies from 6-9 km at the central part of the profile to 18 km at the Antarctic Peninsula margin (Figs. 4 and 5).

Unlike the German refraction seismic studies (HÜBSCHER et al. 1996, JOKAT et al. 1997), our DSS experiment has not revealed the unit with velocities of 6.5 km/s. If the model of HÜBSCHER et al. (1996) is correct (no reversed travel time branches were used for modelling to be convinced in velocity estimates) then the lack of such an unit in the DSS data may be due to sparsely spaced observation systems. A time-distance graph presented by JOKAT et al. (1997) shows that first arrivals with an apparent velocity of 6.6 km/s is identified within short distance intervals of about 5 km, which is less than the interval between DSS recording stations.

A lower-crust layer shows high P-wave velocities varying from 6.7-7.5 km/s. It is about 6-10 km thick beneath Berkner Island and thickens gradually east- and westward to about 15 km at the ends of section. Some records reveal high-amplitude reflections from a boundary below the Moho discontinuity (Figs. 4 and 5). This boundary lies at depths of about 45-55 km and is generally conformable to the Moho.

INTERPRETATION AND DISCUSSION

Sparse station spacing enables us to calculate only a very generalized crustal model. Nevertheless, its combination with magnetic, gravity and geological data from the area of the DSS line contributes considerably to our knowledge of the WSE structure and evolution. The geological interpretation of the model is based on the structure of refracted and reflected boundaries, the values and distribution of P-wave velocities, the analysis of gravity and magnetic anomalies, an extrapolation of surrounding terrestrial geology and worldwide examples of the crust composition.

The upper-crust laminated layer with velocities of 2.6-4.9 km/s is interpreted as a succession of mainly sedimentary and possibly volcanic-sedimentary rocks filling the deep sag basin. Onset of basin formation in the WSE is inferred to have been associated with an extensional phase controlled by Pacific margin plate convergence and/or emplacement of a large mantle plume (megaplume) beneath the Gondwana lithosphere and can be dated at the Early-Middle Jurassic based on the age of Ferrar magmatism, which is considered to be an indicator of this regime (DALZIEL et al. 1987, STOREY et al. 1992, STOREY & KYLE 1997). The top of the 4.6-4.9 km/s velocity unit is supposed to correspond to a post-rift unconformity formed before sea-floor spreading which occurred in the Weddell Sea at the end of the Middle Jurassic (LIVERMORE & HUNTER 1996).

The crustal section underlying the WSE sedimentary basin is variable in parameters along the DSS profiles. Beneath the eastern Filchner Ice Shelf, it is typical of normal continental crust (Fig. 5) and is likely to consist of Precambrian basement of the East Antarctic Craton which crops out just to the east of the DSS profile end (Fig. 1, TINGEY 1991). The increase in velocities with depth from 6.0 km/s to 6.4-6.6 km/s in the upper crust and to 6.7-6.9 km in the lower crust (Fig. 5) is consistent with a general regular trend under the change of rock composition from felsic to intermediate and mafic (WALTER & MOONEY 1982, CHRISTENSEN & MOONEY 1995). Toward the basin, the total thickness of crystalline crust decreases sharply to 20 km beneath the western Filchner Ice Shelf, suggesting the effect of significant crustal extension in this region. The lower crust shows high seismic velocity values of up to 7.3-7.5 km/s (Fig. 5) and increased densities as modelled from the high-amplitude (>60 mGal) positive Bouguer gravity anomaly (KADMINA et al. 1983, ALESHKOVA et al. 2000). These anomalous crustal properties are interpreted as the result of igneous „underplating" and/or intrusion of mantle-derived rocks typical of rifted margins (WHITE & MCKENZIE 1989).

Toward the west, in the area of Berkner Island and the eastern Ronne Ice Shelf, the crust beneath the sedimentary basin shows a reduced thickness ranging between 16-18 km and consists of only two crustal layers with significantly different velocities: 5.3-5.8 km/s and 6.9-7.5 km/s (Fig. 5). In a crustal section modelled by HÜBSCHER et al. (1996) from AWI refraction seismic data a 5.3-5.6 km/s layer was interpreted as the crystalline basement of an upper stretched continental crust. However, these velocity values seem to be too low for a such type of crust and are likely much more typical of over-compacted sedimentary rocks, consolidated (metamorphosed) due to deep subsidence and long-term geological evolution (GREGORY 1977, WALTER & MOONEY 1982, BELOUSOV et al. 1991). Among geological sequences, which can be considered as analogues of a 5.3-5.9 km/s layer, most suitable ones seem to be a Palaeozoic sedimentary strata of the terrains surrounded the WSE in the Antarctic and Gondwana framework (Pensacola Mountains and Ellsworth-Whitmore Mountains in Antarctica, Falkland Islands and Cape Province in South Africa; Fig.1 and 6; CURTIS & STOREY 1996, STOREY et al. 1996). Most of these regions exhibit up to 13 km thick sedimentary succession of Palaeozoic age consisting mainly of continental to shallow marine molasse deposits (GRIKUROV 1980, CURTIS & STOREY 1996). The study of physical properties of Palaeozoic sedimentary rocks from the Pensacola Mountains, carried out in VNIIOkeangeologia (about 300 specimens sampled from a complete section), showed that they are dense enough (2.65 g/cm^3 on the average) and are well corresponded with the modelled velocities of the mid-crustal layer according to general velocity-density relation for the clastic rocks (GREGORY 1977). Thus, it can be suggested that the post Middle Jurassic sedimentary basin is underlain by mostly Palaeozoic depositional rocks akin to that observed in the mountain frame of the WSE. If this interpretation is correct, the sedimentary succession of 20-22 km thick rest directly on the lower high-velocity mafic crust.

Although, such a crustal structure is rare, it is known elsewhere. Similar structures have been discovered, for instance, in the southern Barents Sea shelf (Russian Arctic) and in the North Caspian Depression (south of Russia), where the 20-22 km thick and 200-250 km wide sedimentary basins (presumebly post-mid-Palaeozoic in age) with velocities of 2.1-5.6 km/s overlies a 8-10 km thick lower crust showing velocities of about 7.0 km/s (BELOUSOV et al. 1991, VOLCHEGURSKY et al. 1993, JOHANSEN et al. 1993). Two principal interpretations were suggested to explain the origin of this type of basins. One states that they are underlain by a strongly stretched and magmatically contaminated continental crust which was modified as a result of active intracontinental rifting (VERBA et al. 1985), whereas another infers that the basins are underlain by a relict oceanic crust retained there due to closure of pre-existed Palaeozoic oceans (APLONOV et al. 1996, VOLCHEGURSKY et al. 1993). Suggested interpretations are referred here to as "continental" and "oceanic" models depending on the nature of the lower crust. Development of the WSE, which shows a significant resemblance to the aforesaid regions can also be considered in context of these two models.

The oceanic nature of crust underlying the WSE is best explained in terms of marginal seas. Available geological and geochemical data from the Pensacola and Transantarctic Mountains suggest that during the Neoproterozoic this segment of East Antarctica was the rifted margin of the paleo-Pacific Ocean which was transformed into a zone of convergence with the subducted margin by the end of Cambrian time (Fig. 6, BORG & DEPAOLO 1991, DALZIEL 1992, GRUNOW et al. 1996). If this is the case, from the Neoproterozoic an ocean might occur in the area of the WSE which also was a part of the Gondwana margin (DALZIEL 1992, GRUNOW et al. 1996). Two scenarios of the plate evolution accounting for the conservation of the oceanic crust and formation of marginal seas in this region can be suggested: 1) a subduction zone arose within the oceanic plate to isolate the part of the oldest Neoproterozoic crust in the WSE (Fig. 6A); and 2) a subduction zone formed initially along the rifted margin of East Antarctica (including the margin of western Coats Land) and then jumped (stepped back) to a new position due to reorganization of plate boundaries (Fig. 6B).

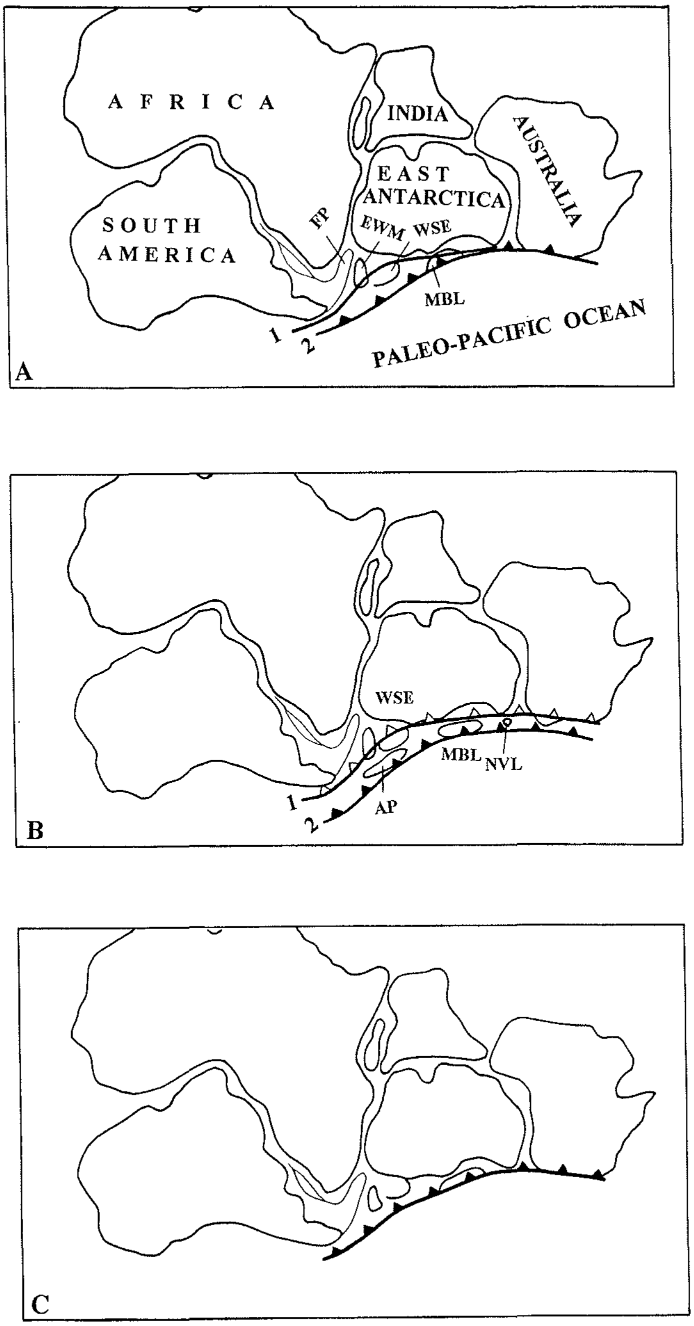


Fig. 6: Palaeozoic reconstructions of Gondwanaland (based on DALZIEL 1992) showing different versions of the WSE development after transformation of the paleo-Pacific rifted margin into the active margin in the Late Cambrian. A and B = "oceanic" model suggesting the conservation of the oceanic crust in the WSE if (A) a subduction zone arose within the paleo-Pacific ocean (A1 = continent-to-ocean boundary of the Neoproterozoic rifted margin, A2 = position of a subduction zone in the Late Cambrian) or (B) if subduction zone jumped (stepped back) due to accretion of allochtonous terranes (B1 = position of a subduction zone in the Late Cambrian B2 = position of a subduction zone in the mid-Palaeozoic). C = "continental" model suggesting that the WSE was the part of Antarctic (Neoproterozoic) rifted margin and subduction zone arose along the continent-to-ocean boundary.
FP = Falkland Plateau, WSE = Weddell Sea Embayment, AP = Antarctic Peninsula, EWM = Ellsworth-Whitmore Mountains, MBL = Marie Byrd Land, NVL = northern Victoria Land.

Abb: 6: Paläozoische Rekonstruktionen von Gondwanaland (basierend auf DALZIEL 1992) zeigen die unterschiedlichen Versionen der Entwicklung von WSE nach der Transformation vom "rifted" Kontinentalrand des Paläo-Pazifiks zum aktiven Kontinentalrand im späten Kambrium. A und B = „ozeanisches" Modell, das die Bewahrung der ozeanischen Kruste im WSE vorschlägt, falls (A) eine Subduktionszone innerhalb des paläo-pazifischen Ozeans entstand (A1 = Kontinent-Ozean-Grenze des im Neoproterozoikum "rifted" Kontinentalrand; A2 = Position einer Subduktionszone im späten Kambrium) oder (B) die Subduktionszone springt (ein Stück zurück) aufgrund der Akkretion allochtoner Terrane (B1 = Position einer Subduktionszone im späten Kambrium; B2 = Position einer Subduktionszone im mittleren Paläozoikum). C = „kontinentales" Modell, welches vorschlägt, das WSE war ein Teil des "rifted" antarktischen Kontinentalrands (neo-proterozoisch) mit einer Subduktionszone, die entlang der Kontinent-Ozean-Grenze entstand.

No Late Cambrian rocks typical of island arcs were revealed in the West Antarctic terranes and so the first scenario is not so far supported by geological data. By contrast, the second scenario is geologically constrained and so appears to be more credible. There is an evidence of jump of the subduction zone in mid-Palaeozoic time when rearrangement of paleo-Pacific plate boundary resulted from accretion of allochtonous terranes (northern Victoria Land, eastern Marie Byrd Land, southern East Australia; Fig. 6B) with Gondwana (BORG & DEPAOLO 1991, RICCI et al. 1997). This event is well consistent with mid-Palaeozoic subduction-related intrusive rocks revealed in the Antarctic Peninsula (MILNE & MILLAR 1991) and suggests the same age for the oceanic crust below the WSE basin. Younger and well-recognized examples of basins developed in a similar manner (i.e. by a step-back in underthrusting) are the Bering Sea in the northern Pacific and the Caribbian Sea in the western Atlantic (KEAREY & VINE 1996).

Apart from the two suggested geodynamic scenarios, describing the conservation of oceanic plate fragments, the oceanic crust in the WSE might be also formed as a result of sea-floor spreading in a back-arc setting, similar to that which widely occurs at present in the western Pacific Ocean (KEAREY & VINE 1996). In this case, the Antarctic Peninsula may be considered as the parental magmatic arc behind which a back-arc basin was developed. The oldest known magmatic rocks from the Antarctic Peninsula which mark the onset of sea floor spreading in the WSE are mid-Palaeozoic (Silurian) in age (MILNE & MILLAR 1991), however, if subduction along the Gondwana margin originated in the Late Cambrian, as it was suggested (DALZIEL 1992, GRUNOW et al. 1996), development of the back-arc basin in the WSE from this time is not excluded.

Thus, according to an "oceanic" model a Neoproterozoic or Early to mid-Palaeozoic oceanic crust may underlie the WSE sedimentary basin. If this interpretation is correct, then the major part of the WSE was not subjected to intensive stretching because the lower crustal layer has the thickness close to normal oceanic crust and, hence, a mechanism other than stretching should be suggested to account for a great magnitude of subsidence and basin thickness. Local crustal extension are suggested, in this case, only for the area of Berkner Island and the western Filchner Ice Shelf (shotpoints 11-17), where the decrease in thickness of both the whole and lower („mafic") crust (up to 6 km compared to 10-12 km in the rest part of section) is modelled from seismic data.

In an alternative "continental" model, the high-velocity layer is interpreted as the extremely stretched continental crust which has been contaminated by mantle-derived rocks to such a degree to take on a mafic composition. The stretching of the WSE crust might start in the late Neoproterozoic to Early Palaeozoic, as a result of pre-Gondwana continent break-up and opening of the paleo-Pacific Ocean (DALZIEL 1997), and then resume during the Palaeozoic and Mesozoic in a back-arc setting which dominated there at that time interval (Fig. 6C). The evidence of extensional tectonics and sedimentation within a back-arc basin in Palaeozoic time is revealed in the geological succession of the Ellsworth-Whitmore Mountains, which likely constituted a single entity with the WSE before the Mesozoic (VENNUM et al. 1992, COLLINSON et al. 1992, CURTIS & STOREY 1996, GRUNOW et. 1996). The Mesozoic (Early to Middle Jurassic) crustal extension was a prominent episode in the evolution of the Gondwana paleo-Pacific margin (STOREY et al. 1992, STOREY & KYLE 1997). It covered a broad province between West and East Antarctica and is marked by back-arc bimodal magmatism along the eastern Antarctic Peninsula and rift-related basaltic (Caroo - Ferrar) magmatism along the East Antarctic margin (DALZIEL et al. 1987, STOREY et al. 1992). In the WSE itself, a rift-related magmatic event is inferred from high-amplitude magnetic anomalies over Berkner Island (HUNTER et al. 1996). The seismic data suggest that the greatest crustal stretching occurred just beneath this area.

The mechanism of modification of a "granitic" crust into a "mafic" crust required by the "continental" model is poorly understood but if such a modification occurs, the contribution of mantle-derived mafic (ultramafic?) rocks to the crust had to be extremely large. Credible examples of a similar process are difficult to find elsewhere, although some theoretical aspects of an increase of seismic velocities due to magmatic accretion has been considered for regions with intensive crustal extension and magmatically active rifted margins (BENZ et al. 1990, WHITE & MCKENZIE 1989). If the 6.5-6.6 km/s crustal unit found by the AWI refraction seismic study (HÜBSCHER et al. 1996, JOKAT et al. 1997) exists, it provides a more conventional and understandable depth-velocity function for the stretched continental crust. However, occurrence of these velocities does not also contradict the "ocenic" model, where it can be considered as a layer 2 of proto-oceanic crust.

Beneath the Antarctic Peninsula margin, the section changes to be more typical of a normal continental crust. Coastal outcrops occurring in the vicinity of the DSS line termination expose Middle Jurassic to Early Cretaceous metamorphosed sedimentary and volcanic rocks deposited in a back-arc setting and intruded by Early Cretaceous granodiorite plutons (Fig. 1 in STOREY et al. 1996). Magnetic data show that the intrusive suite disappears or is deeply submerged in the western WSE (MASLANYJ et al. 1991, GOLYNSKY et al. 2000). According to multichannel and refraction seismic data of British Antarctic Survey and AWI, a back-arc sequence continues into the basin showing velocities of 5.1-5.2 km/s and borders sharply on the WSE basin units at about 59° 30' W (KING & BELL 1996, HÜBSCHER et al 1996, JOKAT et al. 1997). The DSS data do not resolve this transition as well as a boundary between the Antarctic Peninsula crustal block and the WSE basin itself but this boundary is supposed to occur within the abrupt thinning of 5.4-5.6 km/s layer, somewhere between shotpoints 3 and 5 (Fig. 5). Westward, the mid-crustal layer can be interpreted as consisting of pre-Middle Jurassic arc to back-arc basin sequences of the Antarctic Peninsula.

CONCLUSIONS

Three major crustal layers and several interlayer units were identified along the DSS line crossing the Filchner and Ronne Ice shelves. The upper layer constitutes a giant basin with velocities of 2.6-4.9 km/s and a maximum thickness of up to 15 km in the central part of the transect. The basin wedges out toward the East Anatrctic Craton and the Antarctic Peninsula and consists of four units. The mid-crustal layer can be subdivided laterally in two segments with clear differences in velocity values. Beneath the Filchner Ice Shelf, this layer includes a 4-8 km thick unit with velocities of about 6.0 km/s which is underlain by an up to 17 km thick, 6.4-6.5 km/s unit pinching out westward. Under Berkner Island and the Ronne Ice Shelf, the mid-crustal layer shows velocities of between 5.3 and 5.6 km/s and thickness from 6 to 9 km at the central part of basin to 18 km at the Antarctic Peninsula margin. A lower-crust 6-15 km thick layer is characterized by high P-wave velocities ranging from 6.7 to 7.5 km/s.

The upper-crust layer is interpreted as a Mesozoic to Cenozoic succession of mainly sedimentary and possibly volcanic-sedimentary rocks. The crustal section underlying the WSE sedimentary basin is variable in parameters. Beneath the eastern Filchner Ice Shelf, it is typical of normal to stretched continental crust and is likely to consist of Precambrian basement of the East Antarctic Craton. The lower crust velocities (7.3-7.5 km/s) are supposed to be the result of igneous „underplating" and intrusions of mantle-derived rocks. Beneath Berkner Island and the Ronne Ice Shelf the upper layer is likely underlain by a 8-10 km thick Palaeozoic sedimentary succession similar to that which outcropped in mountain terrains surrounded the WSE.

Two principal models are suggested to explain the extraordinary crustal section in which a 20-22 km thick sedimentary cover rests directly on the lower high-velocity mafic crust. The first, "oceanic" model considers the lower-crust layer as a sligtly stretched Neoproterozoic to mid-Palaeozoic relict oceanic crust. This relict crust is supposed to has been retained after transformation of the rifted (Neoproterozoic) margin of East Antarctica into the active (convergent) margin in the Late Cambrian either if a subduction zone arose within the paleo-Pacific plate to isolate part of the Neoproterozoic oceanic crust, or if it jumped back from Antarctic rifted margin to a new position in the mid-Palaeozoic. The oceanic crust in the WSE might be also formed as the result of sea-floor spreading in a back-arc tectonic setting. The second, "continental" model suggests that the lower, high-velocity layer is a strongly stretched and intruded by mafic (mantle-derived) rocks continental crust which was developed in the settings of Late Neoproterozoic rifting and Palaeozoic to Mesozoic back-arc basin.

Our suggested crustal model and interpretations imply that at least from the mid-Palaeozoic the WSE was a sufficiently large crustal block with a stretched continental or proto-oceanic crust and, hence, it must be taken into account in Gondwana reconstructions unlike those, suggested by many scientists, which ignored this region before the Late Mesozoic (e.g. Grunow et al. 1987, Dalziel 1992). More detailed seismic investigations are needed to resolve the problems outlined in this paper and to contribute to a better understanding of the structure and tectonic development of the WSE basin.

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