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A Seismic Study of the Mid- and Lower-Crust Beneath the Sea of Bothnia: BABEL Line 1

Daniel P. Graham

Graduate Society

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A thesis presented for the degree of Doctor of Philosophy

Department of Geological Sciences, University of Durham. December 1994



A Seismic Study of the Mid- and Lower-Crust Beneath the Sea of Bothnia: BABEL Line 1

Abstract

In the Autumn of 1989, Durham University took part in the BABEL Project, a collaboration of scientists from five nations recording wide angle and normal incidence seismic data in the Baltic Shield. Recording stations were set up along the Swedish coast of the Sea of Bothnia to record marine airgun shots at wide angle. Similar stations were operated by Finnish teams on the eastern coast, and by a German team on Åland. The data recorded are of high quality and high resolution in comparison to previous wide angle surveys in the region, with a shot spacing of 75 m.

A large proportion (around fifty percent) of the project involved developing software for processing this data.

The in-line data from Line 1, and also those recorded at two off-line stations, have been interpreted using Cerveny's Gaussian Beam forward modelling package BEAM87, the in-line model being further constrained by 2D gravity modelling. The resulting models are compared and contrasted with normal incidence data from the same line, other models derived from BABEL data in the Sea of Bothnia and older refraction lines in the vicinity.

The models show a highly complex crust whose thickness varies between 50 and 60 km along the profile. The seismic velocity is high, increasing from 5.85 km s⁻¹ near the surface to 7.4 km s⁻¹ at the base of the crust. Lateral velocity variations are seen in the mid-upper crust while discontinuous reflectors and diffracting bodies are seen at 30 km depth.

In the central/northern part of the line the crust thickens and there is a change in seismic velocity. Using other geophysical information from the region, two hypotheses are put forward for interpreting this part of the seismic model. The first is the presence of a large igneous intrusion, and the second is the existence of a shear zone or tectonic boundary cutting Line 1. Further work will be required to confirm either or both of these hypotheses.

Department of Geological Sciences, University of Durham.

Declaration

The work contained in this thesis has not been previously submitted for any other degree or qualification and that unless otherwise stated is the author's own work.

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1. Prologue

In September 1989, 2268 km of marine seismic lines were shot between the north east coast of Germany and the Bothnian Bay (Fig. 1.1). Over 40 000 airgun shots were recorded, both at normal incidence and at wide angle by 68 land based seismic stations spread all around the Baltic coast.

The original aims of the BABEL project (<u>Baltic And Bothnian Echoes</u> from the <u>Lithosphere</u>) were twofold. Firstly the desire to compare the deep marine seismic data obtained around the British Isles and Western Europe with a similar dataset from a different crustal type. Secondly the need for a deep seismic reflection study of the transition from the Mesozoic and Paleozoic crust of Denmark and Germany to the Proterozoic crust of Scandinavia, and the Tornquist Zone, to compliment data from the EUGENO-S project of 1984.

The project quickly expanded, taking on more aims and objectives within the Baltic Sea and Gulf of Bothnia region. Some of these will be discussed further in Chapter 4, after an account of the geological background of the region and the results of previous geophysical investigations. Implicit in many of the aims was the necessity for simultaneous recording of off-line wide angle data to provide three dimensional velocity and reflection information. The experiment became a major international project involving the collaboration of 31 scientists from 12 institutions and 5 nations (Denmark, Finland, Germany, Sweden and the United Kingdom).

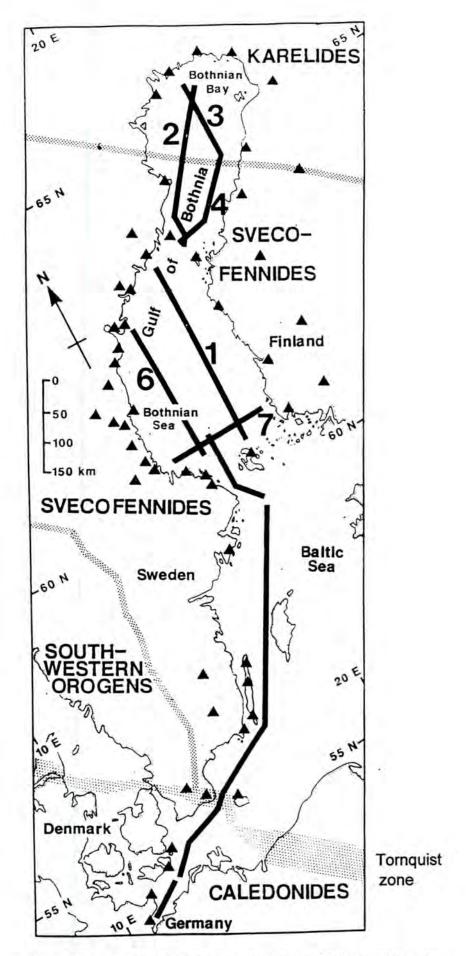


Fig. 1.1 Location map of normal incidence profiles (thick solid lines) recorded during Project BABEL and seismic stations (triangles) used to record the marine seismic source at wide angles.

Stippled lines indicate major tectonic boundaries (BABEL Working Group, 1990).

2. Geological Background

2.1 Introduction

Advances in technology and investigative methods over the last two decades have brought geoscientists closer to understanding the complex geology of the Baltic Shield and its evolution. With increased understanding have come a succession of interpretations and evolutionary models.

The general evolutionary scheme adopted here is that put forward by Gaál and Gorbatschev (1987), which appears to have gained a wide acceptance in more recent publications (BABEL Working Group 1990, 1991; Sundblad 1991; Anderson 1991) although there are still some with alternative viewpoints (Welin, 1987, Witschard, 1984).

The model holds that some form of plate tectonics was active far back into the Archaean and can explain all the known features of the Baltic Shield crust. Five Precambrian orogenic cycles are identified:

7	Saamian	(>3.1 - 2.9 Ga)
Archaean	Lopian	(2.9 - 2.6 Ga)
	Svecofennian	(2.0 - 1.75 Ga)
Proterozoic	Gothian	(1.75 - 1.5 Ga)
	Sveconorwegian	(1.25 - 0.9 Ga)

Most of the Baltic Shield crust was formed during the Lopian, Svecofennian and Gothian orogenies and can hence be divided into three major domains: Archaean (northeast) which also contains some older



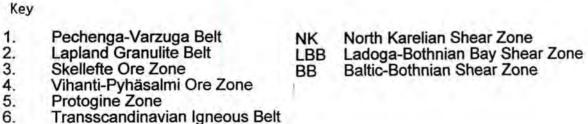
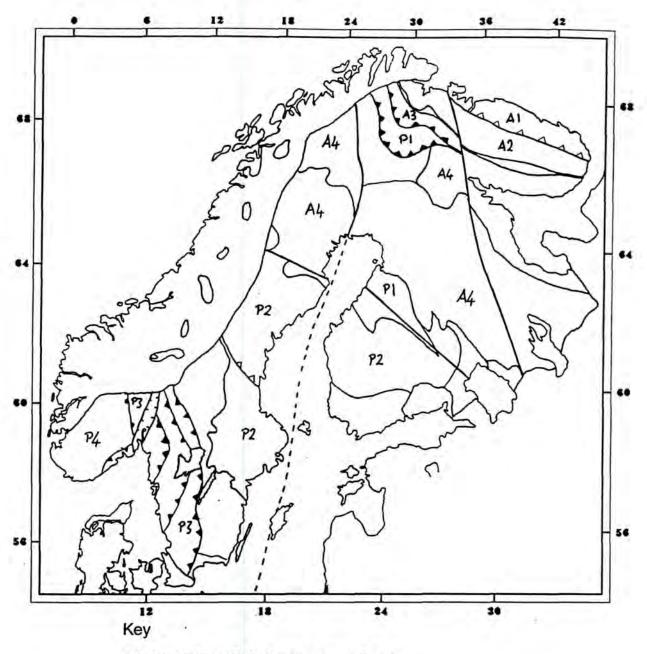


Fig. 2.1a)Tectonic map of the Baltic Shield, after Gaál and Gorbatschev (1987) and Berthelsen and Marker (1986).



A1-A4 Units with Archaean crustal ages

P1	Units with Early Proterozoic crustal ages (~2.0-1.98						
P2		n	Early	· W			(~1.9-1.85 Ga)
P3			Middle				(~1.7-1.65 Ga)
P4	**	Ř	Middle	*		ň	(~1.55-1.5 Ga)

Fig. 2.1 b) Tectonic units in the Baltic Shield based on both time of formation and time of most recent deformation, after Berthelsen and Marker (1986).

Saamian rocks, Svecofennian (central) and South West Scandinavian (Fig. 2.1a). Later orogenies merely deformed this crust with relatively little new crustal generation. Berthelsen and Marker (1986) point out that crustal units can be classified both according to time of original formation and also to time of most recent deformation. They combine these schemes to give a larger number of crustal units (Fig. 2.1b).

2.2 General overview

The major crustal developments are outlined here in chronological order.

2.2.1 Archaean

The Archaean domain consists of three provinces: the Karelian province is made up of granite greenstone belts of low metamorphic grade (Gaál, Mikkola and Söderholm, 1978) whilst in the Belomorian and Kola Peninsula domains high grade gneisses predominate (Gorbunov, Zagorodny and Robonen, 1985). The Proterozoic rocks of the Lapland granulite belt, which will be discussed later, separate the Kola Peninsula province from the rest of the Archaean domain.

The oldest known rocks in the Baltic Shield have been dated at 3.1 to 2.9 Ga old (Kröner, Puustinen and Hickman, 1981), being formed in the Saamian orogeny. They are found in Karelia, Lapland and the Kola Peninsula. Little more is known of this event and it is debatable whether coherent crust was formed over large areas or in smaller blocks which were later joined together (Gorbunov et al., 1985).

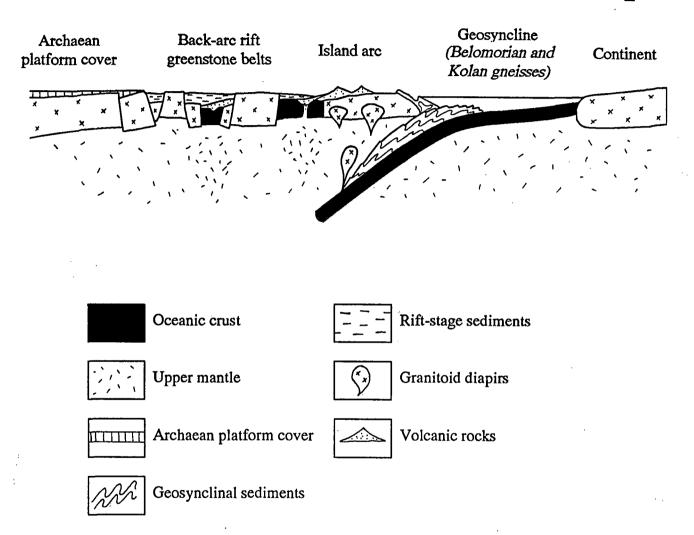


Fig. 2.2 A tectonic model of Lopian orogeny, after Gaál (1986)

The larger part of the Archaean crustal domain was formed during the Lopian orogeny (2.9 to 2.6 Ga ago). A plate tectonic mechanism for this is shown in Fig. 2.2 (Gaál, 1986). The granite-intruded Karelian greenstone belts are identified with the rifted foreland complex of a Saamian craton in the west, whilst the high grade gneisses of the Belomorian and Kola Peninsula provinces represent the mobile belt region and colliding continent in the east.

2.2.2 Late Archaean - Early Proterozoic cratonisation

The Lopian orogeny was followed by a long period of cratonisation lasting for over 500 Ma. During this period, the metasedimentary and volcanic rocks of the Lapponian Supergroup (2.7-2.4 Ga ago, Lapland) and the Sumian-Sariolan Group (2.5-2.3 Ga ago, further south in Finland and Russia) were laid down, controlled by NW trending faulting (Saverikko, 1983, Laajoki, 1986). The Karelian Province subsequently saw the thick platform cover of the Jatulian sedimentary sequence 2.3-2.1 Ga ago (Fig. 2.3). However this is absent in the Belomorian Province and is restricted to volcanic rock in fault-bounded basins in the Kola Peninsula (Gorbunov et al., 1985).

2.2.3 Svecofennian

At the end of this tectonically quiet period, intense rifting and dyke intrusion signalled the development of a passive continental margin trending NW at what is now the western edge of the Karelian Province (Gaál and Gorbatschev, 1987). Svecofennian crustal accretion proceeded

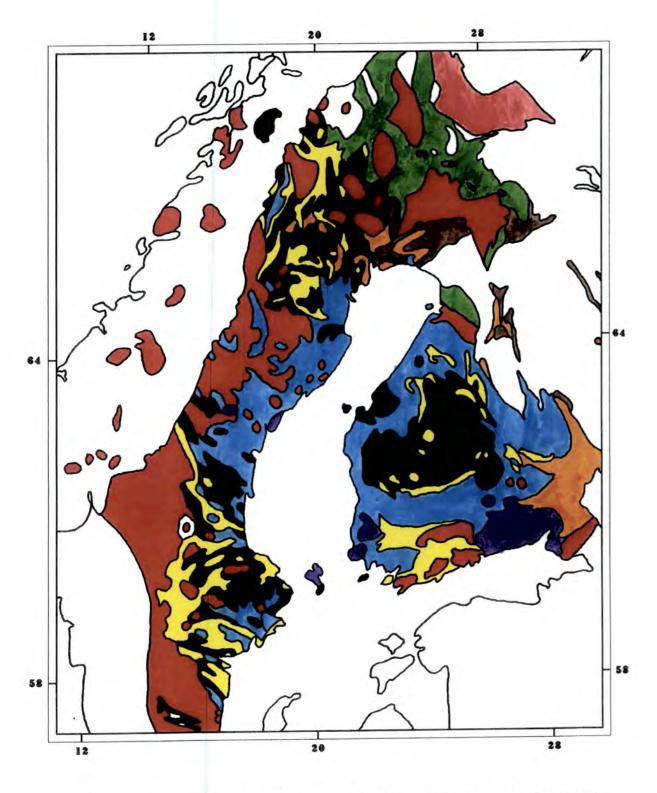


Fig. 2.3 Tectonostratigraphic map of the Svecofennides, after Gaál and Gorbatschev (1987) and Andersson (1991).



Episode 1 granitoids 1.90-1.86 Ga

Episode 2 granitoids 1.83-1.77 Ga

Episode 3 granitoids 1.65-1.56 Ga

Svecofennian metasediments

Svecofennian metavolcanics

Lapland Granulite Belt 2.1-2.0 Ga

Kalevian sediments 2.0-1.95 Ga

Jatulian and Sariolan sediments 2.5-2.1 Ga

Lapponian sediments 2.7-2.4 Ga

by sedimentation along this continental margin (Ward, 1987) and, after its activation, by volcanic activity and a series of plutonic episodes (Andersson, 1991). The bulk of the new crust was formed by intrusion of plutonic rocks into metasediments and metavolcanic belts on an unknown basement between 1.9 and 1.8 Ga ago. This occurred in an island arc environment after the subduction zone had moved to the southwest. Deformation and metamorphism throughout the Svecofennian Domain, and also in the Karelian Province, occurred synchronously with the major orogenic granitoid episodes (Lundberg, 1980, Welin and Stålhös, 1986).

The Lapland granulite belt and Pechenga-Varzuga belt consist of metamorphosed Proterozoic rocks and lie within the Archaean domain. They are considered to have been formed by closure of an oceanic basin 2.0-2.1 Ga ago, at the same time as the extensional phase in the Svecofennian Domain at the start of the Svecofennian orogeny. There is disagreement as to which belt formed the original ocean basin and to the direction of subduction (Barbey et al., 1984, Berthelsen and Marker, 1986).

The Pechenga-Varzuga belt is cut by the North Karelian shear zone, a deep strike-slip fault system with a dextral displacement of about 100 km initiated between 1.9 and 1.8 Ga ago (Fig. 2.1a). As the Svecofennian crust consolidated, another transcurrent fault system developed at the boundary between Archaean and Proterozoic crust: the Ladoga-Bothnian Bay fracture zone. This 50-100 km wide zone runs almost parallel to the previous plate margin and is dated at around 1.8 Ga ago. A further contemporaneous strike-slip shear zone, the Baltic-Bothnian Megashear, is proposed by Berthelsen and Marker (1986) to run roughly north from the Bothnian Bay and south beneath the Gulf of Bothnia and Baltic Sea. Although there has up to now been no geophysical evidence for this, it was

hoped that the BABEL experiment would provide the necessary information. These megashears are thought to have been active at least twice, in opposite senses, and to have caused offsets in the Moho.

2.2.4 Gothian and Sveconorwegian orogenies

Further granitic intrusion in the Svecofennian Domain, including the Rapakivi Granites, occurred in the period 1.65-1.56 Ga ago. These were thought to be anorogenic or related to the Gothian orogeny (Gaál and Gorbatschev, 1987) but more recent work associates them with the tail end of the Svecofennian orogeny (Andersson, 1991) which overlapped with the start of the Gothian. Most of the South West Scandinavian Domain crust was formed during the latter event (1.75-1.50 Ga ago). Sporadic intrusions continued until the Sveconorwegian orogeny (1.25-0.90 Ga ago) in which the SW Scandinavian crust was extensively reworked and intruded. The effects of the Sveconorwegian orogeny are bounded by the Protogine Zone, a region of deep faulting (Fig. 2.1a).

2.3 Svecofennides in more detail

The Svecofennian domain was formed in a series of alternating periods of sedimentation and igneous activity. The domain can be subdivided into three provinces with respect to the palaeoenvironment: a northern and a southern volcanic district are separated by a central marine sedimentary region known as the Bothnian Basin (Figs. 2.1a and 2.4, Welin, 1987). No basement rocks have been identified within the domain.

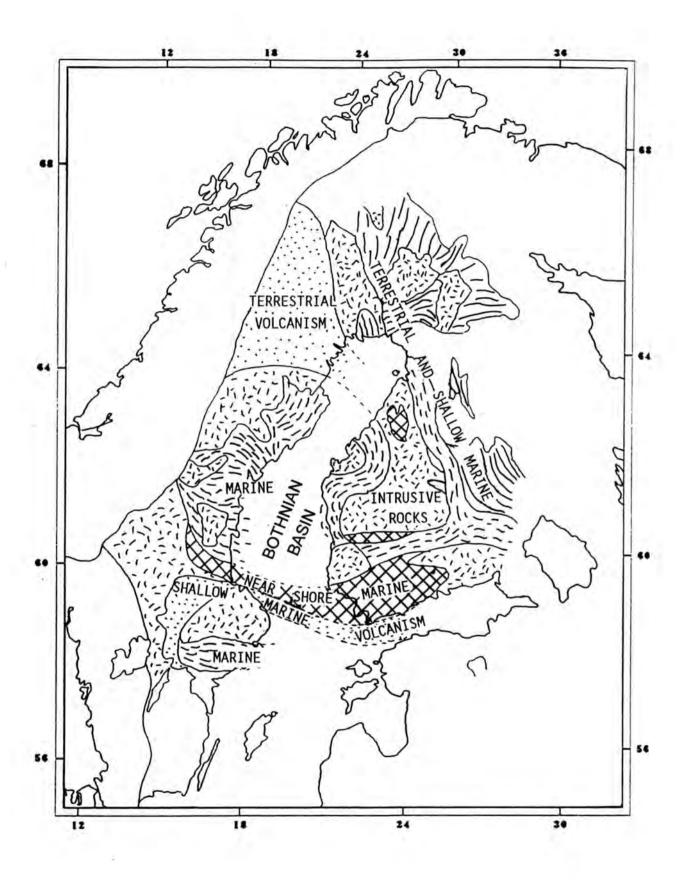


Fig. 2.4 Paleoenvironment map of the Svecofennian, after Welin (1987)

However, stratigraphic studies of the southern volcanic province indicate that Archaean crust may have been present to the southwest (Lundqvist, 1987).

Prior to 2.0 Ga ago, Jatulian sediments were being deposited in basins on the Archaean continent (Fig. 2.3). These were intruded by dykes and sills and unconformably covered by Kalevian turbiditic sediments derived from eroded Archaean and Jatulian bedrock when, between 2.0 and 1.95 Ga ago, a passive continental margin was formed. Displacement along the Ladoga-Bothnian Bay zone may also have been initiated at this time. The Kalevian sediments formed a 100 to 150 km wide belt along the new continental margin. As the marine basin deepened, sediments were carried further to the west to form the Svecofennian greywackes and pelites (Welin, 1987).

The Outokumpu district to the southwest of the Kalevian belt contains distal type turbidites in a separate marginal basin, and an association which has been contentiously interpreted as an ophiolite (Gaál and Gorbatschev 1987). This indicates the activation of the continental margin with subduction to the east, beneath the Archaean craton. The Skelleftea and Vihanti-Pyhasalmi ore zones are considered to be remnants of an early island arc system associated with this subduction which contributed little to the formation of new continental crust. Later, the subduction zone shifted a considerable distance to the southwest, initiating the main stage of Svecofennian crustal accretion in an island arc environment 1.9 Ga ago (Fig. 2.5).

Welin (1987) refutes the ophiolitic interpretation of the Outokumpu association and puts forward a block tectonic evolution as an alternative to the plate tectonic model while Witschard (1984) states the case for

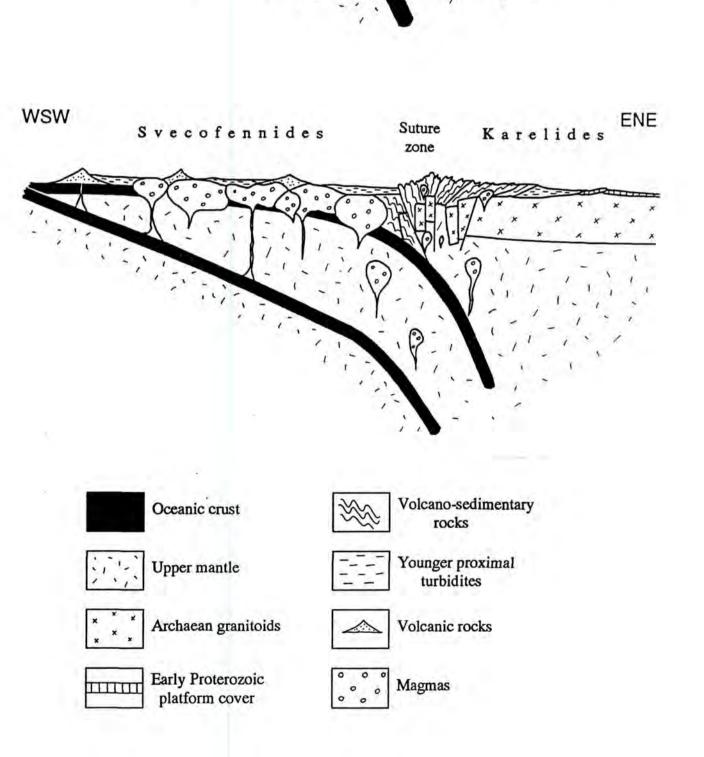


Fig. 2.5 Tectonic model of the Svecofennian orogeny :

a) 1920 Ga ago, b) 1880 Ga ago. (After Gaál, 1986)

basement reactivation. However, although the Outokumpu association has now been shown to be merely the product of primitive igneous activity in a pelagic basin (Park, 1988), a true ophiolite has been discovered at nearby Jormua (Kontinen, 1987). The plate tectonic view is backed up by seismic evidence of dipping reflectors in the lower crust beneath the Bothnian Bay (BABEL Working Group, 1991).

Three major plutonic episodes occurred during the Svecofennian orogeny (Andersson, 1991). The first involved the formation of large volumes of new crust between 1.90 and 1.86 Ga ago. The shallow submarine and subaerial volcanics of the Northern and Southern Svecofennian Provinces (1.90-1.88 Ga) are associated with this episode. They were little affected by large scale fault movements and formed the northern and southern boundaries to the marine basin of the Central Province. Most of the crust formed was juvenile, mantle-derived material although the component of remelted Archaean crust increases to the north, near the Archaean craton. The sedimentary and volcanic processes terminated in the marine basin at around 1.86 Ga ago (Welin, 1987). There followed a guiescent interval interrupted only by a small amount of rifting and dyke intrusion with minimum metamorphism until the second Svecofennian plutonic episode began 1.83 Ga ago. This time only minor quantities of juvenile crustal material were introduced, the main body being made up of remelted episode-1 material. Numerous massifs and dyke networks were intruded in the two volcanic provinces and larger masses emplaced in the former central sedimentary basin and the Archaean Domain of Finnish Lapland. Also included in this group is the Transscandinavian Igneous Belt, a huge batholith forming the southwestern boundary of the Svecofennian domain. The second episode

ended at around 1.77 Ga ago as the main tectonic activity moved west of the Svecofennian craton.

Cratonisation of the Svecofennides with little igneous activity preceded the third episode of granitoid generation (1.65-1.56 Ga ago). The Rapakivi Granites were formed during this period of intracratonic reworking, along with mafic dyke swarms associated with extensional tectonism. A thick sequence of red arkose Jotnian sandstone was deposited over a large area around 1.3 Ga ago but is only preserved locally in deep down-faults and grabens and in the Gulf of Bothnia. The sandstones are intruded by 1.25 Ga old dolerite sills and dykes.

2.4 Paleozoic sedimentary geology of the Bothnian Sea

Although few deposits of Paleozoic sedimentary rocks are to be found around the coastline of the Bothnian Sea, a considerable sedimentary sequence exists in the central and western parts of the Sea (Winterhalter, 1972, Fig. 2.6).

The Svecofennian igneous and metamorphic crystalline basement which predominates around the coast is continuous from the eastern side beneath the Sea, with a shallow sea floor gradient (Fig. 2.9) and no evidence of boundary faulting along the coast (Fig. 2.6). The western side is bounded by strong down-faulting (a). Large areas are covered by Jotnian sandstones which give the first indication of a post-Svecofennian marine environment. Their thickness is unknown over most of their extent due to the similarity in seismic velocity to the basement rocks although boreholes give thicknesses between 500 and 1000 m. The Jotnian rocks have been

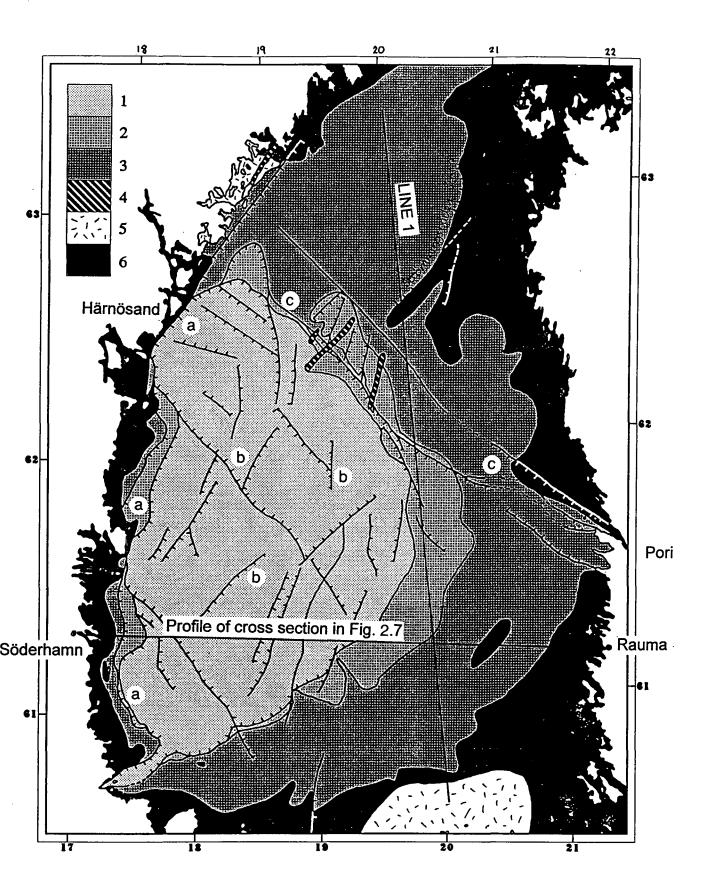


Fig. 2.6 Geology map of the Bothnian Sea, after Ahlberg (1986)

1 Ordovician; 2 Cambrian; 3 Jotnian sst.; 4 Diabase intrusion; 5 Younger granites; 6 Precambrian crystalline basement

a-c: faults - see text.

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considerably faulted and intruded by dolerite dykes and sills during subsequent tectonic activity. After a period of erosion, the sub-Cambrian peneplain underwent a transgression of the sea giving the Cambrian sandstones and clays before the Lower Ordovician shales and Middle and Upper Ordovician limestones were deposited. The shale-limestone boundary is a strong seismic reflector. Fig. 2.7 shows an east-west cross-section of the sea bed across the southern part of the Sea from Söderhamn to Rauma, while Fig. 2.8 shows an isopach map of Paleozoic sediment thicknesses. The sediments have remained for the most part undisturbed but evidence for post-depositional faulting and folding has been observed in central parts of the formations (Fig. 2.6,b) and a large fracture zone runs roughly NW from Pori to Härnösand (c). The current sea basin is of Tertiary age and was produced by intense down-faulting on the western side. Faulting also occurred within the Sea itself.

Tectonic activity was renewed with the glacial loading of the Quaternary. The net effect of glaciation was an accumulation of sediments rather than erosion. The mean thickness of post-glacial sediments is around 1.9 m.

Seismic velocities of the major sea floor formations are as follows (per. com. G. Lindsey, Bullard Laboratories, Cambridge, 1991)

Quaternary till	2120 m s ⁻¹
-----------------	------------------------

" clay 2500 m s⁻¹

Ordovician limestone 3400 - 4100 m s⁻¹

Jotnian sandstone 4780 m s⁻¹

Crystalline basement 5640 - 6230 m s⁻¹

(mean 5850 m s⁻¹)

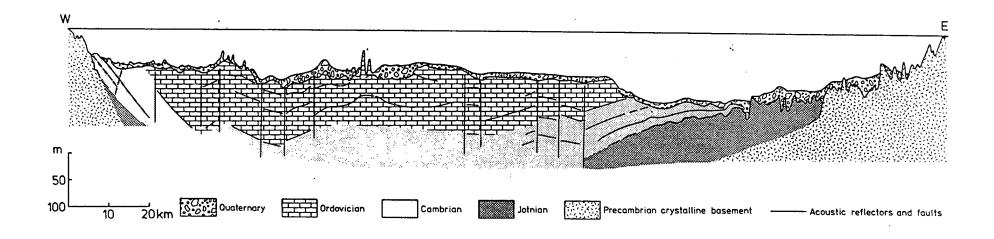


Fig. 2.7 Schematic geological profile (W—E) across the southern part of the Bothnian Sea from Söderhamn in Sweden to Rauma in Finland. (After Flodén and Winterhalter, 1981).

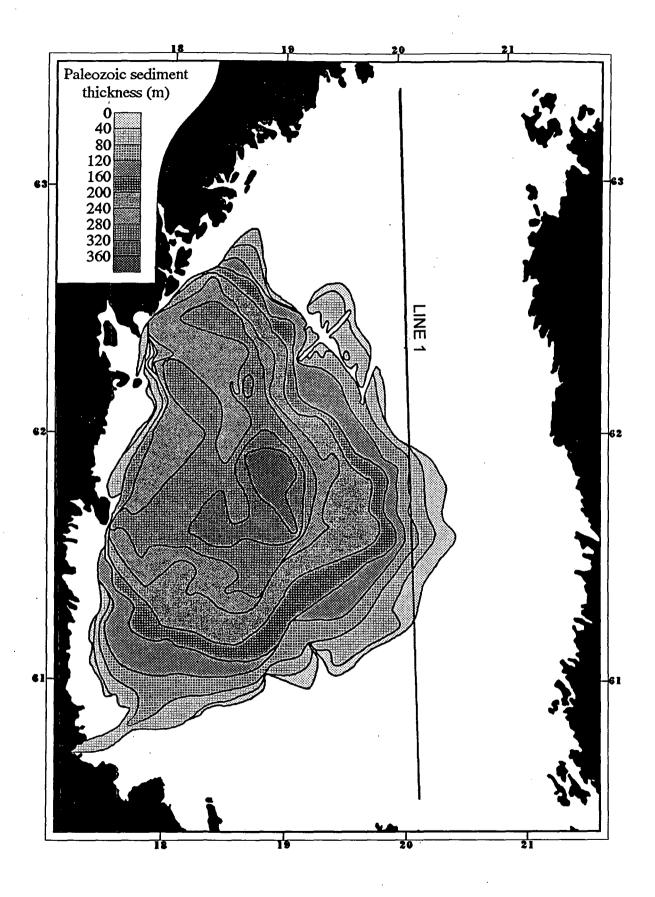


Fig. 2.8 Paleozoic sediments isopach map of the Bothnian Sea. after Axberg, 1981.

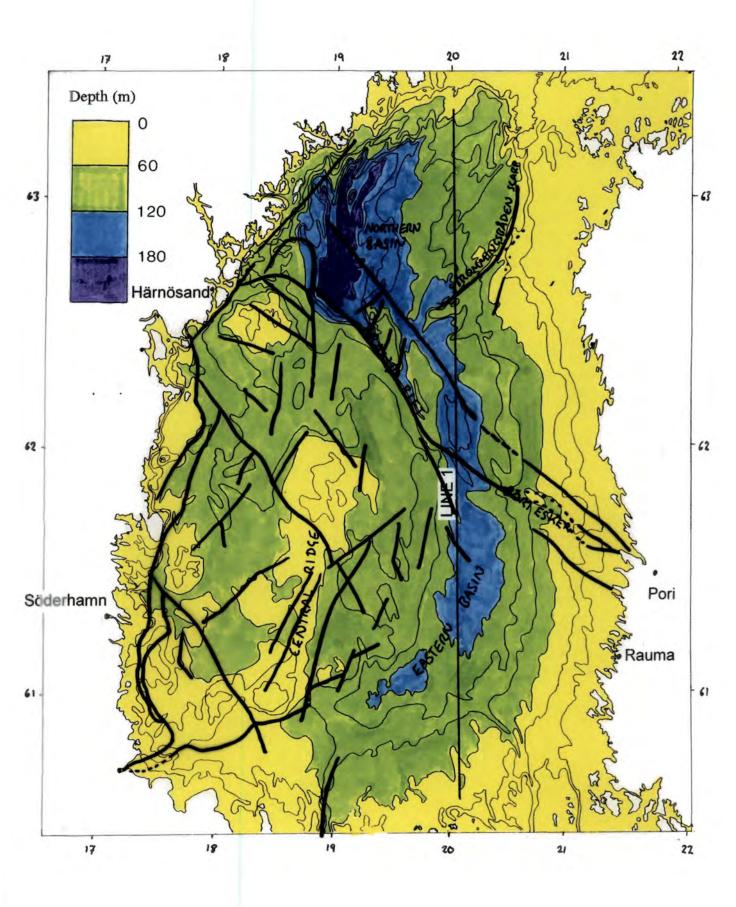


Fig. 2.9 Bathymetry map of the Bothnian Sea, after Winterhalter (1972).

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The sea floor itself exhibits a wide variation in depth, although the mean water depth is only 68 m (Fig. 2.9). The low relief of the Finnish coast extends westwards with uniform shallow gradient into a deep region of the Sea known as the Eastern Basin. The western slope of the basin is much more irregular, rising up to the Central Ridge which is a broad shallow region running N-S in the southwestern part of the Sea. The Eastern Basin is bounded to the North by the junction of the Pori Esker (a narrow glacial outwash deposit) and a narrow, faulted valley called the Aranda Rift. This widens to the northwest and deepens into the Northern Basin, the deepest part of the Sea. In the Northeast, the Strömmingsbåden scarp system runs for about 100 km and reaches 170 m in height at its southern end where it trends SW. Fig. 2.10 shows an echo sounding profile across the scarp in an E-W direction while Fig. 2.11 shows the variation of water depth along BABEL Line 1, as recorded by the survey ship. The overlay for Fig. 2.9 shows that most of the bathymetric features mentioned here are bounded by faults. Winterhalter (1972) claims that most of these faults are of Tertiary age, associated with the formation of the Sea, but some may be older.

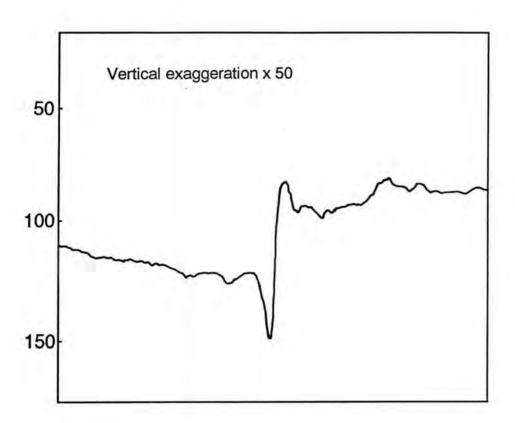
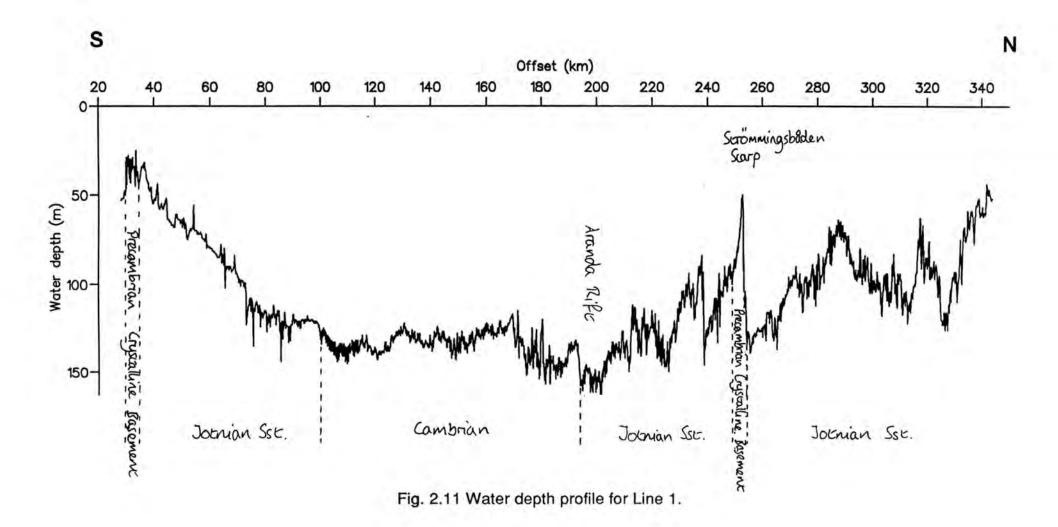


Fig. 2.10 E-W echo sounding profile of the Strömmingsbåden scarp. (After Winterhalter, 1972).



3. Previous Geophysical Surveys

3.1 Seismic surveys

A number of wide angle deep seismic surveys have been carried out within the Baltic Shield over the last thirty years. Those in and around the Bothnian Sea region of the Svecofennides are shown in Fig. 3.1. A summary of the acquisition details of these are given in Table 3.1. All the surveys used large explosive charges (generally underwater in lakes or the sea) with recording stations on land. With the exception of the Sylen-Porvoo line, a small number of sources were shot into a larger number of receivers at a few kilometres spacing and the lines were reversed. The spatial resolution is relatively low compared to the BABEL survey. The few previous surveys over Precambrian shield crust which match BABEL's resolution include the GLIMPCE project in the Great Lakes of North America (shot spacing 50-300 m; GLIMPCE seismic refraction working group, 1989) and the marine parts of the EUGENO-S project of Northern Germany and Southern Scandinavia (shot spacing 300 m; EUGENO-S working group, 1988). Fig. 3.2 shows sample data sections from the EUGENO-S project between Denmark and Sweden and from shot E of the FENNOLORA profile to the west of, and roughly parallel to BABEL Line 1.

The 2D models produced for the five profiles from the Sea of Bothnia are given in Fig. 3.3a-e. From these it can be seen that both low and high velocity zones have been proposed in the upper crust. In the SVEKA survey (Fig. 3.3b), a thick, high velocity lower crustal layer has been modelled.

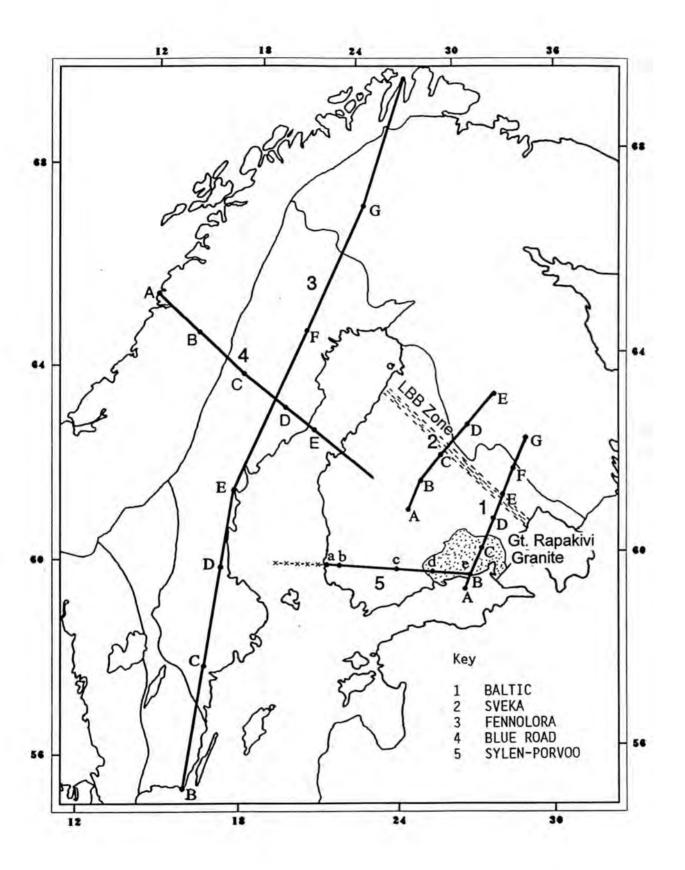
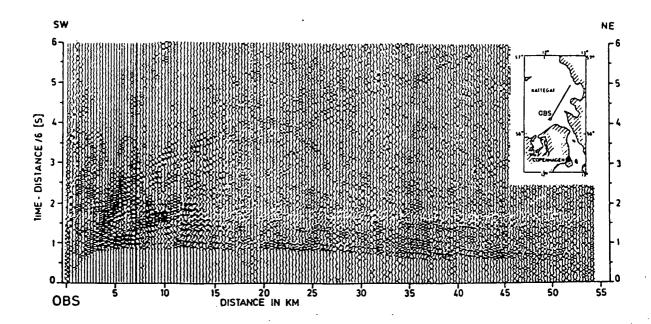


Fig. 3.1. Map of previous seismic surveys, after Luosto, 1990

Profile	Date	Shot separation	Receiver separation	Reversed	Source type
BALTIC	1982	80 km	2 km	Y	explosive 200-1700 kg
SVEKA	1981	80 km	2 km	Y	explosive 100-1000 kg
FENNOLORA Shots D and E	1979	180 km	3 km	Y	explosive 1800-8200 kg
BLUE ROAD	1972	110 km	4 km	Y	explosive 700-1400 kg
SYLEN-PORVOO	1965	3.5 km	60 km	N .	explosive 50-300 kg
BABEL Line 1	1989	75 m	350 km	Y	marine airgun 120.6 I

Table 3.1 Seismic Profiles in the Baltic Shield



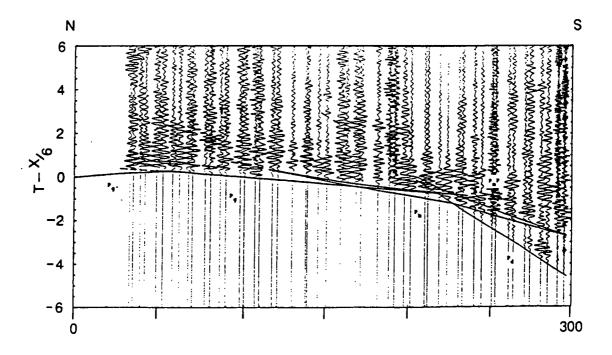


Fig. 3.2 Examples of data from earlier projects
a) EUGENO-S marine airgun data, OBS 1 (EUGENO-S working group, 1988)
b) FENNOLORA shotpoint E south: typical of experiments in the region (Guggisberg et al., 1991)

Perhaps the most dramatic features appear to be the deep depressions in the Moho boundary observed in the FENNOLORA, BALTIC and SVEKA profiles. In the latter two these are directly beneath the Ladoga-Bothnian Bay zone (Figs. 2.1 and 3.1).

3.1.1 BALTIC 1982 (Fig. 3.3a)

This survey, shot in southeast Finland, crosses the Ladoga-Bothnian Bay zone. The Moho is at about 40 km depth at the southern end, below the great Rapakivi granite intrusion. It deepens northwards and disappears in the centre of the profile where the crust extends down to a second boundary, elsewhere within the upper mantle, at a depth of 65 km. The P-wave velocity beneath this boundary is 8.5 km s⁻¹. In the northeast the crust thins again to about 45 km.

There is a high velocity body in the south between 10 and 14 km ($V_P = 6.5 \text{ km s}^{-1}$) with lower velocities below down to about 18 km. A midcrustal reflector known as the *c-boundary* has been widely observed in the Baltic Shield. It is defined as the crustal boundary below which the P-wave velocity exceeds $6.5 - 6.6 \text{ km s}^{-1}$ (Luosto, 1990) and in this case varies between 18 and 22 km.

3.1.2 SVEKA 1981 (Fig. 3.3b)

Located in central Finland, this profile also crosses the Ladoga-Bothnian Bay zone. In this region the crust is modelled as being about 60 km thick, thinning to either side. The upper crust contains a low velocity zone across the whole profile and a locally present high velocity body while

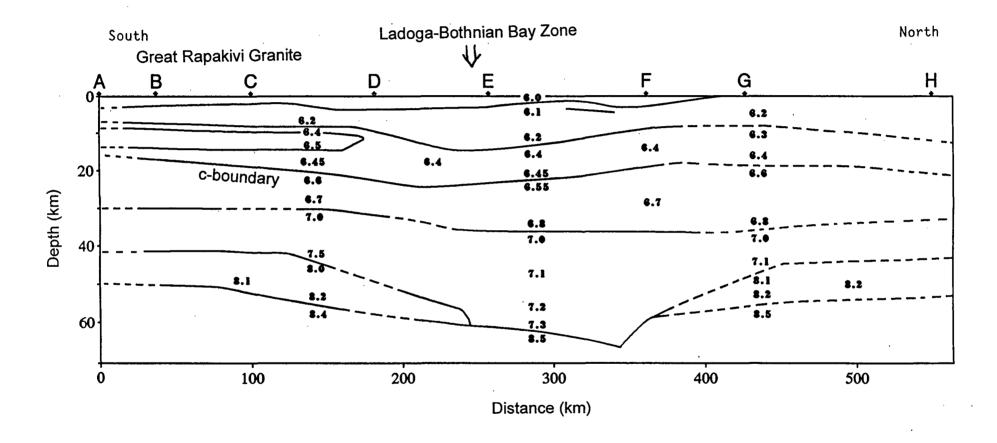


Fig. 3.3. Crustal velocity models from previous surveys:

a) BALTIC 1982 (after Luosto et al., 1990)

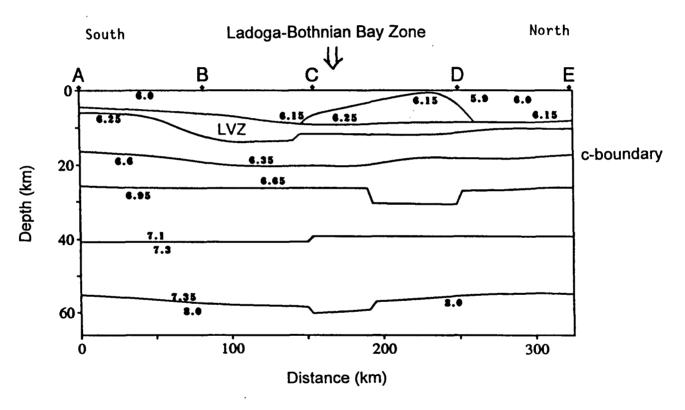


Fig. 3.3. b) SVEKA 1981 (after Grad and Luosto, 1987)

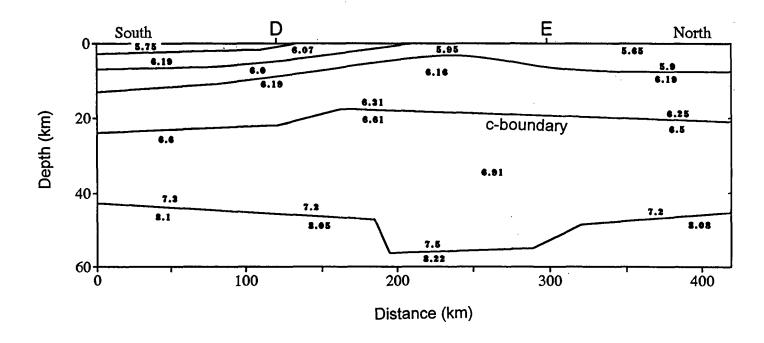


Fig. 3.3. c) FENNOLORA 1979 (after Guggisberg et al., 1991)

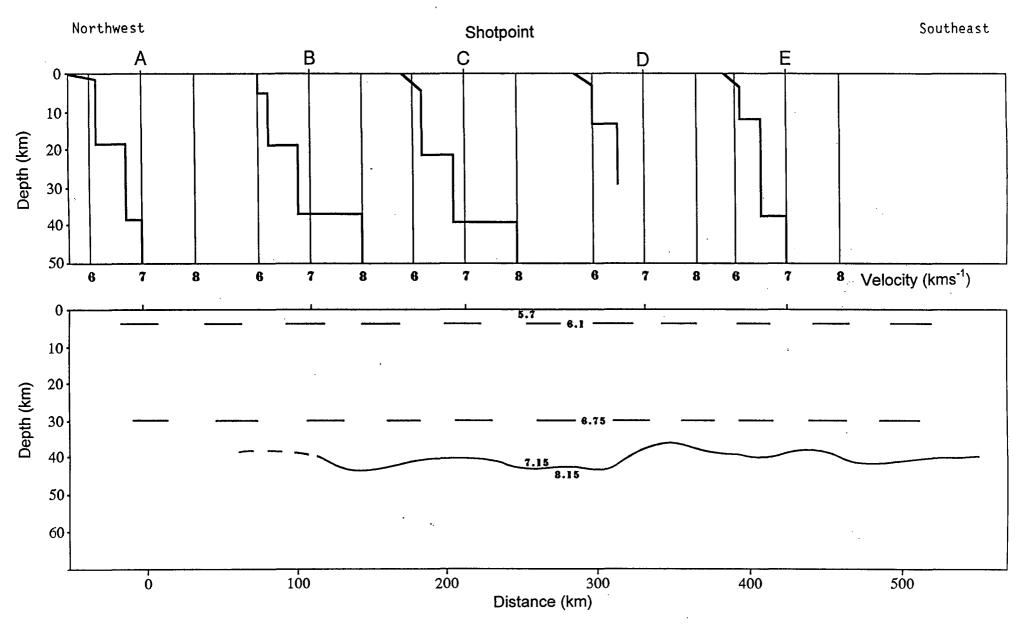


Fig. 3.3. d) BLUE ROAD 1972 (after Cassel and Fuchs, 1979; Lund, 1979)

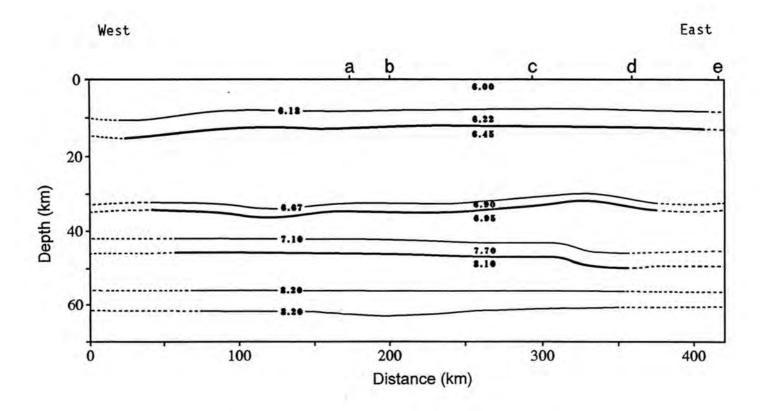


Fig. 3.3. e) SYLEN_PORVOO 1965 (after Luosto, 1986)

Heavy lines indicate velocity discontinuities while light lines are velocity isolines.

in the lower crust there is a 20 km thick layer with V_P greater than 7.3 km s⁻¹. A distinct c-boundary is observed at depth 17 - 20 km with a velocity discontinuity of 6.35 to 6.6 km s⁻¹.

3.1.3 FENNOLORA 1979 (Fig. 3.3c)

The FENNOLORA profile was shot as part of the European Geotraverse (EGT) project and covers a distance of over 2000 km from southern Sweden to northern Norway. The model shown in Fig. 3.3c is from the central section of the line between shotpoints D and E, adjacent to the Sea of Bothnia.

A depression of the Moho to a depth of about 55 km is seen in this region. The P-wave velocity within this depression is over 7.5 km s⁻¹. A similar feature occurs between shotpoints B and C to the south, and a shallower one around shotpoint G to the north.

The c-boundary was found throughout the profile with a velocity contrast of around 6.3 - 6.6 km s⁻¹ at a depth varying between 16 and 24 km.

3.1.4 BLUE ROAD 1972 (Fig. 3.3d)

The Blue Road survey extends from the Norwegian coast near the Arctic circle, across Sweden and into central Finland. The figure shows 1D models from each shotpoint but secondary reflected arrivals were rarely seen on the record sections so a gradational model was preferred. The Moho was modelled using wave-front methods but boundaries within the crust could not be defined. The data has also been used to argue that

there is a series of alternating high and low velocity layers in the upper mantle down to a depth of about 100 km (Lund, 1979; Cassel and Fuchs, 1979).

3.1.5 SYLEN-PORVOO 1965 (Fig. 3.3e)

The data from this survey were originally acquired in 1965 but reinterpreted by Luosto (1986) using modern ray tracing methods. A line of marine explosive shots was fired in the Sea of Bothnia into a number of earthquake stations in southern Finland. The resulting low speed paper recordings did not provide very accurate data.

The Moho depth is 44 km for most of the model, increasing to 49 km in the east. Above this lies a 4 km thick transition zone with velocity increasing from 7.1 to 7.7 km s⁻¹ and, as in the Blue Road profile, there appears to be a low velocity layer in the upper mantle between 56 and 63 km depth.

Reflections are seen from depths of 9 km and 44 km in the western part of the model which do not correspond well with the velocity layer boundaries.

3.1.6 Summary

Moho and c-boundary depths from these and other Baltic Shield surveys outside the region of interest have been compiled by Luosto (1990) to produce two contour maps (Figs. 3.4 (a) and (b)). The major features and trends can be clearly seen but detail cannot be relied upon due to the sparsity of data.

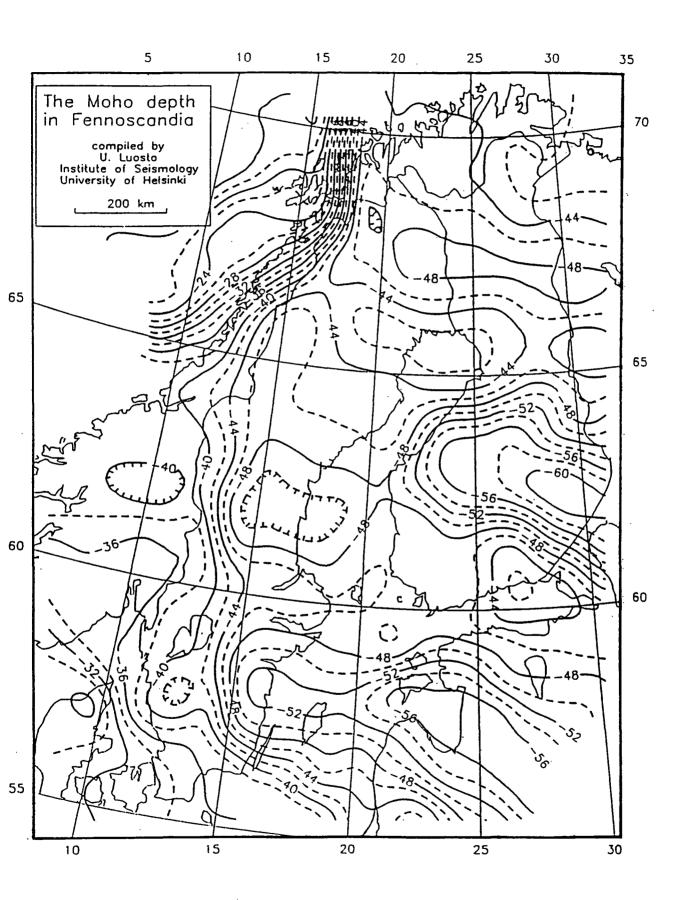


Fig. 3.4. a) Moho depth contour map (Luosto, 1990)

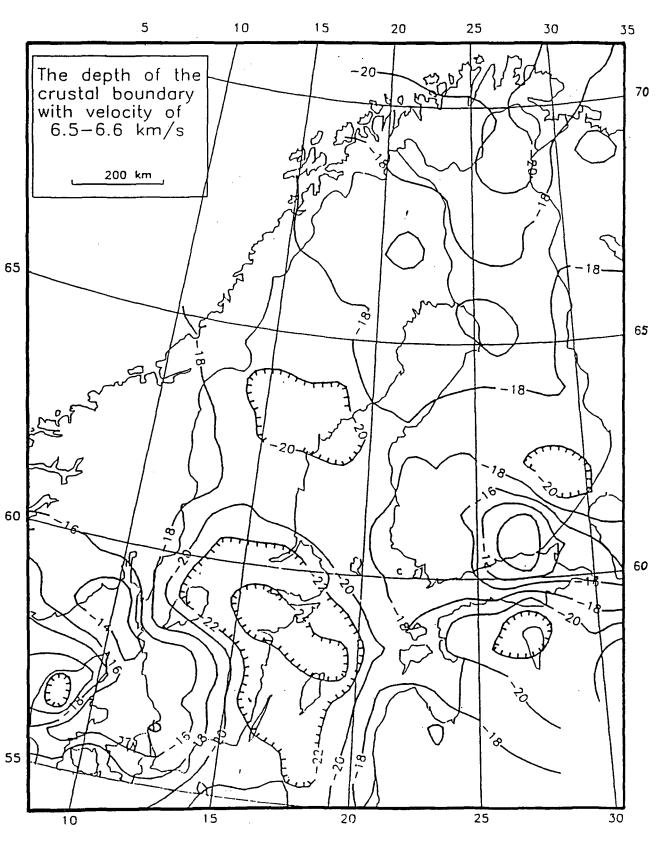


Fig. 3.4. b) c-boundary contour map (Luosto, 1990)

In the Moho map (Fig. 3.4a), the deepest depression is centred in eastern central Finland and extends to the north west, running roughly parallel to the Ladoga-Bothnian Bay zone. It is truncated at the Finnish coast of the Bothnian Bay. A second depression lies further to the south, in the Baltic States. This curves westwards across the Baltic sea into southern Sweden. A smaller depression occurs around the western coast of the Bothnian Sea, running WNW-ESE. The crust thins gradually to the north, south and west, and more steeply along the north west coast of Norway.

The c-boundary (Fig. 3.4b) has depressions in east central Finland and northern Estonia with a large high in between. There is a deep depression in south east Sweden and a shallower one in central Sweden, just north of the Moho depression. The c-boundary over the rest of the region appears to be relatively flat. The pattern of highs and lows in the c-boundary reflects that of the Moho topography described above. However, the features are not quite coincident, i.e. the highs and lows of the c-boundary do not lie directly above those of the Moho.

3.2 Gravity and aeromagnetic data

Gravity and magnetic data are available for the Sea of Bothnia and surrounding area. Fig. 3.5 shows a Bouguer anomaly contour map from Seasat and Geos3 altimetry data, grid spacing 30 km. There is a major gravity low in the northern Sea of Bothnia which seems to be part of a NE-SW trending band. A gravity high of similar trend but lesser lateral extent lies directly to the south. There appears to be no relationship between

these features and the c-boundary contour map but the band of negative gravity anomaly lies approximately on the line between the northwest tip of the Moho depression in central Finland and that in central Sweden. However, since there was no deep seismic data previously available from this area, the Moho contours here are not well defined. The only geological feature in the vicinity which has a similar trend is the southwestern end of the Strömmingsbåden Scarp system and its associated faults (Figs 2.6 and 2.9).

Fig. 3.6 is a contour map of high altitude (3000m) total magnetic field intensity, grid spacing 35 km. A large positive anomaly lies to the northwest of the Åland Archipelago and a lesser one in southern Finland. These may be associated with Episode 3 (Rapakivi) granite intrusions (Fig. 2.3) but are not quite coincident. They appear to be unrelated to any of the other geological or geophysical features already discussed.

A certain amount of 2½ D gravity and magnetic modelling has been carried out along BABEL lines 1 and 7 in parallel with this project (Pedersen, Tryggvason, Schmidt and Gohl, 1992). These models will be reviewed in the discussion in Chapter 8.

3.3 Conductivity data

Several magnetotelluric surveys have been carried out in Finland, the most relevant ones to this study being along the SVEKA wide angle seismic profile (see section 3.1) and near Oulu (Fig. 3.7, Hjelt, 1990). Though there is little direct correspondence between seismic and conductivity models and any given conductivity value cannot be associated

with a specific seismic velocity, one can compare the two types of model by looking for similarities in the size, shape and location of features. Because the SVEKA conductivity profile extends much further to the southwest than the seismic profile, 0 km on the distance scale in Fig. 3.3b corresponds roughly to 150 km in Fig. 3.7b. The depression in the boundary at 25-30 km depth towards the northeast of the seismic model corresponds approximately to the conductive zone at similar depth to the northeast of the Ladoga-Bothnian Bay (LBB) zone in the conductivity model. The region of higher upper crustal velocity directly above this in the seismic model (between shotpoints C and D in Fig 3.7b) may be related to the same feature. The deep conductive layer in the conductivity model (30 - 60 km depth) does correspond directly to the lower crust in the seismic model, there being much greater variation in depth in the conductivity model, especially at the northeastern end. However, the general trend of thicker crust in the central part of the seismic model (beneath the LBB zone) is echoed in the conductivity profile. On the basis of this, there is a case for suggesting that the crust is also thickened to the southwest, beneath the Tampere Schist Belt conductivity anomaly.

Fig. 3.8 shows the surface projections of crustal conductivity anomalies (Hjelt, 1992) while Fig. 3.9 shows an interpretation of magnetovariational surveys by Pajunpää (1987), dividing the crust into blocks based on changes in conductivity.

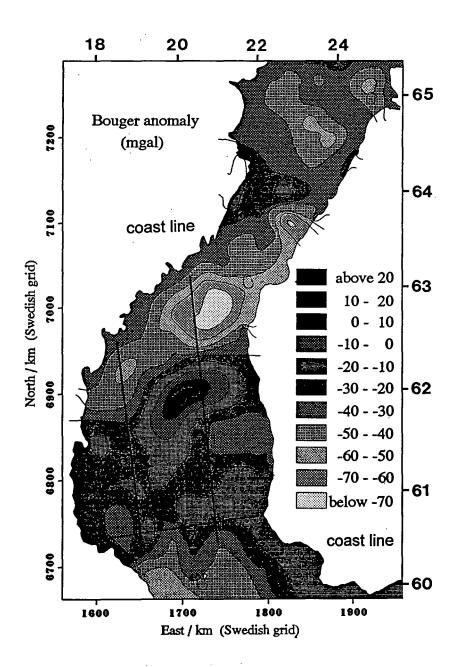
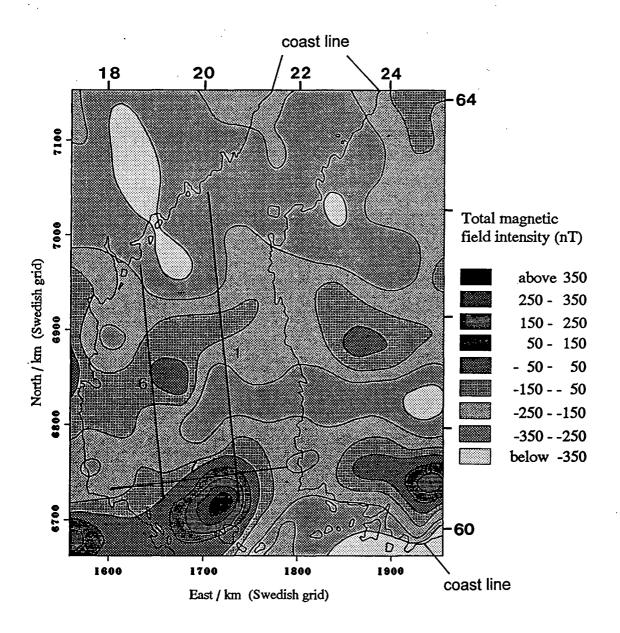
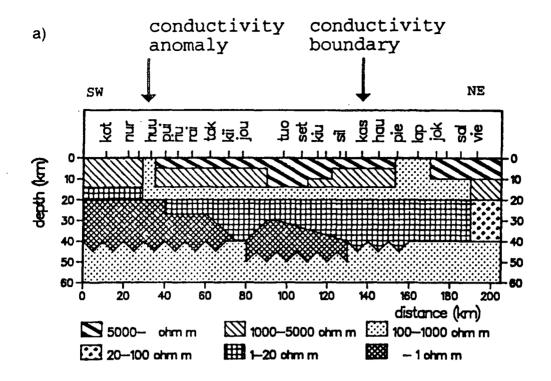


Fig. 3.5 Bouguer anomaly map of the Sea of Bothnia (after Pedersen et al., 1992).

Fig. 3.6 Aeromagnetic total intensity map of the Sea of Bothnia, altitude = 3000 m (after Pedersen et al., 1992)





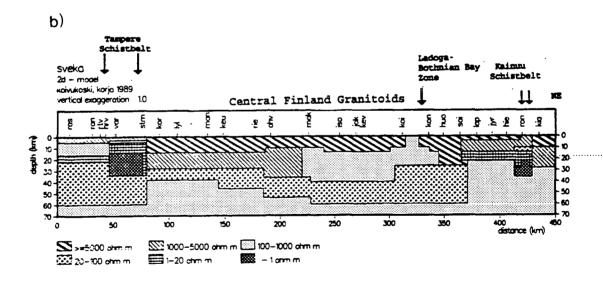


Fig. 3.7 Magnetotelluric conductivity models (Hjelt,1990):
a) Oulu IV profile
b) SVEKA profile

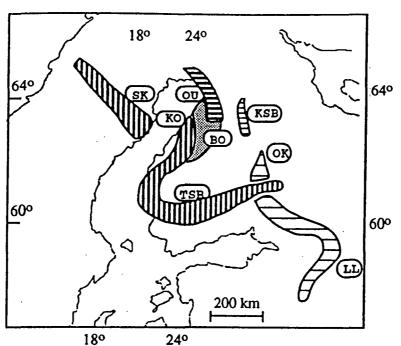


Fig. 3.8 Surface projections of crustal conductivity anomalies from magnetovariational studies (Hjelt,1992)

Conductors of the BB area: BO = Bothnian; KO = Kokkola; OU = Oulu; SK = Skellefteå-Storavan anomalies. Others: KSB = Kainuu Schist Belt; LL = Lake Ladoga; OK = Outokumpu; TSB = Tampere Schist Belt anomalies. The latter is a part of the SFCA = South Finland Conductivity Anomaly.

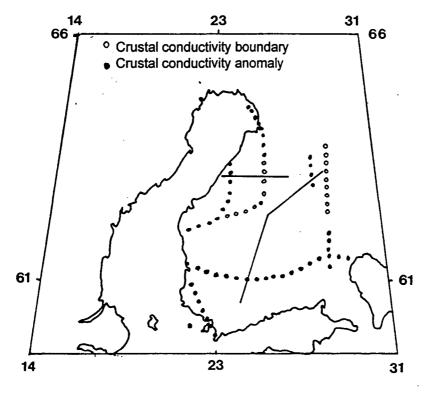


Fig. 3.9 Division of crust into blocks based on changes in conductivity, with the magnetotelluric profiles in Fig. 3.7 shown (after Pajunpää et al., 1987)

4. Field Work: Acquisition of the Data

4.1 Introduction: Aims of the Experiment

A number of questions and problems arise from the geological background and the results of previous geophysical investigations. Among these are: the exact location of the division between Archaean and Proterozoic crust; the relationship between the Skellefte Ore Zone and the Ladoga-Bothnian Bay Shear Zone (Fig. 2.1a); the presence of the Baltic-Bothnian Megashear; the cause of depressions in the Moho and the relationship between them; the cause of gravity and aeromagnetic anomalies in the Bothnian Sea; and the tectonic significance of bathymetric features such as the Aranda Rift and Strömmingsbåden Scarp (Fig. 2.9)

The BABEL project in the Gulf of Bothnia was designed with many of these questions in mind (Fig. 1.1). The Bothnian Bay experiment (BABEL Lines 2, 3 and 4) concentrated on the Archaean - Proterozoic boundary and the Skellefte Zone - Ladoga-Bothnian Bay Zone relationship.

In the Bothnian Sea, Line 1 was positioned to intersect the large gravity anomaly in the north (Figs. 3.5, 4.1). By running the line longitudinally along the axis of the Sea, a great enough length (>300 km) could be achieved to obtain velocity information from the lower crust and upper mantle at wide angle. This should allow any Moho depression running NE across the Sea to be imaged. The line also passes directly over the Strömmingsbåden Scarp. Line 6 runs parallel, to the west, so that rays shot into stations on the Finnish coast from Line 6 would have their midpoints beneath Line 1, and vice versa.

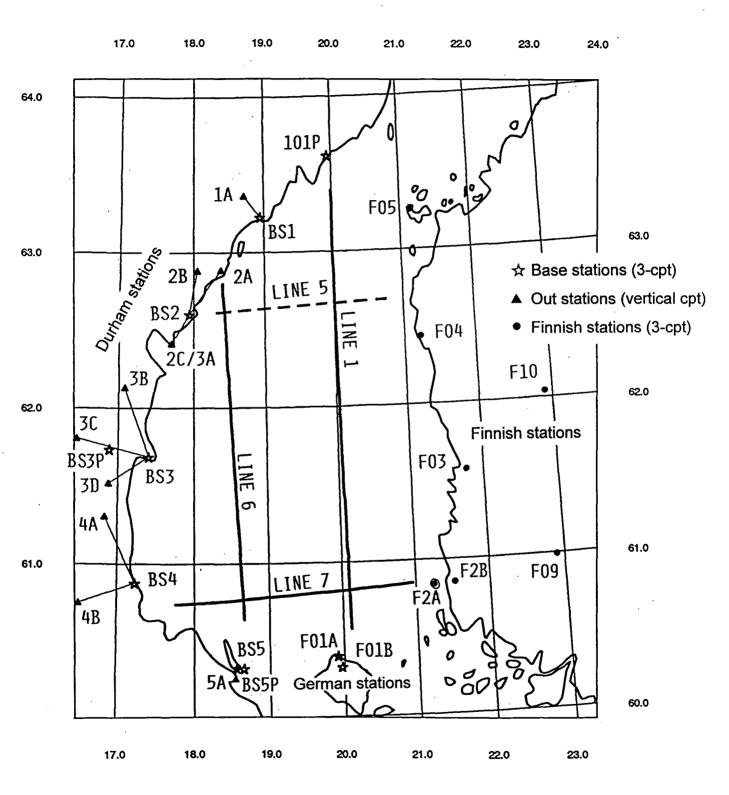


Fig. 4.1 Shots and recording stations of the BABEL project in the Sea of Bothnia

The wide angle recording stations were distributed all around the coastline of the Bothnian Sea to give a large set of intersecting raypaths, effectively giving three dimensional coverage of the region (Fig. 4.1). The station - shot separations were calculated so as to target mainly the mid and lower crust, and the Moho. To achieve a large enough offset, some stations were located well inland.

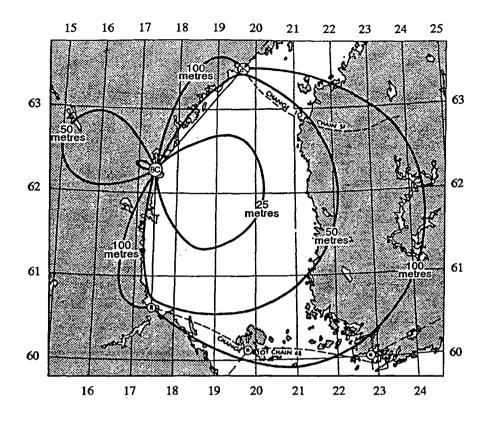
Two perpendicular lines (5 and 7) were planned at the northern and southern ends of the Sea in order to tie in the north-south profiles, and also to look for evidence of the Baltic-Bothnian Megashear. Line 7 had the additional aim of identifying the cause of the magnetic anomaly northwest of Åland. Unfortunately, due to limited funds, Line 5 could not be shot.

4.2 Marine work

The marine work was carried out by the Prakla-Seismos ship S. V. Mintrop.

4.2.1 Ship Navigation

The navigation system used aboard ship was the DECCA system. Fig. 4.2 shows the full daylight coverage and 68% fix repeatability for the Southern Bothnian chain (8C). Table 4.1 gives the random fixing errors for the accuracy contours in Fig. 4.2b. The appropriate light conditions for Line 1 are found in Fig. 4.3. Where possible, two DECCA chains were used, Doppler sonar was continuously recorded and all possible Transit satellite fixes were taken. This decreased the shot location errors considerably and



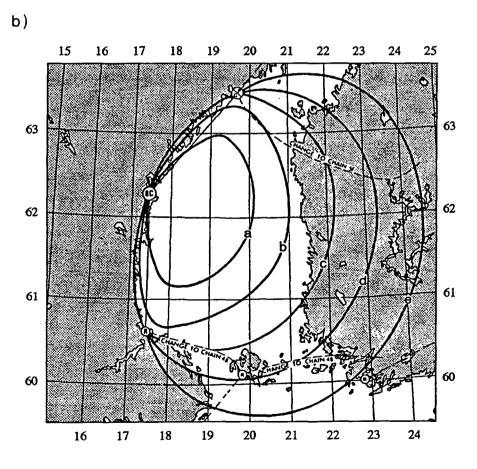


Fig. 4.2 DECCA navigation system in the Sea of Bothnia:

- a) full daylight coverage
- b) 68% fix repeatability (see also Table 4.1 and Fig. 4.3)

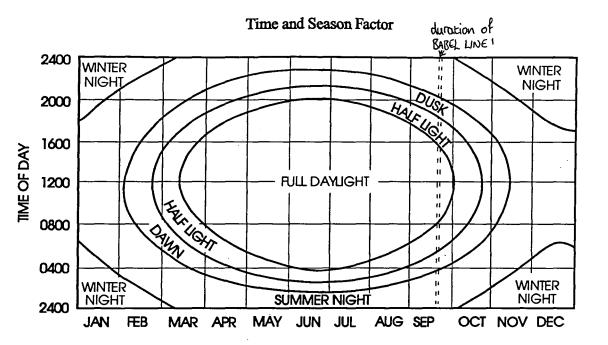


Fig. 4.3 Daily and annual variation in light conditions in the Sea of Bothnia

Random fixing errors at sea level (m): 68% probability level

DECCA period	Contour					
See Time and Season Factor diagram	a	b	С	d	e	
Half light	<200	<200	<200	250	450	
Dawn / Dusk	<200	<200	250	450	950	
Summer night	<200	250	450	950	1850	
Winter night	200	350	690	1400	2800	

Table 4.1 DECCA navigation system random fixing errors for the accuracy contours in Fig. 4.2b (DECCA manual)

the relative position of shots can be considered accurate to within a few metres, with a constant error in the line position of up to 200 m.

Line 1 was shot in three separate segments, the start and end points of which are given in Table 4.2. These are shown diagrammatically in Fig. 4.4.

4.2.2 Source specifications

The source used for the profiles was the Prakla-Seismos "F120/090/7.5" array of 42 airguns arranged in 6 strings of 8 as shown in Fig. 4.5. The total size of the array was 120.6 I (7359 cu. in.) and it was towed at a depth of 7.5 m. The source signature recorded by a hydrophone in the far field and its frequency spectrum are given in Fig. 4.6. The airguns were fired every 25½ seconds giving a nominal shot spacing of 75 m.

4.2.3 Hydrophones

Normal incidence data was collected with a 3 km long hydrophone streamer towed at a depth of 15 m. The hydrophones were divided into groups of sixtyfour with a group spacing of 50 m. 25 seconds of data were recorded for each shot with a sample interval of 4 ms. A low cut frequency filter was applied at 3 Hz and a high cut at 102 Hz.

Line		shot point	latitude	longitude	date	time
1	start	101	60° 33' 59.04"	20° 06' 05.00"	21-Sep	19:20:37.98
	end	2710	61° 57' 32.09"	20° 02' 54.11"	22-Sep	13:34:16.86
1A	start	3148	61° 56' 47.74"	20° 02' 56.10"	22-Sep	17:08:03.48
	end	4507	62° 51' 36.67"	20° 00' 47.23"	23-Sep	05:01:33.23
1B	start	5454	62° 49' 35.05"	20° 00' 51.20"	23-Sep	07:12:27.99
	end	6306	63° 23' 59.19"	19° 59' 59.87"	23-Sep	14:34:20.39

Table 4.2 Line coordinates for the three segments of BABEL Line 1

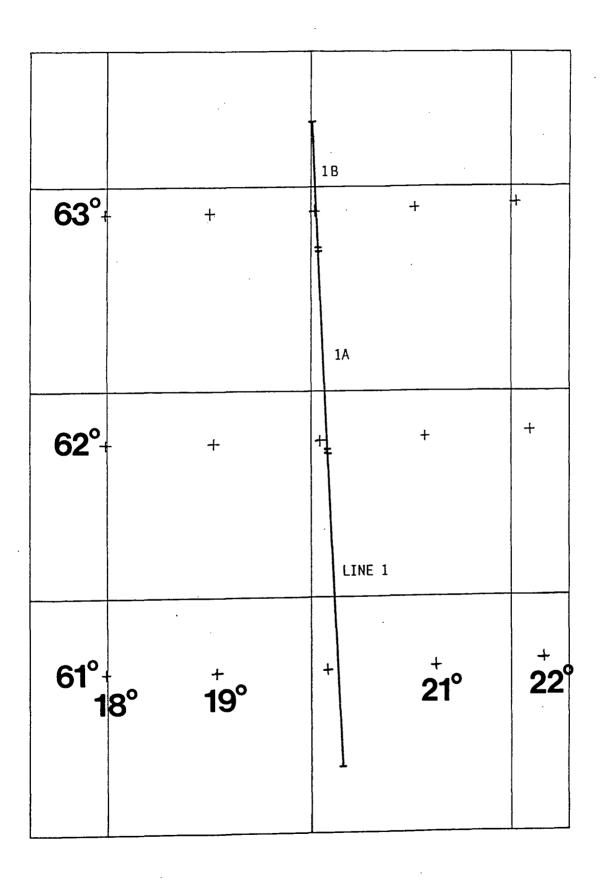


Fig. 4.4 Line 1 coordinates

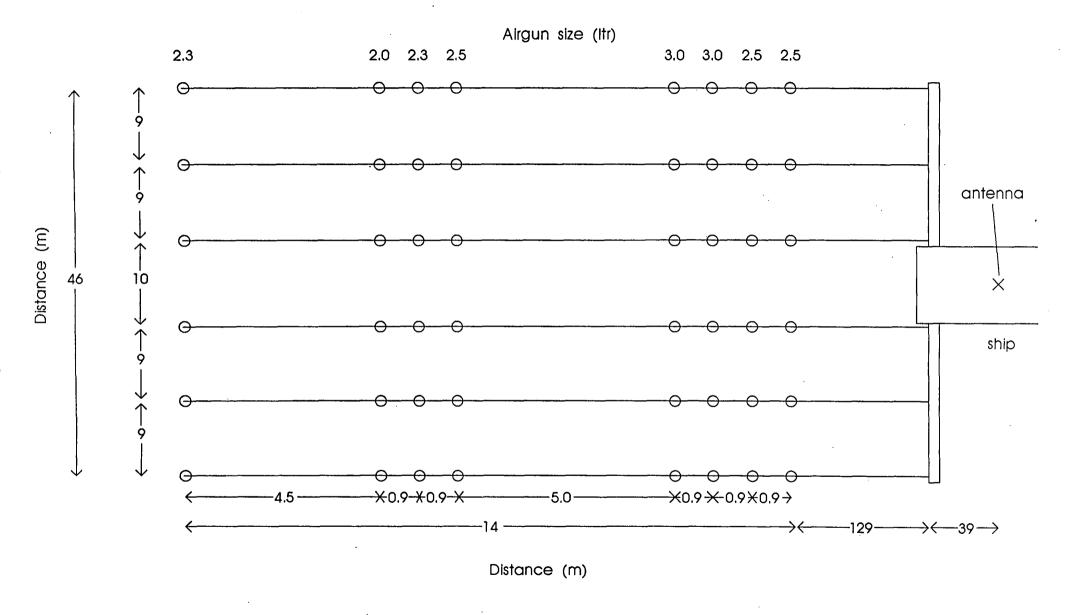
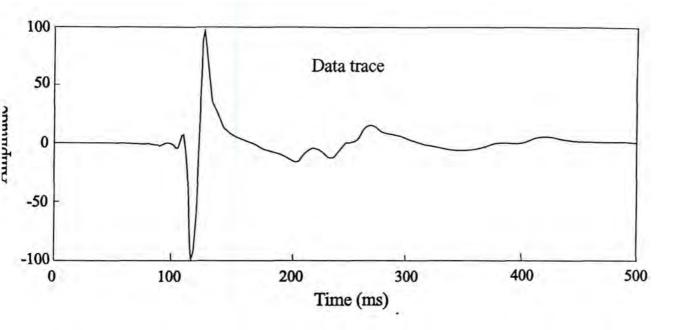


Fig. 4.5 Prakla-Seismos F120/090/7.5 airgun array



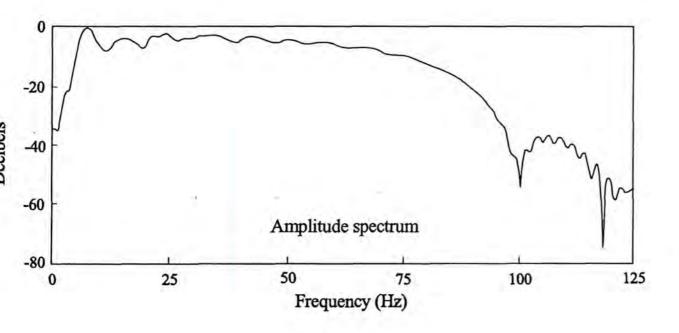


Fig. 4.6 Far field source signature and frequency spectrum recorded by hydrophone.

Source array depth = 6.0 m

Hydrophone depth below source = 108 m

4.3 Land stations

4.3.1 Station setup

Durham's part in the fieldwork involved installing and operating the wide angle seismic stations along the Swedish coast of the Sea of Bothnia (Fig. 4.1).

A system of up to four outstations linked by radio telemetry to a central recording station was employed to increase the coverage. Five such base stations (BS) were deployed in the low lying coastal regions while another ten outstations were set further inland at greater elevations to give line of sight between base station and outstation. Three component data were acquired at each base station whilst only the vertical component was measured at the outstations.

Each outstation consisted of a vertical seismometer, an amplifier modulator, a radio transmitter, an aerial and a 12-volt battery power supply. Most of the seismometers were positioned directly on bedrock which was found commonly outcropping in Sweden. In a few cases, a shallow pit had to be dug to reach the bedrock. At one station (2A, Fig. 4.1), solid bedrock could not be found and the seismometer was sited on loose, crumbly, weathered sedimentary rock. The amplifier modulator was placed near the seismometer and both were protected from the elements either with an upturned plastic bucket or with a wide piece of plastic piping covered by a sheet of plywood. The transmitter was strapped, inside a waterproof bag, to the aerial mast which was erected nearby.

The base stations required more hospitable conditions than the outstations and were therefore sited in various sheds and houses, or in the

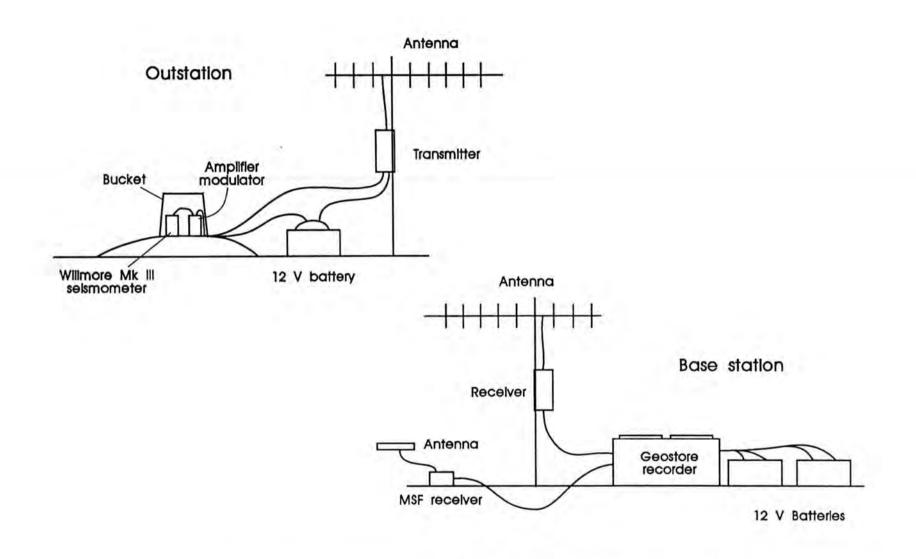


Fig. 4.7 Wide angle recording outstation - base station arrangement

case of BS3, in a tent. Each consisted of three seismometers (one vertical and two horizontal), a Geostore recorder, aerials and receivers, and an MSF radio time signal receiver. Power was supplied by two 12-volt batteries. The seismometers were installed as for the outstations. A schematic diagram of the outstation - base station arrangement is shown in Fig 4.7.

All the stations used Willmore Mk III variable period seismometers. These generate an E.M.F proportional to the ground velocity. The seismometers dominate the low frequency response characteristics of the acquisition system. This response is controlled by the resonant frequency and the damping. The frequency response curve is optimally flat at a damping of h = 0.7, where h is the ratio of damping to the critical damping. Fig. 4.8 shows the frequency response for the Willmore Mk III at three values of h. For BABEL, the seismometers had resonant frequencies of about 1.5 Hz and the damping was set at $h \sim 0.7$.

The amplifier modulator amplifies the seismometer output and converts it to an F.M. signal. The gain was set at 7 for all seismometers except those at BS5 where it was increased to 8. The UHF radio links between outstation and base station operated at frequencies ranging between 439.7 and 440 Mhz with a bandwidth of 25 kHz.

In addition to the Geostore stations, three component data were recorded digitally with two Geotech PDAS (Portable Data Acquisition System) instruments. One of these (BS3P) was located near BS3 for the duration of the experiment while the second was moved to record in-line data from both the northern end of Line 1 (station 101P) and the southern end of Line 6 (station BS5P).

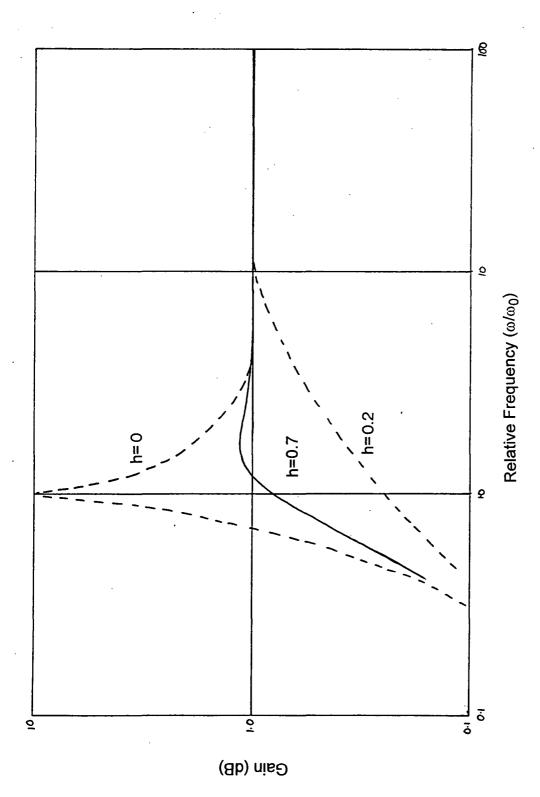


Fig. 4.8 Frequency response of the Willmore Mk III seismometer (resonant frequency $\omega_0 \approx 1.5~\text{Hz}$)

Station	Equipment	Component	Latitude	Longitude	Elevation (m)	Comments
101P	PDAS	x, y, z	63° 36' 45.6"	19° 58' 23.4"	0	In garage of a house
BS1	Geostore	x, y, z	63° 13' 29.4"	18° 57' 39.6"	35	Stubbsand, in cellar of a house
1A	Geostore	z	63° 22'28.2"	18° 42' 03.0"	180	Nr Klingre
BS2	Geostore	x, y, z	62° 36' 31.2"	17° 57' 55.8"	130	Härnön, in amateur radio shed
2A	Geostore	z	62° 52' 55.8"	18° 21' 42.6"	115	Kåstaänget, "shaky hill"
2B	Geostore	Z	62° 52' 37.8"	18° 02' 00.0"	135	Nr Milstabbana
2C/3A	Geostore	z	62° 24' 51.0"	17° 41' 33.6"	50	Nr Sörsidan, military training area
BS3P	PDAS	x, y, z	61° 44' 38.4"	16° 55' 27.0"	40	Nr Forsa, in house
BS3	Geostore	x, y, z	61° 41' 17.4"	17° 23' 48.6"	65	Nr Arnöviken, in a tent
3B	Geostore	z	62° 08' 16.2"	17° 05' 12.0"	330	Västansjökullen, military observation tower
3C	Geostore	z	61° 49' 04.8"	16° 24' 34.2"	245	Klotjärnsasen
3D	Geostore	z	61° 31' 11.4"	16° 53' 28.8"	245	Nr Storäsen
BS4	Geostore	x, y, z	60° 52' 25.2"	17° 17' 27.6"	20	Iggön, in farm shed
4A	Geostore	z	61° 12' 35.4"	16° 50' 19.8"	200	Nr Gullberg
4B	Geostore	z	60° 45' 09.6"	16° 30' 00.0"	290	Kungsberget
BS5P	PDAS	x, y, z	60° 18' 37.8"	18° 32' 16.8"	5	Rävsten
BS5	Geostore	x, y, z	60° 18' 42.0"	18° 36' 37.8"	10	Gräsö, old blacksmith's workshop
5A	Geostore	z	60° 15' 04.8"	18° 35' 55.2"	10	Nr Sundsveden

Table 4.3 Site locations of wide angle recording stations operated by Durham in Sweden

In total, these formed an array of 18 stations spanning a distance of over 500 km along the Swedish coast of the Sea of Bothnia. A summary of the site locations and station details is contained in Table 4.3. The coordinates are estimated to be accurate to ±100 m. This relatively high error estimate is due to the lack of significant landmarks on which to take compass bearings and the prevalence of dense forestation at many sites, obscuring the view.

4.3.2 Geostore recorder

The Geostore is an F.M. analogue recorder with 14 channels. Two of these are flutter tracks and a third records internally generated VELA time code. One of the remaining channels (channel 14) was used to record the MSF radio time signal from the Rugby transmitter, the reception of which varied from site to site and also with time of day. The data was recorded to ½ inch magnetic tape at a speed of 15/160 inches per second. This gave a bandwidth of 31.2 Hz whilst allowing a recording time of between two and three days per tape, essential for continuous recording given the distance between base stations and the time needed to travel between them. As an analogue system, no anti-alias filter was applied during acquisition or playback on a Store-14 tape deck. However, the signal was low pass filtered on demodulation to give a bandwidth dependent on the tape speed during recording. At 15/160 inches per second, the 3dB point was 31.2 Hz with a roll-off of 20 dB/octave (Fig. 4.9).

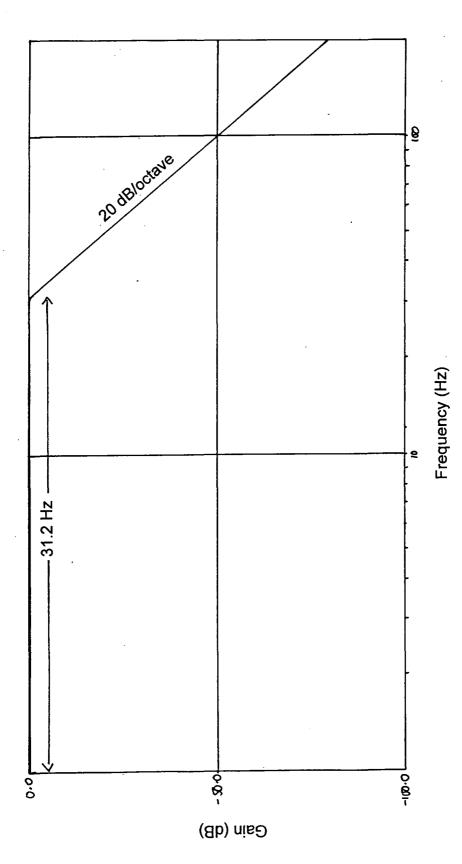


Fig. 4.9 Frequency response of the Store14 analogue demodulating filter.

4.3.3 PDAS recorder

The PDAS used a sample interval of 10 ms, chosen to give a bandwidth of 40 Hz whilst permitting a reasonable continuous recording length before the memory was full. Two anti-alias filter were applied to the data: a 6 pole (36 dB/octave) Butterworth analogue filter with a bandwidth of 200 Hz, and a sample rate - dependent digital filter. For the chosen sample rate, this had a flat frequency response up to 40 Hz with 372 dB/octave anti-aliasing filtering (Fig. 4.10). To obtain the maximum dynamic range for minimum memory consumption, data was stored in gainranged integer format, i.e. as 2 byte integers with a 14 bit mantissa and a 2 bit gain code. Since the PDAS only had a small memory capacity (1.6 Mbytes), the data had to be off-loaded to the hard disk of an IBM compatible laptop computer (Zenith or Toshiba) every 20 minutes. This operation took approximately 3 minutes each time during which no data could be recorded. The data on the hard disk were dumped to tape once an hour with no interruption to acquisition. Due to a technical hitch in the link between the PDAS, laptop computer and tape drive, no data were acquired from the southern third of Line 1 by the instrument at station 101P. PDAS internal clock time was written into the header at the start of each 20 minute data file. The MSF time signal was also recorded at each PDAS station.

4.3.4 Other stations

The stations at the southern end of Line 1 (F01A,B) on the island of Åland were operated by a group from the GEOMAR Institute in Kiel,

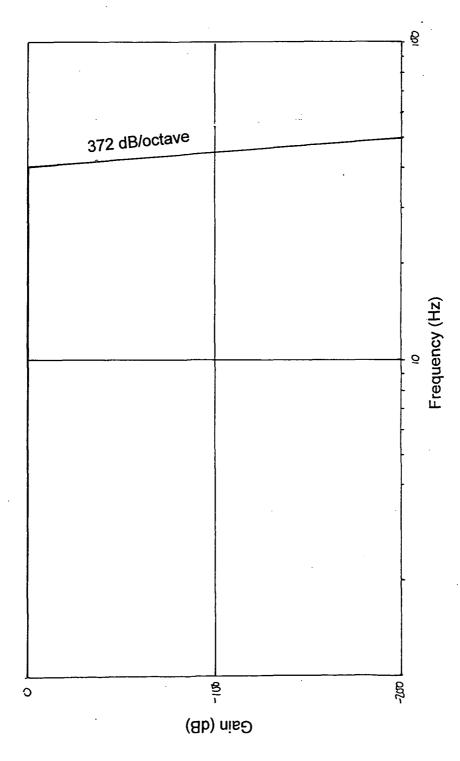


Fig. 4.10 Frequency response of the PDAS digital anti-alias filter.

Germany. Two types of geophones were used here: a three component instrument with a low frequency cut off of 2 Hz and a single, vertical component geophone, low cut 4.5 Hz. The vertical component geophones were grouped into linear arrays of six and crossed arrays of twelve, each geophone being cemented to the ground with gypsum plaster to improve coupling. Two 3-component geophones, five chains of six and one crossed array of twelve geophones were located around each of two sites (F01A and F01B) on the island (Table 4.4). An estimate of the error in the site coordinates is not available so the estimate for the Durham stations is assumed. The data were recorded with a sample interval of 5 ms using 4 and 8 channel PCM 5800 instruments.

Groups from Helsinki and Oulu Universities operated the stations in Finland, also using digital instruments. Table 4.5 shows the site locations and again the accuracy of these is not known. These data were not available in digital form for use in this study, although paper record sections were obtained.

Station	Equipment	Component	Latitude	Longitude	Elevation (m)	Comments	
F01A 114/1,3	PCM 5800	x, y, z	60° 23' 50.5"	19° 53' 51.0"	70	3-component Lippman geophone (2 Hz)	
4		Z	60° 23' 48.5"	19° 53' 55.0"	65	chain of 6 geophones (4.5 Hz), linearly spaced	
F01A 118/1,3	PCM 5800	x, y, z	60° 23' 51.0"	19° 53' 52.0"	70	3-component Lippman geophone (2 Hz)	
4		Z	60° 23' 50.5"	19° 53' 40.0"	75	2 chains of 6 geophones (4.5 Hz), crossed	
5		z	60° 23' 49.5"	19° 53' 27.0"	85	chain of 6 geophones (4.5 Hz), linearly spaced	
6		z	60° 23' 57.5"	19° 53' 35.0"	85	chain of 6 geophones (4.5 Hz), linearly spaced	
7		Z	60° 23' 58.5"	19° 53' 59.0"	55	chain of 6 geophones (4.5 Hz), linearly spaced	
8		Z	60° 23'54.0"	19° 53' 57.0"	60	chain of 6 geophones (4.5 Hz), linearly spaced	
F01B 124/1,3	PCM 5800	x, y, z	60° 19' 26.0"	19° 58' 26.0"	45	3-component Lippman geophone (2 Hz)	
4		z	60° 19' 22.5"	19° 58' 26.0"	55	chain of 6 geophones (4.5 Hz), linearly spaced	
F01B 128/1,3	PCM 5800	x, y, z	60° 19' 27.0"	19° 58' 16.0"	45	3-component Lippman geophone (2 Hz)	
4		z	60° 19' 29.0"	19° 58' 29.0"	40	2 chains of 6 geophones (4.5 Hz), crossed	
5		z	60° 19' 26.5"	19° 58' 08.0"	65	chain of 6 geophones (4.5 Hz), linearly spaced	
6		Z	60° 19' 21.0"	19° 58' 05.0"	60	chain of 6 geophones (4.5 Hz), linearly spaced	
7		z	60° 19' 02.0"	19° 58' 05.0"	65	chain of 6 geophones (4.5 Hz), linearly spaced	
8		z	60° 19' 39.5"	19° 58' 10.0"	55	chain of 6 geophones (4.5 Hz), linearly spaced	

Table 4.4 Site locations of wide angle recording stations operated by Kiel in Åland

Station	Latitude	Longitude	Elevation (m)
F2A	60° 50' 52.1"	21° 14' 48.6"	2
F2B	60° 51' 22.8"	21° 31' 29.0"	17
F03	61° 39' 03.2"	21° 35' 31.5"	5
F04	62° 26' 30.9"	21° 13' 32.2"	0
F05	63° 18' 52.4"	21° 10' 11.1"	5
F09	60° 59' 45.2"	22° 53' 47.8"	92
F10	62° 02' 44.2"	22° 53' 44.3"	165
S13	56° 07' 01.6"	15° 50' 15.0"	0
S04	55° 30' 01.3"	14° 14' 07.8"	0

Table 4.5 Site locations of wide angle recording stations operated by Helsinki and Oulu in Finland

5. Processing

5.1 Introduction

Data collected by the Durham group using the PDAS and Geostore equipment were processed entirely at Durham. Since very little software was available to us at the start of the project, most of the processing programs were written by the author, with some also by P. A. Matthews (Appendices 1-4). This software development comprised a major part of the project. The processing sequence is show in Fig. 5.1.

The data from station F01A which were acquired by the Geomar Institute, Kiel, were converted to SEGY format before being sent to Durham. The normal incidence data were processed initially by the contractors (Prakla Seismos) with further processing carried out by BIRPS and the Bullard Laboratories, Cambridge.

5.2 Wide Angle Processing

5.2.1 PDAS data: conversion to internal trace format (Stage 1)

Since the PDAS data were already in a digital format, these were the first to be processed. The raw data consisted of a series of 20 minute long files on DC 2000 magnetic tape cartridges, one MSF time code and three data channels being recorded in separate file sequences. Each file header, an example of which is given in Table 5.1, contains the start-of-file time as measured by the internal clock.

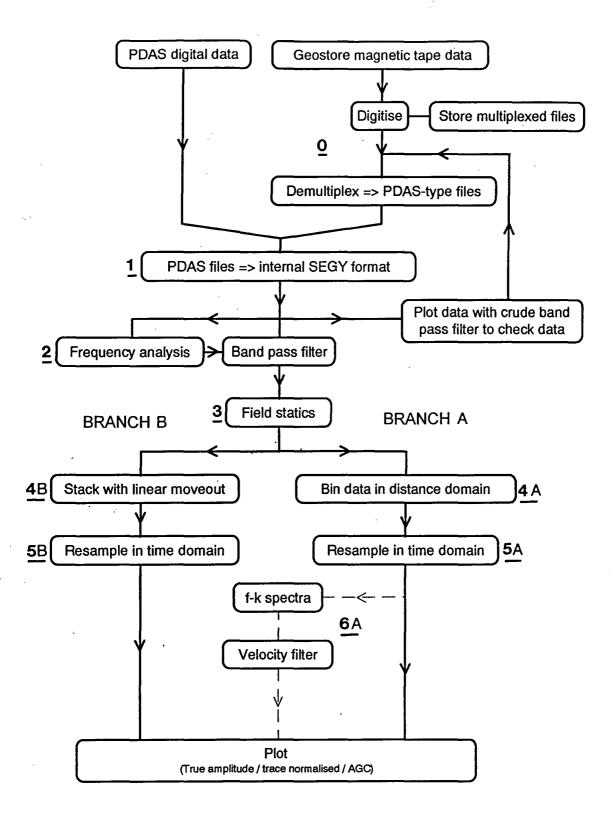
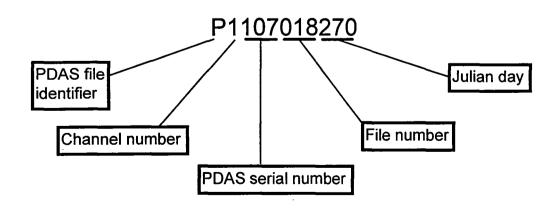


Fig. 5.1 Processing sequence for wide angle data

Table 5.1. a) PDAS file header specification

<u>Header</u>		<u>Description</u>
DATASET	P1107018270	File name
FILE_TYPE	LONG	Data type (integer=2 byte, long=4 byte)
VERSION	next	Set filename to next sequence number
SIGNAL	Z	Channel name
DATE	9-27-89	Date at start of file
TIME	13:22:56.50 (500)	Time at start of file
INTERVAL	0.010	Sample interval (seconds)
VERT_UNITS	Counts	Always counts
HORIZ_UNITS	Sec	Always seconds
COMMENT	GAINRANGED	Data type
DATA		Beginning of binary data

b) Breakdown of PDAS file name



CHAPTER 5: PROCESSING

Table 5.2 Internal SEGY specification

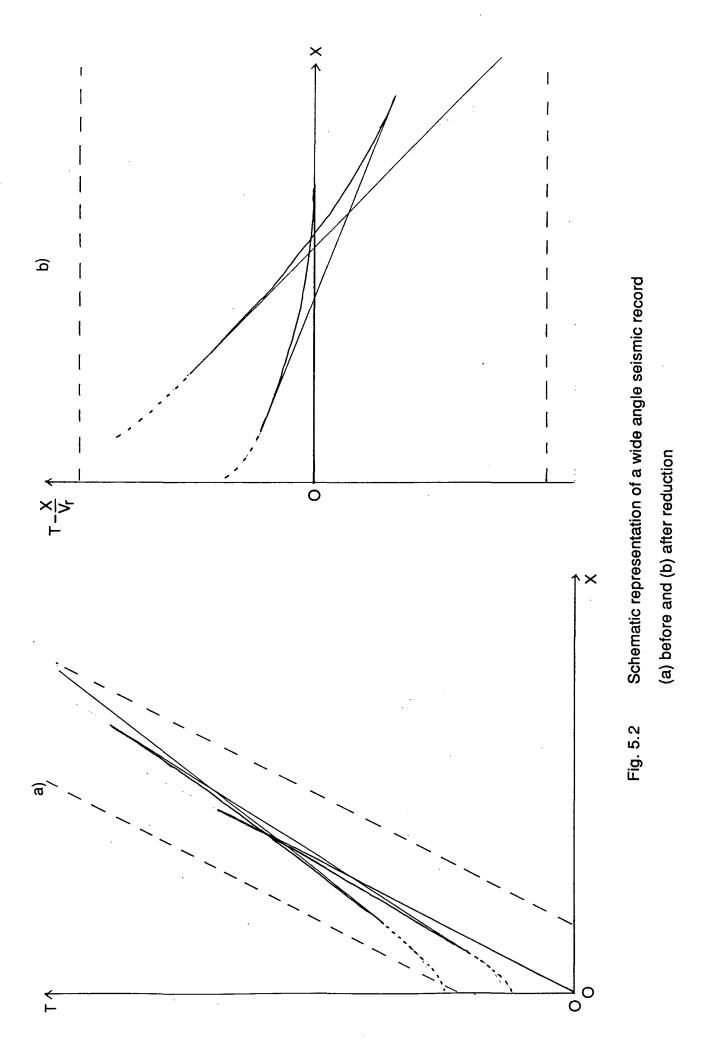
- a) ASCII file header (3200 bytes) project name, processing details, etc.
- b) Binary file header (4 byte integers) 400 bytes

1- 4	Number of trac	es per record				
5- 8	Number of non-seismic traces per record					
9- 12	Not used					
13- 16	Sample interva	Sample interval (s)				
17- 20	Not used	Not used				
21- 24	Number of san	Number of samples per data trace				
25- 52	Not used					
53- 56	Data format :	1=floating point (4 byte)				
	•	2=fixed point (4 byte)				
		3=fixed point (2 byte)				
		4=fixed point w/gain code (4byte)				
57-200	Not used					
201-204	Reel number for this line					
205-208	Line number					
209-212	Measurement s	Measurement system : 1=metres, 2=feet				
213-400	Not used					

Table 5.2 (continued)

c) Binary trace header - 512 bytes / record

	trace/ channel/ station number shot/ event number			
	trace identification code:	119-120	not used	
20 00	1=seismic data	121-122	instrument gair	n constant
	2=dead channel	123-140	not used	· oonotant
	3=dummy channel	141-142	alias filter frequ	iency
31- 36	not used	143-144	alias filter slope	
37-40	horizontal distance shot-		not used	-
00	receiver		low cut frequer	ncv
41- 44		151-152	not used	7
45- 48			low cut slope	
49- 52	source depth below surface			
53- 56	datum elevation at receiver	157-158	year	
57- 60	datum elevation at source	159-160	day	
	water depth at source	161-162	hour	time at start
65- 68	water depth at receiver	163-164		of trace
69- 70		165-166		
	values : positive - multiplier,	167-168	time basis : 1=	local, 2=UT
	negative - divisor	169-186	not used	
71- 72	scaler for 73-88 to give real	187-188	msec - time at	start of trace
	values : positive - multiplier,	189-190	not used (
	negative - divisor	191-192	year	
73- 76	source coordinate X (longitude,	193-194	day	
	positive to east)	195-196	hour	time of
77- 80	source coordinate Y(latitude,	197-198	minute	event
	positive to north)	199-200	sec	
	receiver coordinate X	201-202		
	receiver coordinate Y		not used	
89- 90		207-208		
04.400	2 = sec arc	000 040	and start of trac	ce (sec part)
91-108		209-210	not used	a. a1v
109-110	delay between shot instant	211-214	reduction veloc	city (km s ⁻¹)
	and start of trace (msec part)	215-216	reduced time a	t start of trace
	not used	217-220		
115-116	number of samples in this		four character :	
447 440	trace	225-228		cnannel code
117-118		229-512	not used	
	(μs)			



This was checked against Universal Time (U.T.) by viewing the MSF time code channel and calculating the actual start-of-file time to the nearest sample (10 ms) to give a time correction value. Comparing values from several different points along the line showed there to be no measurable drift in the internal clock so the time correction could be applied as a constant offset.

After degainranging, i.e. converting the data from 2 byte 14/2 gainranged format to 4 byte integers, the data were put into an internal trace format using software developed by P. A. Matthews (1993) (CONVERT, Appendix 4). This format, based on the SEGY system, was devised by D. L. Stevenson of Durham University. It consists of an ASCII file header, a binary file header and two direct access binary files, the first containing one data trace per record and the second containing one trace header for each data trace. Table 5.2 shows the content of the binary file and trace headers. This format will hereafter be referred to as ISEGY.

Data were read in from successive PDAS files and, based on the start-of-file time, clock correction and shot instant, 40 second traces were written out. To fit all the useful data into 40 seconds for the entire distance range and cut out most of the unwanted information prior to the first arrival, a reduced form was used in which the trace start time t_s is given by:

$$t_s = t_e + \frac{X}{V_r} - t_l$$

where t_e = event time (shot instant), X = shot-receiver distance, V_r = reduction velocity (6 km s⁻¹) and t_l = trace lead-in time (6 seconds). The shot-receiver distance was calculated from the shot and receiver coordinates, both of which were entered in the trace headers.

The effect of this transformation is that a first arrival with apparent velocity equal to V_r will occur 6 seconds into the trace, reducing the required trace length.

Time from the start of the trace is thus the reduced travel time T_{r} rather than the actual travel time, where

$$T_r = T - \frac{X}{V_r}$$

Plotting reduced travel time against offset allows the expansion of the time axis to reveal more detail (Fig. 5.2).

The conversion to ISEGY format was carried out on an IBM-compatible DELL PC under MS-DOS but since all subsequent processing would be done on UNIX-based SUN workstations, the output binary trace and header files were written in SUN binary format rather than IBM. Although the hard disk capacity of the DELL was over 300 Mbytes, the version of MS-DOS used required that this be partitioned into nine separate 'drives' of 32 Mbytes each, and one of 16 Mbytes. A whole line would not fit on a drive at one time so several files were produced for one line and transferred to the SUN workstation separately. The files were then combined into one using the COMBINE9 program, written by the author (see Appendix 1). This program simply reads in data from each fileset in turn and writes it out sequentially to a single new fileset.

5.2.2 Digitisation of Geostore magnetic tape data (Preliminary stage 0)

The analogue data recorded on magnetic tape by the Geostore recorders were played out using a Store-14 tape player at 80 times the

recording speed. The data were digitised via the DT2821 data acquisition board and Global Lab software package (Data Translation, Inc.) on the DELL PC. These were controlled by a series of batch files and macros devised by Dr R. E. Long and extensively tested by the author.

Multiplexed digital data were acquired onto seven of the 32 Mbyte disk drives in turn. To keep the process reasonably fast and the data length acquired in one go large, only the internal time code and two data channels were read at one time.

Although no anti-alias filter was applied prior to digitisation, demodulation of the F.M. signal by the Store-14 playback system introduced a low pass filter with a bandwidth of 31.2 Hz and a slow 20dB/octave roll-off (see Chapter 4). A nominal sample interval of 5 ms was chosen in order to utilise this as an anti-alias filter, giving 45 dB of alias protection at the Nyquist frequency (100 Hz). At a sample interval of 5 ms, 12000 seconds of data from each channel could be stored on each disk drive so the whole of Line 1 fitted onto 13 such drives. The multiplexed data were copied to the Sun workstations for storage.

The data were demultiplexed into files similar to those produced by the PDAS equipment (not gainranged) so that they could be dealt with by the same software. The multiplexed internal time code data were read and automatically decoded with routines written by Dr R. E. Long so that a PDAS file could be written for every three minutes of data. The start of file time and mean sample interval over the length of the file was written into the header. Since the real time digitising frequency was constant, slight fluctuations in the tape speed caused variations in the data sample interval which was therefore not necessarily equal to the specified value of 5 ms. The mean sample interval for each 3 minute file was found by dividing 180

seconds by the number of samples in the file. Each drive was demultiplexed to the one free drive in turn and the ISEGY trace data written back over the multiplexed data on the original drive.

The internal and MSF time codes were compared independently at intervals along each tape reel by acquiring a short length of data from both channels and decoding the internal clock code at the same position as the first MSF minute marker. This gave an idea of the drift on the internal clock and a clock correction value for each tape reel.

Due to the variation in sampling rate over the whole dataset, the length in time of each trace produced after running through the PDAS_ISEGY software (Stage 1) was slightly different, although the number of samples per trace was necessarily constant.

After conversion to ISEGY format, the separate filesets for each channel (one from each drive of multiplexed data originally acquired from tape) were combined to give one fileset per channel per line using the program COMBINE9, as for the PDAS data. The data were plotted out with a crude boxcar band pass filter (4 - 25 Hz) to check for obvious timing errors (e.g. a step-out in the first arrival) and lost or corrupted data.

5.2.3 Frequency Analysis and Filtering (Stage 2)

5.2.3 a) Analysis

Firstly, any D.C. component in the data was removed using the program RMDC (see Appendix 1). The frequency content of a number of traces was then found by taking the amplitude spectrum of the Fourier transform (Fig. 5.3).

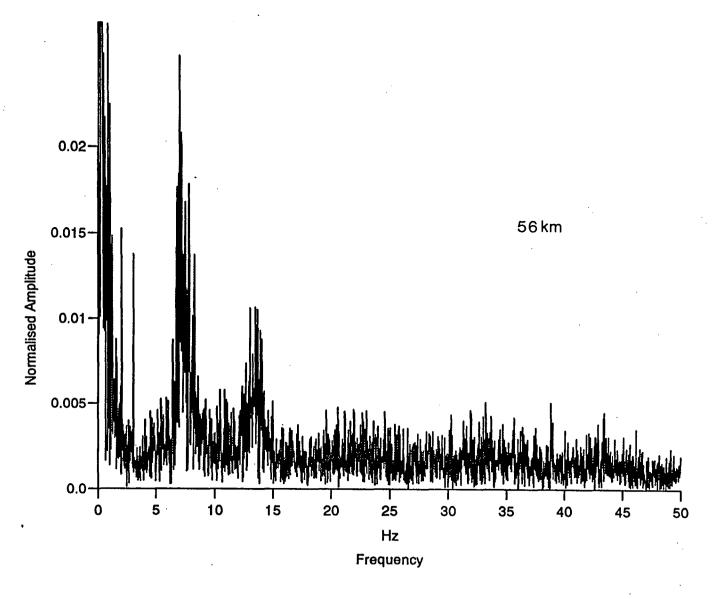


Fig. 5.3 Frequency amplitude spectrum of a single trace from station 1A.

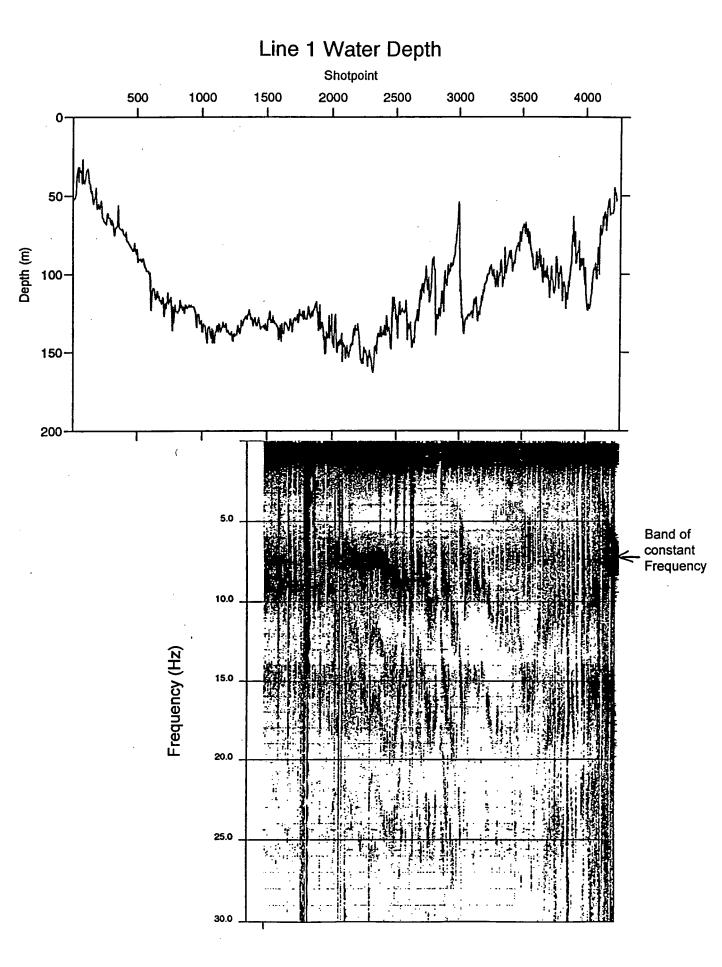


Fig. 5.4 a) Station 101P frequency amplitude spectrum vs. shotpoint



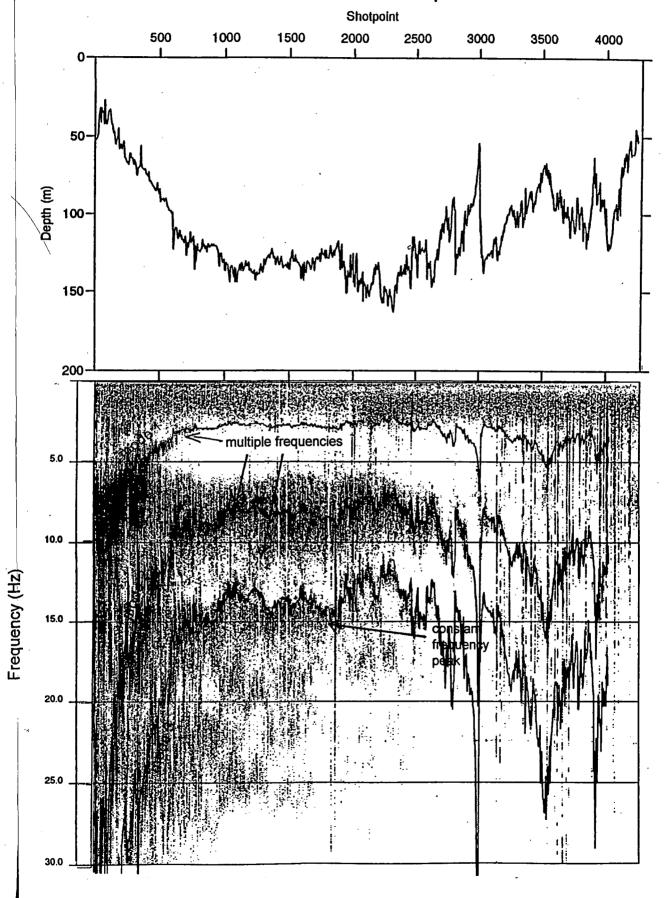


Fig. 5.4 b) Station F01A frequency amplitude spectrum vs. shotpoint

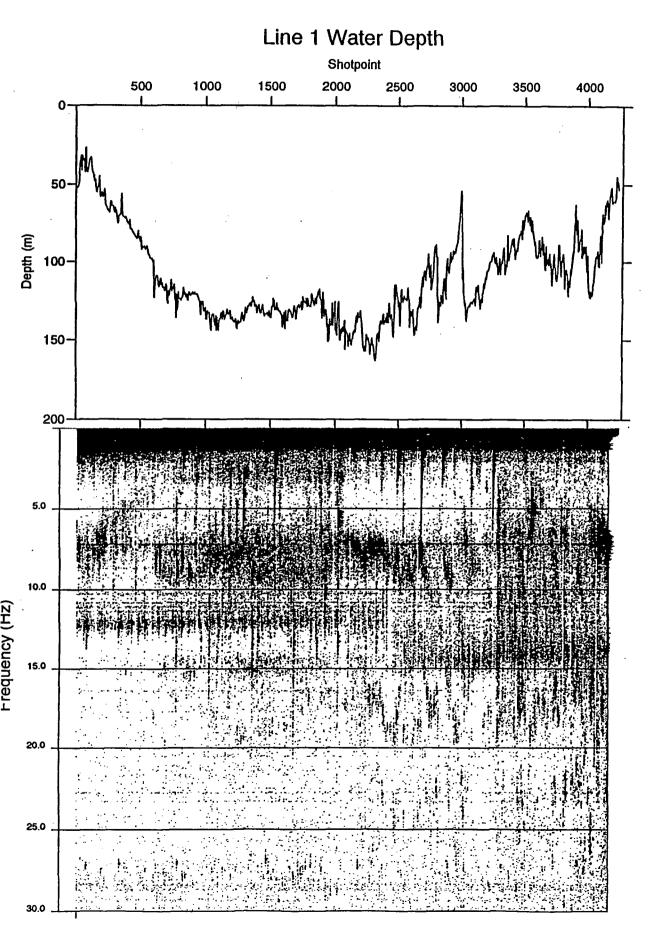


Fig. 5.4 c) Station 1A frequency amplitude spectrum vs. shotpoint

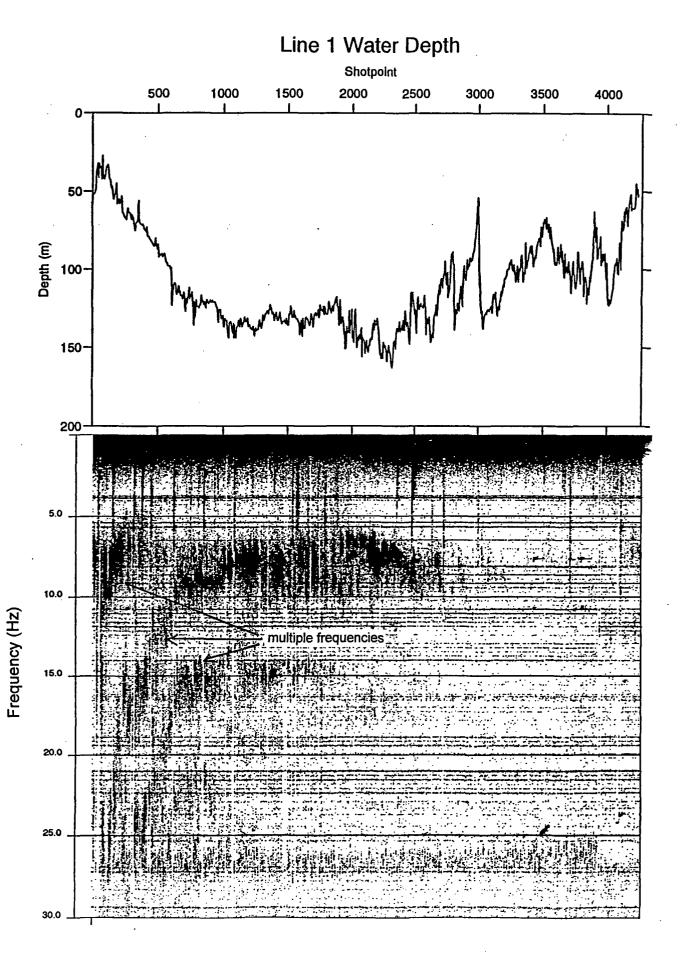


Fig. 5.4 d) Station 5A frequency amplitude spectrum vs. shotpoint

To determine the presence of water layer multiples, a correlation between frequency content and water depth was looked for. To do this, the frequency amplitude spectrum was taken for every tenth trace along the line using the program F-T (see Appendix 1). These were plotted as variable area traces against shotpoint. The water depth as determined from the survey ship for each shotpoint was extracted from the trace headers (program WATERD, Appendix 1) and also plotted on the same distance scale (Fig. 5.4).

Finally, a number of test panels were filtered using a range of band pass frequency windows in order to find the range of frequencies which would optimise the record section clarity. The program PANEL (see Appendix 1) was written by the author for this purpose. An example of this is shown in Fig. 5.5.

5.2.3 b) Frequency content of the data

In many of the individual amplitude spectra there were three large peaks (Fig. 5.3). The first and largest of these between 0 and 2.5 Hz could be ascribed to low frequency microseismic noise (e.g. from tree motion and waves on the shore), obviously incoherent from an unfiltered record section (Fig 5.6). This noise does not appear strongly on data from station F01A due to the low frequency response of the geophones used there (low frequency cutoff ~ 4.5 Hz)

The cause of the other two peaks, however, was not so obvious. It is clear that for some of the data, especially for stations F01A and 5A (Figs. 5.4b and 5.4d), there is a strong correlation between the variation of peak frequency and water depth with offset.

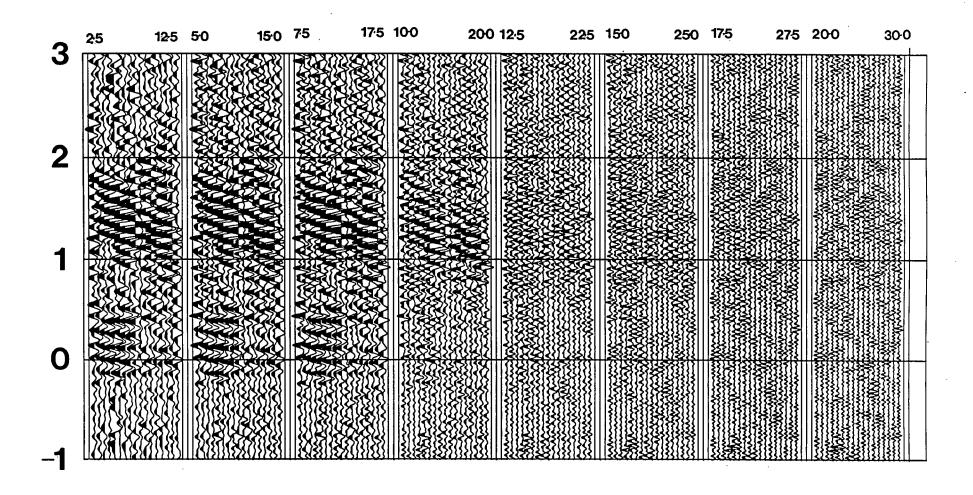
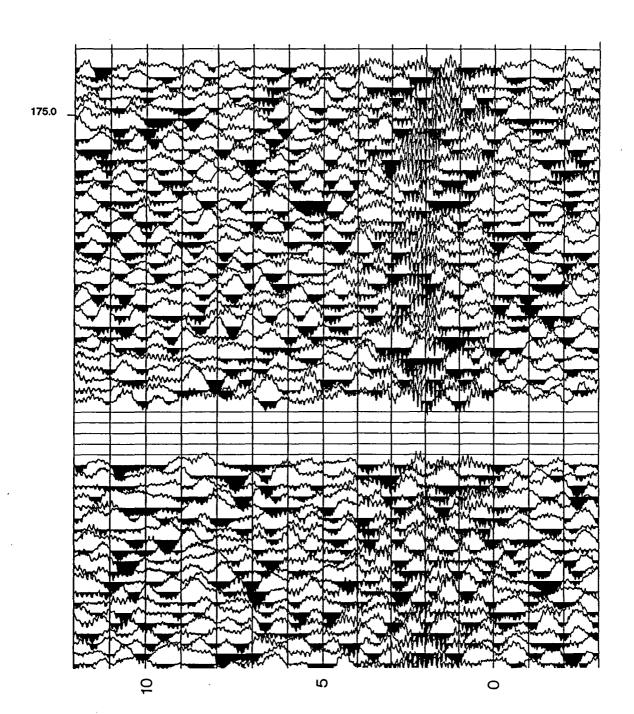


Fig. 5.5 A small panel of traces from station 5A, distance 120 km, band pass filtered with different windows

Example of raw data from station 101P



reduced travel time $T - \frac{X}{6}$ (s)

Using the formula

$$n^{th} \text{ multiple frequency = } \begin{array}{c} (2n - 1) \times V_w \\ \hline 4h \end{array} \text{ where } \begin{array}{c} h = \text{ water depth} \\ V_w = \text{ water vel.} \end{array}$$

it can be shown that two of the varying peaks in Fig. 5.4b are the second and third water layer multiples (see overlay). The first can be seen at the far left-hand edge of the figure, the rest of it merging with the low frequency noise.

In addition to these variable frequency peaks, bands of relatively constant frequency can be seen (Figs 5.4 a,b and c). Two prominent ones can be seen on Fig. 5.4c (station 1A) at frequencies around 12 and 14 Hz. These may be caused by multiples in layers beneath the receiver of around 200 - 250 m thickness. Although no reflections from such layers are directly observed in the wide angle dataset, indications of sill-like features in the upper crust are seen in the normal incidence data (see Chapter 6, section 2).

The major frequency content of the data appears to lie in the range 5 to 20 Hz. This was confirmed by the band pass filtered data panels (Fig. 5.5), with no coherency being observed above around 20 Hz. Although the far field source signature (Fig. 4.6) has a relatively flat frequency spectrum up to around 75 Hz, the high frequency energy is cut out by the demodulating and anti-alias filters. Even so, little of the mid-range frequency energy between 20 Hz and 40 Hz reaches the land based receivers. Significant tuning seems to be occurring at low frequencies through water layer multiples.

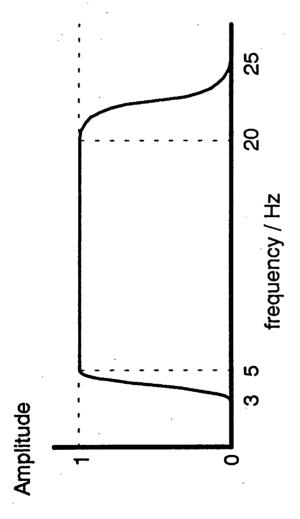


Fig. 5.7 Hanning band pass filter window used to filter all the data.

5.2.3 c) Band pass frequency filter

All the data were band pass frequency filtered using a Hanning window with parameters based on the conclusions reached in the frequency analysis, i.e. all frequencies outside the range 5 - 20 Hz were to be removed. The design of the filter is shown in Fig. 5.7. The actual 3dB points are 4 and 22 Hz, giving a little leeway at either end. The filter was applied with the program BPFILT written by the author (Appendix 1).

5.2.4 Field statics (Stage 3)

A field static correction was made to each trace reducing both the shotpoints and receiver location to a datum in an attempt to remove the effects of the water layer on primary (non water layer multiple) arrivals. The program used for this was STATICS (see Appendix 1), written by the author. The water depth measured by the survey ship for each shotpoint varied between 30 and 160 m with an average of 110 m. The source point datum was taken at a depth of 170 m beneath the surface. Since the source was towed at a depth of 15 m, this also had to be taken into account. The receiver datum was taken at sea level.

In order to calculate the static correction, i.e. the *delay time*, it was necessary to estimate the velocity of the media above and below the datum. A water velocity of 1.45 km s⁻¹, a sea bed rock velocity of 4.8 km s⁻¹ and a near surface land bedrock velocity of 5.8 km s⁻¹ were assumed. The delay time calculation is dependent on the ray parameter *p* and is therefore different for arrivals of different apparent velocity. To apply a single correction value to each data trace, a certain value for the ray

parameter had to be assumed. The ray parameter chosen was based on an arrival with apparent velocity 6.5 km s⁻¹(= $^{1}/_{p}$). This is approximately the mean apparent velocity of crustal diving rays estimated from the data sections. The formula used for calculation of the source static correction is as follows:

$$Ts_{source} = p \times \frac{(water \, depth \, - \, source \, depth) \times \sqrt{\frac{1}{p^2} - V_{water}^2}}{V_{water}}$$

$$(receiver \, elevation \, - \, receiver \, datum) \times \sqrt{\frac{1}{p^2} - V_{seabedrock}^2}$$

$$+p \times \frac{V_{seabedrock}}{V_{seabedrock}}$$

That used at the receiver is:

$$Ts_{receiver} = p \times \frac{(receiver\ elevation\ -\ receiver\ datum) \times \sqrt{\frac{1}{p^2} - V_{bedrock}^2}}{V_{bedrock}}$$

The maximum source static correction applied was 0.1 seconds while the largest receiver correction used in this study (constant for each station) was 0.02 seconds for station 1A.

5.2.5 Processing Branch A

At this point, the processing sequence forked into two separate branches (Fig. 5.1), the first leading towards velocity filtering in f-k space.

5.2.5 a) Binning data (Stage 4A)

Line 1 was shot in three parts with a small overlap at each end so that at these overlaps, the data density was doubled. For the off-line stations, trace spacing at the shortest offsets also became very small. In order that processing requiring a constant trace spacing such as f-k analysis and velocity filtering could be carried out, the data were binned. Binning was chosen over spatial resampling as the latter is far heavier on computer resources and gives less reliable results with a wide angle dataset. The program used for this was TRACEBIN, written by the author (see Appendix 1).

Within each line segment, the trace spacing was relatively constant for the in-line stations. A bin width of 75 m was therefore used to preserve density of data. For most of the line, this meant that only one trace fell into each bin interval. The distance error introduced by this was too small (max. ±37.5 m) to produce scatter (i.e. timing errors · 1 sample) in arrivals with apparent velocities in the range 4.3 to 10.0 km s⁻¹ for data with a sample interval of 5 ms, and 3.3 to 30.0 km s⁻¹ for a sample interval of 10 ms. All the arrivals of interest on the section lie within the narrower of these ranges.

5.2.5 b) Resampling in time domain (Stage 5A)

Having band pass filtered and binned the data, resampling was carried out in order to regularise the sample rate for the Geostore data (see section 5.2.2), and reduce it to the minimum necessary to preserve the frequency content without aliasing. Since, after band pass filtering, the

data contained no signal with frequency greater than 25 Hz, the new sample rate was set at 50 samples per second (sample interval = 20 ms). This had the effect of decreasing the volume of data by one half for the PDAS data and three quarters for the Geostore data, making it easier to handle and also allowing much faster plotting. The program, written by the author, to perform the resampling was called EXTR (see Appendix 1).

5.2.5 c) F-K spectra and velocity filtering (Stage 6A)

A 2-D Fast Fourier Transform was applied to a 512 x 512 square array of data in order to examine its f-k amplitude spectrum, using the program F-K, written by the author (see Appendix 1). At a sample rate of 50 samples / second and trace separation of 75 m, the window dimensions were 10.24 seconds x 38.4 km. Since the data was already reduced at 6 km s⁻¹, all the P-wave arrivals within the distance range could be included in the time window. At near offsets, S-wave arrivals also appear on the spectra. An example is shown later, in Fig. 6.5a.

The effect of reduction on the f-k plot is to cause arrivals with apparent velocity equal to the reduction velocity (6 km s⁻¹ in this case) to lie along the vertical axis. Fig. 5.8 shows some apparent velocities as they would appear on the reduced f-k plot.

In an attempt to remove the high amplitude S-wave arrivals which at short offsets interfered with sub-critical reflection phases, a pie-slice filter was applied to a window of data from station 101P in the f-k domain. A pie-slice filter with cosine taper was chosen as it would cut out all data outside a given velocity range and was easy to define and apply. The filter was applied to the real and imaginary parts of the 2-D Fourier transform in order

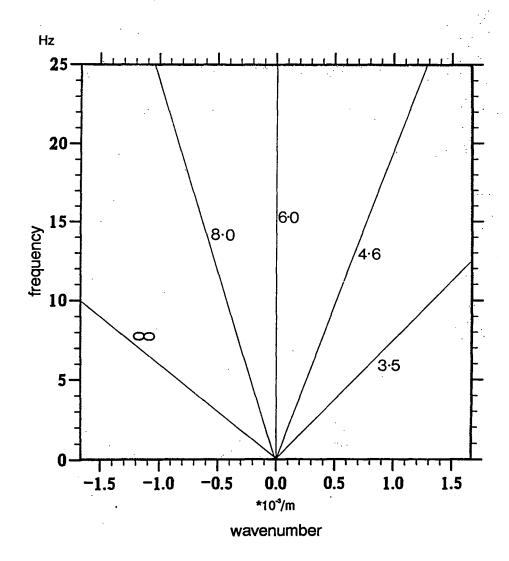
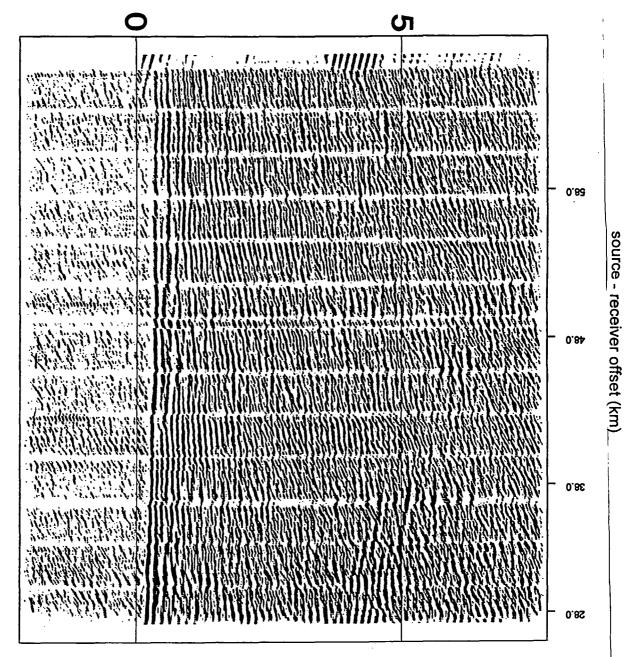


Fig. 5.8 Some examples of apparent velocities on an f-k spectrum of data reduced at 6 km s⁻¹

reduced travel time $T - \frac{X}{6}$ (s)

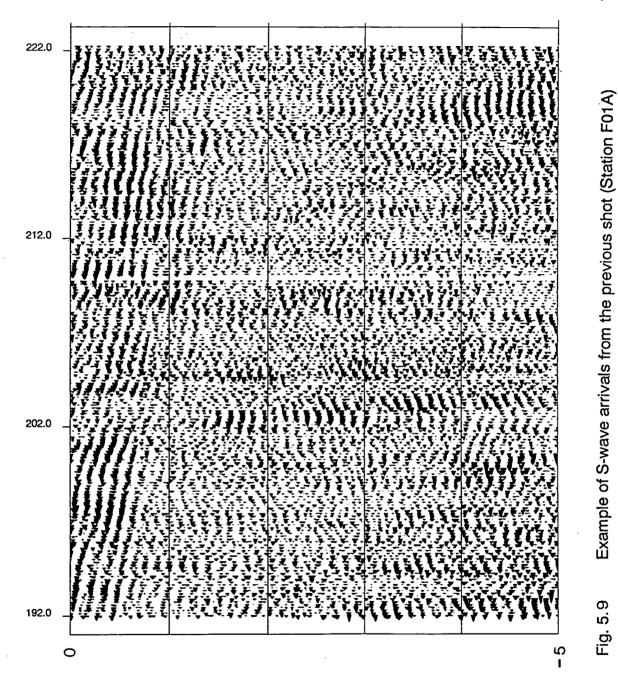


to filter out all arrivals with apparent velocities below 4.5 km s⁻¹ whilst retaining virtually all the higher velocity arrivals. The results of this are shown in Chapter 6 (Figs. 6.4 and 6.5).

An attempt was also made to filter out the S-wave arrivals from the previous shot which interfered with the P-wave arrivals between offsets 170 and 320 km. Four adjacent windows were required to cover this distance range. A pie-slice filter was again applied to each window, chosen to filter out all arrivals with apparent velocity below 5.0 km s⁻¹. The f-k spectra and results of velocity filtering for station F01A are shown in Chapter 6 (Figs. 6.9, 6.10 and 6.11). The success of this filtering was limited as much of the noise was smeared out at the cutoff velocity rather than being removed. This could be due to the steepness of the taper and also to the fact that, due to small timing differences between shots, the arrivals from the previous shot were in short, broken segments rather than continuous (Fig 5.9). Such broken segments introduce step functions in the x domain of the data which produce side lobes or 'ringing' in the wavenumber domain. If these side lobes are then filtered out, the result is ringing in the x domain. A filter in f-k space in which the cut off taper is too steep has a similar effect of producing side lobes in the data in x-t space after the inverse Fourier transform.

5.2.6 Processing Branch B: Stacking with linear moveout (Stage 4B)

As an alternative to binning and f-k filtering, a five-trace rolling stack with *linear moveout* was applied to the data in an attempt to enhance arrivals of a given velocity. The program used for this was STACK, written by the author (see Appendix 1). In stacking with linear moveout, a



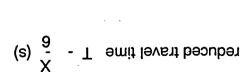
reduced travel time T - T (s)

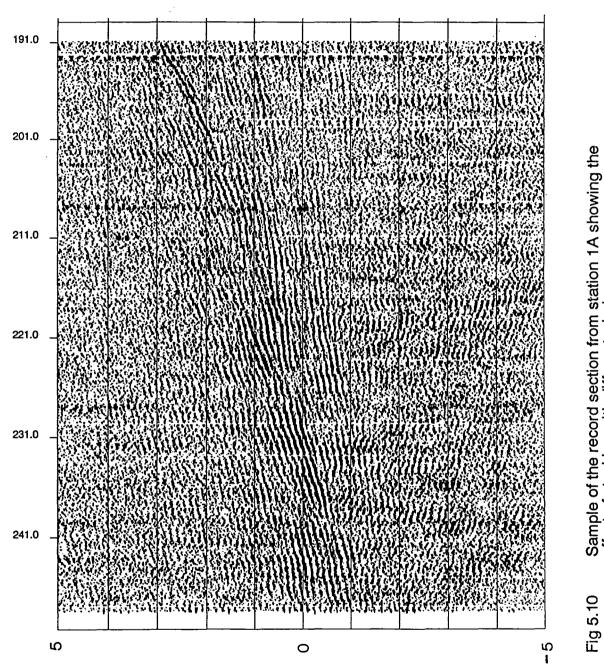
correction is applied to each trace within the window before stacking. The correction varies linearly with offset from the window origin. This is equivalent to re-reducing the data within the window at the selected velocity before stacking (see section 5.2.2). The velocity chosen was 6.5 km s⁻¹, approximately the mean crustal velocity as estimated from the record sections. Due to the short width of the stack window, the range of velocities stacked coherently was large enough to cover all the crustal diving rays. Smaller windows were found to be ineffectual while larger ones tended to distort the data beyond usefulness (Fig. 5.10). After stacking, this data was also resampled in time as for the binned data (section 5.2.5b).

5.2.7 Plotting

The data was plotted with a program initially written by C. Prescott at Durham University, modified and adapted by C. Peirce (DAZZLE, Appendix 4), which uses the UNIRAS graphics library. In general, true relative amplitude sections were plotted, the whole dataset being scaled according to an estimate of the mean amplitude on the section. However, in the data from the southern end of Line 1, the amplitude dropped off severely at large offsets so trace-normalised sections were plotted in which all the traces were scaled individually so that the maximum amplitude in each trace was constant across the section. In addition, sections with an a.g.c. applied were plotted in order to bring out weaker arrivals. However, since an a.g.c window of 100 ms was used, weak arrivals closer than this to strong ones were suppressed.

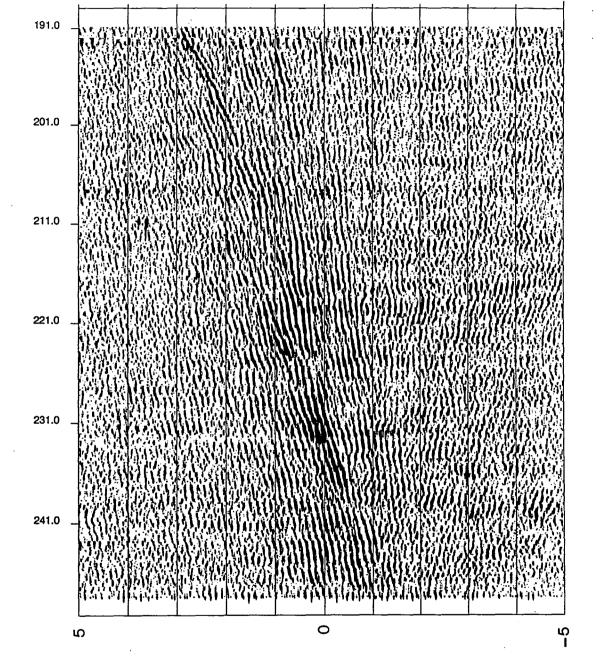
For interpretation purposes, the data were plotted as wiggle traces with positive variable area fill. Twenty seconds of data were plotted on a 24



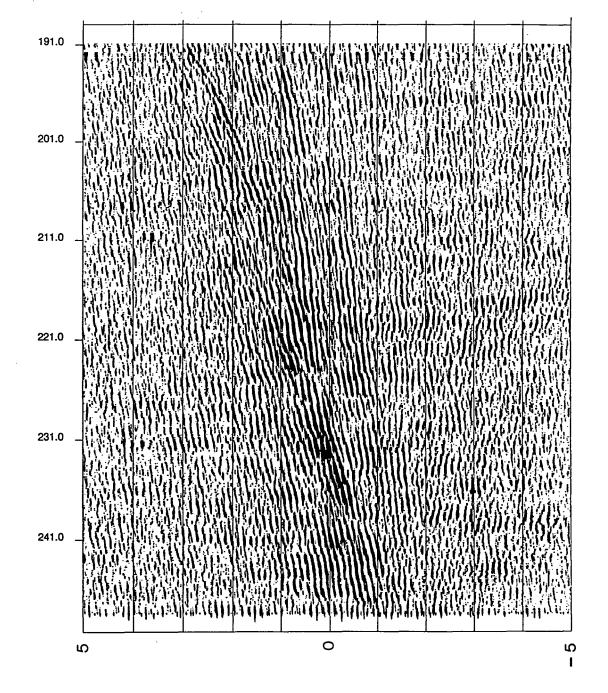


Sample of the record section from station 1A showing the effect of stacking with different windows:

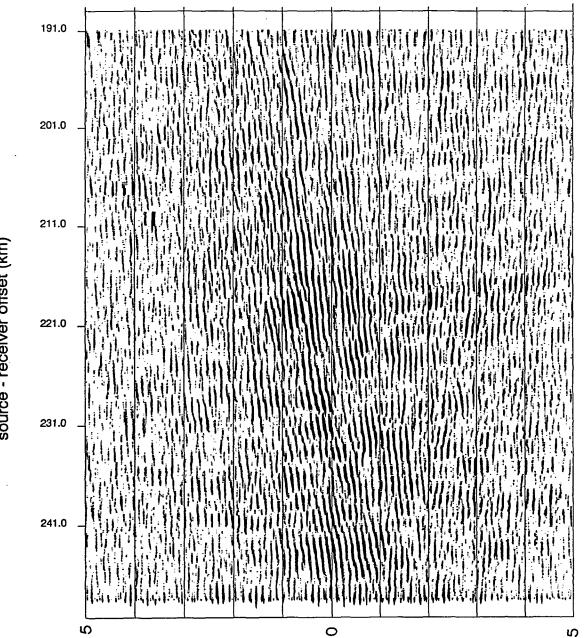
a) no stacking



reduced travel time $T - \frac{X}{6}$ (s)



reduced travel time $T - \frac{X}{\delta}$ (s)



(s) $\frac{x}{9}$ - T emit levert becuber

inch electrostatic Versatec plotter with a distance scale of 150 m/mm. For smaller plots, the wiggle traces became so densely spaced that they obscured the data so only the variable area was used. For A4 sized plots, every 5th trace was plotted for similar reasons, with a distance scale of 1600 m/mm. The software allowed the overall amplitude scaling, threshold level and high cutoff to be controlled so that low amplitude noise could be cut out. These parameters were adjusted on a trial and error basis to give the clearest plot.

5.3 Normal Incidence Data

All the normal incidence processing was done by the contractors PRAKLA SEISMOS and BIRPS. The processing sequence shown in Table 5.3 is taken from the information panel of the final stacked paper sections of the normal incidence data sent to Durham by BIRPS. These sections were too large to handle easily, with a distance scale of 50 m/mm so a much smaller plot with an a.g.c. applied, also acquired from BIRPS, was used to get a better impression of the overall pattern of reflectors. The digital data was also acquired from BIRPS and plotted at a similar scale with true relative amplitude.



CHAPTER 5: PROCESSING

Table 5.3 Normal Incidence processing sequence: Final Stack

- 1. INPUT: TAPE FORMAT SEG-D, 9-TRACK, 6250 BPI SAMPLE RATE 4 MS. 60 TRACES
- 2. S.O.D. CORRECTION -41 MS
- 3. FREQUENCY FILTER 5-48 HZ, SLOPE 24 DB/OCT
- 4. EDITING
- 5. RESAMPLING 4 MS TO 8 MS
- 6. AMPLITUDE CORRECTION FOR SPHERICAL DIVERGENCE
- 7. WHOLE TRACE EQUALIZATION, GATE: 3000 17000 MS
- 8. RECEIVER ARRAY SIMULATION BY MIXING IN COMM.-SOURCE DOMAIN

TIME VARIANT NO MIX:TO 0.5 S; FULL MIX:4 S - END (1.2.4.2.1)

9. DECONVOLUTION:

FIRST GATE / SECOND GATE DESIGN:

ON SHOTNEAR TRACE: 500 - 6000 MS / 6000 - 14000 MS

ON SHOTFAR TRACE: 3000 - 6000 MS / 6000 - 14000 MS

APPLICATION: 0 - 5000 MS / 7000 - END

OPERATOR LENGTH: 392 MS / 528 MS

PREDICTION INTERVALS: 32 MS / 48 MS

PREWHITENING FACTOR 1%

- 10. NMO CORRECTIONS
- 11. MUTING
- 12 HORIZONTAL STACKING 2400 %
- 13. SHOT AND STREAMER CORRECTION 15 MS
- 14. FK FILTER: TYP: PASS; POLYGONAL (2.5 - 50 HZ, +/- 60% WAVENUMBER, +/- 18 MS/TRACE)
- 15. DECONVOLUTION:

APPLICATION:

FIRST GATE / SECOND GATE

500 - 6000 MS / 6000 - 14000 MS DESIGN:

0 - 5000 MS / 7000 - END OPERATOR LENGTH: 392 MS / 528 MS

PREDICTION INTERVALS: 32 MS / 48 MS

PREWHITENING FACTOR 1%

16. TV FREQUENCY FILTER: 10/24 -40 /24 HZ/ DB/OCT AT 3S

5/24 -20 /24 HZ/ DB/OCT AT 20S

6. Data

6.1 Wide Angle Data

6.1.1 Introduction

As stated in chapter 5, all the data shown here are plotted as variable area with no wiggle. A distance scale of 1600m/mm (1:1600000) was chosen so that each data section would fit on one A4 sheet. Much larger plots (1:400000 and 1:150000) were used for interpretation and four of these have been included in Appendix 5. Distances are measured from the receiver and the sections are plotted from south to north, left to right. All the data shown are the vertical component.

True relative amplitude sections were produced for all the datasets considered. In some cases the amplitude fell off so markedly with distance that little could be seen at the greater offsets without completely saturating the near offset traces. For these datasets normalised sections were also produced in which the peak amplitude in each trace was normalised to a constant value.

In picking arrivals on the section, as little initial interpretation of individual arrivals was done as possible so that preconceptions would not be carried over into the modelling process. An attempt was made to ignore multiples of both long- and short-period. These were identified as arrivals of similar shape and character to phases appearing earlier in the section. The short period multiples appeared to have frequencies similar to those expected for mode 2 water layer multiples (see Chapter 5, section 2.3b),

i.e. around 7 Hz. The longer period multiples, observed mainly at shorter offsets, had periods of a few seconds. Some of these are pointed out in the data sections in Appendix 5.

Emphasis was put on picking first arrivals and high amplitude later arrivals although a number of low amplitude phases were also identified by virtue of their coherency over short distances alone. No attempt was made to join together isolated arrivals with a continuous curve if intervening phases could not be seen.

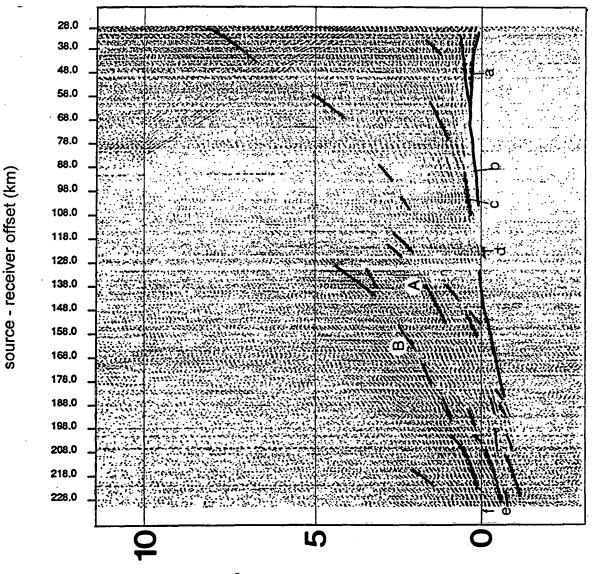
6.1.2 Station 101P

Comparing the binned and stacked sections for this station (Figs 6.1 and 6.2), the stacking process has reduced the prominence of the white vertical stripes (caused by loss of data whilst off loading from the PDAS to lap-top computer in the field - see chapter 4) by smearing data across them. This smearing effect makes individual P-wave arrivals, especially the first arrivals, easier to see and pick but also has a tendency to delocalise and obscure the major packets of energy. Although this could be minimised by using a smaller stacking window, smaller windows were found to have little beneficial effect either. The window chosen was a compromise between enhancing the P-wave arrivals and delocalising the energy.

The near offset first arrival obviously has an apparent velocity of just below 6 km s⁻¹ (a). This increases to 6 km s⁻¹ at 50 km and remains roughly constant to 80 km where it peters out and is overtaken by an upwardly concave arrival (b). This can be traced back to the nearest offset traces where its amplitude becomes much lower. A much stronger arrival lies directly behind it (c), also upwardly concave but with an odd kink at



Fig. 6.1



reduced travel time $T - \tilde{\delta}$ (s)

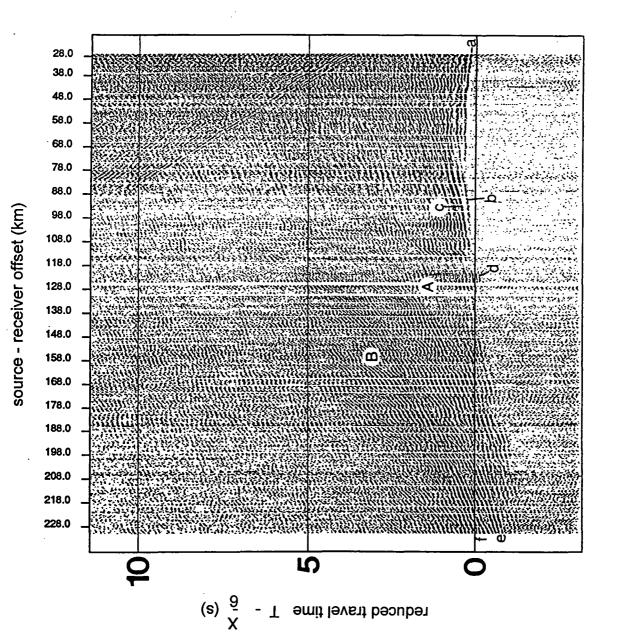


Fig. 6.2 BABEL Line 1, Station 101P: stacked dataset, true relative

about 85 km. This arrival appears to have higher curvature than earlier ones at near offset and takes over as first arrival at about 110 km. At about this offset all the arrivals steepen abruptly for a short distance. The corresponding shotpoints are directly above the Strömmingsbåden scarp system (Fig. 2.9). The arrivals do not have the characteristic hyperbolic shape of a diffraction and the effect seems to occur over the whole duration of the section. It is therefore thought to be a near surface effect associated with the scarp system, probably an incorrect removal of statics. Beyond this, between 120 and 130 km, an anomalously early first arrival is seen (d). At longer offsets, the first arrival increases in apparent velocity while generally decreasing in amplitude, fading out at 220 km.

Most of the energy at offsets beyond 120 km lies in two packets of arrivals, marked A and B in Fig. 6.1. The first (A) is prominent between 120 and 180 km. The general trend of the energy has higher curvature than one would expect of a reflection from a plane horizontal boundary. However, individual arrivals within it do not all run parallel to the trend of the energy packet or to each other, some having lower apparent velocities, others higher, but significant amplitude only within the region of the energy packet described.

The same is true to an even greater extent of the later energy packet (B) between 120 km and the farther end of the section. A number of individual branches can be made out and at the longest offsets, two major arrivals can be seen running parallel to each other about 0.5 s apart (e), (f). The earlier of these is not seen closer than 180 km from the station. A lower curvature, lower amplitude arrival can be traced out nearer than the upward turn of the major energy packet. This type of forking is also seen elsewhere within both energy packets.

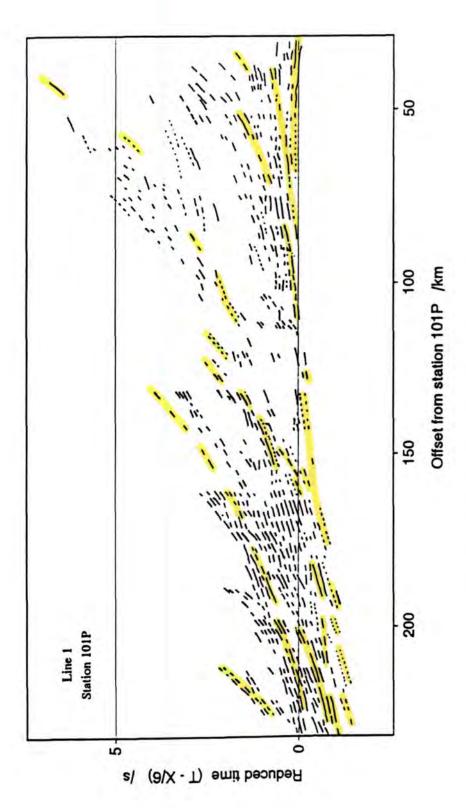
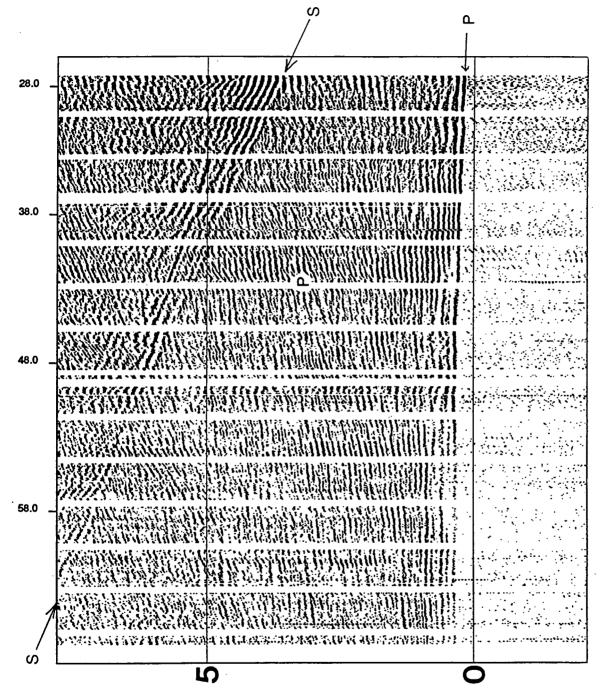


Fig. 6.3 BABEL Line 1, Station 101P: line drawing

BABEL Line 1, Station 101P: near offset data

Fig. 6.4



reduced travel time T - T emit leavest teaver

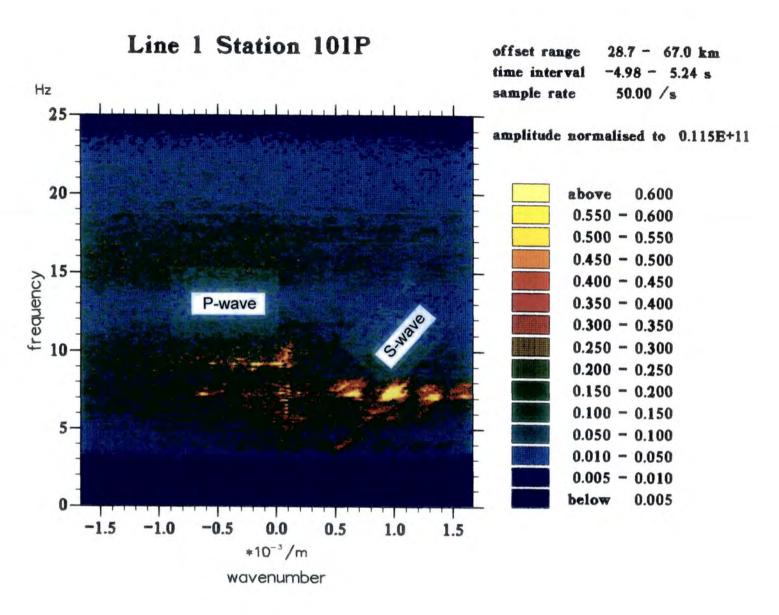


Fig. 6.5 a) BABEL Line 1, Station 101P: f-k spectra for the data shown in Fig. 6.4 before velocity filter

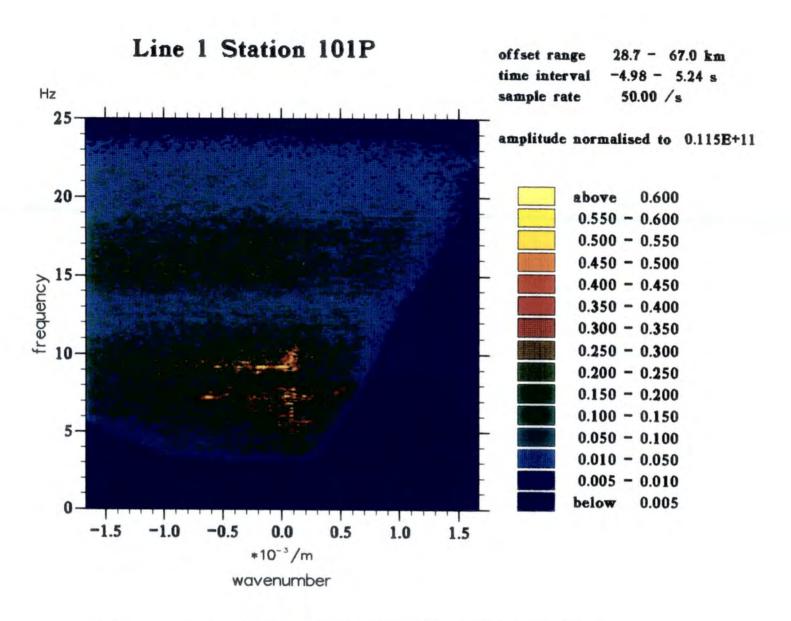


Fig. 6.5 b) BABEL Line 1, Station 101P: f-k spectra for the data shown in Fig. 6.4 with velocity filter applied

The overlay for Fig 6.1 shows the picks used for modelling while Fig. 6.3 shows a line drawing of the section with the picks highlighted.

There is some evidence for pre-critical reflections in the later part of the section at near offset, which is partly obscured by the strong S-wave arrival. An f-k spectrum of this region was examined and a pie-slice velocity filter applied to remove all arrivals with velocity below 4.5 km s⁻¹, as described in the previous chapter. Figs 6.4 and 6.5 show the original and the filtered data and f-k spectra respectively. Although most of the S-wave diving ray energy has been removed, the pre-critical reflected S-wave energy remains. These arrivals have apparent velocity very close to that of the P-wave first arrival and are thus extremely difficult to remove without disturbing the P-wave data.

6.1.3 Station F01A (114)

For this station there are three sections to compare: binned and stacked, the former plotted with true relative amplitude and normalised amplitude, the latter normalised only (Figs 6.6, 6.7 and 6.8). On the true amplitude section, little can be seen beyond 220 km. For this reason the stacked true amplitude section has been omitted. In the normalised amplitude plots much more can be seen at larger offsets before the signal disappears into background noise at about 280 km. However the penalty for this is the down weighting of near offset data which becomes less distinct. An example of this is the first arrival up to 60 km which, although clearly visible on the true amplitude section, is barely discernible on the normalised section, being followed by a much higher amplitude arrival. This is a problem of data representation which is overcome by considering both

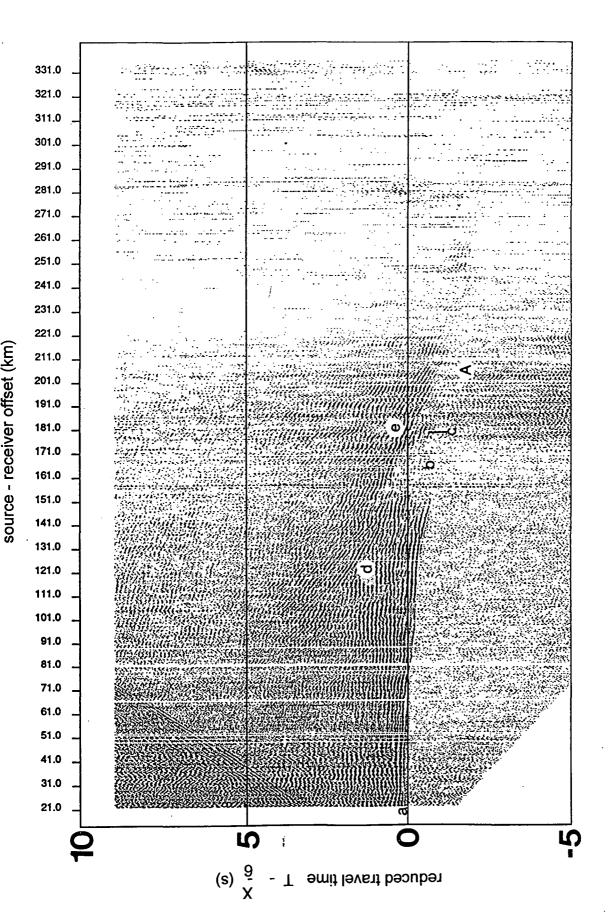


Fig. 6.6 BABEL Line 1, Station F01A(114): binned dataset, true relative amplitude

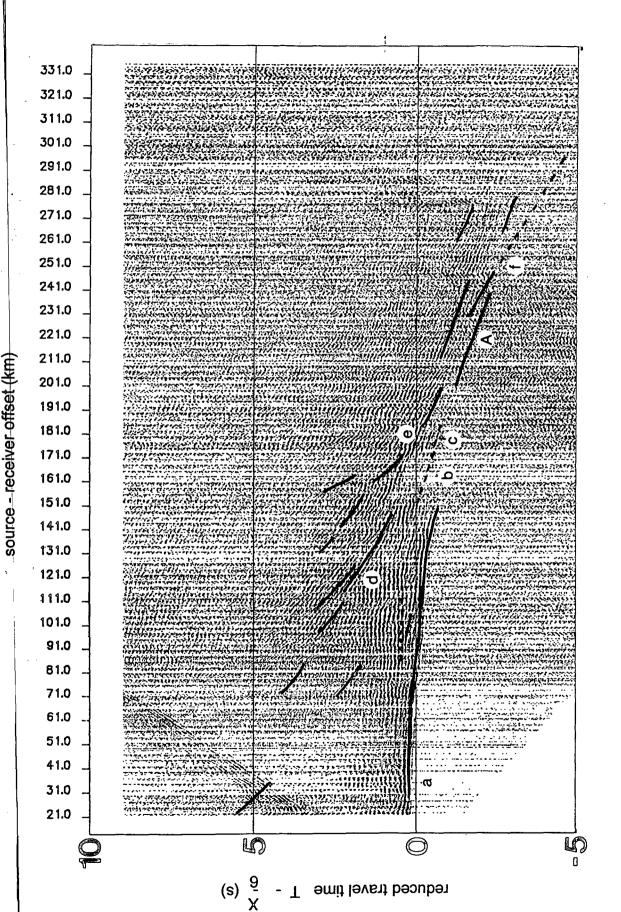
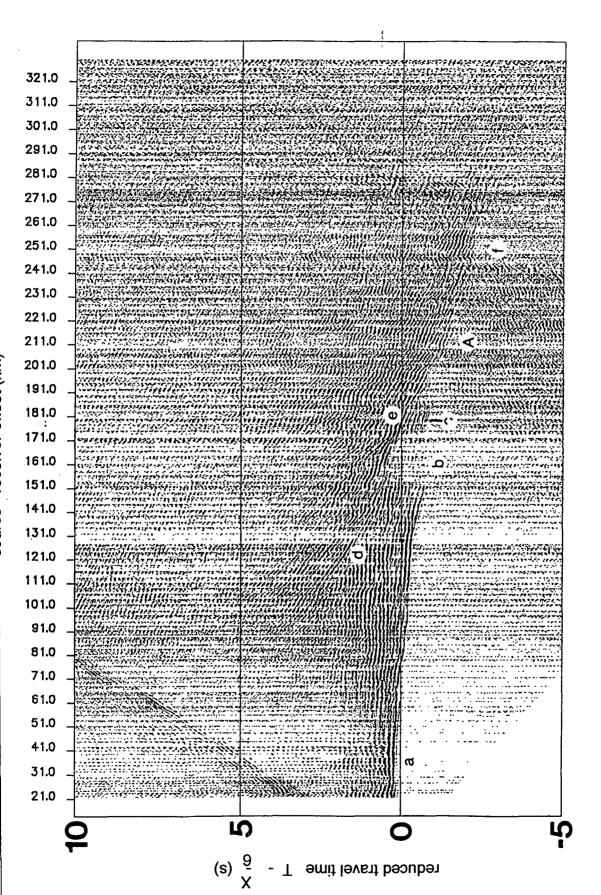


Fig. 6.7

Fig. 6.8

normalised amplitude



source - receiver offset (km)

types of plot in parallel. The stacked section brings out some of the longer offset arrivals but is otherwise little different from the binned normalised section.

The first arrival appears at the near offset end of the section with a velocity of roughly 6 km s⁻¹ (a). There is a large amount of ringing or short-period multiple energy behind this which would seem to obscure any near surface pre critical reflections. This ringing is prevalent over the whole section. The first arrival gradually increases in apparent velocity although the increase is not smooth and the arrival appears broken in places, almost as a series of en-echelon arrivals. At a distance of 130 km the arrival becomes somewhat steeper and then seems to terminate abruptly at 150 km. Although much fainter arrivals continue at a slightly later time, there is a significant low amplitude region between 150 and 175 km (b) in the first arrival which then continues out to 185 km (c) before disappearing again. A steeply dipping curved arrival of high amplitude with the characteristics of a reflection (d) also appears to be truncated at 150 km while a similar one just behind it (e) continues out to greater distances, becoming the first arrival at about 190 km.

Beyond 250 km offset there is faint evidence for a much higher apparent velocity first arrival (f) which also extends nearer to the station as a secondary arrival. Little can be said about the data beyond 260 km as the signal-to-noise ratio is too low.

The dark patch of energy early in the record section between 170 and 250 km is caused by the S-wave from the previous shot. This results in some interference with the first arrivals in the region marked (A) in Fig. 6.7. F-k velocity filtering was applied to remove the S-wave component, as described in Chapter 5. Due to a limit on the maximum size of array

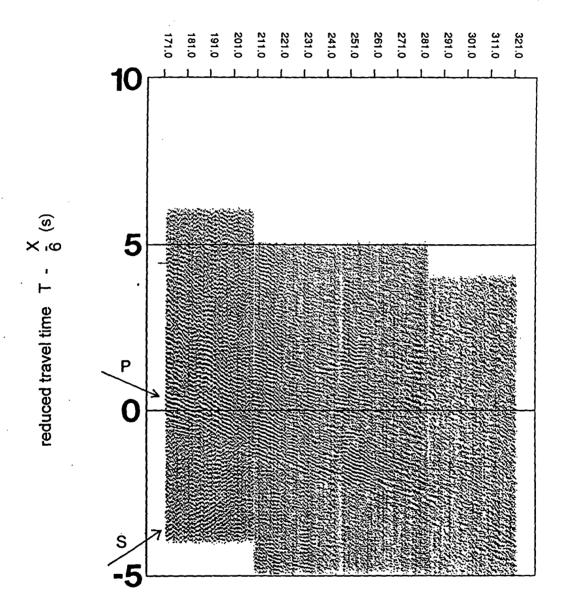


Fig. 6.9 BABEL Line 1, Station F01A(114): far offset data before velocity filtering

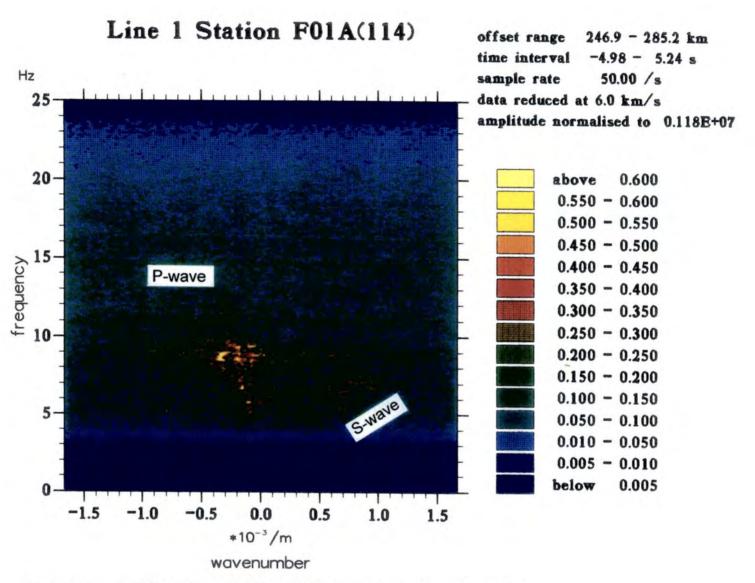
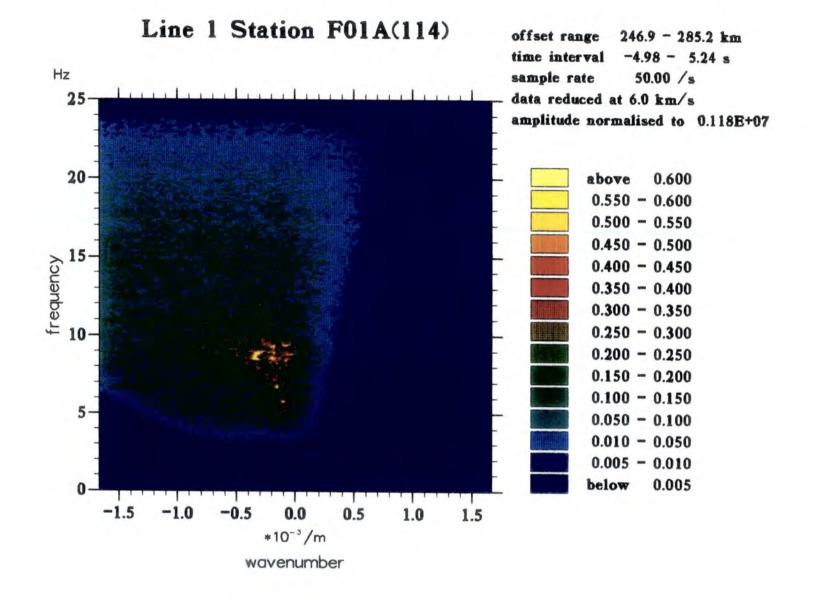


Fig. 6.10 a BABEL Line 1, Station F01A(114): f-k spectrum for part of the data shown in Fig. 6.9



b) after velocity filtering

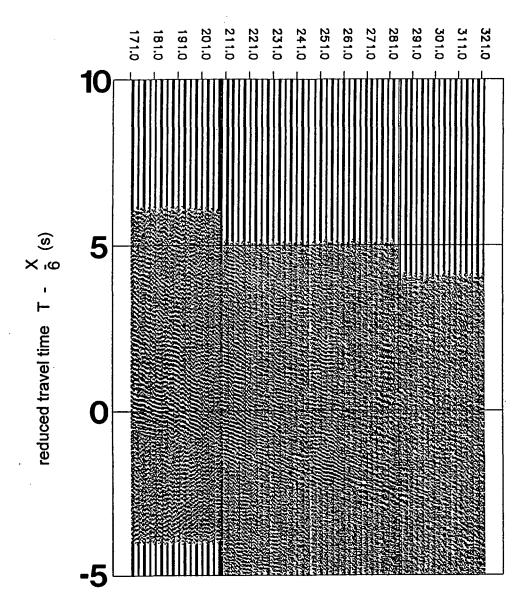


Fig. 6.11 BABEL Line 1, Station F01A(114): the same data as in Fig. 6.9 after velocity filtering

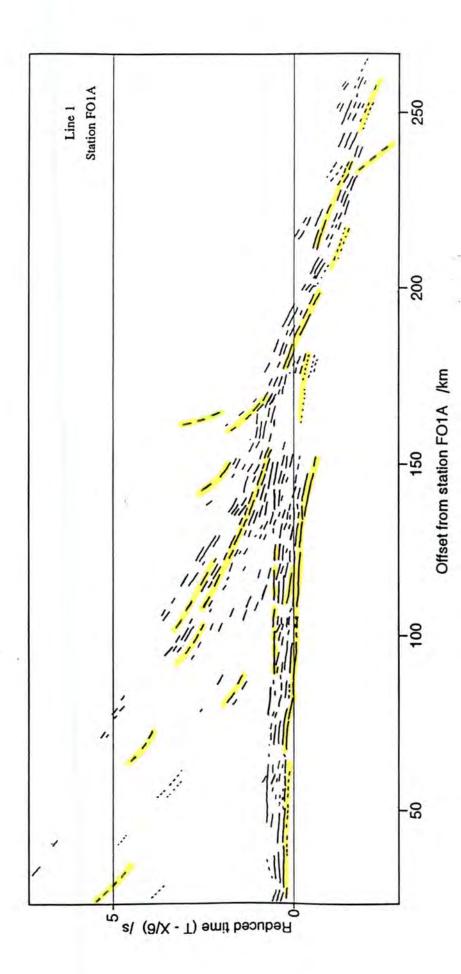


Fig. 6.12 BABEL Line 1, Station F01A(114): line drawing

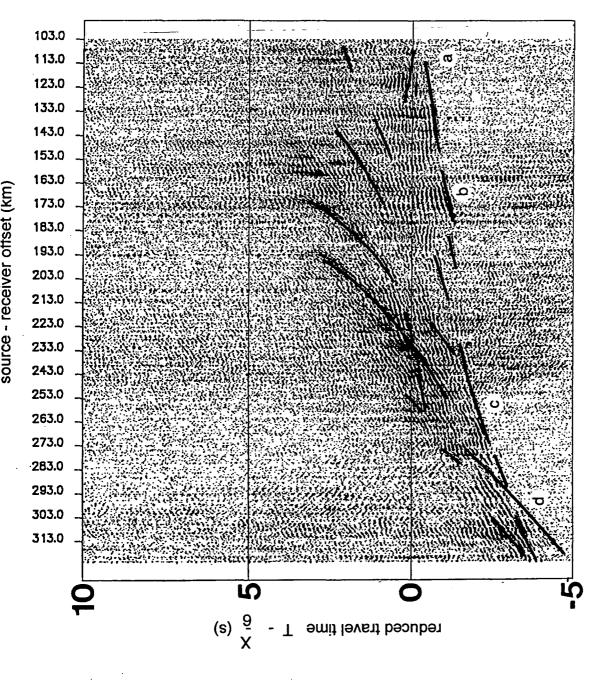
definable on the computer used, four separate windows of data were taken between 170 and 320 km (Fig. 6.9). It proved difficult to distinguish between the wanted and unwanted data in the f-k spectra, an example which is given in Fig. 6.10, so the results of velocity filtering (Fig. 6.11) were again not very successful and no new P-wave energy was revealed.

The overlay for Fig. 6.7 shows the picks used in modelling and Fig. 6.12 shows a line drawing of the data.

6.1.4 Station 1A

In contrast to the previous station, the data arriving at station 1A was of high relative amplitude to as far out as 320 km so amplitude normalisation was not necessary. However an a.g.c. was applied to the stacked section with a 100 ms window to see whether this would bring out previously hidden arrivals. The true amplitude binned, stacked and a.g.c stacked sections are shown in Figs 6.13, 6.14 and 6.15 respectively. The stacking in this case appreciably increased the signal-to-noise ratio without obviously affecting the data otherwise.

The first arrival (a) appears at the northern end of the section already exceeding 6 km s⁻¹ quite considerably. Its amplitude is variable, fading out almost completely before being overtaken by a faster arrival (b) which, as in the F01A data, stops at about 175 km. Close inspection of the sections, especially that to which an a.g.c has been applied, again shows a faint continuation of this arrival to beyond 275 km which is on the threshold of discernibility. A much stronger, approximately parallel arrival (c) comes in about one second later between 185 and 285 km which is itself overtaken by a higher velocity arrival (d). The latter extends northwards



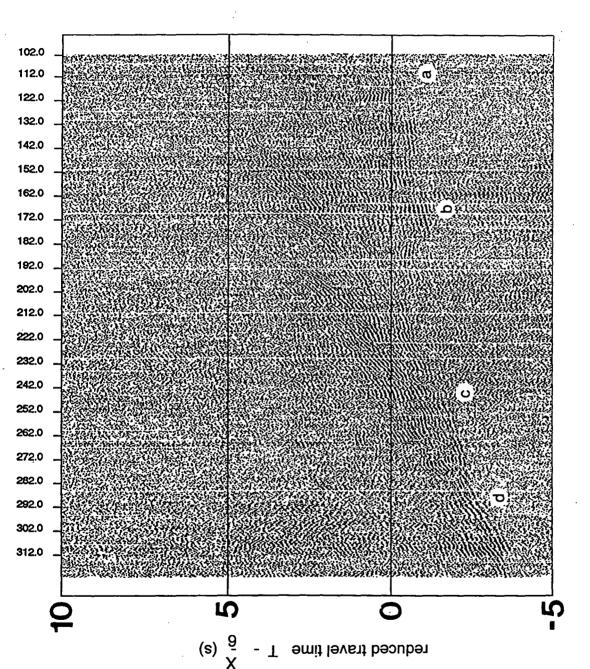


Fig. 6.13 BABEL Line 1, Station 1A: binned dataset, true amplitude

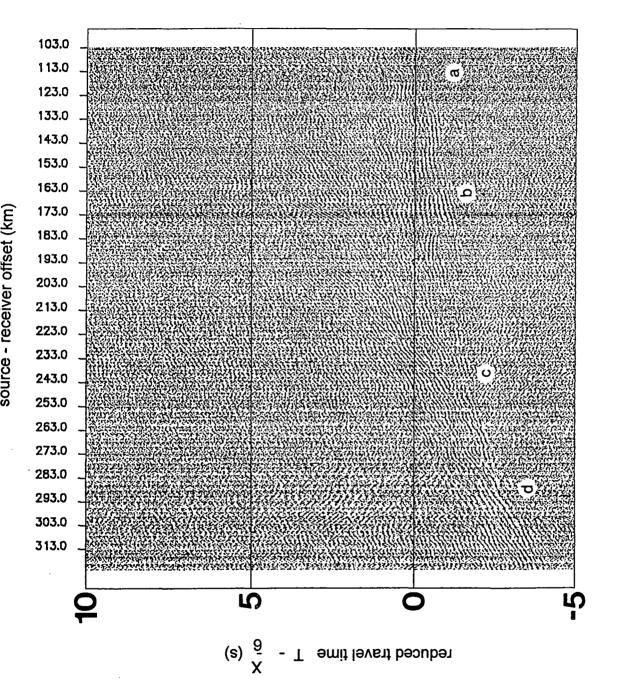


Fig. 6.15

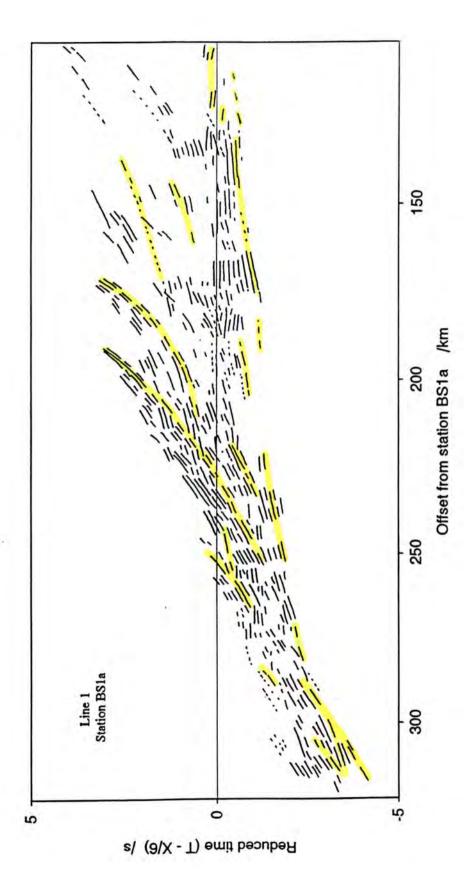


Fig. 6.16 BABEL Line 1, Station 1A: line drawing

across most of the section and appears to fork into several high amplitude, high apparent velocity branches.

The picks and line drawing are shown in the overlay for Fig 6.14 and Fig. 6.16 respectively.

6.1.5 Station 5A

All three varieties of amplitude plot were made for this station but, to avoid needless repetition of data sections, only the three most informative are shown. Fig. 6.17 is the true amplitude binned section, Fig. 6.18 the normalised stacked section and Fig. 6.19 the stacked section with a 100 ms a.g.c. applied.

The first arrival (a) appears to oscillate curiously about an apparent velocity of 6 km s⁻¹ to around 170 km. On the a.g.c'd section this looks more like a series of arrivals of differing velocities. A higher velocity arrival is truncated at 185 km just as it becomes the first arrival. Another phase just behind this never actually becomes the first arrival due to the appearance of a much steeper phase at 200 km (b). This becomes indistinct between 250 and 290 km but an even steeper, relatively high amplitude arrival (c) is seen beyond 290 km. F-k velocity filtering once again had little beneficial effect on the region where S-waves from the previous shot interfere.

The highest amplitude on the section is seen in the new first arrival at 200 km (b) and at a steep secondary arrival to the south (d) which would appear to be a continuation of the former were it not displaced slightly in time. There is evidence for the presence of more than one arrival here.

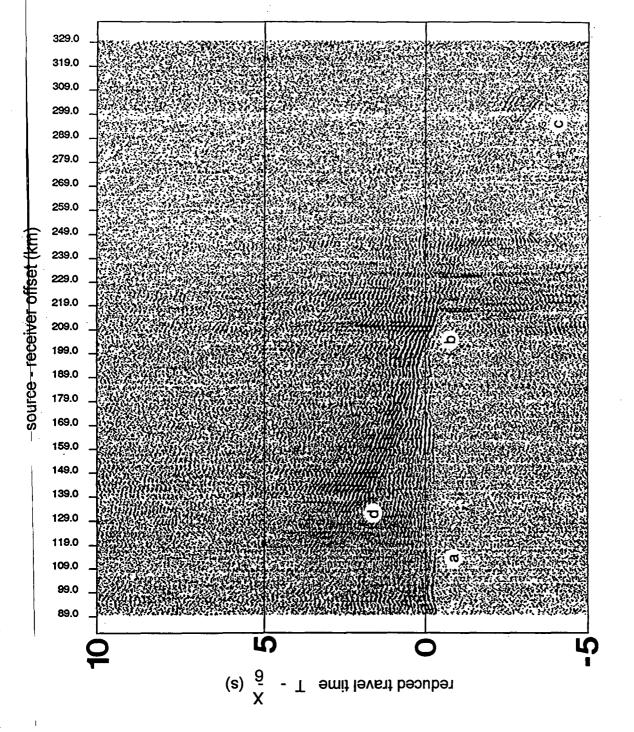
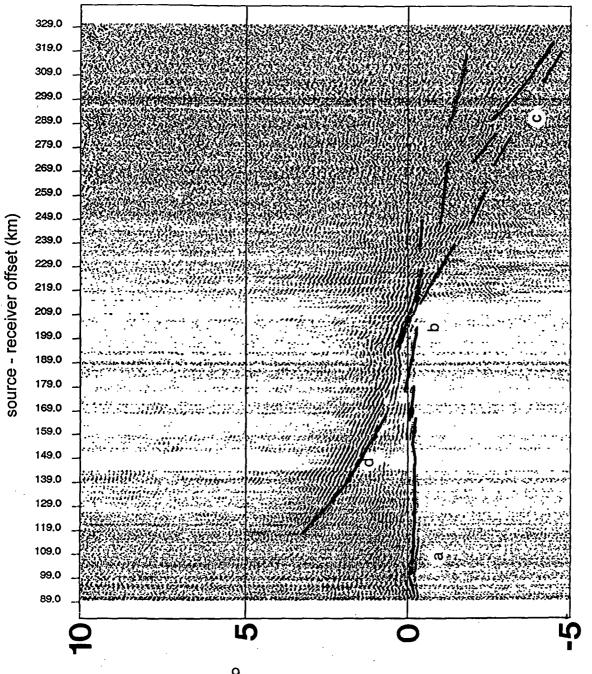




Fig. 6.18



(s) $\frac{x}{\delta}$ - T əmit ləvsit bəcubər

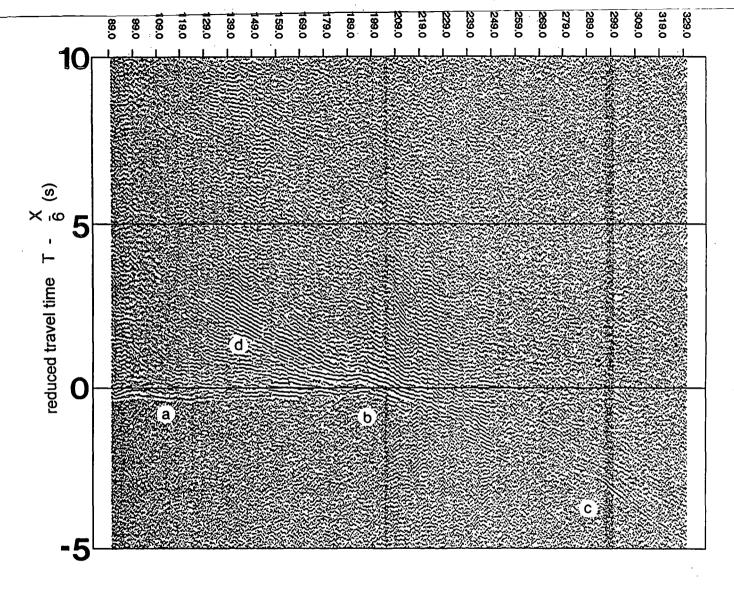


Fig. 6.19 BABEL Line 1, Station 5A: stacked dataset, 100 ms a.g.c.

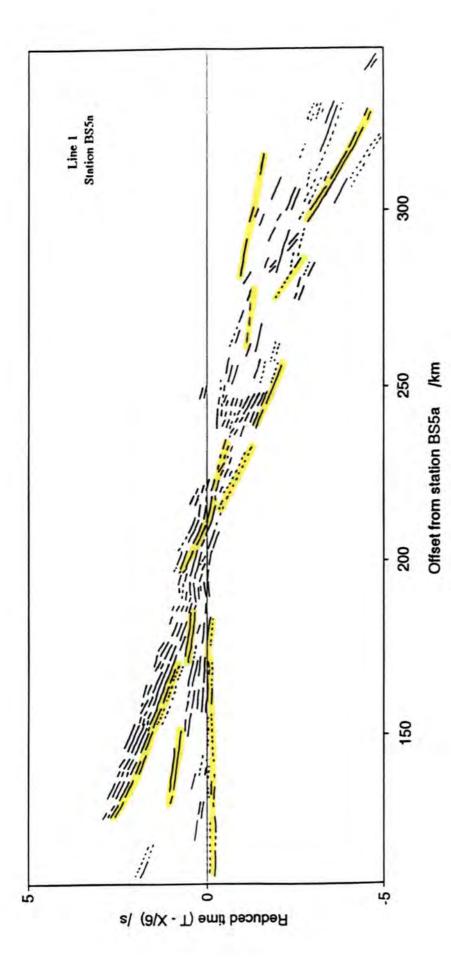


Fig. 6.20 BABEL Line 1, Station 5A: line drawing

The picks and line drawing are shown in the overlay for Fig. 6.18 and Fig. 6.20.

6.1.6 Summary

In general, the stacked sections look clearer, i.e. the signal-to-noise ratio is higher. Stations F01A and 5A exhibit strong attenuation of arrivals from shots further than about 220 km away. For this reason trace amplitude normalisation is required to see data from the whole section. Applying an a.g.c. can in some cases help to show up indistinct arrivals. However any of these types of section must be accompanied by the true relative amplitude binned (i.e. unstacked) plot for a complete interpretation.

In some of the sections, the S-wave from the previous shot interferes with the first arrival between 170 and 290 km. However f-k velocity filtering to remove the S-wave energy did not improve matters, tending instead to smear out the incoherent noise and unwanted signals at the apparent velocities of interest. This is probably explained by the low signal-to-noise ratio in the region and the fact that arrivals from the previous shot are not continuous due to slightly different shot time intervals causing step functions in the x-domain. This should also affect stacking with linear moveout but, in fact, stacking seems to be less affected by this.

In all the datasets, arrivals were found to be made up of short segments with no one phase extending continuously over more than a few tens of kilometres. In addition, amplitudes vary quite dramatically over short distances. This may possibly be explained by the interference of phases of slightly different apparent velocities. Another interesting feature of the data is the large number of high curvature, high apparent velocity

(> 10 km s⁻¹) arrivals which have the characteristic hyperbolic shape of diffractions but are also relatively high in amplitude.

6.2 Normal Incidence Data

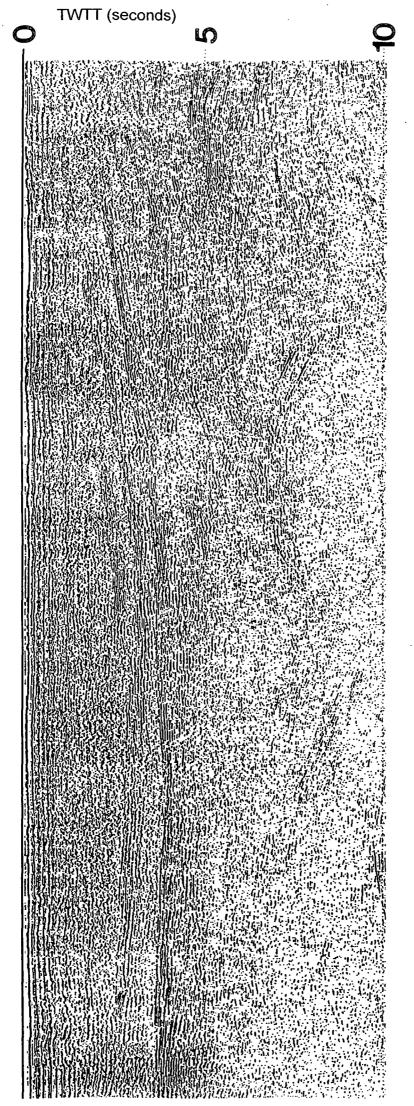
Large plots (1.5 x 5.5 m) of the normal incidence data from Line 1 were acquired directly from BIRPS. They were plotted with wiggle traces and variable area fill on a horizontal scale of 50 m/mm (1:50000) and vertical scale of 0.02 s/mm. These were found to be difficult to handle and too large to gain an overall impression. The plots shown here (Figs 6.21 and 6.22) contain every fifth trace and are plotted at a scale of 625 m/mm (1:625000).

A true amplitude plot (Fig. 6.21) shows the general variation in overall reflectivity with travel time and lateral position. However, details of individual reflectors are for the most part difficult to make out. In the southern part of the line, a patchily reflective crust appears to overlie a non-reflective mantle, the base of reflectivity lying between 13.5 and 15 s TWTT. Further north, the reflective upper and lower crust also sandwich a transparent middle crust between them and the reflective crustal base occurs a little later between 15 and 16 s.

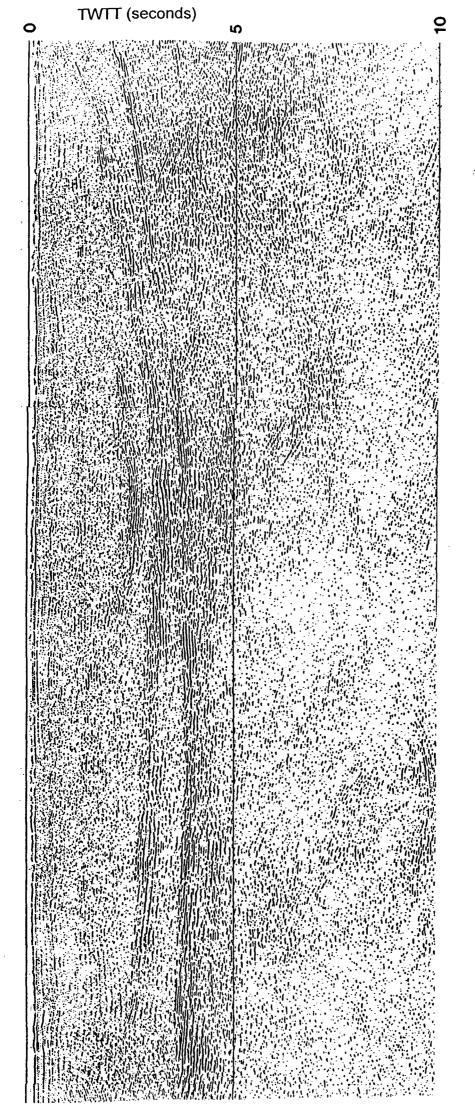
A large window a.g.c (3 seconds) allowed more detail to be seen (Fig. 6.22), most of the observed arrivals being upwardly convex and diffraction-like. The majority of these arrivals originate from the middle crust towards the southern end of the line, although the reflectivity at Moho level appears to be also of this type. The Moho is not everywhere clearly defined, especially in the central part of the profile where the decrease in reflectivity appears to be gradational between 10 and 20 seconds. The

a.g.c'd section shows up many dipping events in both directions at the base of the reflective region. These appear to have the hyperbolic shape indicative of diffracted energy.

The upper 4 seconds of the section are fairly featureless, probably due to the source array configuration and processing which was targeted on the lower crust. Exceptions to this are the two prominent reflectors at the very northern end of the profile (boxed in Fig. 6.22). An expanded plot of these is given in Fig. 6.23. A migrated plot of the brute stack (Fig. 6.24) shows there to be, in fact, three features here, all upwardly concave and extending over about 80 km. The characteristic shape, brightness and continuity of these reflectors, and their proximity to outcropping dolerite sills on the Swedish coast, cause them to be interpreted as such (McBride, Snyder and Hobbs, 1992). Similar features are seen in normal incidence profiles from the Siljan region of Sweden and these have been confirmed dolerite sills by borehole logs (Fig. 6.25, Juhlin, 1990). as



6.23 BABEL Line 1, normal incidence: near surface reflectors in the north



3. 6.24 BABEL Line 1, normal incidence: brute stack of near surface reflectors migrated at 6.5 km s⁻¹

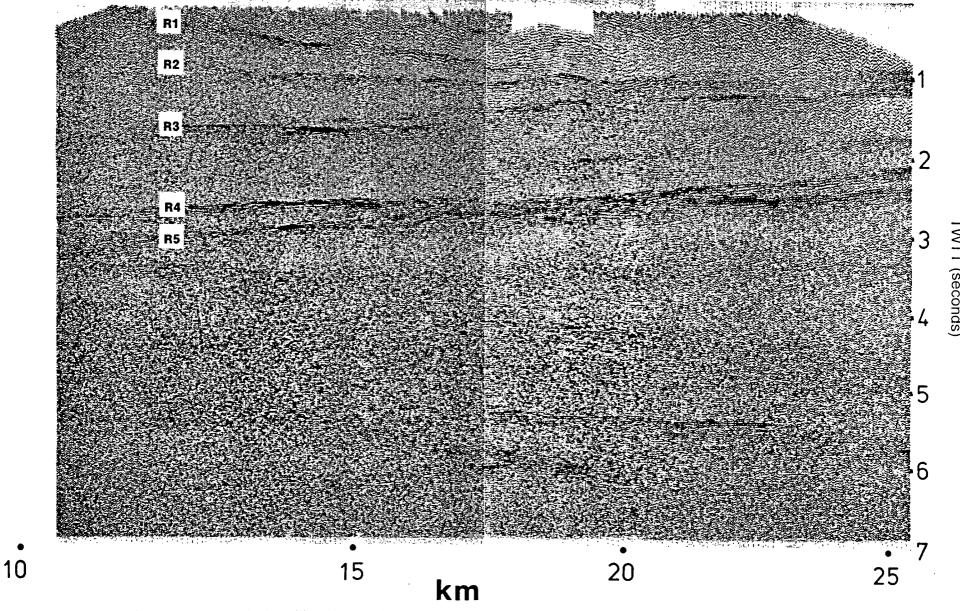


Fig. 6.25 Dolerite sills observed in normal incidence profiles near the

Gravberg1 borehole in the Siljan Ring in south central Sweden (Juhlin, 1990)

7. Modelling

7.1 Introduction

The seismic modelling package used in this study was BEAM87 written by Dr. V. Cerveny at the University of California, Berkeley (Cerveny, 1985b). It uses the Gaussian beam method to calculate synthetic seismograms, a modification of asymptotic ray theory. A 2D gravity modelling program written by Prof. M. H. P. Bott at the University of Durham was also used to constrain the in-line seismic model.

Several techniques are available for the modelling of wide angle seismic data and the calculation of synthetic seismograms, of which the reflectivity method, finite difference and finite element methods, and asymptotic ray theory (A.R.T) are the most well known. These are compared by a number of authors (e.g. Fuchs and Müller, 1971, Kennett and Harding, 1985, Weber, 1988). The only exact method is the reflectivity method; all the others are approximations which introduce their own errors. However, the application of the reflectivity method is limited to laterally homogeneous media and it is therefore unsuitable for modelling where strong lateral inhomogeneities are expected. Of the other methods, the finite difference and finite element methods give the closest approximations provided the grid is sufficiently fine to avoid artifacts. They are very powerful, yielding accurate seismograms for complicated media. Their major drawbacks are the vast amount of computing power required to use them with a fine grid, and the difficulty in interpreting the highly complex resultant seismograms (Weber, 1988). Ray theory, despite being less

exact, is simpler and faster, making much smaller demands on computational resources.

In the ray theory approach, employed by BEAM87's predecessor SEIS83, the wavefield is broken down into a number of elementary waves based on the path taken through the model. The trajectory and travel time of a series of rays are calculated for each elementary wave (Cerveny, 1985a). These rays are traced through the model from a starting point to specified endpoints by varying the initial take-off angle. This is called twopoint ray tracing (other methods of specifying the rays may also be used). Amplitudes are modified by transmission and reflection at interfaces and corrected for geometric spreading. Summation of all the elementary seismograms obtained in this way yields the final synthetic section. The method is a high frequency approximation, based on the assumption that the seismic wavelength is shorter than the dimensions of the structures in the model. Thus the velocity field must not vary too rapidly. As the method does not give a full solution for the complete wavefield, the theory also breaks down where the ray field is not regular, such as in the critical region and caustics, and edge diffractions cannot be calculated. The technique's advantages lie in its flexibility in modelling 2D laterally inhomogeneous media and in its speed.

Some of the drawbacks of A.R.T can be overcome by modifications and extensions to the theory. The most well known of these are the WKBJ-Maslov method (Chapman, 1985) and the Gaussian beam method (Cerveny 1983, 1985b, Weber 1988). The latter was used in modelling BABEL Line 1, implemented by V. Cerveny in the BEAM87 package.

The Gaussian beam method uses beams of seismic energy of finite width with bell-shaped amplitude cross-section instead of the infinitesimally

narrow rays considered above. The wave equation is solved close to the central ray which removes the singularities apparent in the ray method.

Ray tracing is carried out as before and ray amplitudes determined, without the geometric spreading correction. The contributions of the Gaussian beams are then evaluated, the beam width and phase front curvature being modified at each model interface. The receiver response is calculated by superposition of all the beams arriving in the vicinity of the receiver.

The method is more stable than the pure ray theory in singular regions such as caustics and critical regions and it produces more reliable amplitudes whilst retaining the advantages of speed and flexibility. It is also less sensitive to minor details in the model (Cerveny 1985b). However the effects of surface curvature are not taken into account in the treatment of reflections and transmissions and, although diffractions may be represented, amplitude and phase information are not accurate (Kennett and Harding, 1985).

The BEAM87 package itself, in the form used, consists of four main programs with an additional one written at Durham by P. A. Matthews to convert the synthetic data to the same format as the real data. Fig 7.1 shows a flow diagram of the modelling process. The model is defined by a number of interfaces, each specified by up to 30 points and interpolated by a cubic spline. The interfaces also represent isovelocity lines, velocities being specified immediately above and below each interface. A vertical linear interpolation is applied within each layer to evaluate the velocity field. Two other options are included in the package which involve either a piece wise bilinear interpolation or a cubic spline applied to a grid of velocity specifications within each layer. In these last two methods, the interfaces

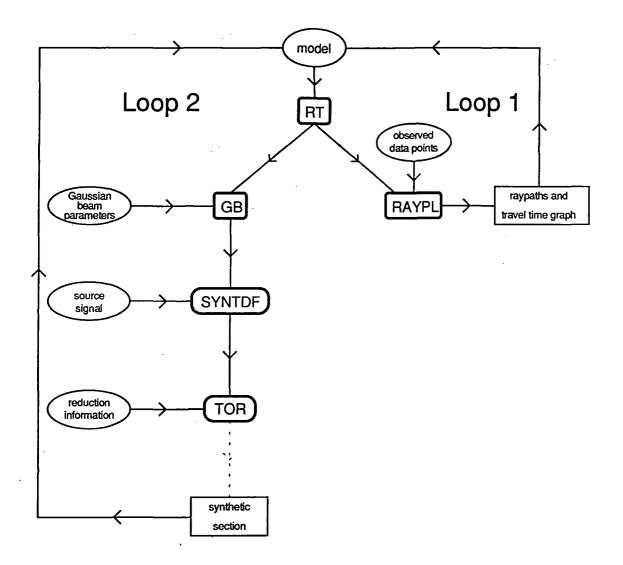


Fig. 7.1 Flow diagram of the modelling process

are not velocity isolines and have the advantage that lateral velocity variations can be represented within a layer. However the bicubic spline produces oscillations in the velocity field even after smoothing and the bilinear interpolation method can give unstable results (Lewis, 1986, West, 1990). Thus, as the most reliable method, the linear interpolation procedure was the only one implemented in the version of BEAM87 used.

The main program RT performs the raytracing between the source and a specified set of receivers along the Earth's surface. Travel times, ray paths and amplitudes are evaluated for each elementary wave. The amplitudes are reduced to have unit vertical amplitude at the source. The travel times, ray paths and amplitudes can then be plotted by the program RAYPL (modified by C. Prescott and P. A. Matthews to use the UNIRAS graphics library) along with the picked arrivals which are digitised and included in the control file. This is generally the first stage in modelling and is repeated iteratively, adjusting the model each time to get a better fit to the digitised travel time data.

In the second stage, GB calculates the frequency response at the receivers for each elementary wave by the summation of Gaussian beams, taking into account source radiation pattern and dissipation effects. The method depends on having a high density of rays near the receiver as the response is calculated by a weighted summation of several overlapping beams.

Seismograms are produced by SYNTDF with a user-specified source signature. The seismogram at each receiver is calculated by combining the frequency responses for all the elementary waves to give one frequency response. This is multiplied by the Fourier transform of the source signal, and the inverse Fourier transform gives the synthetic

seismogram. The far field source signature supplied by Prakla Seismos was used as the input signal for Line 1 synthetics. A double cosine filter is included in the program, mainly to filter out low frequencies as the Gaussian beam method is based on a high frequency approximation. The limits chosen for this were similar to those used in band-pass filtering the real data. The program was adapted from the original to output the synthetic data in ISEGY format. This could then be reduced and written out in the same way as the real data by TOR, written by P. A. Matthews, and plotted out.

This second modelling stage can also be repeated iteratively to match amplitudes as far as possible. It must be noted, however, that the synthetic trace amplitudes are normalised so that the maximum amplitude in each trace = 1. The section as a whole cannot therefore be compared directly with true amplitude data sections.

One must also be aware that BEAM87 is designed to model one shotpoint with many receivers while for the BABEL data we have many shotpoints and one receiver. Whilst raypaths are totally reversible, amplitudes are not and another source of error is introduced. Fortunately, the difference is very small unless P to S converted phases are being modelled (Matthews, 1993).

The programs in the package were also adapted by P. A. Matthews to model normal incidence data.

7.2 Preparation of data for modelling

Before the first stage of modelling could be carried out, the picks of seismic arrivals on the data sections had to be digitised. This was done semi-automatically on a digitising table attached to a SUN workstation. A deskewing transformation was applied to remove the effect of misalignment of the paper section on the table. The input file to RAYPL requires that the data are in unreduced form so a further operation was performed on the digitised data points to dereduce them. The program TRANSFORM performed both the deskewing and dereduction. It was written by the author and can be found in Appendix 1.

In order to model a reversed profile, it is necessary to locate the receivers on the model and modify the x-coordinates of the picked data points to maintain the correct shot-receiver separations. Stations F01A and 101P are near enough to the strike of BABEL Line 1 to be considered as in-line (Fig. 7.2a). For this reason, F01A was taken as the horizontal origin of the model. F01A and 101P are separated by 358.4 km so the transformation applied to the x-coordinates of the data points for 101P is:

$$x' = 358.4 - x$$
 where $x' =$ new coordinate $x =$ old coordinate

With the off-line stations 1A and 5A, the situation was three dimensional. A problem therefore arose in how to model the data with a 2D modelling package. In order to get around this problem, a transformation was applied to the station and shotpoint coordinates so that they all lay along the model profile. To do this, the station position had to be projected on to the line of strike of the profile whilst maintaining the shot-receiver

CHAPTER 7: MODELLING

offset. The approximation to in-line stations is most accurate at the greatest offset where the angle between the raypaths and the line is at a minimum. The furthest shotpoint was therefore held stationary during the transformation of the shot and station coordinates.

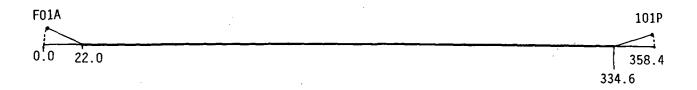
Firstly the shotpoints were rotated in the horizontal plane about the receiver so that they lay on a straight line between the receiver and the furthest shotpoint. This has the effect of making the shotpoints appear closer together but shot-receiver ranges are unaffected. The whole line was then rotated again about the furthest shotpoint so that it was colinear with the model profile. Figs. 7.2b and c show the geometry of the two stages of this operation for the two off-line stations. For convenience, the same model coordinate system as for the in-line stations was used, i.e. the origin was taken as the location of station F01A. The mathematical operations applied to the two sets of data points are as follows:

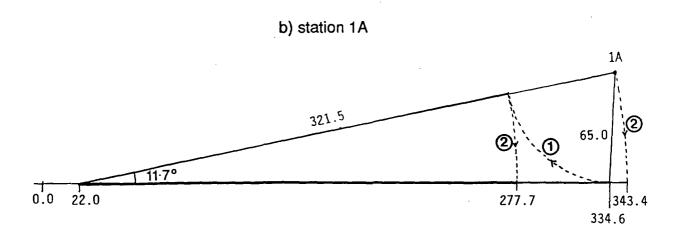
1A:
$$x' = 343.4 - x$$
 where $x = \text{shot-receiver offset}$

5A:
$$x' = x - 24.0$$
 $x' = model coordinate$

Obviously the shotpoints were dislocated from their true locations with respect to the in-line model, only the furthest shotpoint in each case retaining its original position. This fact must be remembered when comparing and interpreting the models.

a) stations 101P and F01A





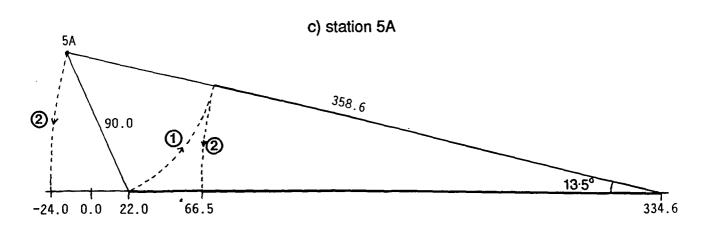


Fig. 7.2 Relationship of Line 1 and wide angle stations to the model coordinate system

7.3 The Models

7.3.1 Introduction

The first dataset to be modelled was that recorded at station 101P. After producing an unreversed model for the 101P data, the F01A data was also modelled independently. These two models were then combined, modelling alternately from each end of the line until a good fit had been obtained to both datasets. Several revisions of the model were made, mainly in an attempt to curtail arrivals produced by the model which were not seen in the data and to match amplitudes (in a qualitative rather than quantitative sense). Two dimensional gravity modelling was then carried out based on the seismic model and gravity data published by the BABEL Working Group (1993). The seismic model was further revised to comply with the constraints of the gravity modelling.

A feature of the data is the complexity of the arrivals with several arrivals of differing apparent velocity, sometimes quite high, often being superposed. Large variations in amplitude over short distances are also common. It was postulated during the modelling process that these features may result from the interaction of the seismic energy with an undulating boundary. To investigate this further, a series of hypothetical models were created with undulations of various wavelengths on the Moho. Fig. 7.3 shows the basic model with no undulations. It consists of a simple three layer crust 50 km thick. Diving rays in the lower crust and upper mantle are shown, along with the Moho reflection. Below this is the synthetic seismogram generated from the model with the indicated raypaths using the source wavelet given in Fig. 4.6. The synthetic section

shows a certain amount of ringing. This is an artifact of the synthetic generation program produced by filtering of the wavelet. Figs. 7.4 to 7.7 show the effect of different wavelength Moho undulations on the seismic record. For the longer wavelengths, the position of the receiver relative to the peaks and troughs of the undulation has a strong influence on the outcome (Figs. 7.4 and 7.5).

Obviously for the shorter wavelengths, the amplitude of the oscillation is unreasonable and merely serves to emphasise the effect. However, isolated offsets in the Moho modelled in previous surveys in the Baltic Shield do have comparable magnitude and boundary curvature (see Chapter 3).

In the last of these models (Fig. 7.7), not enough points were available in the interface definition for the oscillations to extend across the whole model. From the undulating part of the boundary it is clear that a highly complex set of individual arrivals are merged into one broad band of energy, even when the ringing artifacts are discounted. A similar effect has been created by Gibson and Levander (1988) with a mathematical model generated by imposing small 2D random velocity variations (or scatterers) on a uniform vertical velocity gradient and using a finite difference technique to obtain a synthetic seismogram.

From these hypothetical models it can be concluded that structures and irregularities on a seismic boundary have a large effect on the seismic record. It is possible for a small section of an interface with high curvature to produce an arrival over a large distance range. The limiting case of this would be a diffraction.

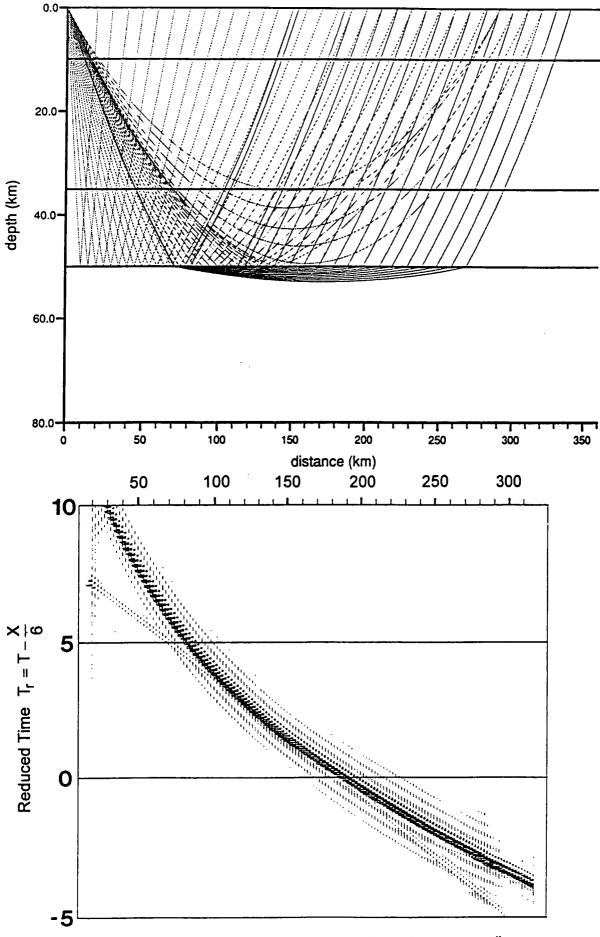


Fig. 7.3 Lower- and sub-crustal raypaths and corresponding synthetic section for a simple three-layer crustal model with no lateral variations

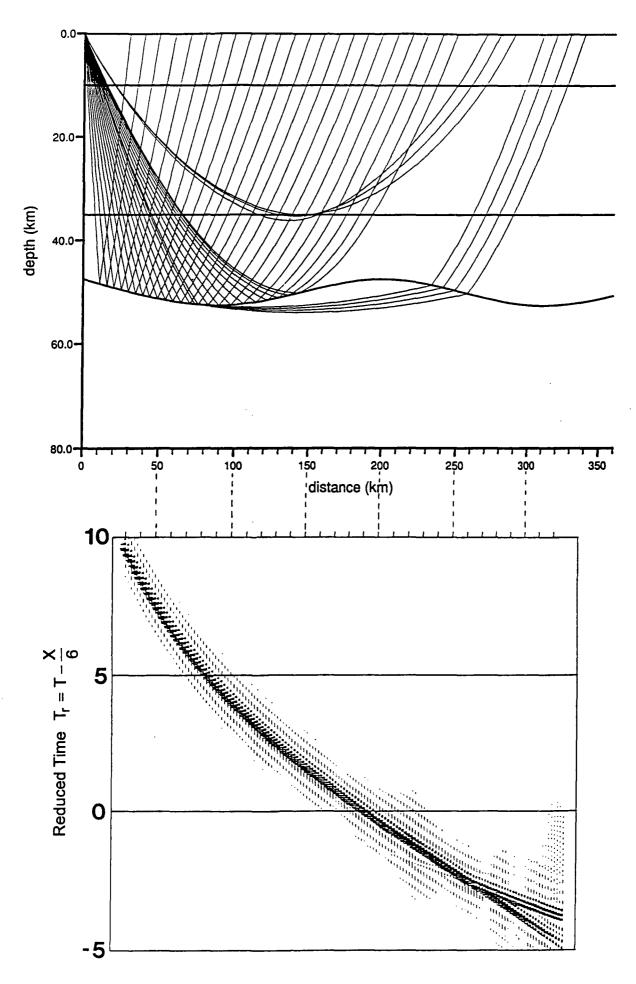
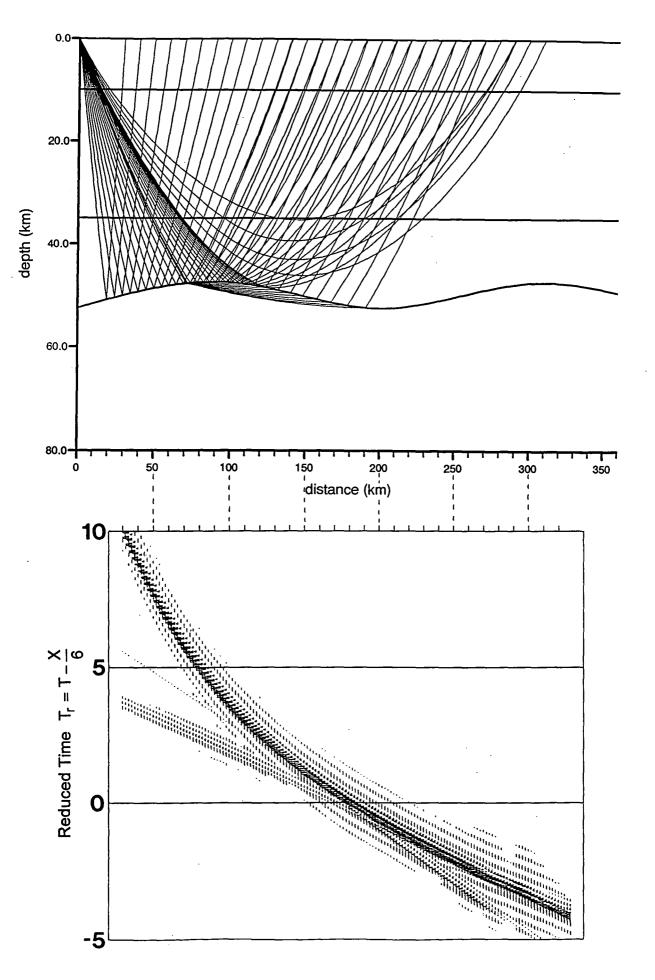


Fig. 7.4 As for Fig. 7.3 but with a long wavelength undulating Moho

a) and b) show the effect of receiver location with respect to
the undulation

b) Long wavelength undulations on the Moho



a) Medium wavelength undulations on the Moho

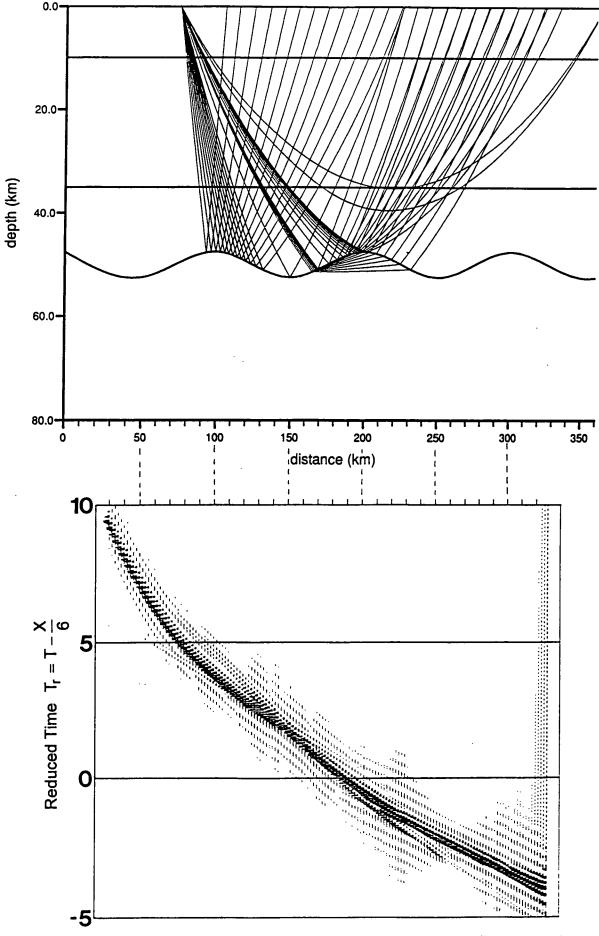
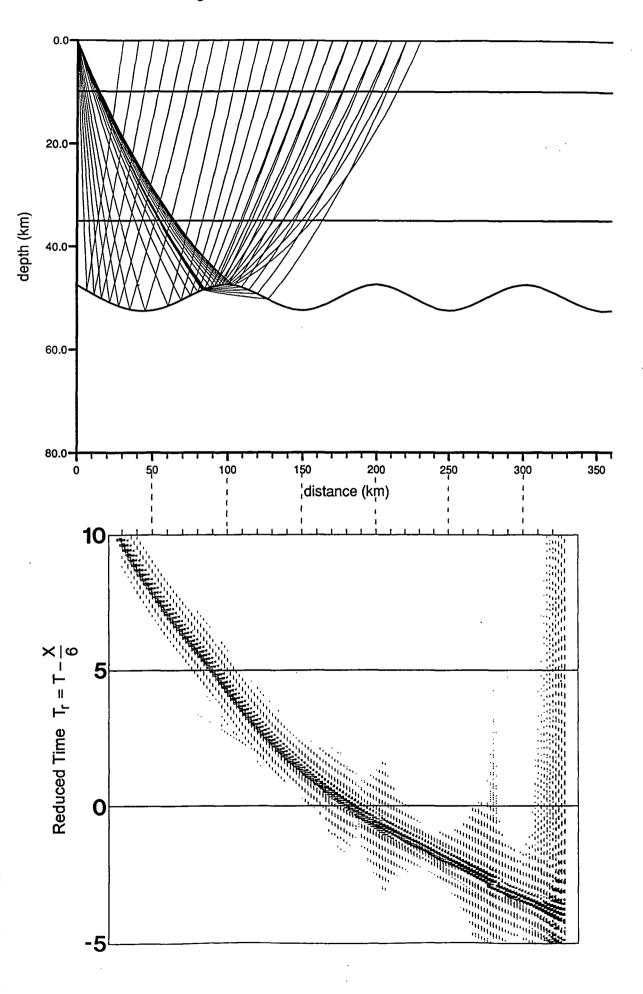


Fig. 7.5 As for Fig. 7.3 but with a medium (100 km) wavelength undulating Moho: a) and b) show the effect of receiver location with respect to the undulation

b) Medium wavelength undulations on the Moho



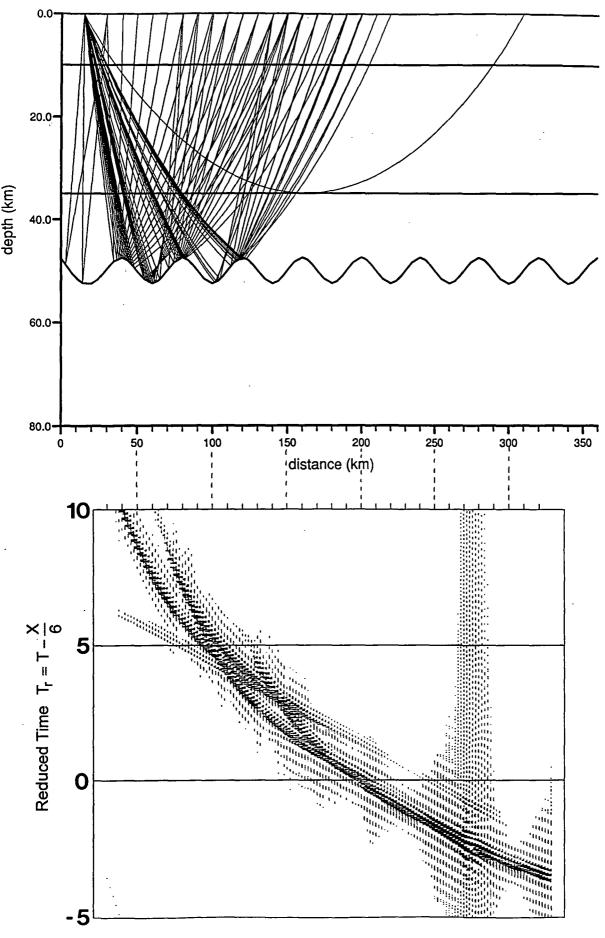


Fig. 7.6 As for Fig. 7.3 but with a short wavelength (40 km) undulating Moho

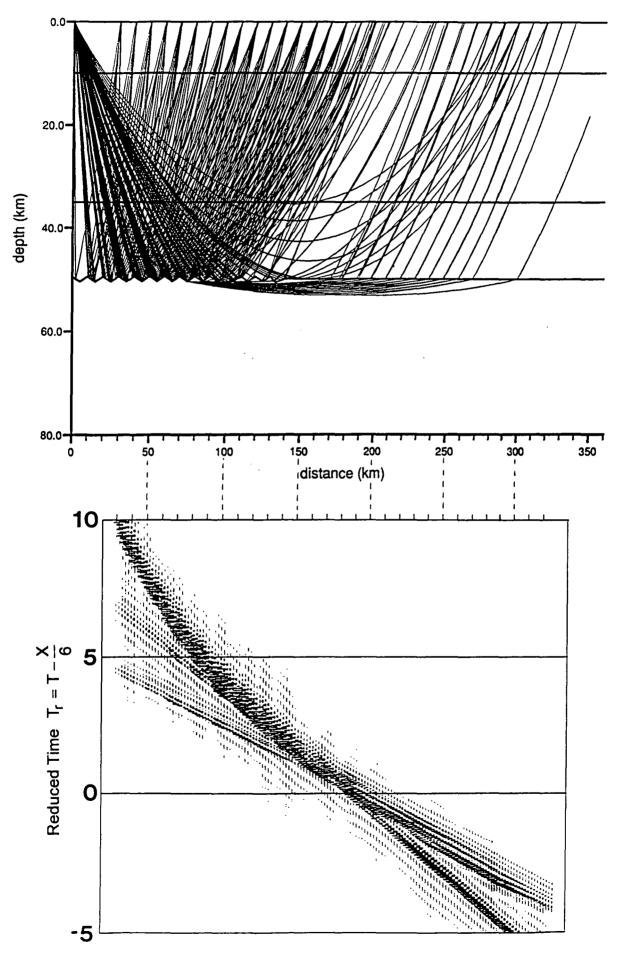


Fig. 7.7 As for Fig. 7.3 but with a very short wavelength (10 km) undulating Moho

7.3.2 Model A: 101P and F01A

The model produced for the in-line data before gravity modelling is given in Fig. 7.8. Figs. 7.9 and 7.10 show the synthetic sections generated from the model for stations 101P and F01A respectively, with Figs. 7.11 and 7.12 showing the relevant raypaths and travel-time graphs.

The model shows a fairly uniform upper and middle crust, disrupted by a low velocity body between 10 and 20 km depth in the central part of the model, and by thin reflective and diffractive bodies at 30 km depth. The central one of these thin bodies is defined only by diffractions from either end and neither are thick enough for their velocities to be determined. The lower crust is more complex, with a depression in the Moho separating two distinct lower crustal blocks.

This model was used as the basis for gravity modelling in two dimensions. The model boundaries were extended to±1000 km, and initial densities were estimated from the Nafe-Drake curve, with a reference value taken as 2970 kg m⁻³. All density contrasts in the model are calculated with reference to this value. The crustal density contrasts were then adjusted to give the best fit to the data (Fig. 7.13). Two things are obvious from this model: (a) that the upper crustal block in the centre of the model has a high density rather than a low one as expected from its low velocity in the seismic model; (b) this same block must extend upwards, nearer to the surface in order to account for the short-width positive anomaly. Fig. 7.14 shows a model into which such an extension has been introduced. The upper crustal density contrasts have been adjusted for the best fit. It appears from this model that the high velocity upper crustal block should have greater mass towards its southern tip and

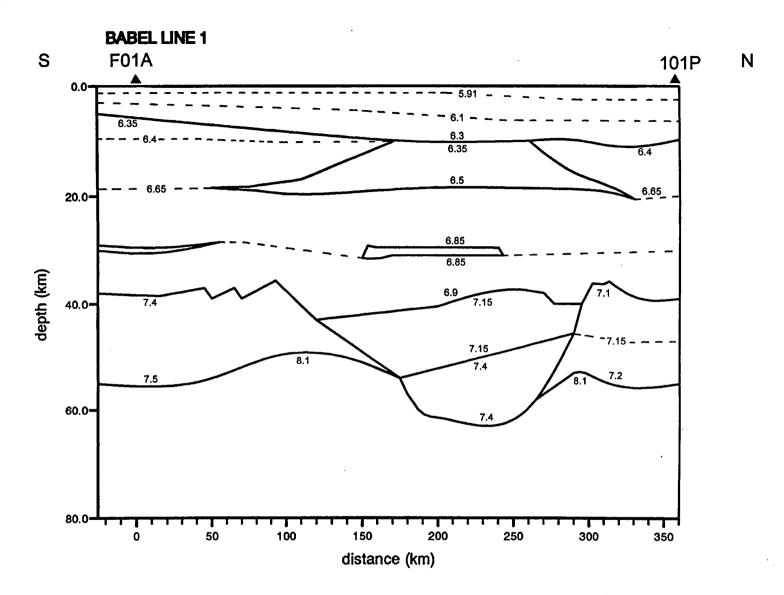


Fig. 7.8 Initial velocity model for in-line stations 101P and F01A without constraint from gravity

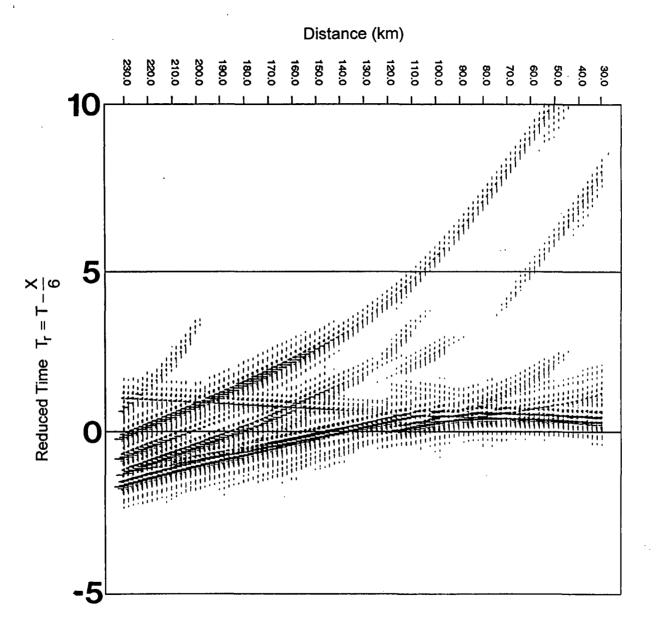
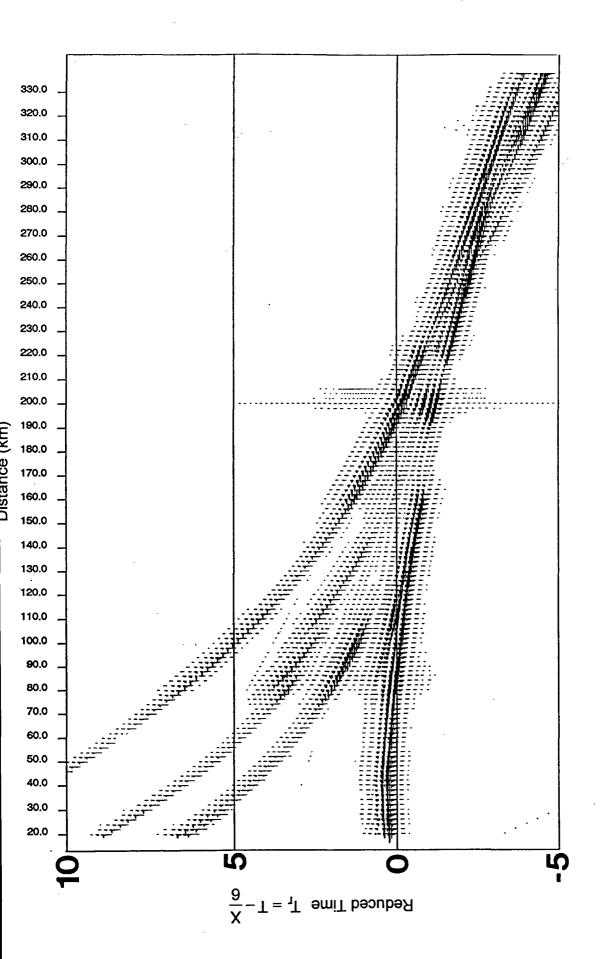


Fig. 7.9 Synthetic section generated for station 101P from initial velocity model. without constraint from gravity



Fig. 7.10



BABEL Line 1 Station 101P

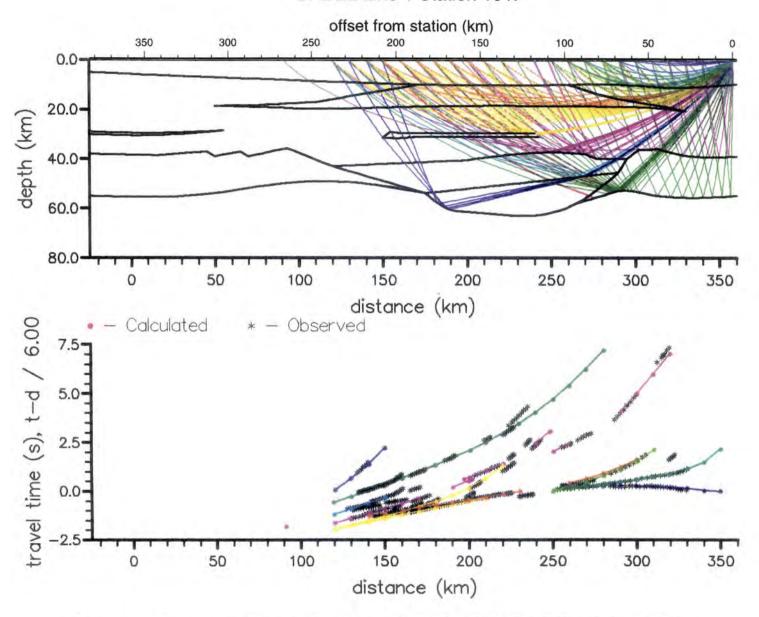


Fig. 7.11 Raypaths and travel time curves for station 101P in initial velocity model.

BABEL Line 1 Station F01A(114)

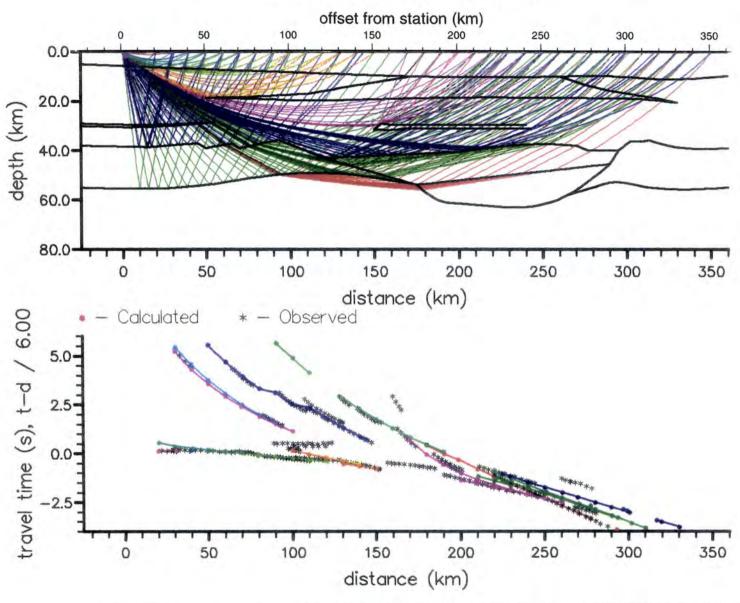


Fig. 7.12 Raypaths and travel time curves for station F01A in initial velocity model.

should not extend so far north. However, the northern upper boundary of the block is defined by the seismic model. Bearing this in mind, a low velocity block was introduced in place of the northern tip of the high velocity block with a similar upper boundary. The boundaries of these two blocks, and associated densities were altered minimally to again optimise the fit to the data (Fig. 7.15).

Referring back to the seismic data, a best fit model to both datasets was found by iteratively carrying out seismic and gravity modelling. During this process, the high density upper crustal block was reassigned a high velocity since a low velocity rock of such high density was considered unfeasible. Other boundaries and velocities below were altered to take this into account and maintain the fit to the seismic data.

Fig. 7.16 shows the final gravity model, while Fig. 7.17 shows the final seismic model. This will be referred to as Model A. The only difference between the gravity model and the seismic model which could not be resolved is the thickness of the southern tip of the high velocity/density block in the upper crust. The gravity model indicates a greater thickness here for the body than the seismic model allows. This could be accounted for if the third dimension were considered. The step in the gravity data at 300 km was not modelled since, if it was not merely an error in the processing of the data itself, its short width indicates that it is caused by a small near surface feature not imaged by the seismic data and not affecting the overall model.

The synthetic sections generated from Model A are shown in Figs. 7.18 and 7.19. They do not differ significantly from those in Figs. 7.9 and 7.10, generated from the initial seismic model, except that the diffracted arrivals are more prominent and the spurious low velocity phase at long

offsets in the section for 101P has been eliminated. The full ray diagrams and travel time curves, together with layer-by-layer breakdowns, are given in Figs. 7.20 to 7.23.

The velocity at the top of the model is 5.85 km s⁻¹ and increases without discontinuity to a value of 6.3 km s⁻¹, the gradient decreasing from south to north as the depth of this first interface increases from 5 to 11 km (layer 1, Figs. 7.22a, 7.23a). Below this, the velocity increases from 6.35 at the southern end, 6.45 in the north to 6.55 km s⁻¹ at a depth of between 18 and 20 km (layers 2 and 3). In the centre of the model at the same depth is a high velocity block with velocity increasing from 6.6 to 6.7 km s⁻¹ (layer 4). Its southern boundary is defined by reflections of limited lateral extent (arrivals k, l, Fig. 7.23b) while its upper and northerly boundaries are obtained from gravity modelling. To the north of this is a region with a lower velocity of 6.35 km s⁻¹ (layer 5). The northern sloping boundary of this region is defined by a reflected arrival (c) seen at station 101P (Fig. 7.22b).

At 30 km depth, the velocity has reached 6.8 km s⁻¹ (layer 6). The two thin layers at the southern end at this depth (layer 7) account for laterally limited reflected phases in the data (*m*), while a high curvature reflection (*n*), interpreted as a diffraction, arises from a feature at the northern end of the more northerly of the two (Fig. 7.23c). The small body further to the north of the model at the same depth is defined only by a diffraction event (*e*, Fig. 7.22c), with no associated reflected arrival. The velocity within these bodies cannot be obtained from the data except in a qualitative way from the reflection amplitude. They have been assigned an arbitrary high velocity of 7.2 km s⁻¹ but their thickness does not allow them to have a great effect on the travel times of rays passing through them.

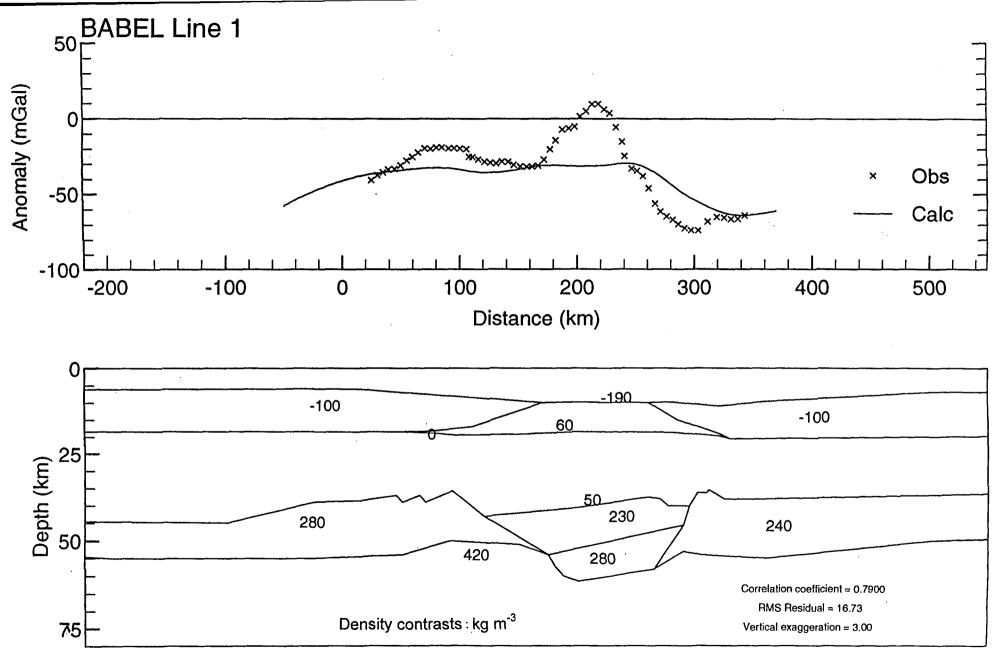


Fig. 7.13 Initial gravity model based on seismic model for Line 1.

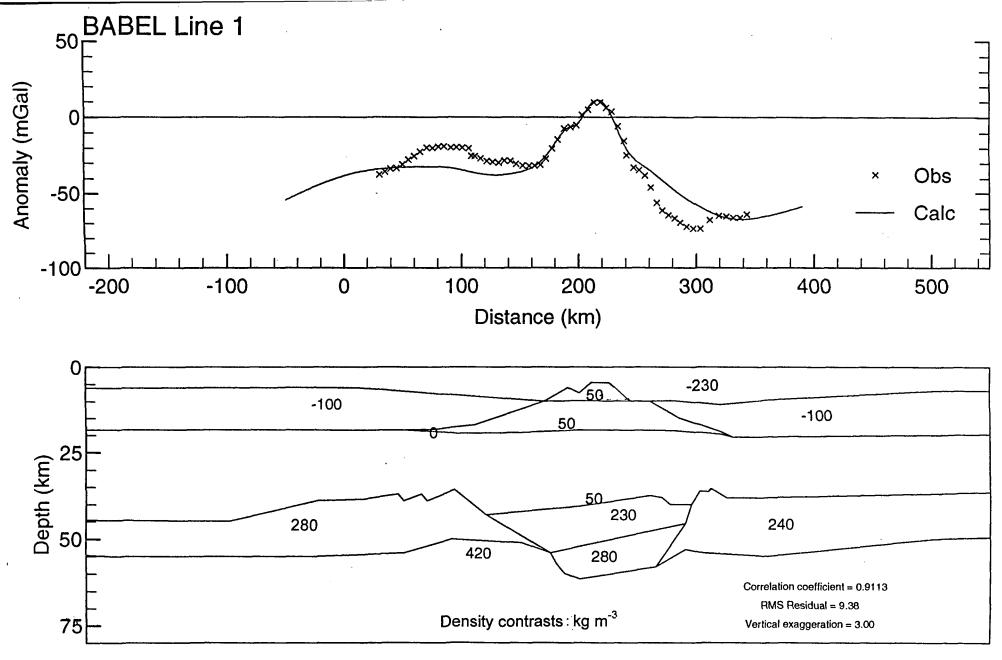


Fig. 7.14 First intermediate gravity model with additional high density upper crustal block.

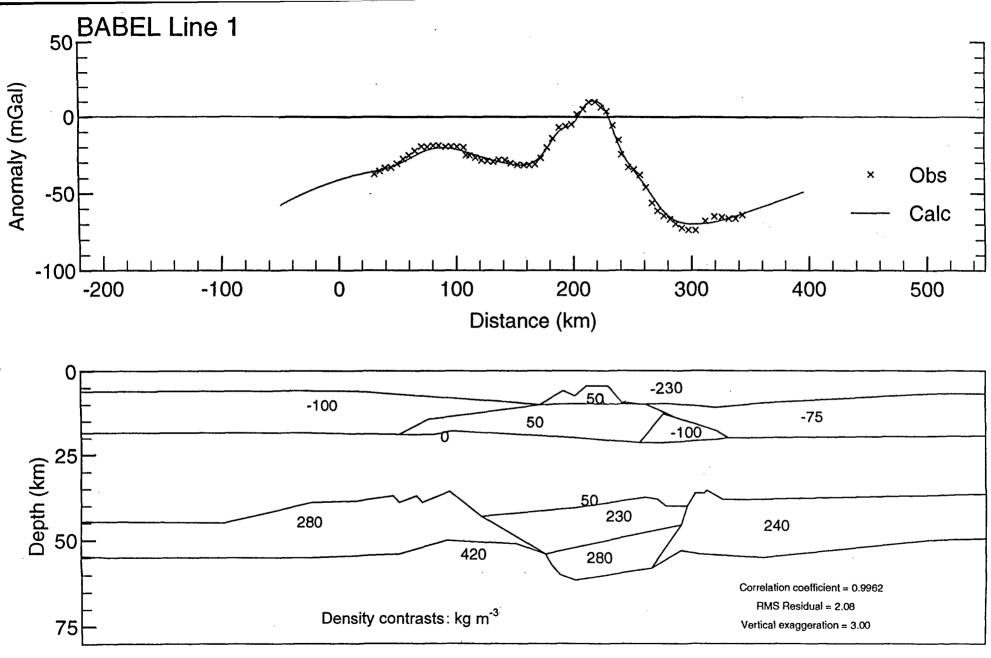


Fig. 7.15 Second intermediate gravity model with upper crustal boundaries adjusted minimally for best fit and low density upper crustal block added.

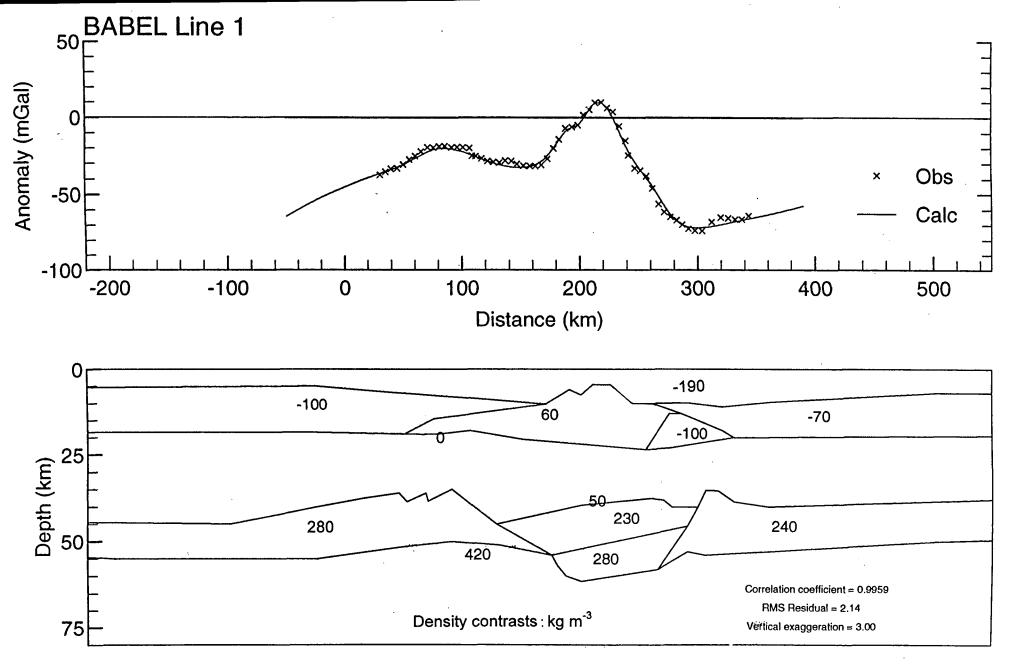


Fig. 7.16 Model A: final gravity model for Line 1.

BABEL LINE1 MODEL A

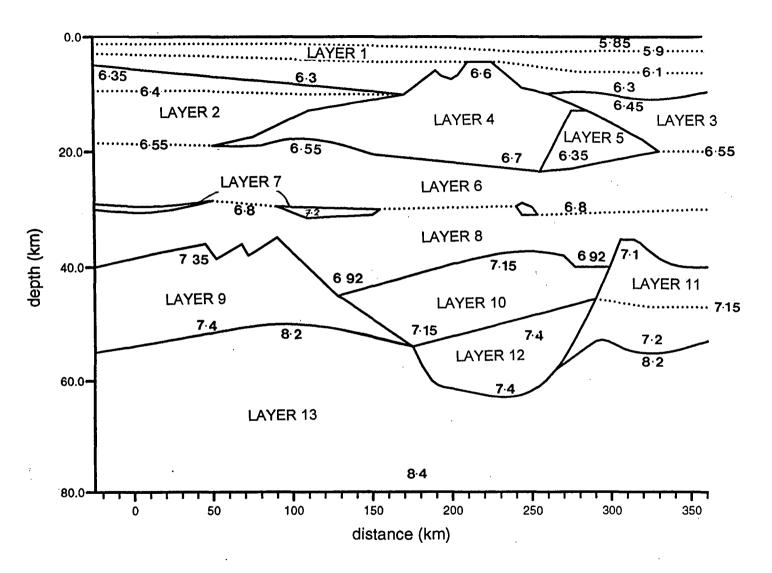


Fig. 7.17 Model A: final velocity model for in-line stations 101P and F01A.

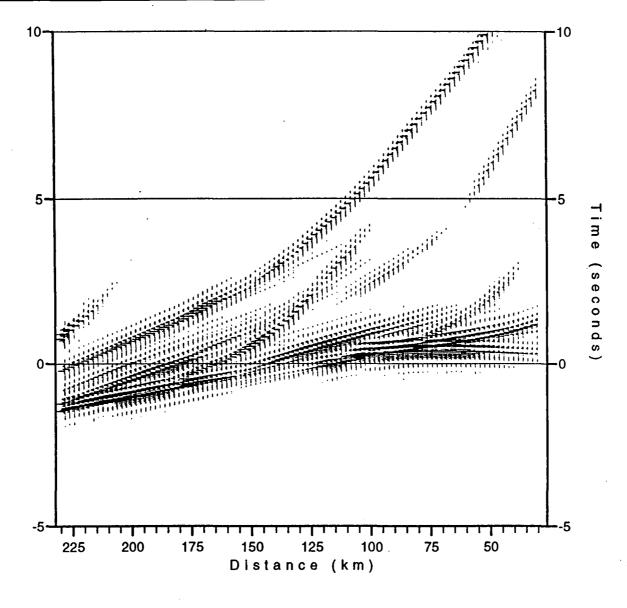


Fig. 7.18 Synthetic section generated for station 101P from Model A.

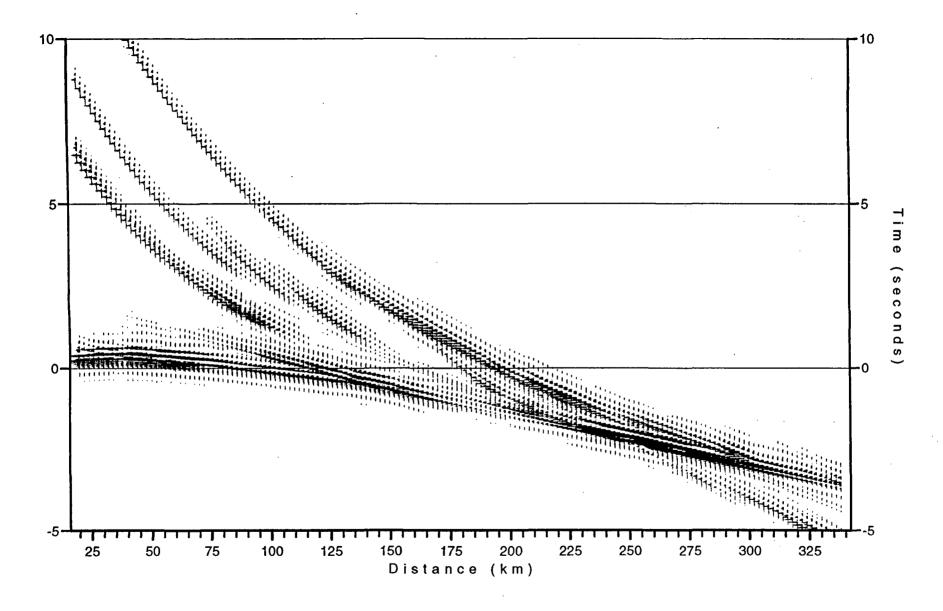


Fig. 7.19 Synthetic section generated for station F01A from Model A.

BABEL Line 1 Model A Station 101P

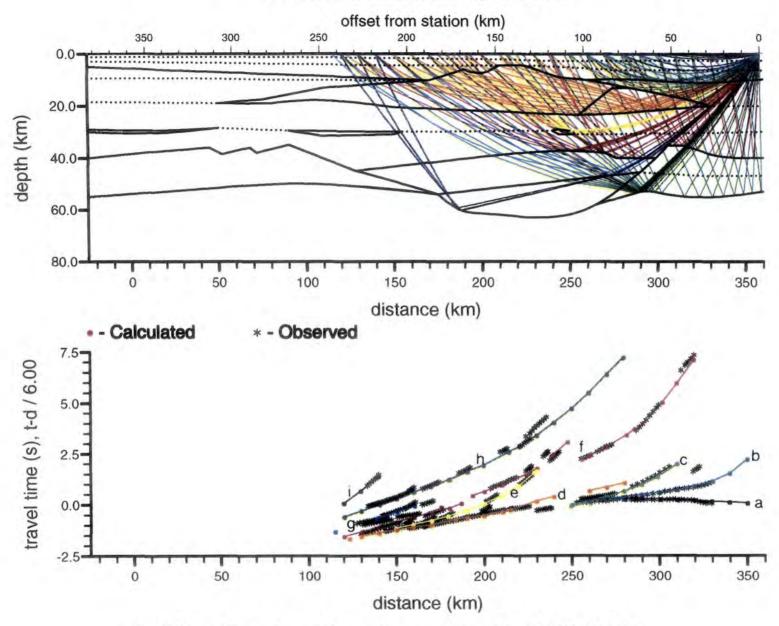


Fig. 7.20 Raypaths and travel time curves for station 101P, Model A.

BABEL Line 1 Model A Station F01A(114)

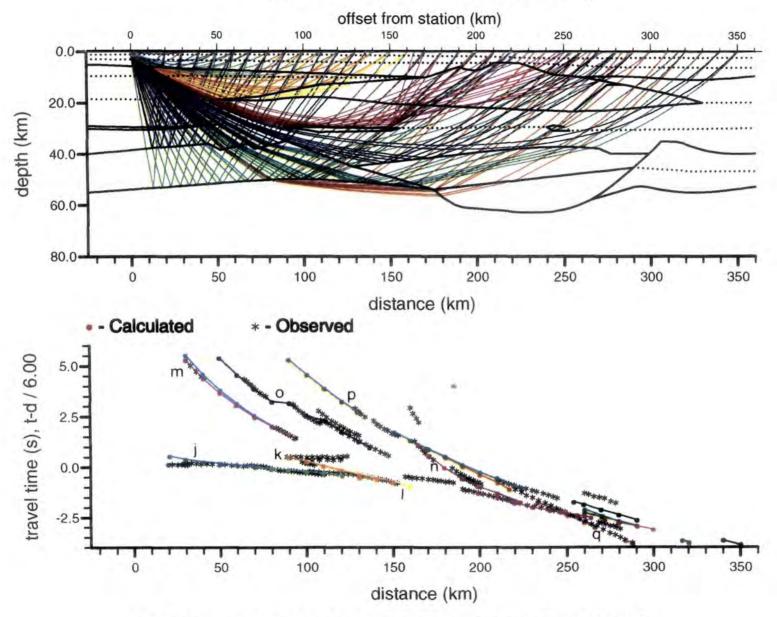


Fig. 7.21 Raypaths and travel time curves for station F01A, Model A.

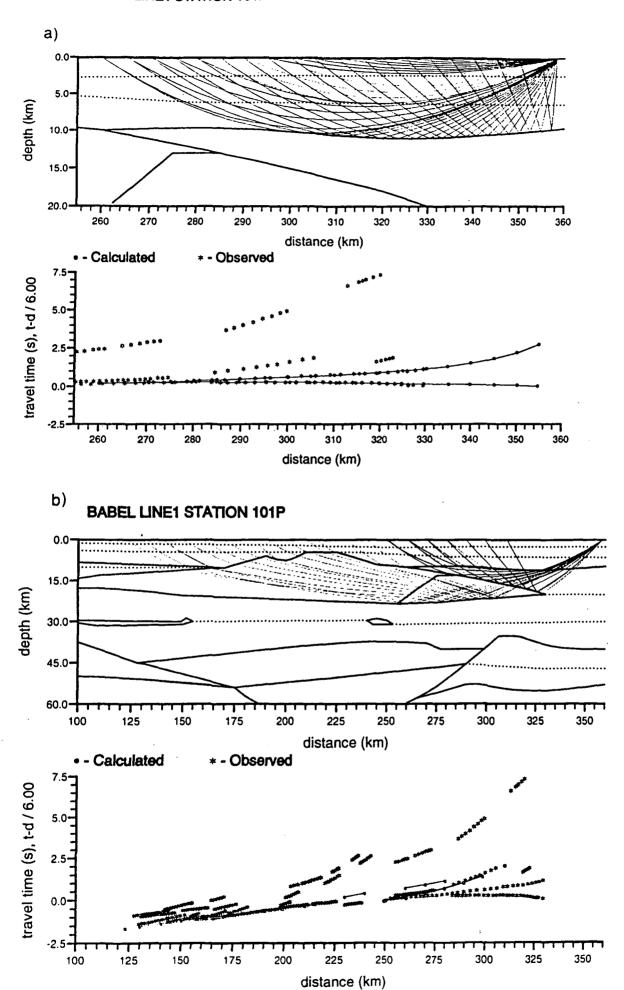


Fig. 7.22 Breakdown of raypaths and travel time curves for station 101P

a) Layer 1

b) Layers 3 and 5

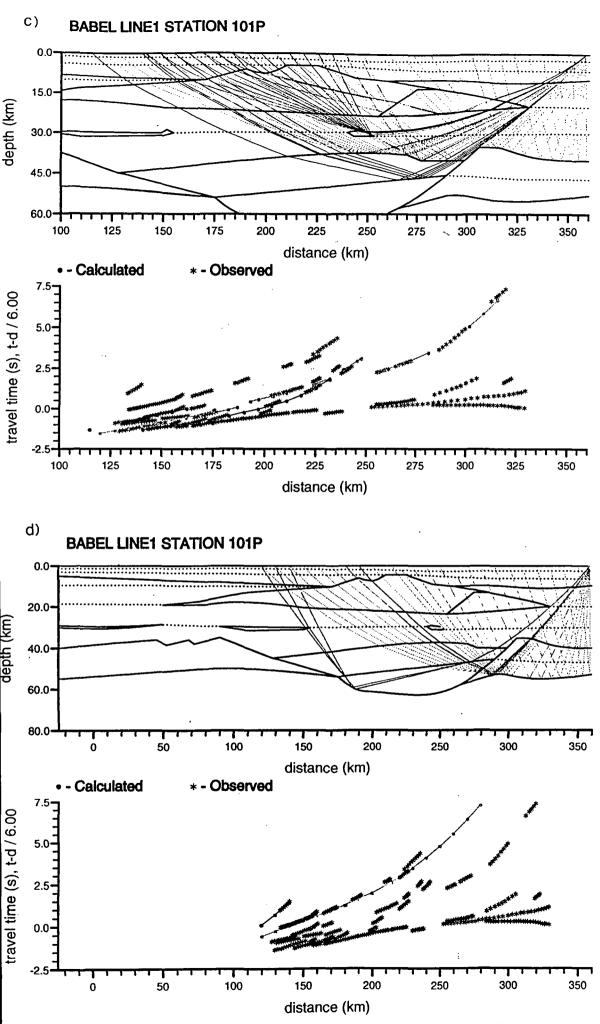
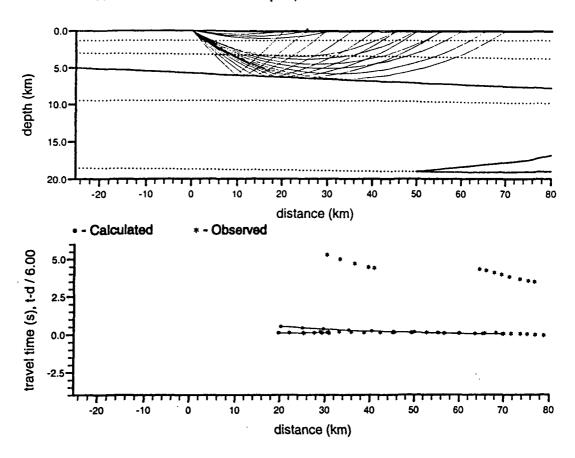


Fig. 7.22 (cont.) Breakdown of raypaths and travel time curves for station 101P c) Layers 6, 8 and 10

d) Layers 11 and 12





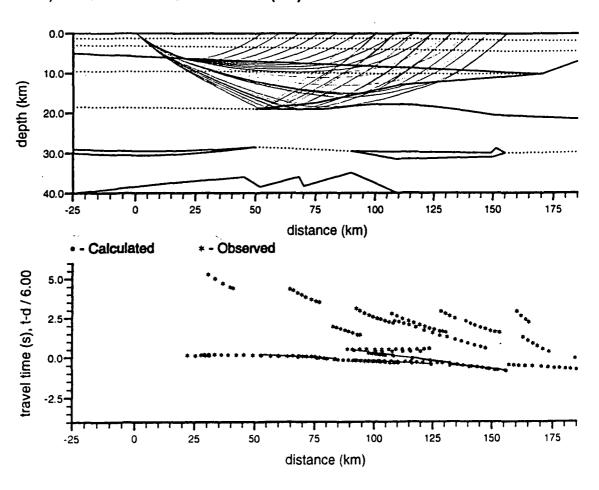


Fig. 7.23 Breakdown of raypaths and travel time curves for station F01A.

a) Layer 1

b) Layers 2 and 4

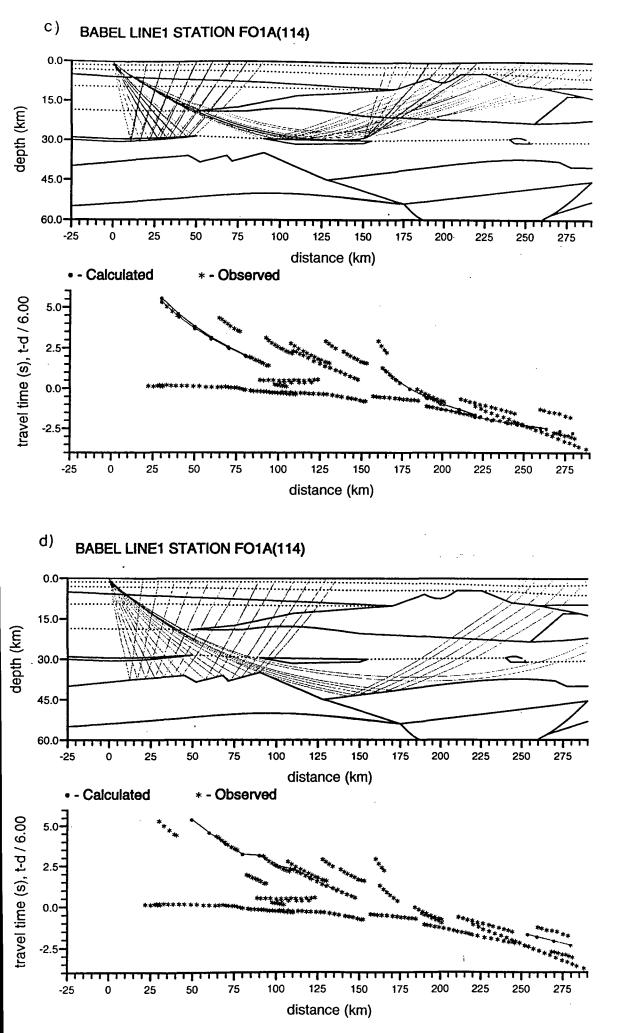


Fig. 7.23(cont.) Breakdown of raypaths and travel time curves for station F01A.

c) Layer 6

d) Layer 8

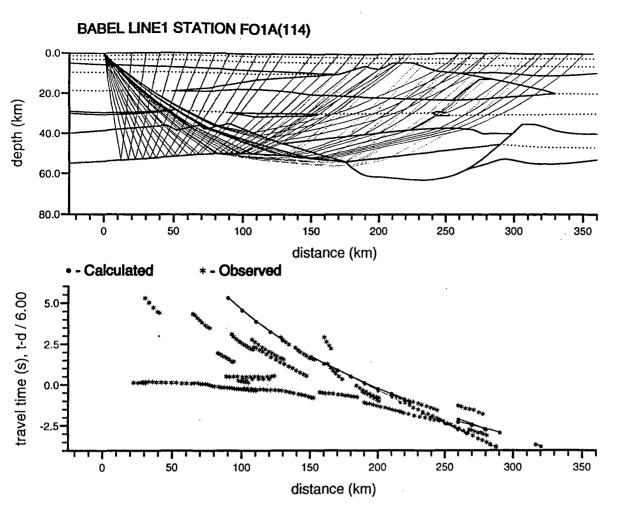


Fig. 7.23(cont.) Breakdown of raypaths and travel time curves for station F01A.

e) Layers 9 and 13

These bodies also mark the lower limit of crustal diving rays observed in the data.

The lower crust is the most complicated part of the model. At station F01A two arrivals are seen which are interpreted as lower crustal reflections (o and p). The earlier of these (o) appears to be segmented, made up of shorter arrivals of slightly greater apparent velocity than the general trend of the energy. This has been modelled using a jagged interface (boundary between layers 8 and 9, Fig. 7.23d). The high amplitude of this arrival indicates a large velocity contrast across the boundary. However, no diving ray is associated with layer 9 below this boundary. The second of the two reflected phases (p) seems to arise from the base of the crust as it ties in with the subcrustal diving ray (q), although its amplitude is lower at nearer offsets than the first (Fig. 7.23e).

From the northern end, again two major lower crustal arrivals have been modelled (*f* and *h*). The first of these (*f*) is the lower in amplitude and is in fact only seen as short coherent segments in the data. To model this it was necessary to have high relief on the reflecting boundary (boundary between layers 8 and 10,11, Fig. 7.22c). It is not certain that all the arrival segments arise from a continuous boundary. The second arrival (*h*) is a reflection from a deeper boundary. This has been interpreted as the Moho although no subcrustal diving rays are seen from station 101P to verify this due to the loss of data beyond 230 km offset (Fig. 7.22d). This interpretation is not unreasonable due to the arrival's high amplitude and lower crustal origins. The Moho reflection is often regarded as the highest amplitude long offset arrival on the record section though the strict definition of the Moho is the point where the velocity exceeds 8 km s⁻¹.

The latter arrival (h) is preceded by a shorter parallel arrival of similar amplitude which only appears beyond an offset of 180 km (g). It is therefore modelled by an interface at depth ~48 km (between layers 10 and 12) which ends at 290 km in the model (Fig. 7.22c). It is interesting to note that the Moho reflection arises from only a short length of the actual boundary between 270 and 300 km. A high apparent velocity arrival at the southern end of the 101P record section (i) is modelled as a reflection from a steeply dipping part of the Moho representing the far wall of a trench (Fig. 7.22d).

The subcrustal diving ray (arrival q) recorded at station F01A indicates that the velocity below the Moho is 8.2 km s⁻¹ (Fig. 7.23e).

The overall impression given by the model is of a three layer crust cut by a wide disrupted zone. The middle and upper crust are similar at the northern and southern extremes of the model while the seismic velocity of the lower crust appears to be higher at the southern end than at the northern end. The central segment is a combination of the two.

7.3.3 Model B: Station 1A

When the two off-line stations (1A and 5A) were added to Model A in order to constrain it further, it became clear that they would have to be modelled separately, the upper- and mid-crustal arrivals being quite different.

The nearest offset of data for station 1A is 100 km so no structure is determined for most of the upper crust. The velocities have been chosen so that the apparent velocity and travel time of the first observed arrival is correct. Figs. 7.24 and 7.25 show the velocity model and synthetic section

for station 1A respectively while Figs. 7.26 and 7.27 shows the raypaths and travel time graphs. The velocity increases steeply from 5.95 km s⁻¹ to 6.2 km s^{-1} at a depth of 3 km and then with a shallower gradient to 6.4 km s^{-1} at 10 km and 6.65 km s^{-1} at 18 km (layer 1, arrivals a and b, Fig. 7.27a). This last interval is similar in velocity and gradient to the northern and southern extremes of Model A described above.

Below 18 km there is a lower velocity zone, the velocity dropping to 6.45 km s^{-1} across the boundary and then rising to 6.5 km s^{-1} at 24 km and 6.75 km s^{-1} at an interface which increases in depth from 30 to 36 km between 200 and 300 km in the model (layer 2). The decrease in velocity at 18 km depth is required to explain the step out in the first arrival at 170 km offset (phases *b* and *c*, Fig. 7.27b).

The next interface also dips gently to the north from 43 to 47 km depth, the velocity above reaching 7.0 km s⁻¹. At 190 km along this boundary there is an irregularity, represented by a hump, from which a diffraction-like event occurs (arrival e). The boundary to the south of this feature is not defined by reflected arrivals in the data (Fig. 7.27c). A similar feature occurs on the Moho at 55 km depth, 175 km along the model (arrival g, Fig. 7.27d). The velocity above the Moho increases from 7.4 to 7.6 km s⁻¹, similar to the southern end of Model A. A third diffracting event (i) occurs in the upper mantle at a depth of around 65 km, 135 km along the model (Fig. 7.27e). No reflecting boundary is seen to the north of this so it has been modelled as the northern end of a thin low velocity body (layer 6). Laminations of the upper mantle have been modelled before in the Baltic Shield (Cassel and Fuchs, 1979; Lund, 1979). If these three diffracting features form part of the same structure, they may be related to the northern wall of the trench-like feature in Model A.

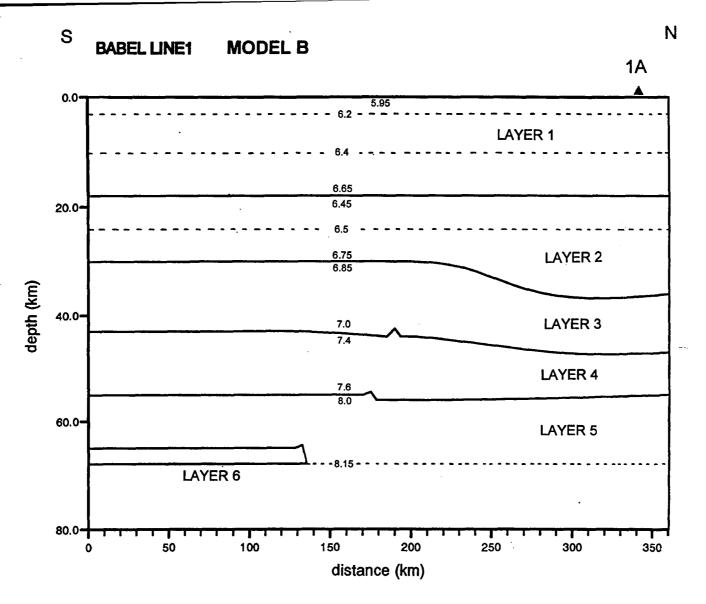
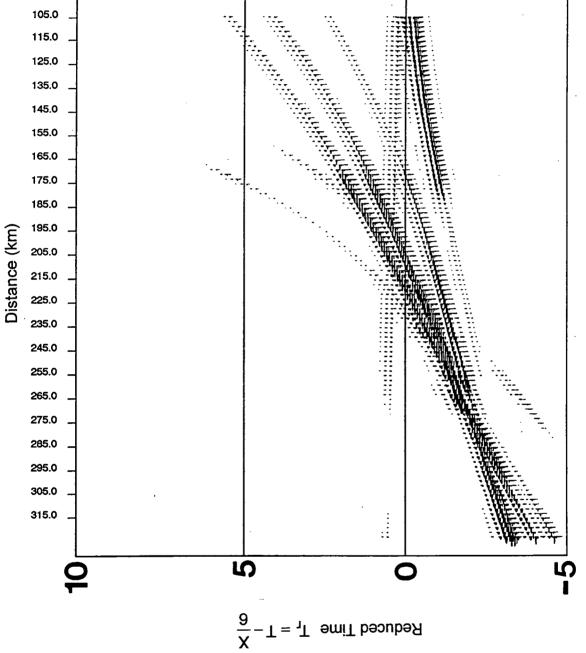


Fig. 7.24 Model B: Velocity model for off-line station 1A.





BABEL Line 1 Model B Station 1A

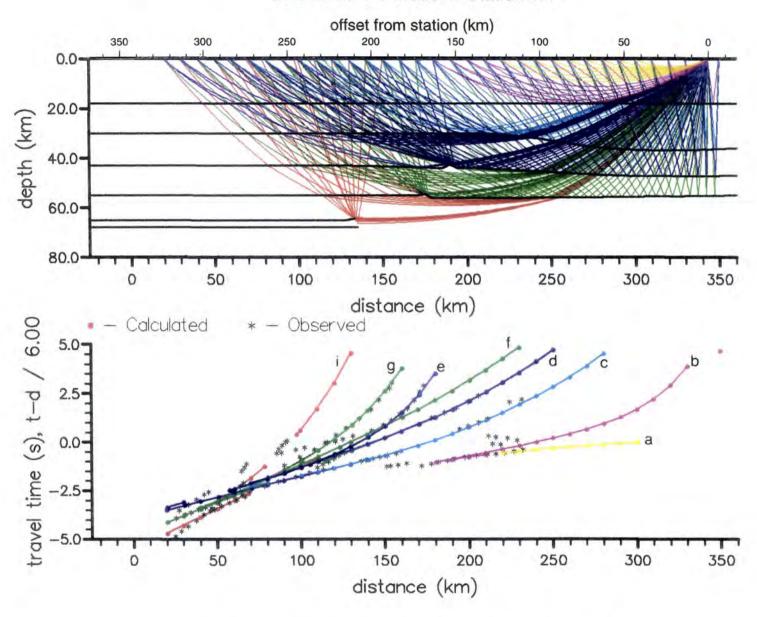
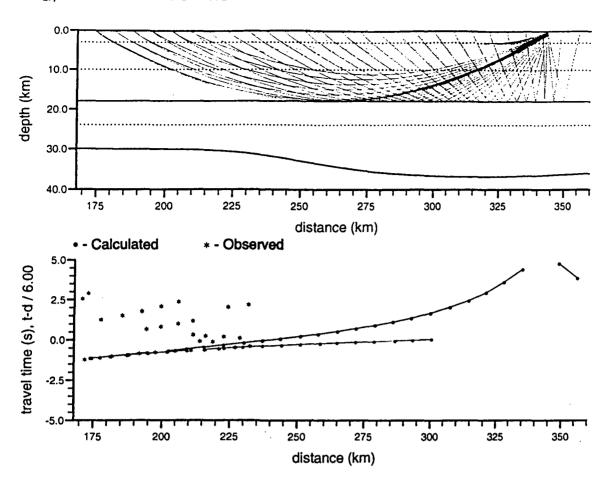


Fig. 7.26 Raypaths and travel time curves for Model B, station 1A.

a) BABEL LINE1 STATION 1A



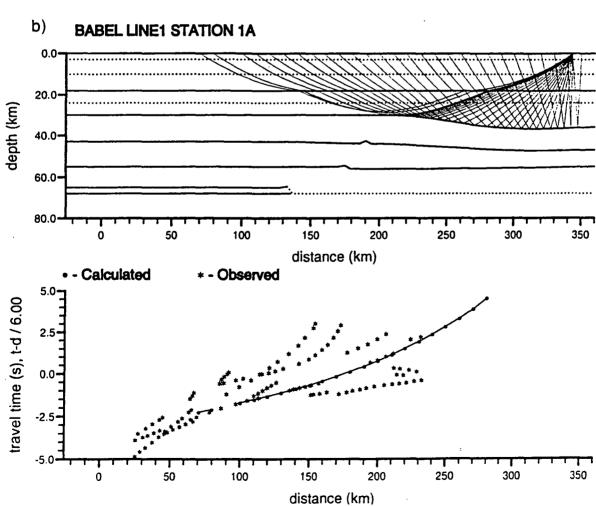


Fig. 7.27 Breakdown of raypaths and travel time curves for Model B, station 1A.

a) Layer 1

b) Layer 2

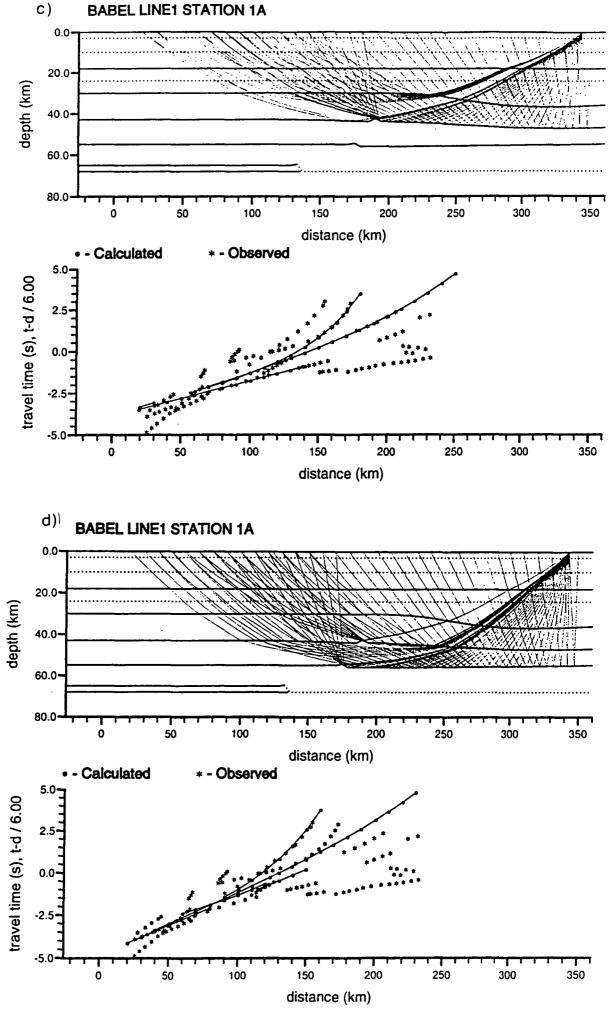


Fig. 7.27(cont.) Breakdown of raypaths and travel time curves for station 1A.

c) Layer 3

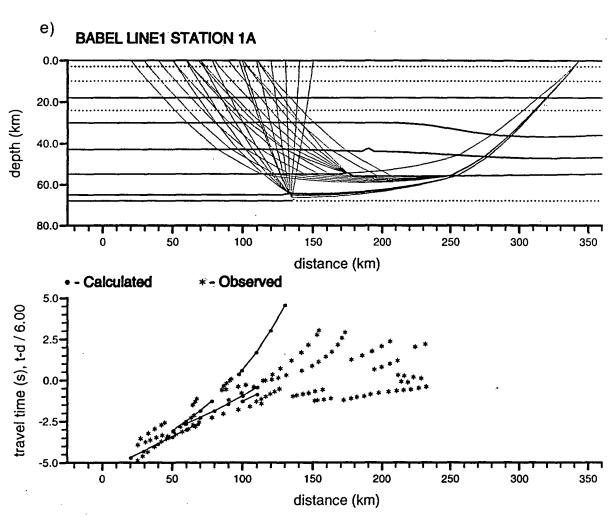


Fig. 7.27(cont.) Breakdown of raypaths and travel time curves for station 1A.

e) Layer 5

7.3.4 Model C: Station 5A

The model for the southern station 5A bears greater resemblance to Model A (Figs. 7.28 to 7.31). The upper crust (layer 1) is again not defined by the data. The early travel time of the first arrival with an apparent velocity of around 6 km s⁻¹, however, proved difficult to model. This arrival appears to have a varying apparent velocity and is interpreted as being made up of a higher velocity arrival (*b*) from a diving ray in a high velocity layer between 5 and 9 km depth (layer 3) followed by a lower velocity reflection (*a*) from the boundary between layers 2 and 3 (Fig. 7.31a). The high velocity layer 3 pinches out toward the centre of the model. The middle crust is fairly featureless with only one reflecting interface between layers 4 and 5 which dips from 25 km depth at the southern end to 31 km at the centre of the model and is defined by arrival *c* (Fig. 7.31b).

From the lower crust, again there are two strong reflections (d and e), the earlier of which is apparent only at shorter offsets (d, Fig. 7.31c) whilst the later is seen at longer offsets (e, Fig. 7.31d). Thus the first reflector is cut away to form a trench, as in Model A. Here, however, the northern wall is imaged from the south (arrival f). The upper mantle velocity is found from arrival g to be 8.1 km s⁻¹ (Fig. 7.31e).

In theory, gravity modelling could be used to constrain Models B and C further, as for Model A. However, since both models are derived from off-line data, the interfaces at depth do not lie in the same vertical plane so 2D gravity modelling is not really appropriate.

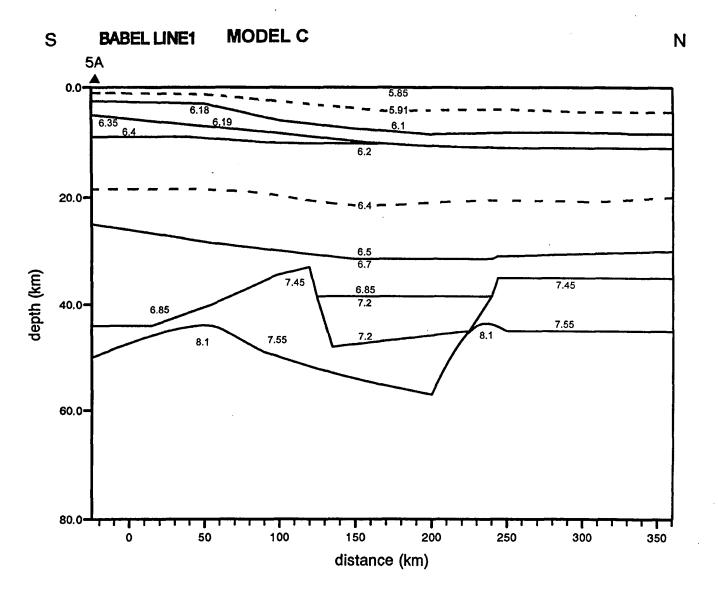
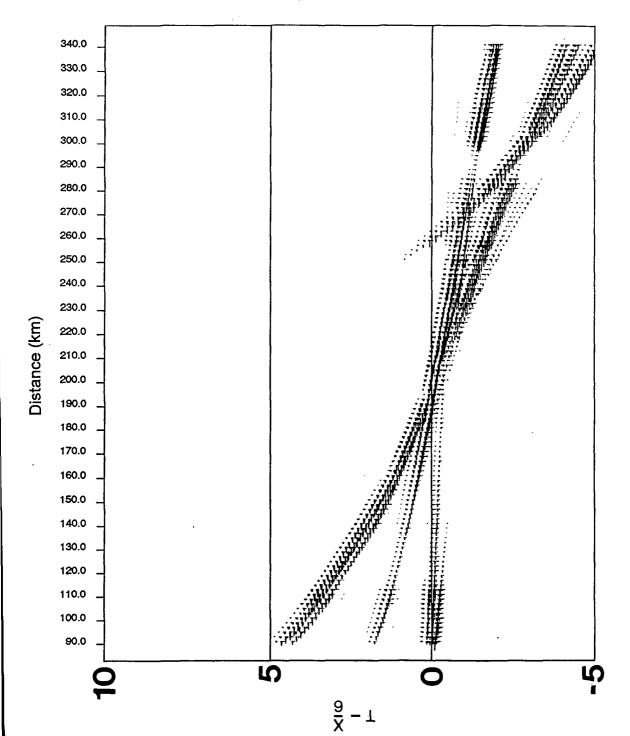


Fig. 7.28 Model C: Velocity model for off-line station 5A.



.29 Synthetic section generated for station 5A from Model C.

BABEL Line 1 Model C Station 5A

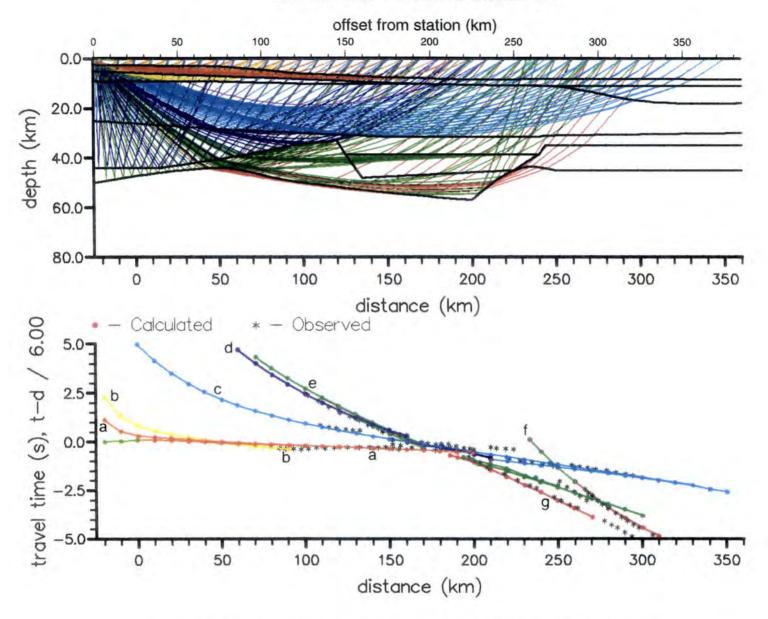


Fig. 7.30 Raypaths and travel time curves for Model C, station 5A.

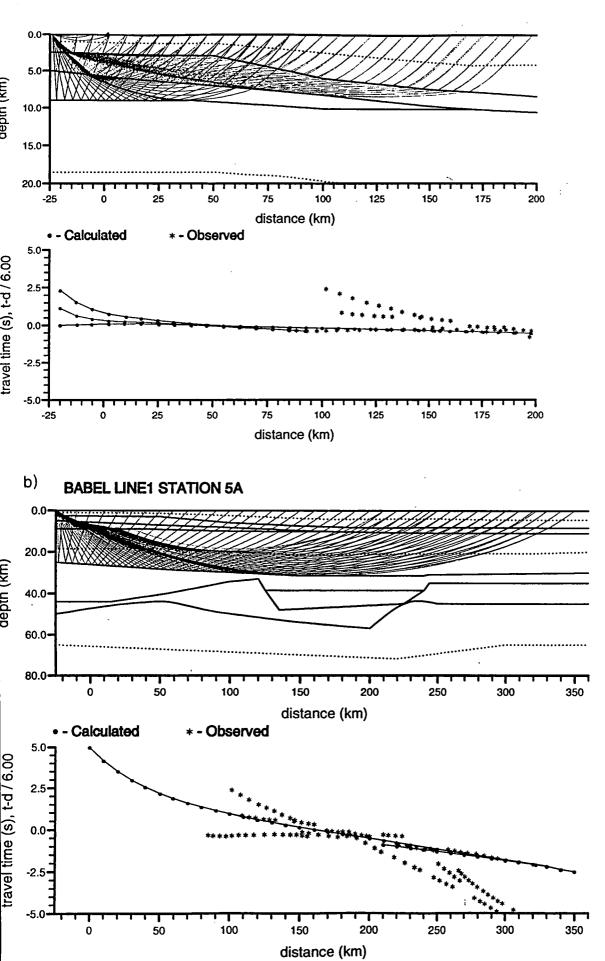


Fig. 7.31 Breakdown of raypaths and travel time curves for Model C, station 5A.

a) Layers 1, 2 and 3

b) Laver 4

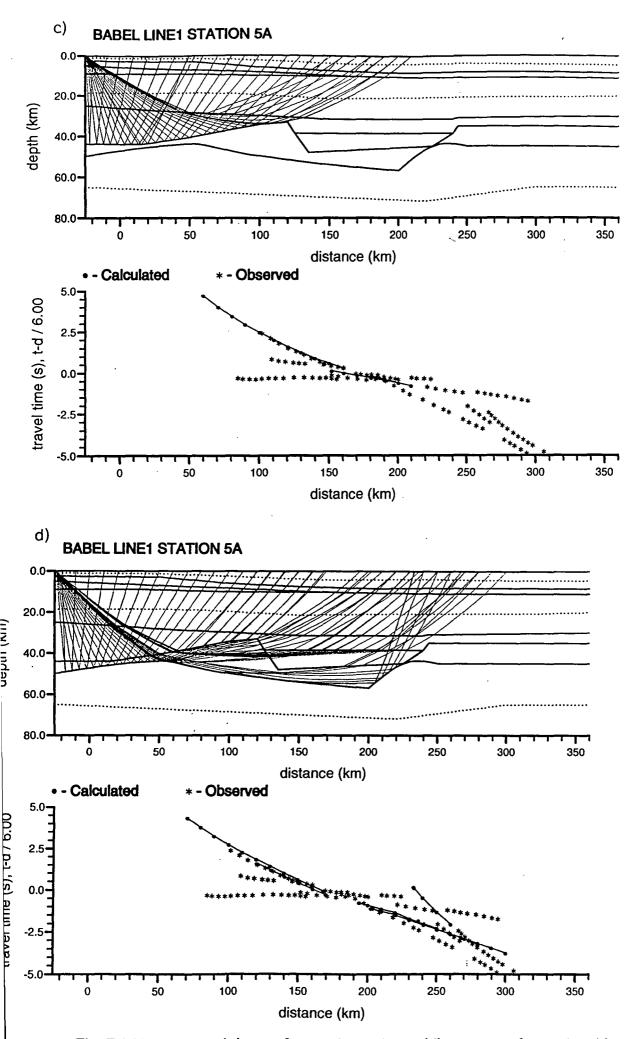


Fig. 7.31(cont.) Breakdown of raypaths and travel time curves for station 1A.

c) Layer 5

d) Laver 7

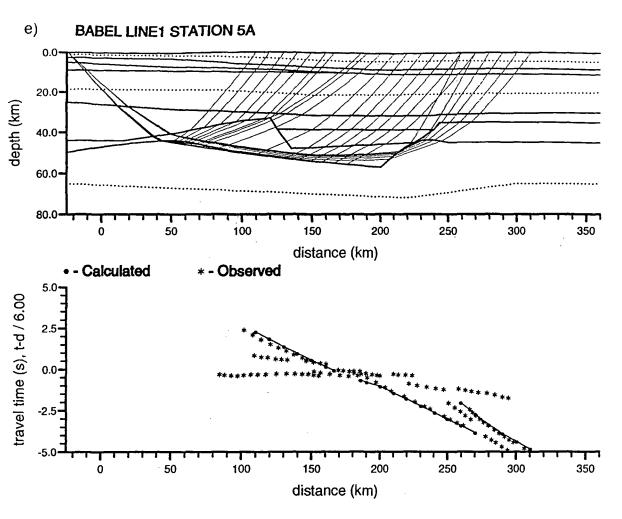


Fig. 7.31(cont.) Breakdown of raypaths and travel time curves for station 1A.

e) Layer 8

7.4 Accuracy of the model

The major sources of error in the model arose from the shot and receiver locations, the picking of arrivals, and the fitting of calculated travel time curves to digitised, picked arrivals. As stated earlier, the shot location error was taken to be ±50 m and that of the receiver locations ±100 m. The arrivals could be picked and digitised to an accuracy of ±10 ms (~±1/4 wavelength) and the modelled travel time curves fitted to a similar accuracy. The total resultant error in the model itself is harder to assess. The ray diagrams show that large regions are poorly covered and some not at all (Figs. 7.20, 7.21, 7.26 and 7.31). Few diving rays pass through the lower crust so the velocities here are theoretically not well constrained. However, the reflected rays from the lower crustal boundaries, especially divergent reflections from curved boundaries, give velocity information at large offsets similar to diving rays. This provides a certain level of constraint on velocities.

In the upper crust, little velocity information is known for the extremes of the model, or for the uppermost central part, where all the rays are near vertical. This lack of accurate velocity information for the uppermost crust leads to increased uncertainty in the rest of the model. In the deeper regions of the model where velocity is not well constrained, i.e. at the northern and southern extremes, trade-offs between velocity and depth are possible. On the other hand, many of the reflecting boundaries, especially those of high curvature (such as the mid- and lower-crustal diffracting points in Models A and B and the northern wall of the Moho trench in Model C), need only be displaced by tens of metres to destroy the fit of the travel time curve.

Gravity data provides further constraint to the model, especially in the upper crust from where most gravity anomalies arise. Two dimensional gravity modelling by itself cannot produce a uniquely determined model but, combined with the seismic model, it is invaluable in helping to determine the structure in parts of the model poorly covered by seismic rays and give a general idea of appropriate velocities from the density information. The resulting changes to the seismic model only go to demonstrate the non-uniqueness of travel time modelling alone, i.e. seismic data also fails to adequately constrain the detail of a model.

7.5 Three dimensional aspects of the model

The major problems in working with three dimensional data were the limitations of the modelling package (i.e. the model itself is limited to two dimensions) and the presentation of three dimensional information.

Although a 3D ray tracing package became available at a late stage during this project (ANRAY86, Gajewski and Psencik, 1986), it had several major drawbacks which made it unsuitable for modelling the BABEL Line 1 dataset. The main disadvantage was the severe limitation in the complexity of the model which could be defined, i.e. no merging boundaries, steps on interface surfaces or laterally varying velocities were allowed. In addition, modifications were necessary in order to model off-line stations which made the program extremely long to run even for simple models (the package was designed to model 3D anisotropic media along a profile) and the Gaussian Beam approximation was not available. These limitations,

coupled with the difficulty in defining and adjusting the model precluded the use of ANRAY86 in this study.

Section 7.2 described how the fan spread data from stations 1A and 5A were approximated to two dimensions and modelled as such. In order to get an idea of the three dimensional implications of these models, it was necessary to carry out the reverse process. Figs. 7.32a-c show the reflectors in Models A, B and C which were actually imaged in the data. For Models B and C, the modelled rays corresponding to the observed arrivals were traced back to their shotpoints. For each ray, the reflection point was marked on a plan view of the area at the correct distance from the receiver along a straight line between the shot and receiver. It was assumed that the rays lay entirely in the vertical plane containing the source and receiver, i.e. no out of plane reflections were occurring, and also that the velocity structure close to each off-line station did not vary greatly with azimuth. For Model A, the reflection points were all assumed to lie in the vertical plane of the profile. Figs. 7.33a-d show the loci of reflection points resulting from this transformation. The reflecting boundaries in the three models were roughly correlated into four groups of similar depth and velocity.

The uppermost crust was ignored for the three dimensional interpretation as it was not imaged by station 1A, though there is a good correlation between the boundary at the southern end of both Model A (6.30 - 6.35 km s⁻¹) and Model C (6.19 - 6.35 km s⁻¹) at ~7 km depth. Fig. 7.33a shows upper crustal boundaries across which the velocity decreases from between 6.55 and 6.7 km s⁻¹ to between 6.35 and 6.55 km s⁻¹, from 6.4 to 6.2 km s⁻¹, and increases from between 6.35 and 6.55 km s⁻¹ to between 6.55 and 6.6 km s⁻¹. These are too few and too far

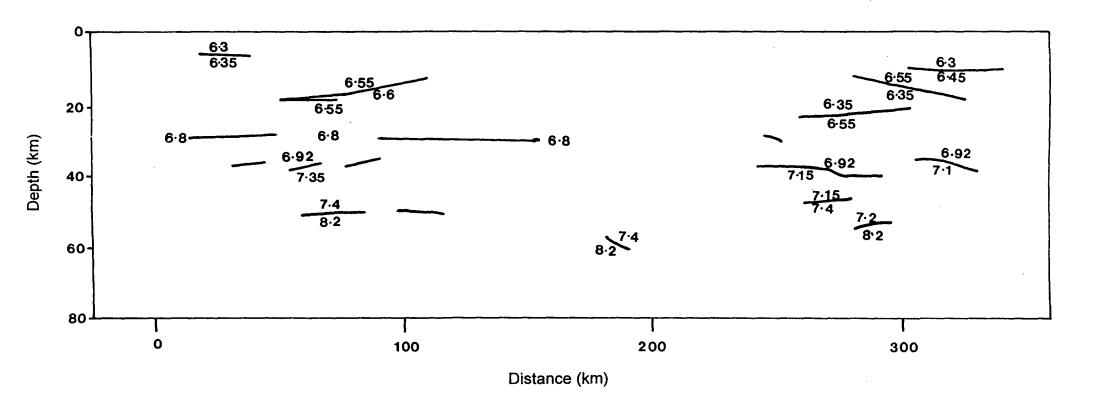


Fig. 7.32 a) Reflectors in Model A imaged in the wide angle data.

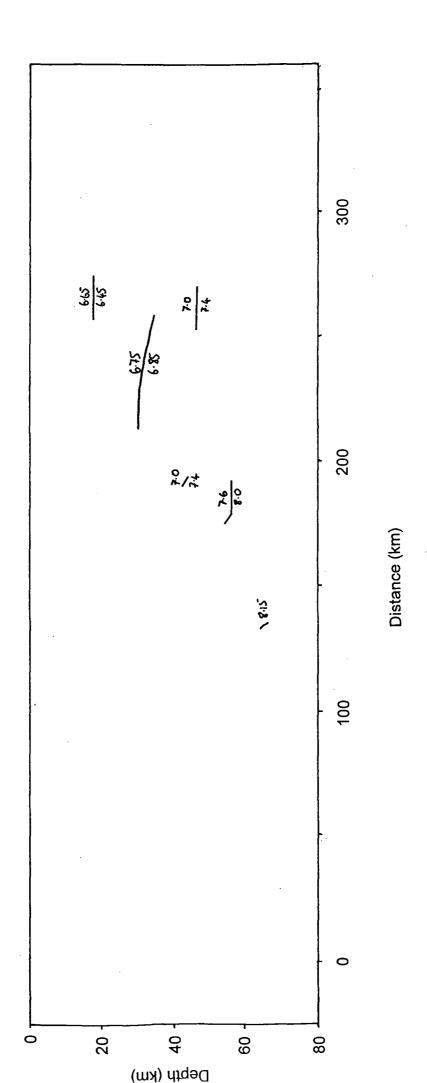


Fig. 7.32 b) Reflectors in Model B imaged in the wide angle data.

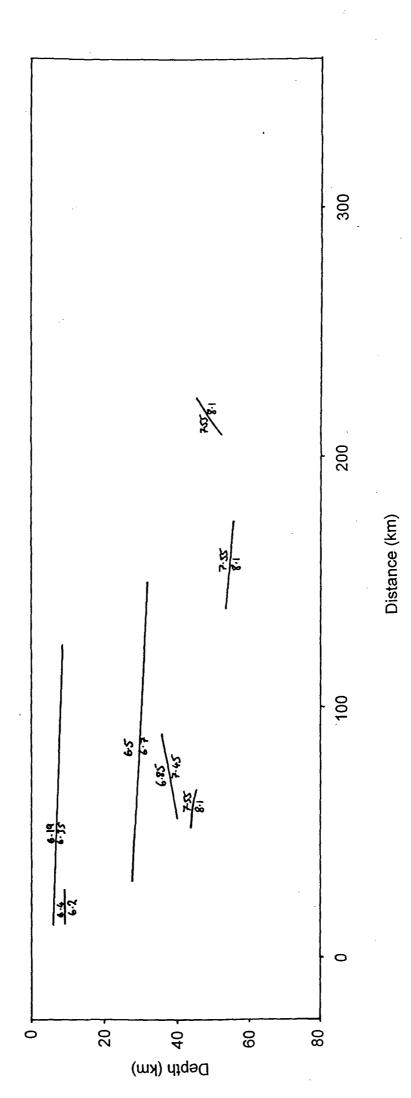


Fig. 7.32 c) Reflectors in Model C imaged in the wide angle data.

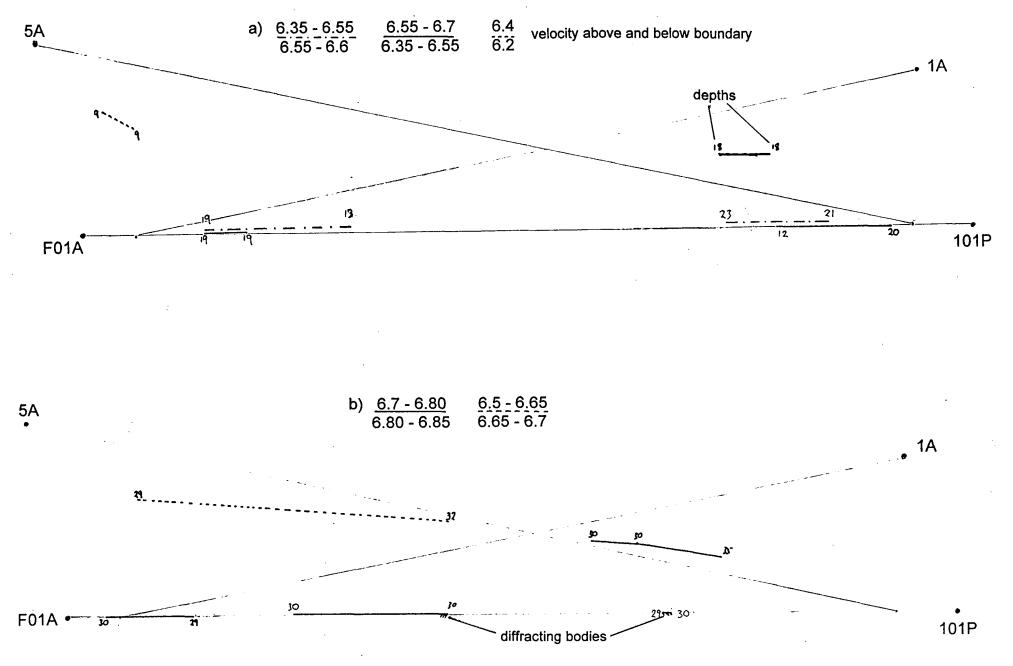
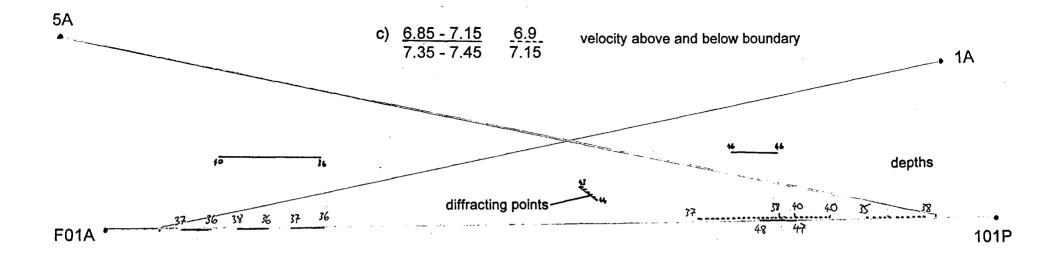
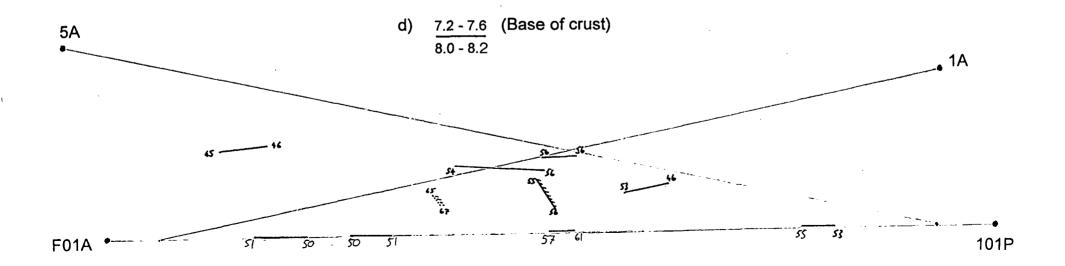


Fig. 7.33 3D aspects of the model: a plan view of the loci of reflection points in the three models.





apart to make any meaningful correlation between them. Fig. 7.33b shows the boundaries between 6.5 km s⁻¹ and 6.85 km s⁻¹, including the thin reflecting layers and diffracting bodies in Model A. It is obvious from the diagram that there is a wide spread discontinuous reflector of some sort at around 30 km depth.

The boundaries between mid and lower crust are grouped in Fig. 7.33c. There appears to be some correlation between the short dipping reflectors at the southern end of Model A and that in Model C. The layer of velocity 7.1-7.2 km s⁻¹ at the northern end of Model A does not appear to extend westwards as it is not seen in Model B. The boundary separating velocities ~7.0 and ~7.4 km s⁻¹ is deeper to the north.

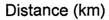
Much more detail can be seen in the base of the crust (Fig. 7.33d). The boundary dips from all directions towards a point roughly in the centre of the region. It is not clear whether this region of thickened crust extends either to the east or to the northeast of Line 1 but the evidence from stations 1A and 5A seems to indicate that the trend is approximately NE-SW and the dip is laterally limited to the west. The deep diffracting body seen in Model B does not appear to be related to any other feature in the three models.

If the structures controlling gravity in Model A (i.e. the high density upper crustal block and the Moho depression) could be linked with similar features in Models B and C, this could assist in defining the 3D structure. However, as mentioned above (section 7.3.4), 2D gravity modelling would be difficult for the off-line models and the upper crustal structures which give rise to much of the observed gravity anomaly are not imaged in these models due to the long offsets involved. Having said this, the NE-SW trend

of both the positive and negative gravity anomalies (Fig. 3.5) agrees with the trend of the Moho depression observed in the seismic models above.

7.6 Normal Incidence

The BEAM87 modelling package, designed for wide angle work, was modified by P.A.Matthews for normal incidence. Fig. 7.34 shows a normal incidence synthetic section generated by this for the in-line wide angle model. A discussion of the fit of the synthetic to the real data, together with an overlaid diagram, is given in the next chapter.



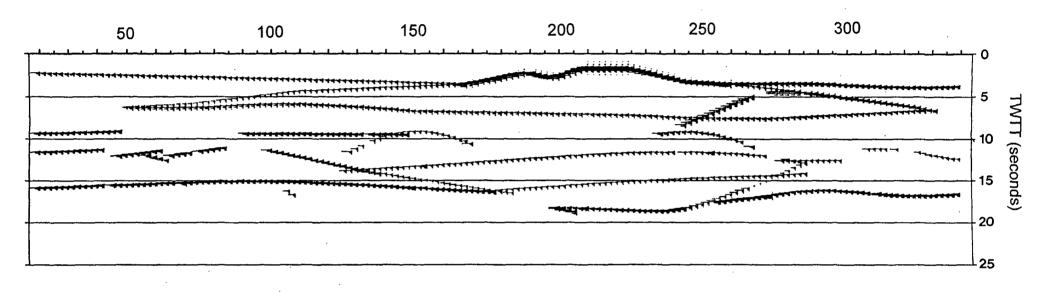


Fig. 7.34 Synthetic normal incidence section generated for the in-line model. True relative amplitude - no a.g.c. applied.

8. Discussion and Conclusions

8.1 Suitability of modelling software

The most obvious thing that can be said about the crustal models resulting from this study is that the ray theory approximation used is not really suitable for modelling such strong lateral velocity and structural variations.

Ray tracing packages such as BEAM87 are designed for modelling a horizontally layered crust with only small lateral variations. This is a reasonable assumption for traditional, low resolution refraction and wide angle reflection surveys in which continuous arrivals are traced over large distances. Each such arrival is considered to arise from a single continuous layer or boundary.

Modern high resolution datasets such as BABEL Line 1 reveal that in many instances this kind of interpretation is not accurate. Short length broken arrivals and large amplitude variations with offset appear to be more usual. The normal incidence data also show little indication of horizontal layering, nor does the geological history of the Svecofennides support this idea. Episodic igneous intrusions are thought to be part of the process of cratonisation (Nelson, 1991) and this would distort the original reflectivity patterns. There is plenty of evidence at the surface for such intrusions of various ages and sizes in the Svecofennides.

A modelling package designed for horizontal layers will bias the resultant model towards horizontal layers and these will obviously be employed in any part of the model with little or no data coverage. Although

selection and picking of arrivals at the interpretation stage may have a greater effect on the final outcome, as suggested by Ansorge et al (1982), the initial assumption of horizontal layering undoubtedly affects the interpretation. This was avoided as much as possible in the interpretation of the BABEL Line 1 model by picking only coherent sections of arrivals and not attempting to join them together at this stage.

In addition to the validity of the horizontal layer assumption, there are also other limitations of the modelling package. The method of defining the model employed here (i.e. linear vertical interpolation of velocities between isovelocity interfaces) means that the vertical velocity gradient in a layer which pinches out can become unreasonably large. Also, the velocity field in the vicinity of a strong fluctuation in a boundary becomes difficult to predict.

True diffractors cannot be modelled, only approximated by surfaces of high curvature. This may, in fact, be a more accurate representation of geological features. However, the Gaussian beam method does not give accurate amplitudes for reflections from highly curved interfaces so diffraction amplitudes cannot be used to constrain the model to any great extent.

Despite these drawbacks, the wide angle synthetic sections produced from the models are beginning to reflect the amplitude variations seen in the observed data.

Nearly all the seismic models in the Baltic Shield region were produced using BEAM87 or its predecessor SEIS83. Thus it must be borne in mind that similarities between the models may be due in part to the limitations and bias of the modelling package.

8.2 Normal incidence data and synthetic section

8.2.1 Comparison of observed and synthetic sections

It is clear that the synthetic normal incidence section as a whole (Fig. 7.34) does not tie up well with its observed counterpart (Fig. 6.22). Fig. 8.1 shows the synthetic section overlain on the real data. Those reflections from boundaries observed at wide angle are highlighted (see also Fig. 8.3). Major discrepancies include the lack of continuous reflectors seen in the observed data, and the transparent zone in the central part of the record section. The highlighted reflections, however, seem to have a closer correspondence to the observed data.

At the southern end, the reflection from the observed part of the upper crustal boundary in the model (~2.5 s, 20-40 km) ties in well with a short length reflector in the normal incidence data though its continuation to the north is not apparent in the data. Interestingly, a stronger reflector just below this at 3 s has no counterpart in the synthetic section. The strong reflection from the top of the modelled high velocity body in the synthetic section (2-4 s, 170-230 km) is not seen in the data but there is a patch of high reflectivity here and evidence for a northward dipping reflector between 230 and 245 km. The reflection from the observed part of the upper crustal boundary in the model (~4 s) at the northern end ties in well with a short length reflector in the normal incidence data while to the south of this it seems to merge with the lower of the strong reflectors previously interpreted as dolerite sills.

The reflection at 7.5 s (260 - 310 km) ties in with an observed reflection which marks the lower limit of upper-crustal reflectivity. The

dipping reflector between these (5 - 7 s) also has its counterpart in the data, especially at the bottom, and at the top where it merges with one of the strong reflectors interpreted as dolerite sills. The reflections at the southern end of the synthetic section at ~5 and 6 s (50 - 110 km) also tie in with observed reflections, the lower of these again appearing to be the base of a reflective zone.

The strong horizontal reflector seen near the middle of the synthetic section at about 9 s, 90 - 145 km, does not appear as a continuous arrival in the normal incidence data but there is evidence for short length reflectors close to the diffracting endpoint of the modelled reflector (140 km) and to its southern end (90 - 105 km). A similar reflector at the southern end of the model (9 s, 20 - 45 km) is quite well imaged in the normal incident data.

The normal incidence data show that the actual situation in the mid-to lower crust at the southern end of the model is far more complex than the simple jagged reflector modelled would suggest. Many short length horizontal and dipping reflections are seen, some of which can be tied in with the synthetic reflections from the parts of the jagged reflector observed at wide angle (~12 s, 30 - 80 km). The reflections at the northern end at similar travel times correspond closely with the top of lower crustal reflectivity.

The deepest reflector at the southern end of the synthetic section (~15 s) does not agree in travel time or dip with the deepest major reflector in the observed section although there is a case for it corresponding to the base of reflectivity. Further to the north, between 100 and 180 km, the reflector at 15 - 16 s does correspond well to the base of reflectivity.

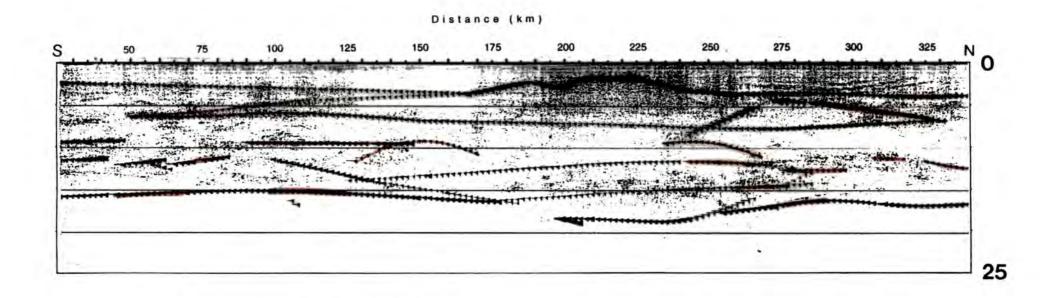


Fig. 8.1 Normal incidence synthetic section overlain on the real data. Reflections from boundaries observed at wide angle are highlighted. An a.g.c has been applied to the real data but not to the synthetic data.

At the northern end, the deepest boundary in the model can be tied in with a strong, short-length reflector in the normal incidence data which again marks the base of reflectivity (~16 s, 270 - 285 km), though the observed reflection has a slightly earlier arrival time than the synthetic one.

The only evidence for the modelled Moho depression is the continuation of reflectivity to deeper levels than the surrounding regions at the corresponding part of the observed section. No base to this is seen but the reflectivity gradually fades out. In addition, the base of crustal reflectivity on either side dips towards the position of the modelled depression.

Overall, it can be claimed that nearly all the synthetic reflections arising from the parts of modelled boundaries defined by wide angle reflections can be matched with observed normal incidence arrivals. However a great many more reflected arrivals are seen in the data which are absent from the synthetic section. The reasons for this are unclear. It may be that the short reflectors at the extremes of the dataset only appear in the wide angle data as low amplitude subcritical reflections which are not easily distinguished from multiple reverberations and background noise. Other reflectors may be of such short length and thickness that they are not seen as individual reflectors at wide angle but merely contribute to the complexity of other arrivals by scattering the energy.

8.2.2 Problems and assumptions made in the comparison

In comparing a normal incidence synthetic section generated from a model based on wide angle observations with the real normal incidence data, assumptions are made and several problems arise. It is assumed

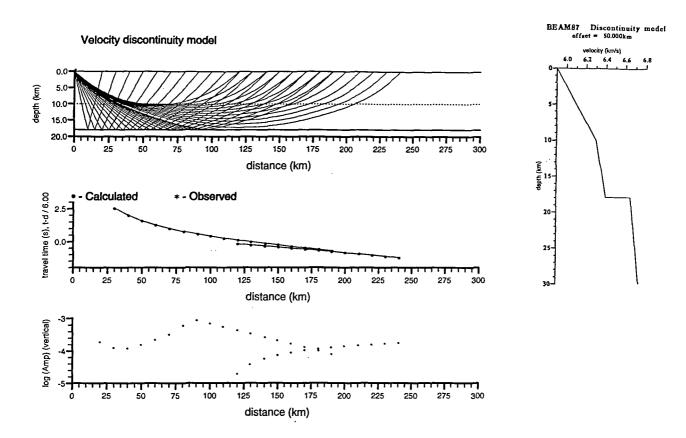
that features producing wide angle reflections will also produce normal incidence reflections and vice versa, i.e. wide angle and normal incidence reflections arise from the same geological features.

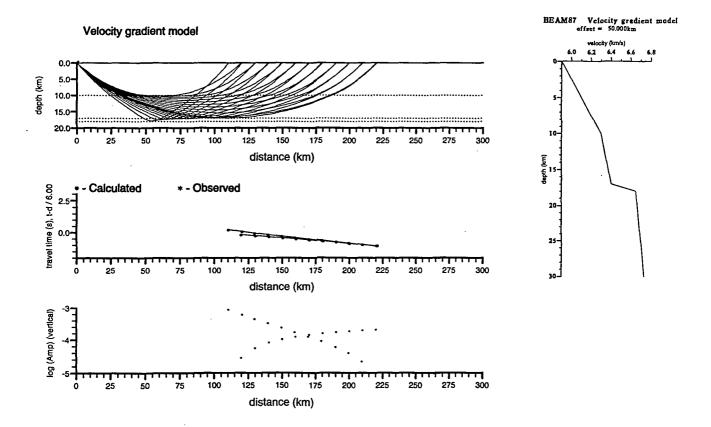
The first problem is that the wide angle model is produced from diving rays and a limited number of reflection events, many of which arise from short segments of a reflecting boundary. As mentioned in section 8.1, the modelling package requires long continuous boundaries. Therefore the reflectors actually giving rise to observed phases are extrapolated across the model and joined up with other such reflecting boundaries. Related to this is the fact that, due to the ray geometry, many reflectors are not imaged at all at wide angle, especially near-surface features at relatively long offsets from any receiver. These reflectors will be seen in the normal incidence data but will be absent from the model and hence from the normal incidence synthetic.

A related problem is the fact that near surface rocks beneath the source are not imaged in wide angle data and therefore not included in the wide angle model. In the real normal incidence section reflection amplitudes will be affected by the transmission qualities of these rocks but in the synthetic section they will not.

The down- and up-going wavefields for each phase in wide angle data experience a different geological column whereas in normal incidence data the up- and down-going wavefields experience the same geological column. The result of wide angle modelling will be to a certain extent an average.

Wide angle arrivals are frequently complex and often have a long wave train. They are generally interpreted as simple impulsive arrivals and modelled as such. The complex nature of the true arrival may be due to





Ray diagrams and travel time curves comparing reflected arrival with diving ray from a thin, high velocity gradient layer.

8.2

scattering from a group of short-length reflectors which will be modelled as a single reflector. In the normal incidence data such a cluster of short reflectors would appear as a patch of high reflectivity rather than a continuous reflection event.

Wide angle data generally contain less high frequency information than normal incidence data due to the longer raypaths involved. The limit of resolution for thin layers is therefore smaller for normal incidence data. Thus layers which are just resolved at normal incidence may appear as a single boundary at wide angle. Conversely, a transition zone between two velocities with thickness intermediate between the dominant, longer wide angle and shorter normal incidence wavelengths will appear as a reflector in wide angle data, where it approximates a velocity step and produces a reflection in the normal incidence synthetic section, but be entirely absent, from, or very weak in, the real normal incidence data.

In a similar vein, it is very difficult to distinguish between a true reflected arrival in wide angle section for which the subcritical part is not apparent, and a diving ray in a thin layer with a high velocity gradient (Fig. 8.2). The former would give rise to a reflected arrival at normal incidence whereas the latter would not.

Reflection amplitude varies with angle of incidence, being greatest near the critical angle. Certain reflectors will therefore appear prominent at wide angle and might be modelled as large velocity discontinuities while others, due to a different incidence angle, may have a much lower amplitude and be overlooked at the interpretation stage. Both reflectors would appear in the observed normal incidence data while only the first would appear in the model and synthetic section.

8.3 Comparison of BABEL models

BABEL Line 1 has also been modelled by Heikkinen and Luosto (1992) using off-line data from recording stations along the Finnish coast (Figs. 4.1, 8.6). Line 6 was modelled by Matthews (1993, Fig. 8.7) and Line 7 by both Bruguier (1992, Fig. 8.8) and Heikkinen and Luosto (1992, Fig. 8.9), all from in-line stations. Fig. 8.10 shows 1D velocity-depth profiles from different parts of each model.

The different models show similar velocity-depth trends, if possible lateral variations are taken into account. However, discontinuities are placed at different depths and the velocity contrasts correspond to these depths so that the models appear somewhat different. If the general velocity-depth trends are to be believed, this would point to a fairly continuous change of velocity with depth broken by short, discontinuous reflecting bodies which do not affect the overall velocity gradient. Since the models are produced from different datasets with different viewpoints, different short length reflectors are imaged causing velocity discontinuities to be placed at different levels in the model.

A noticeable difference between the models is the low velocity zone in Heikkinen and Luosto's Line 1 model (hereafter referred to as Model 1H, Fig. 8.6) which corresponds in depth to the high velocity block in Model A (Fig. 8.3) of this study. Line 6 (Fig. 8.7) has high velocity blocks in the upper crust at a similar depth to those in Model A although they are somewhat thinner. This is in agreement with the gravity anomaly due to the high density of this block which decreases in magnitude towards Line 6. The southern end of Line 1 Model C (Fig. 8.5) also has a high velocity

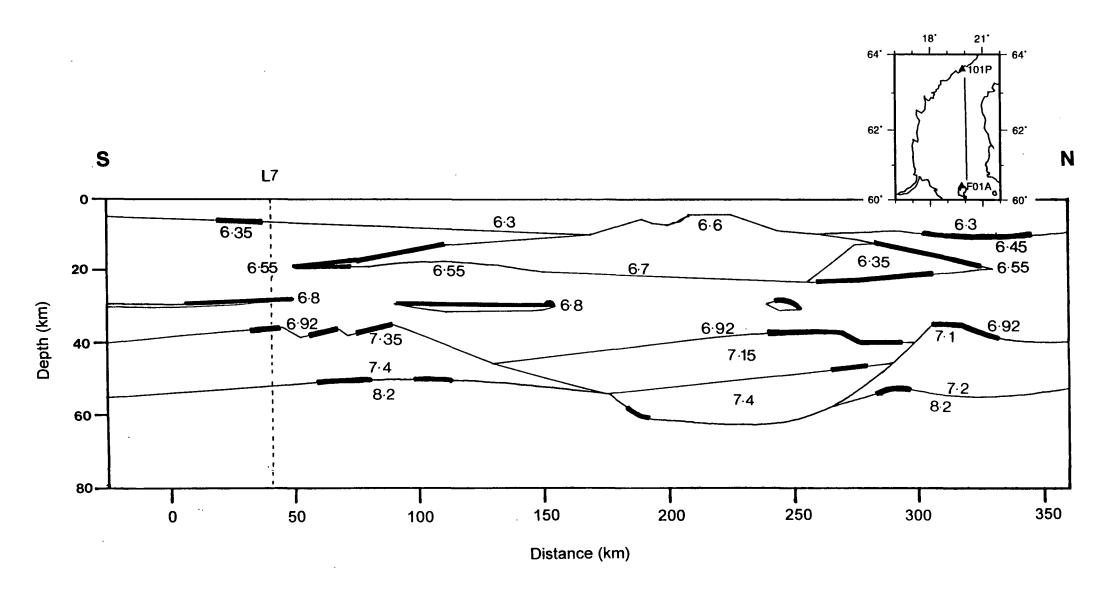
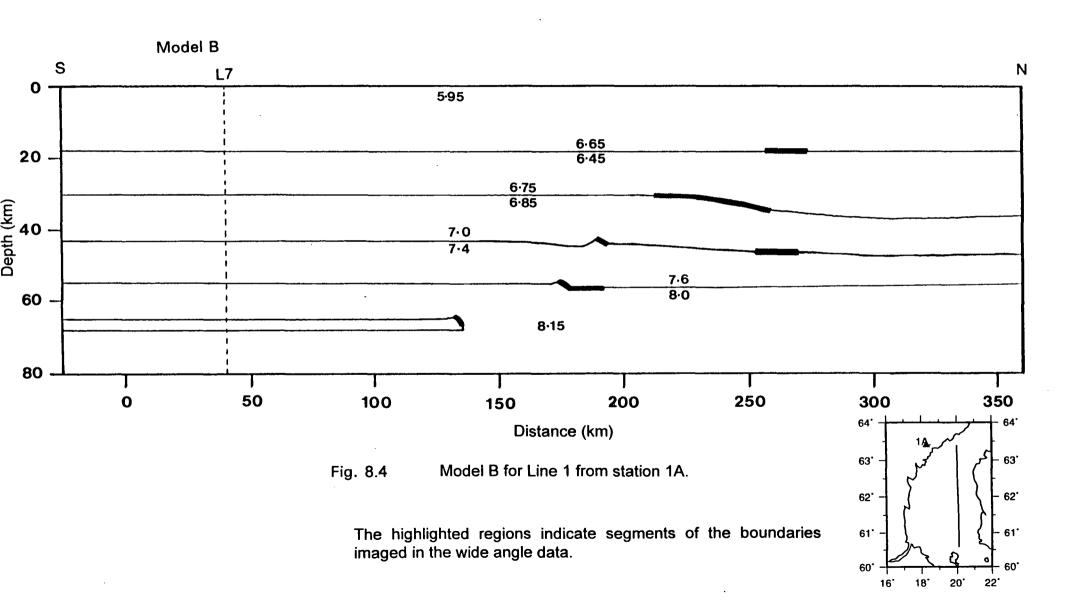
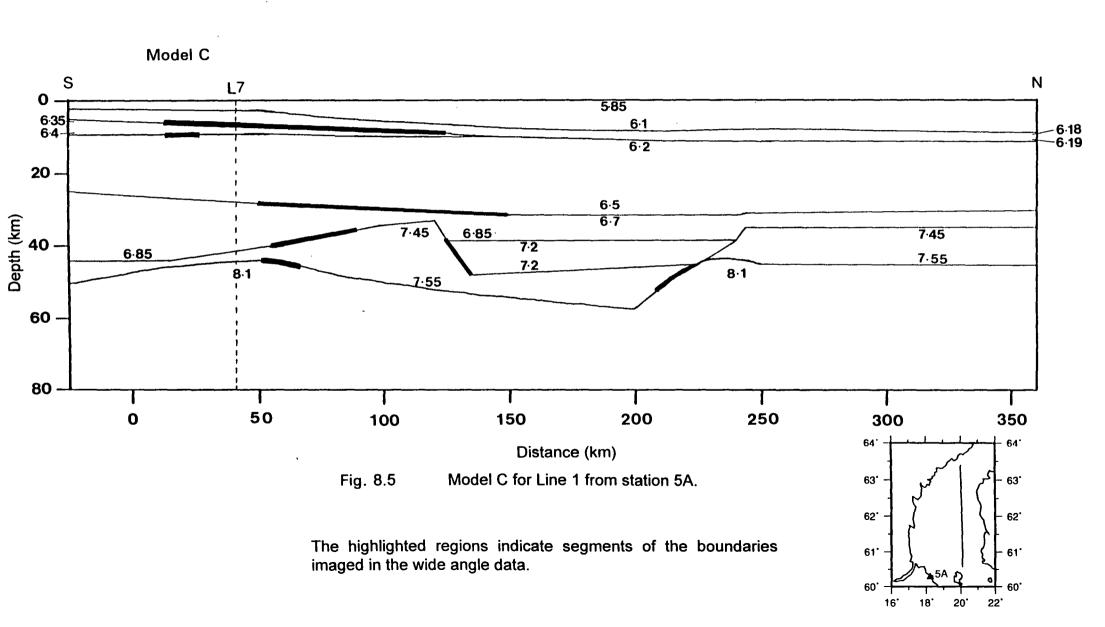


Fig. 8.3 Model A for Line 1 from stations F01A and 101P. Heavy lines indicate segments of boundary imaged in the wide angle data.





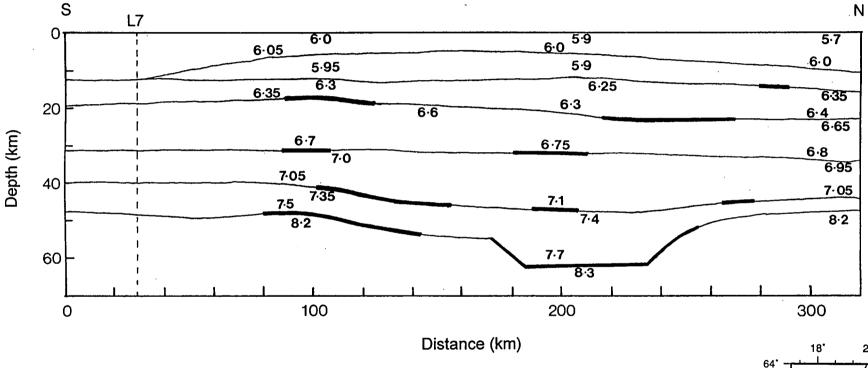
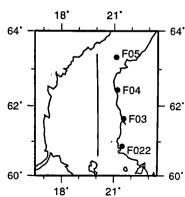


Fig. 8.6 Model for Line 1 from stations in Finland, after Heikkinen and Luosto, 1992.



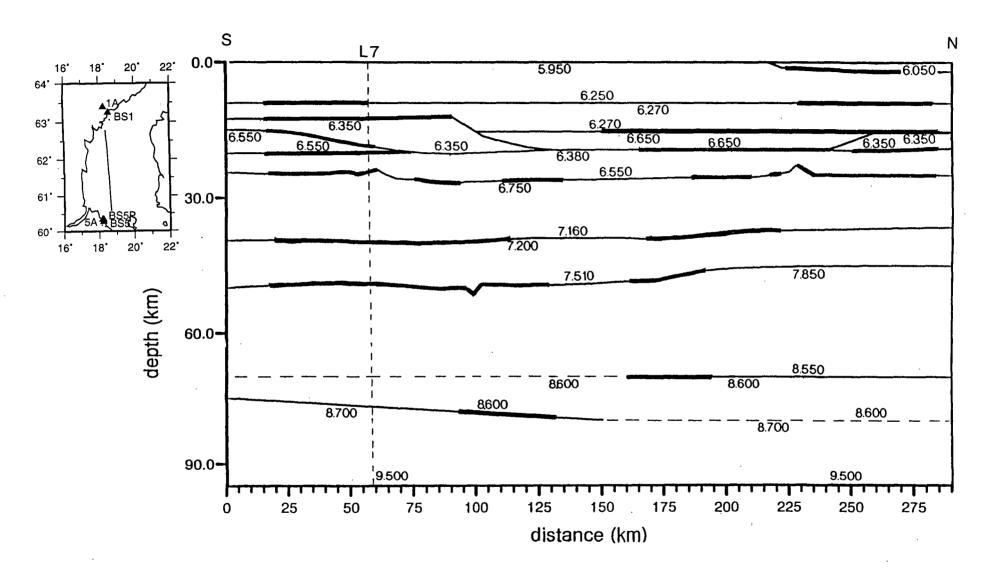


Fig. 8.7 Model for Line 6, after Matthews, 1993.

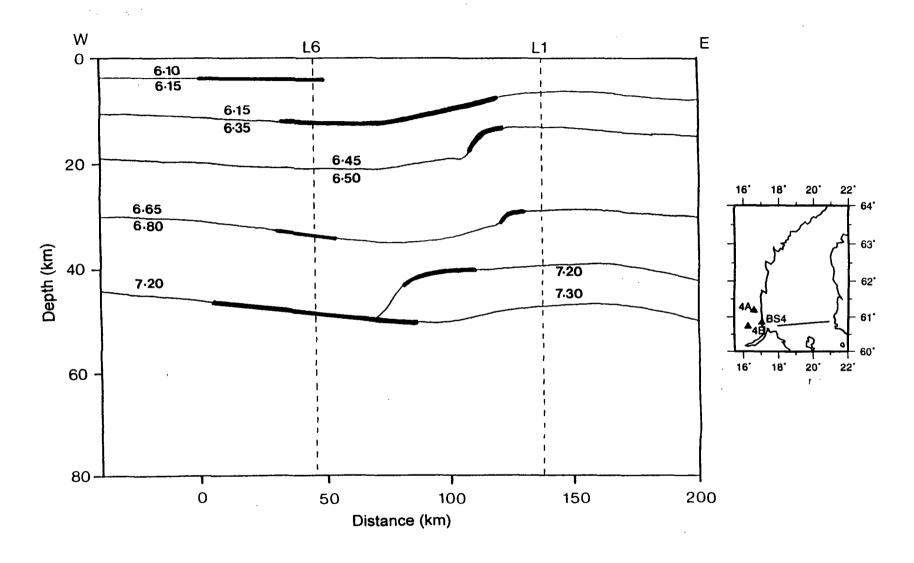


Fig. 8.8 Model for Line 7, after Bruguier, 1992.

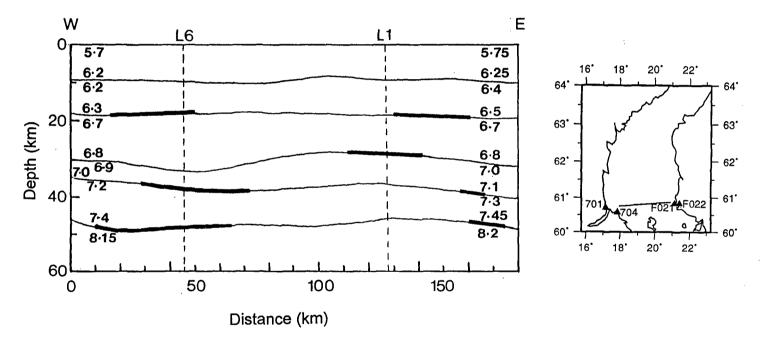


Fig. 8.9 Model for Line 7, after Heikkinen and Luosto, 1992.

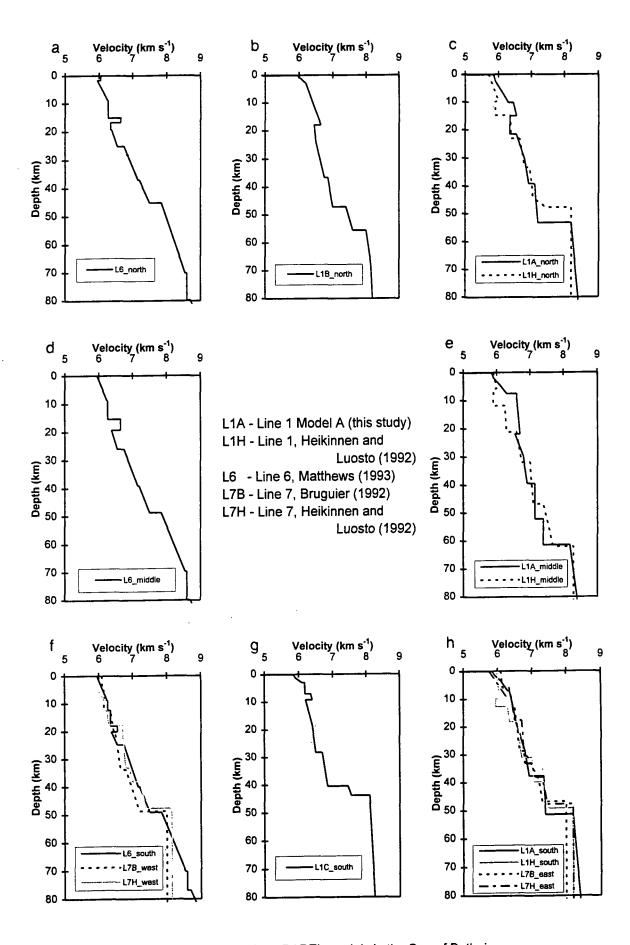


Fig. 8.10 Velocity profiles from BABEL models in the Sea of Bothnia

block which may correspond to that at the south of the Line 6 model though it is nearer to the surface.

In the model for Line 1 station 1A (Model B, Fig. 8.4), although structure in the uppermost crust is not imaged due to the distance of the nearest shot, the upper crustal velocity depth profile is similar to that at the northern end of the Line 6 model. The drop in velocity at 18 km depth corresponds roughly to the bottom of the high velocity zones in both Model A and Line 6.

Both Model A and the Line 6 model exhibit what amount to two diffracting points at a depth of around 30 km, though in Line 6 these have been modelled as irregularities at a velocity boundary rather than isolated bodies. In Model B a dipping reflector is modelled at the equivalent position to the northern diffractor in Model A, but Model C and Heikkinen and Luosto's Model 1H have only continuous reflectors at this depth. It should be noted that only short portions of the reflector are imaged in the Finnish model leading to the consideration that this may alternatively be modelled as an intermittent reflector similar to that in Model A.

The differences in lower crustal velocity structure between Model A and Model 1H may be explained in part by the different datasets used. This means that different 'viewing angles' are employed, and the lateral displacement of the Finnish stations from the line means that the depth points modelled are also displaced to the east of the line in a similar way to those for the off-line stations 1A and 5A (see Chapter 7 section 5), though Heikkinen and Luosto do not specify how they treat their off-line data. They also used a different method of specifying their model so that lateral variations could be incorporated into each layer. However, the depression of the Moho is still apparent in both models at the same position (0 km in

the Finnish model corresponds roughly to 25 km in the reversed model from this study).

The lower crust of the Line 6 model (Fig. 8.7) seems to bear out the suggestion made in Chapter 7 section 5 that the dip in the Moho in Model A shallows out to the west (Fig. 7.33d). Matthews (1993) attempted to model a depression in the Moho or deepest crustal reflector beneath Line 6 but obtained a better fit with upper mantle sub-horizontal reflectors beneath a relatively flat Moho. The Moho lies at around 50 km depth which at the southern end corresponds quite well to Line 1 Model A, though that in Model C is a few km shallower. At the northern end of the Line 6 model the crust is much thinner than that in Model A and Model B. This could be put down to the effects of the Moho depression beneath Line 1 thinning to the west though Matthews (1993) suggests that there is crustal underplating in this region not imaged in the wide angle data. It is interesting to note that the reflecting boundaries in the mid and lower crust of Model B correspond closely in depth with those of the northern end of Line 6. The overall velocity gradient, however, is steeper in the Line 6 model so the Moho along Line 6 is modelled at the same depth as a lower crustal reflector in Model B, ~10 km above the Model B Moho.

Of the Line 1 models, only Model B shows any indication of subcrustal reflected arrivals. This appears in the form of a diffraction as opposed to the horizontal and subhorizontal reflectors modelled for Line 6.

The Line 7 models should provide a way of tying in Lines 1 and 6, intersecting them both at their southern ends. Figs. 8.10 f) and g) show the velocity-depth profiles at the intersections of Line 7 with Lines 6 and 1 respectively. If the models are consistent, the velocity functions at these cross-over points should be identical. Heikkinen and Luosto's model

(Model 7H, Fig. 8.9) is reversed whereas Bruguier's (Model 7B, Fig. 8.8) is unreversed, using data from the western end only. Bruguier's model shows large steps or diffracting points in boundaries at offsets between 80 and 120 km along the model. These features occur at similar depths to laterally limited features in Line 1 Model A. The largest offset is not great enough for reflectors deeper than about 50 km to be imaged but the model suggests that a lower crustal layer exists at the eastern end of the line which is not present in the west. It also implies that the middle crust undergoes some sort of change from west to east, the changeover occurring between the intersections of the two north-south lines. This would explain the differences between Lines 1 and 6 and provides some evidence for the existence of the Baltic-Bothnian megashear proposed by Berthelsen and Marker (1986) in that large scale movement on the shear could give rise to a such a change in crustal structure across it. The evidence, however, is hardly conclusive since the model is unreversed.

The velocity structure of the reversed Line 7 model produced by Heikkinen and Luosto (Fig. 8.9), on the other hand, shows no signs of boundary steps or diffractors but bears greater resemblance to both Line 1 and Line 6. The correlation with Model A is in fact extremely good, and that with the Line 6 model only breaks down in the upper crust. No evidence is seen for the slight crustal thinning between the two lines seen in Model C. This Line 7 model provides a link between the velocity profiles beneath Lines 1 and 6 but it is too far south to explain the disappearance of the Moho depression from west to east.

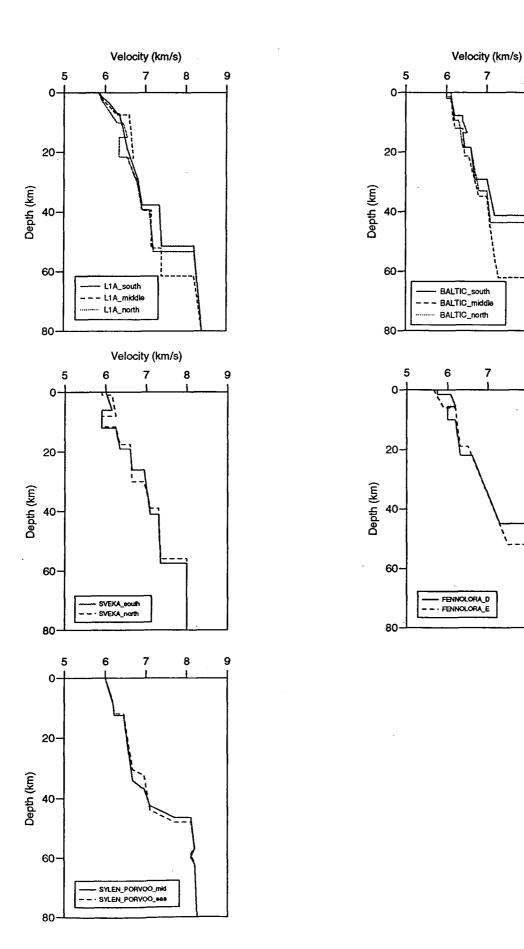
The 2½D magnetic modelling carried out by Pedersen et al. (1992) along Line 7 gives no information about deep structures but indicates a magnetic body in the upper crust at 10 to 15 km depth, between the

intersections with Line 1 and Line 6. It is claimed that a domed reflector can be seen in the normal incidence data, however neither of the wide angle seismic models for Line 7 show any evidence for such a body. According to the magnetic model, the body crosses the intersection point with Line 1. Again little evidence is seen for this in any of the Line 1 seismic models except for Model C which features a thin high velocity layer between 5 and 10 km depth at the southern end, pinching out to the north (Fig. 7.28 Layer 3).

8.4 Comparison with previous projects

In comparison with previous seismic projects (see Chap. 3 and Fig. 8.11), BABEL Line 1 Models A and B have a relatively steep velocity gradient in the upper crust, exceeding 6.55 km s⁻¹ at a depth of less than 20 km, and have no distinguishable 'C-boundary'. There is a gradational increase in velocity from ~6.4 km s⁻¹ at 10 km depth to 6.8 km s⁻¹ at 30 km depth in Model A while Model B undergoes a decrease in velocity at 18 km depth, increasing to 6.75 km s⁻¹ at 30 km depth. In the models from previous surveys the velocity only exceeds 6.6 km s⁻¹ below the C-boundary at approximately 20 km depth. The C-boundary would appear to occur somewhat deeper at around 30 km depth in Model C and the Line 6 model. Both the BALTIC and FENNOLORA models (Figs. 3.3a and 3.3b respectively) exhibit high velocity zones in the upper crust at their southern ends which may correlate with similar zones in the Line 1 and Line 6 models, while in the SVEKA model (Fig. 3.3b) there is a low velocity zone at ~10 km depth.

Fig. 8.11 Comparison of 1D velocity profiles from BABEL Line 1 with previous seismic projects in the Baltic Shield (See Chapter 3 for references).



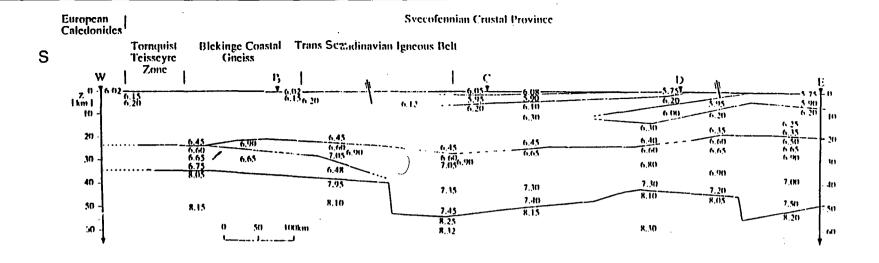
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Between 20 and 40 km depth, all the models are fairly similar in terms of velocities and overall gradients, though the depths of discontinuities vary considerably from model to model.

The boundary at ~40 km depth in all three Line 1 models is taken as representing the top of the lower crust. Below this significant velocity discontinuity, the velocity exceeds 7.0 km s⁻¹ and at the northern and central parts of the line there is a distinct increase in the normal incidence reflectivity (Fig. 8.1). Pavlenkova (1979) and Nelson (1991) cite both of these as characteristics of Precambrian lower crust.

This boundary corresponds well to the top of the lower crust in the SVEKA model (Luosto, 1990) and western end of the Sylen Porvoo model (Luosto, 1986) though in other models such as BALTIC and BLUE ROAD, the Moho lies at this depth. The depth of the Moho depression in the middle of Model A is similar to that in the BALTIC model though the Moho depth to either side correlates better with an upper mantle reflector in the BALTIC model. This poses the question of whether the Moho has been correctly identified in the BALTIC model (that in BABEL Line 1 Model A being corroborated by the base of reflectivity in the normal incidence data) or whether the crust is actually thinner. The crustal thickness beneath shotpoint E of the FENNOLORA profile is also in good agreement with that at either end of Model A and Model B.

The BALTIC, SVEKA and FENNOLORA profiles all have dips in the Moho reaching down to around 60 km depth. That in the BALTIC model bears the closest resemblance to Line 1 Model A. Also present in the BALTIC model are laterally limited reflectors at 30 km depth similar to those modelled in Model A. The SVEKA model contains boundary irregularities at 30 km depth which may be comparable to diffracting



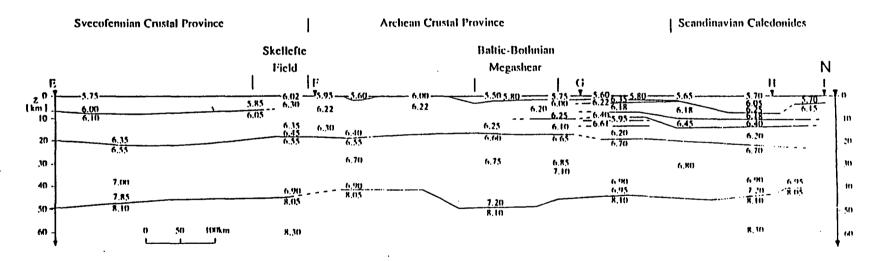


Fig. 8.12 Velocity model of the whole FENNOLORA profile (Guggisberg et al, 1991).

features in Model A, and another at 40 km comparable to the one seen in Model B. That two of these profiles run directly across the Ladoga-Bothnian Bay shear zone lends weight to the possibility of there being a similar megashear beneath the Bothnian Sea (see section 8.3). Fig. 8.12 shows the model of the whole FENNOLORA line with surface geology indicated (Guggisberg et al, 1991). The three Moho depressions here can also be related to surface faulting. On the other hand, this does not explain there being a Moho depression beneath the FENNOLORA line, and not one beneath BABEL Line 6. It may be that such Moho irregularities are common within the Precambrian Baltic Shield, or the answer may lie in Matthew's proposed crustal underplating at the northern end of Line 6 being equivalent to the Moho depressions modelled in Line 1 and FENNOLORA.

No upper crustal structures similar to that in Model A have been modelled above the Moho depressions in the BALTIC or FENNOLORA lines while a high velocity block has been proposed in the upper 10 km of the SVEKA line. However, the spatial resolution of the seismic data along these profiles was much poorer than for the BABEL lines so the same complexity of arrivals will not have been modelled, and without integrated gravity modelling it is difficult to say whether the combination of a high density upper crustal block with a Moho depression is unique to Line 1 or typical of the region.

8.5 Gravity modelling

Gravity modelling based on the seismic model achieved a good fit to the gravity data in two dimensions (Figs. 7.16 and 8.13a). The main, long wavelength, negative anomaly (80 - 350 km in Fig. 7.16) was modelled by a Moho depression and a lateral change in lower crustal density. Superimposed on this is a shorter wavelength positive anomaly which was modelled by a high density body in the upper crust.

If the reference density (0 kg m⁻³ in the model) is taken to be 2880 kg m⁻³ then the top layer has an average density of 2690 kg m⁻³, the high density body 2940 kg m⁻³, the lower crust 3110 - 3160 kg m⁻³ and the mantle 3300 kg m⁻³ (shown in brackets in Fig. 8.13a). These are reasonable values for this type of crust and compare well with models from other Precambrian regions (Fig. 8.14, Goleby et al 1990, Braile 1989). Fig. 8.15 shows a plot of velocity against density for the Line 1 model compared with data from several other Precambrian regions and the Nafe-Drake curve.

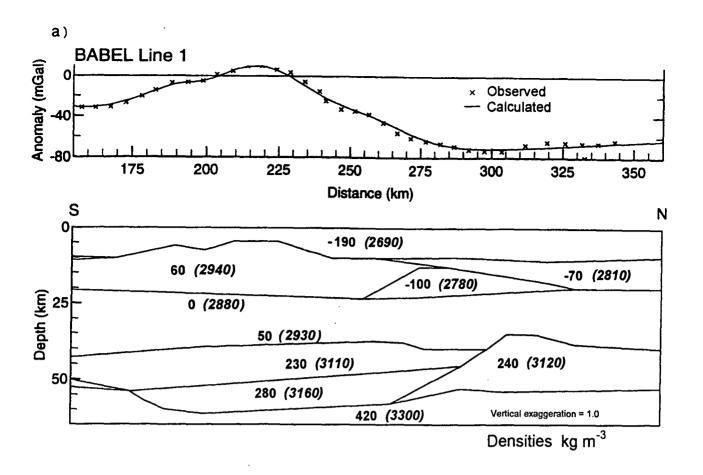
Pedersen et al. (1992) also carried out 2½D gravity modelling along Line 1 using a smoothed gravity dataset. Fig. 8.13b Shows Pedersen's model in comparison with the equivalent part of the model from this study. Pedersen's density contrasts are relative to other values at the same depth only and so the modelled values are not directly comparable. However, densities using the same constant reference value (2880 kg m⁻³) are shown in brackets to give a rough comparison with Fig. 8.13a. The gravity high is modelled by a 100 km long, 30 km thick body with a density contrast of +120 kg m⁻³, in a similar position to the high density body in the model from this study. Pedersen interprets this as a dioritic pluton, citing outcrops in nearby Uppland, Sweden, of density 2810 kg m⁻³ as supporting evidence.

Pedersen's model also indicates a region of crustal thickening to account for the negative anomaly. However this is 60 km north of the Moho depression in the seismic/gravity model from this study and has no supporting evidence from either wide angle or normal incidence seismic

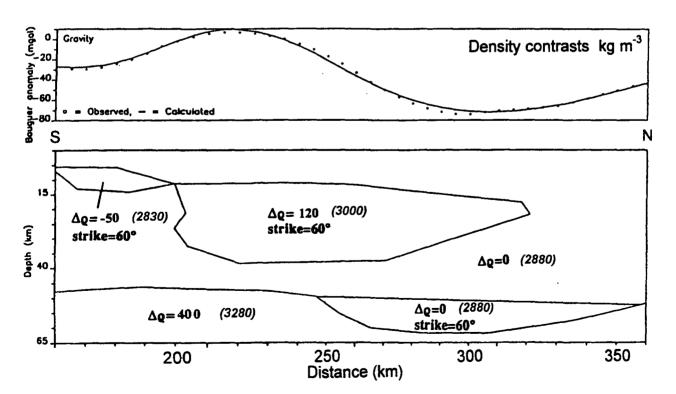
data. Neither is there any evidence for the small, near surface, low density block towards the southern end of Pedersen's model. Clearly, the integrated seismic and gravity model from this study, despite being only 2D, is better constrained than Pedersen et al's 2½D gravity model.

Taking the third dimension into consideration, one must refer back to the gravity anomaly contour map (Fig. 3.5). The extent of the high density near surface body causing the positive anomaly can be inferred from this map (Fig. 8.16b). From this information, the possible location and extent of the Moho depression may be deduced by estimating the gravity anomaly contours if the high density body were absent. To do this, the 2D gravity anomaly for Model A with the high density block removed was calculated (Fig. 8.16a). This shows that the small gravity minimum to the southeast of the positive anomaly is part of the underlying negative anomaly due to the Moho depression and can be correlated with the southern extent of the observed negative anomaly to the west of the positive anomaly. The result is a wide negative anomaly with a general E-W trend, extending onshore into Sweden and dying out to the west, rather than the NE-SW trend apparent from the actual anomaly map.

The upper crustal high density block appears from the gravity map to be more limited in its extent than the Moho depression. It may be that it is only the thickest part of the body, where its top nears the surface, which is so limited (compare Figs. 7.13 and 7.16). The thinner extremes probably extend much further, tying in with the upper crustal high velocity zone in the central part of Matthews' Line 6 model.



BABEL CDP PROFILE 1



8.13 Comparison of BABEL Line 1 gravity models. Actual densities, given reference value of 2880 kg m³ are shown in brackets.

- a) 2D gravity model along BABEL Line 1 from this study.
- b) 2½D gravity model along BABEL Line 1 (Pedersen et al, 1992).

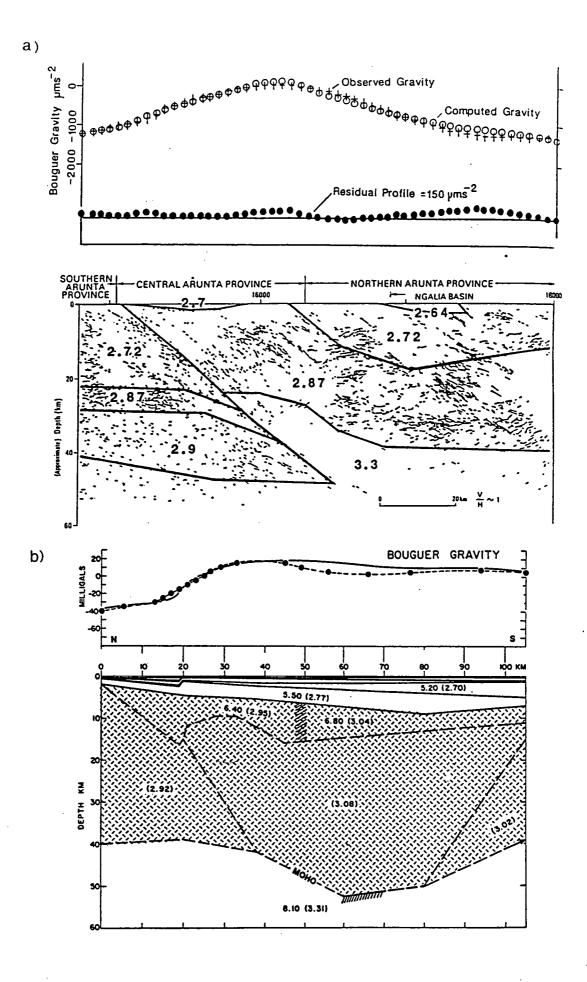


Fig. 8.14 Gravity models from other Precambian regions
a) Proterozoic Arunta Block, Central Australia (Goleby et al, 1990)
b) Western Lake Superior, North America (Braile, 1989).

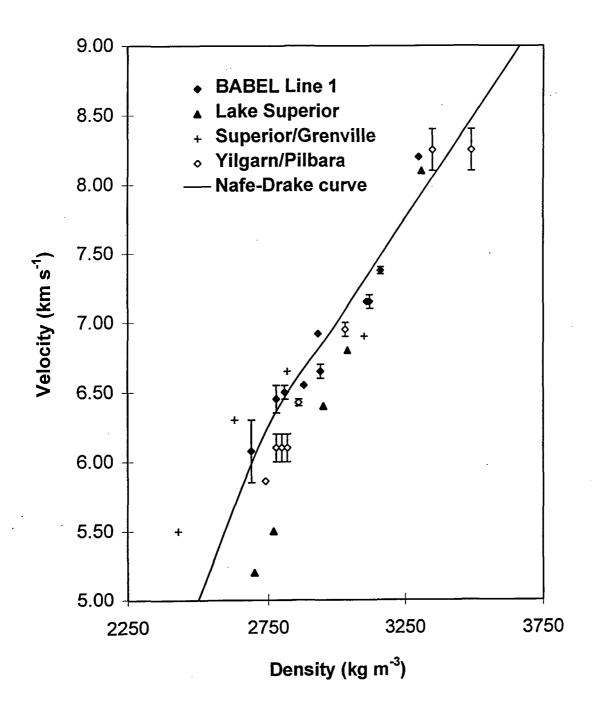


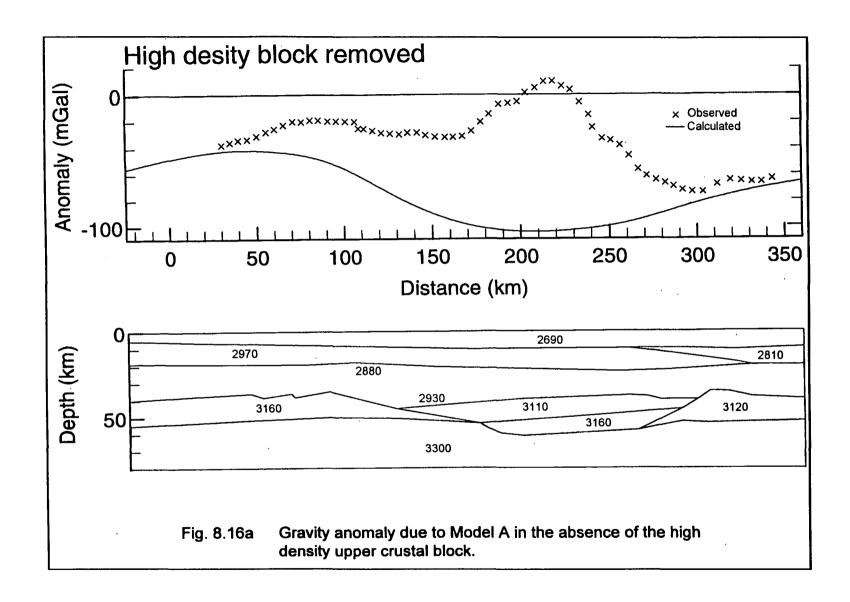
Fig. 8.15

Velocity vs. density for BABEL Line 1 and other Precambrian regions compared with the Nafe-Drake curve.

Lake Superior, N. America (Braile, 1989)

Superior/Grenville Provinces, N. America (Berry and Fuchs, 1973)

Yilgarn and Pilbara cratons, SW Australia (Wellman, 1988)



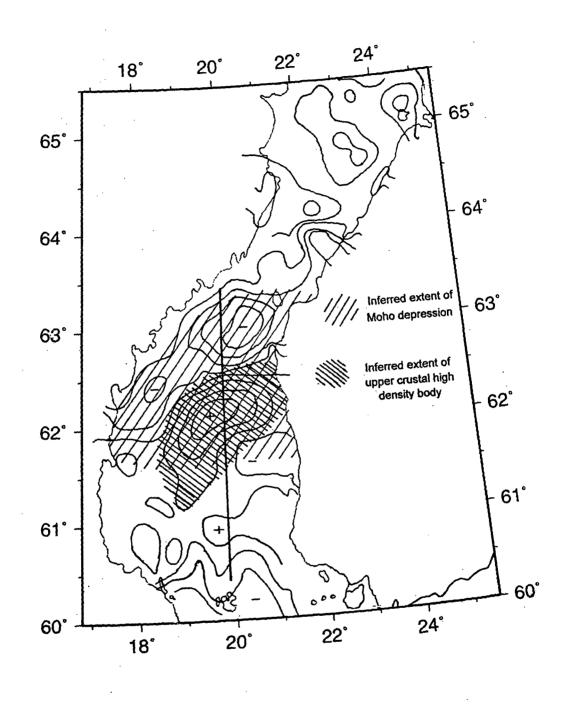


Fig. 8.16b Bouguer anomaly contour map of the Sea of Bothnia with inferred extents of the upper crustal high density body and the Moho depression.

8.6 Geological interpretation

In the upper crust at the northern end of Line 1, the two bright reflectors seen in the normal incidence data have been interpreted as dolerite sills, as has been explained in Chapter 6. These were not imaged directly by the wide angle data, being too near the surface and not close enough to the receiver. For this reason they were not included in the model. They may, however, be responsible for some of the multiples seen in the data at the northern end of the line.

The source of mid-crustal diffractions at around 30 km depth is not known but the normal incidence data would suggest that diffracting or scattering bodies are not uncommon in this section of shield crust, especially towards the southern end of the line. Indeed, two short reflectors are seen in the normal incidence data quite close to the modelled diffracting points (Fig. 8.1). The question should perhaps be why do not more such features appear in the model?

The most significant part of the model seems to be the central structure. The general shape implies either a large, rounded structure, possibly a large, crustal scale igneous intrusion, or two related structures: one in the upper, and one in the lower crust. A large Episode 1 granitoid intrusion (Andersson's nomenclature, 1991) of comparable lateral dimension is seen immediately to the east, on shore in Finland (Fig. 2.3). Gravity modelling, however, indicates a dense intrusive body in the upper crust and also corroborates the thickened lower crust (i.e. Moho depression) and lateral change in lower crustal seismic velocity.

A large mafic intrusion in the upper crust is not implausible. Such a body has also been modelled by Pedersen et al. (1992) and interpreted as

a large dioritic pluton (section 8.5, Fig. 8.13b). It is possible that the body extends deeper into the middle crust where the density and seismic velocity of the surrounding rocks will be more similar. Evidence in favour of this is the transparent region of the normal incidence section in this region. Such transparent zones have previously been associated with plutons in the upper crust which provide a 'window' to the lower crust (Matthews, 1987). Against this view is the presence of reflectors in the normal incidence data which correlate well with the base of the modelled body (see Fig. 8.1).

The presence and cause of the Moho depression is more controversial. The most obvious questions arising are how was it formed? Why is it still there when one would expect it to relax and flatten over geological time? Indeed, could it merely be an effect of complex velocity variations above?

The presence of the depression as a true geological feature is supported by the reflected wide angle arrivals from its sides (Models A and C), Heikinnen and Luosto's model from data recorded at different locations, and the gravity model. Moho depressions have been modelled elsewhere in the Baltic Shield: beneath the BALTIC and SVEKA lines, three sections of the FENNOLORA line and perhaps also the Blue Road Line. It may be that the same explanation was used for similar data in each successive survey because it worked before, but no alternative models have been published.

Kusznir and Matthews (1988) showed that given an offset on the Moho, different wavelengths would relax at different rates, decaying by ductile flow. Intermediate wavelengths (around 10 km) decay more rapidly than longer and shorter wavelengths, effectively notch filtering the Moho

topography and giving rise to the remnant structure shown in Fig. 8.17, hereafter referred to as the Kusznir-Matthews structure.

This type of structure has been used to model crustal faults which cut the Moho (West 1990). Such a structure is not clearly seen at normal incidence so no obvious Moho offset is observed in the data, though it may be seen in the wide angle data. The Moho depression seen in BABEL Line 1 may be related to the Kusznir-Matthews structure, or possibly two such structures side by side.

To derive a possible explanation for the origin of the Moho topography, one must consider all the available information: locations of seismically modelled depressions, gravity anomalies, conductivity models, the surface geology, and tectonic and fault maps. In Fig. 8.18, all this information is portrayed on the same map.

As explained in section 8.5.2, it is postulated that the gravity low due to the Moho depression beneath Line 1, in the absence of the high density upper crustal body, would be much wider and extend onshore into Sweden, coinciding with the Moho depression beneath shotpoint E of the FENNOLORA profile. A similar gravity low is seen at the Moho depression beneath FENNOLORA shotpoint C in Southern Sweden. To the east, the gravity low appears to coincide with the boundaries of the Central Svecofennian tectonic unit, the edges of the Central Finland Granite complex, strike-slip faults and the Tampere Schist Belt conductivity anomaly. Unfortunately, gravity data for Finland itself was not available.

The Tampere Schist Belt anomaly and associated electromagnetic anomalies form a 500 km long zone running E-W from the Finnish-Russian border to the Bothnian sea (Pajunpää, 1987). The conducting bodies have been interpreted as the result of the collision of crustal terranes on the

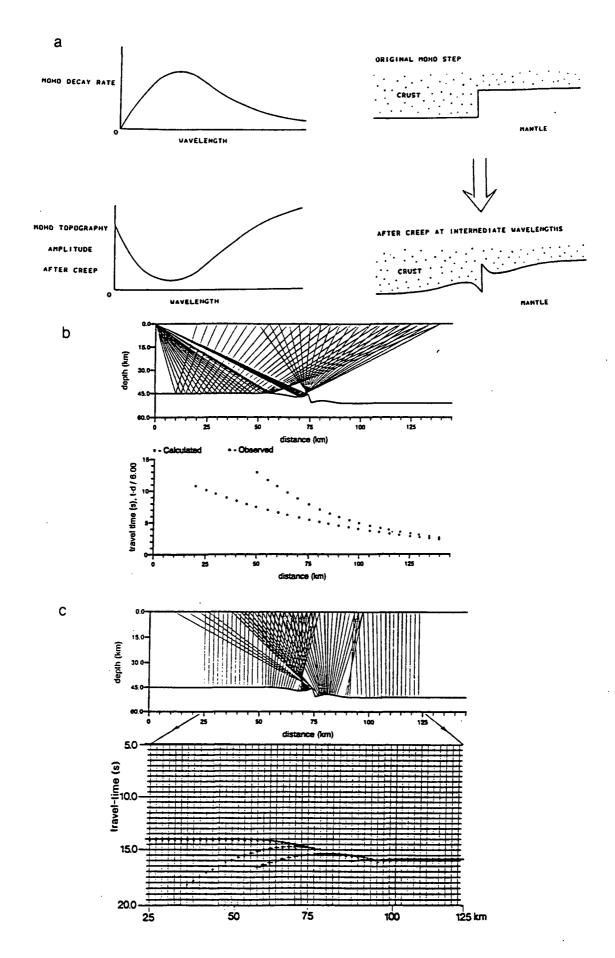


Fig. 8.17

a) Decay of a Moho step over geological time (Kusznir and Matthews, 1988).
b) Effect of the Kusznir-Matthews remnant structure on the wide

angle travel time curve.

c) The same structure imaged at normal incidence.

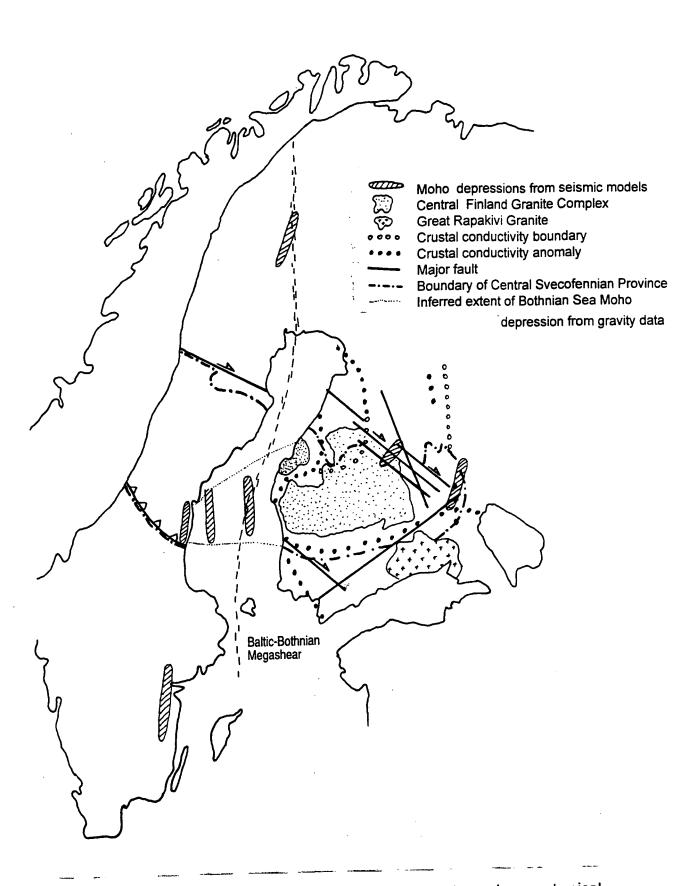


Fig. 8.18 Map showing synthesis of geological and geophysical information in the vicinity of the Bothnian Sea.

carbon-bearing sedimentary rocks of a closed oceanic basin (Korja and Koivukoski, 1994). The conductor has also been linked to the Storavan-Skelleftea anomaly in northern Sweden, marking the boundary between the Northern and Central Svecofennian terranes.

It is noticeable from the SVEKA magnetotelluric profile (Fig. 3.7a) that there are deep crustal conductive zones beneath both the Tampere Schist Belt anomaly and the Lagoda-Bothnian Bay shear zone. The Tampere schist belt anomaly extends beneath the Bothnian sea to the west and would appear to intersect BABEL Line 1 above the location of the Moho depression (Fig. 3.9). If the lower crustal conducting zone follows the same trend, the two features may be related.

Moho depressions have previously been associated with crustal scale fault zones (BALTIC, SVEKA profiles: Lagoda - Bothnian Bay shear zone; FENNOLORA shotpoint G: Baltic-Bothnian Megashear; FENNOLORA shotpoint E: Ljusnan thrust zone). There are two possible faults coinciding with the Line 1 Moho depression: the southward continuation of the Baltic-Bothnian Megashear (Berthelsen and Marker, 1986) or the tectonic zone separating the Central and Southern Svecofennian Provinces in Sweden and Finland (Berthelsen and Marker, 1986, Strömberg, 1976). The latter has been used to explain the Moho depression modelled in the FENNOLORA profile between shotpoints D and E (Fig. 8.19). The main objection to the Baltic-Bothnian megashear theory is the lack of corroborating evidence from either Line 6 or Line 7, although Bruguier's model leaves room for speculation. The 3D interpretation of the Line 1 models (Chapter 7, Fig. 7.33) also suggests that the Moho dip is laterally limited to the west and does not join up with the feature beneath the

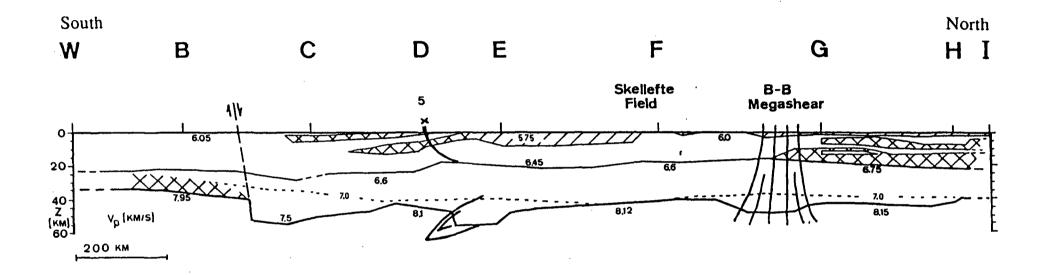


Fig. 8.19 Tectonic interpretation of FENNOLORA model (Guggisberg et al, 1991).

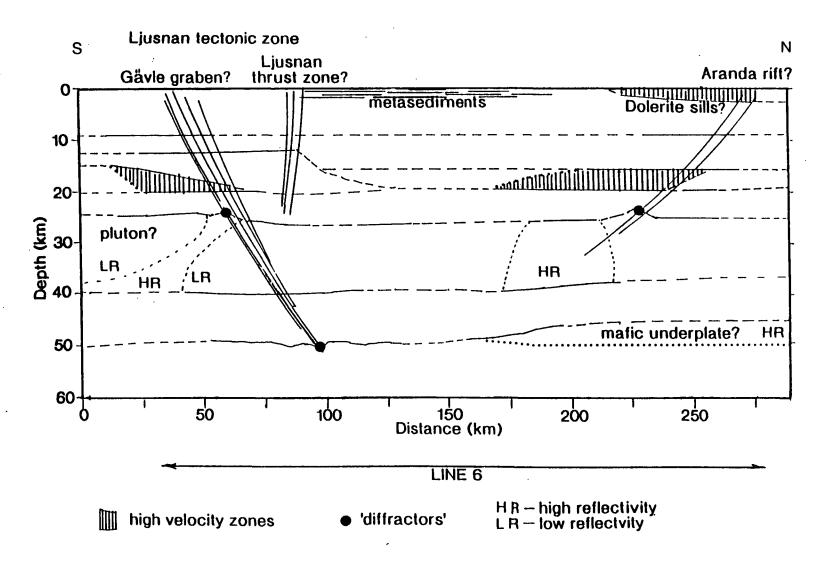


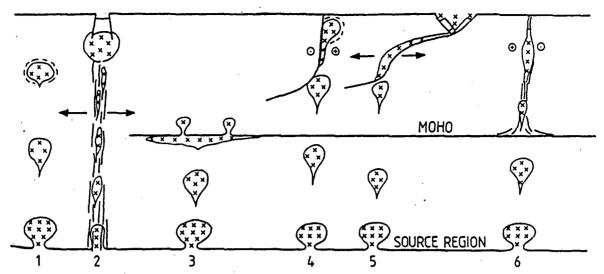
Fig. 8.20 Tectonic interpretation of BABEL Line 6 (Matthews, 1993).

FENNOLORA line, though this interpretation is only a first approximation which ignores the possibility of out of plane reflections.

The lack of a Moho depression in Matthews' Line 6 model affects the correlation of Line 1 with the FENNOLORA profile. However the crust in Line 6 is modelled as thinning to the North with a relatively low upper mantle velocity of 7.85 km s⁻¹. This is at odds with the other Baltic Shield models which have upper mantle velocities of at least 8.05 km s⁻¹. Matthews suggests that the highly reflective zone in the normal incidence data beneath the modelled Moho indicates a high velocity layer at the base of a thickened crust, not imaged in the wide angle data (Fig 8.20). This would enable the correlation of the Moho depressions beneath FENNOLORA and Line 1.

A further possibility is that the depression beneath Line 1 lies close to the intersection point of the Baltic - Bothnian Megashear and the southern boundary of the Central Svecofennian province.

The presence of a crustal scale fault may also explain the origin of the upper crustal high density body. Hutton (1988) and Hutton and Reavy (1992) have shown that large intrusive events may commonly be related to tectonic activity with а strike-slip component (transpressive transtensional regimes). Hutton (1988) explains possible emplacement mechanisms for different tectonic regimes (Fig. 8.21), giving examples from around the globe. Hutton and Reavy (1992) give a more detailed model of emplacement along the Highland Boundary Fault during the Caledonian in Britain in which large volumes of magma with a high mantle component are generated at a Moho-detaching listric fault in a transpressional system (Fig 8.22). The crustal thickening associated with transpression is enhanced around the main and secondary faults giving



Six generalised modes of ascent and emplacement of granitoids; all begin with initial diapiric detachment and uprise of melts: (1) continued diapric uprise, in the absence of tectonics, leading to final arrest due to density equilibration followed by late ballooning; (2) uprise into major vertical tectonic extensional fault system, magmas rise to high levels, with uppermost crustal ponding and cauldron/caldera behaviour; (3) diapiric uprise arrested by viscosity/strength changes at Moho—this leads to lateral spreading with possible late spawning of crustal plutons; (4) diapiric rise into middle crust, intercepting an intra crustal strike slip fault zone leading to elongate plutons with late ballooning; (5) diapiric uprise intercepting intra crustal listric extensional fault/shear zone leading to listric granite sheets and possible generation of asymmetric cauldrons and calderas; (6) uprising melts intercept trans crustal vertical transcurrent fault/shear zone—jogs, pull apart and large tension gash features, etc., create space for magma ponding; note that in all these scenarios the "source region" is arbitrarily located in the lithospheric mantle.

Fig. 8.21 Six generalised modes of ascent and emplacement of granitoids, after Hutton, 1988

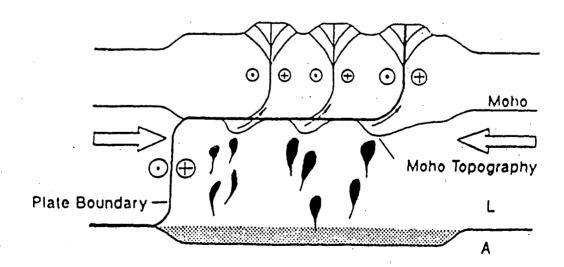
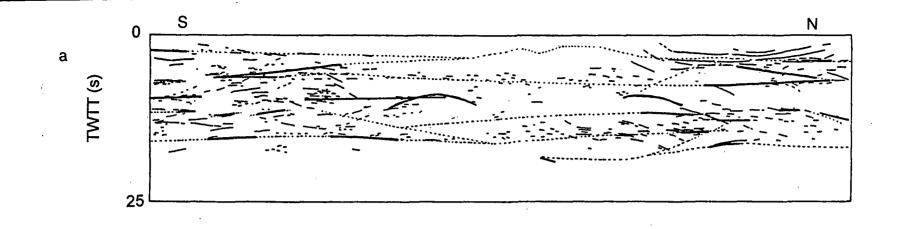


Fig. 8.22 A syntectonic igneous emplacement model for the Highland Boundary Faultsystem in the British Caledonides, after Hutton and Reavy, 1992

rise to Moho topography. The lithospheric mantle keel melts and rises to the Moho where continental crust is then melted, removing the Moho topography. Granitic magma, with a large mantle component, then rises up the shear zones which control ascent and emplacement. Although the Moho topography is removed in this model, the overall crustal thickening remains. The Kusznir-Matthews model, mentioned above, suggests a mechanism by which the topography may also be retained. The change in lower crustal properties across the depression (seismic velocity and density) may have an influence on its continued existence. Unfortunately, since there are no accessible igneous outcrops beneath the Bothnian Sea on which to look for strain indicators, this syntectonic emplacement model cannot be confirmed.

Fig. 8.23a shows a line drawing of the normal incidence data for Line 1 along with the reflectors from the synthetic section. The normal incidence data shows little structure which is of help in the tectonic interpretation, with patchy reflectivity and few reflectors greater than 10 km in length. However, changes in reflectivity between different parts of the profile suggest changes in structure. In Fig. 8.23b a tectonic model for Line 1 is suggested. The southern end of the profile is heavily intruded throughout the mid and lower crust, with both northward and southward dipping reflectors in the lower crust. The mid crust at the northern end is much less reflective but the normal incidence data shows evidence of steeply northward dipping reflectors which are interpreted as faults. The reflective lower crust at the northern end dips toward the south, ending approximately at the southern wall of the modelled Moho depression. The reflectivity at the base of the crust in the vicinity of the Moho depression decreases gradationally downwards. This system is interpreted, in a similar



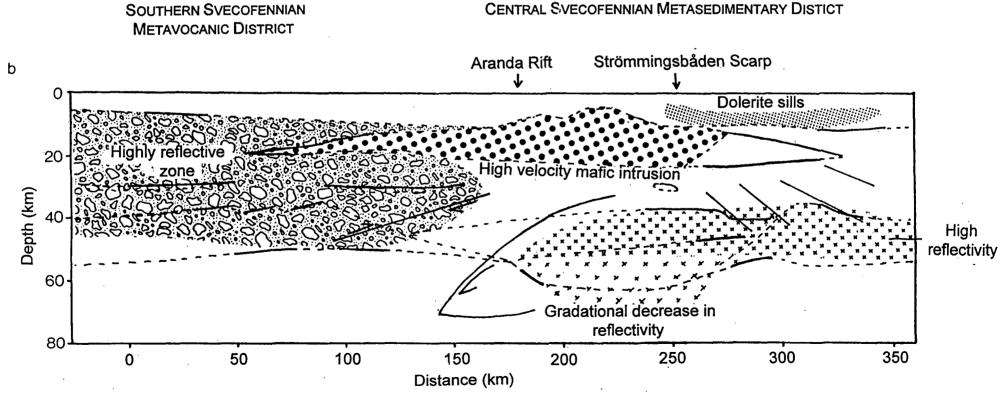


Fig. 8.23

a) Line drawing of Line 1 normal incidence data with normal incidence synthetic superimposed (bold reflections arise from parts of reflectors imaged at wide angle)

manner to the FENNOLORA line, as a crustal scale thrust fault, the southern section overriding the northern one. It is possible that the Baltic-Bothnian Megashear also cuts the section, the most probable location of the intersection being at 250 km along the line, near the Strömmingsbåden Scarp system. The only evidence for this is the disruption of reflectors in this region, the dipping reflectors which were interpreted above as faults, and the low velocity/density body in the upper crust.

8.7 Comparison with other regions

One of the initial aims of the BABEL project was to compare deep seismic information from a Precambrian shield region with that from Phanerozoic crust such as that around Britain and Western Europe. It should be noted before comparisons are made that the central part of Line 1 is probably atypical of Baltic Shield crust; the ends of the model are likely to be more representative.

Phanerozoic continental crust has a mean thickness of around 28km and crustal velocity of 6.2 km s⁻¹ (Meissner, 1986). Its bulk composition is that of andesite and it is overprinted by late extensional structures (Nelson, 1991). Normal incidence seismic data show a transparent upper crust overlying a reflective laminated lower crust. Various explanations exist for the cause of reflections from the lower crust such as mafic sills, trapped fluids, cumulate layering and ductile stretching fabric. Of these, the intrusion of mafic sills is currently believed to be the most plausible (Nelson, 1991, Mooney and Brocher, 1987). There is a sharp subhorizontal transition at the base of the lower crust to the unreflective upper mantle.

This boundary is widely regarded as coinciding with the wide angle reflection Moho.

Meissner (1986) calculates the mean thickness of Precambrian continental crust as 41 km with a crustal velocity of 6.6 km s⁻¹. The bulk composition is intermediate between andesite and basalt. Reflectivity patterns are complex and variable throughout the crust. The base of crustal reflectivity is sharp in some places, gradational in others and can change within the same region. Drummond and Collins (1986) and Durrheim and Mooney (1991) suggest that the increased crustal thickness may be due to basaltic underplating and that the preponderance of basaltic dike swarms contributes to the complex reflectivity patterns and lack of laminated reflectors. Durrheim and Mooney make an additional distinction between Archaean and Proterozoic crust, the latter being much thicker (average 45 km compared to 35 km for Archaean crust) and having a thicker high velocity layer at the base.

Pavlenkova (1979) and Nelson (1991) distinguish three general layers within Precambrian crust based on average velocities and velocity gradients. The middle layer has a lower gradient than the other two and is also more seismically transparent. Fig. 8.24 shows 1D velocity profiles from BABEL Line 1 compared with profiles from other Precambrian regions around the world.

The steep gradient and relatively high velocities in the uppermost 10 km of the BABEL Line 1 model bear most resemblance to the Russian and West Siberian Platforms and also the Grenville-Superior boundary in North America. High and low velocity layers are, with one exception, confined to the top 23 km. These are seen in the North Australian Craton, the Russian and Turanian Platforms and the Grenville-Superior Front.

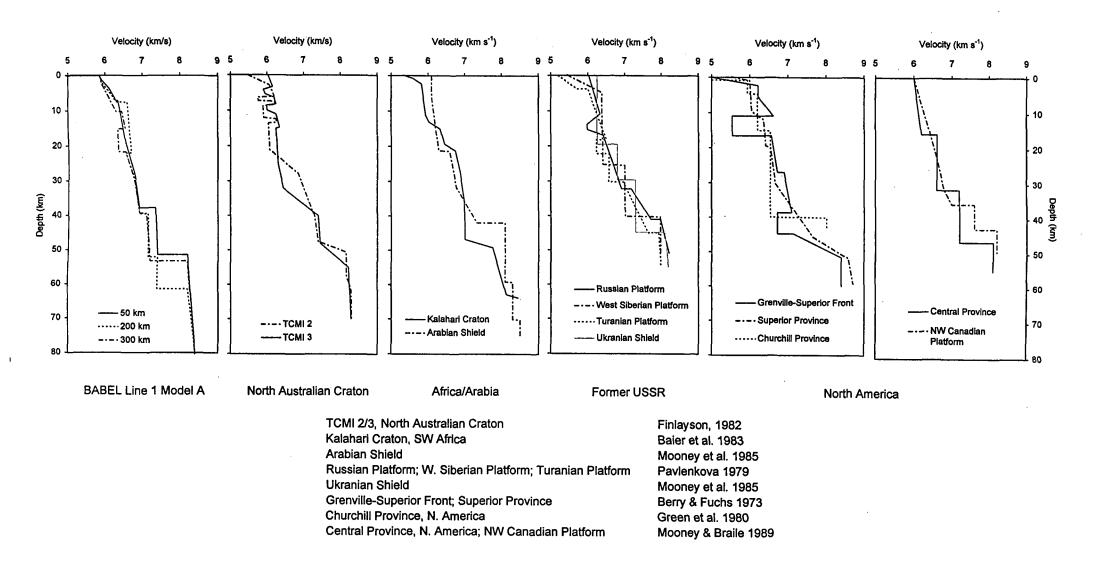
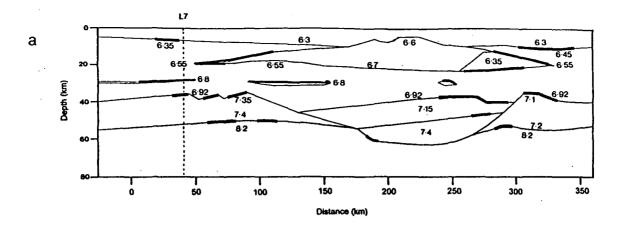
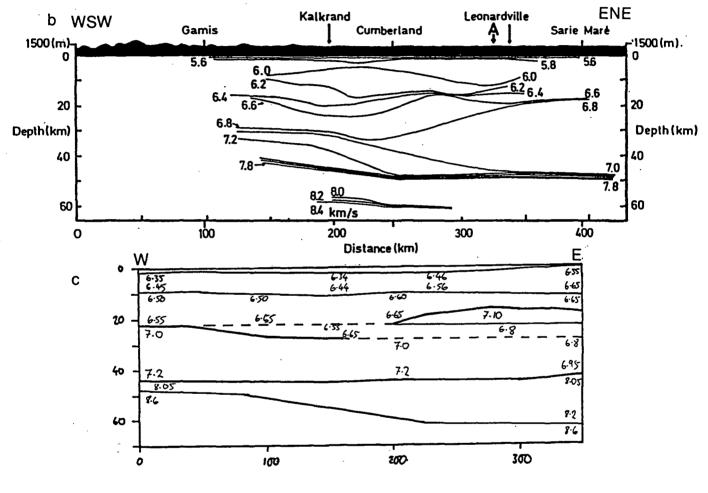


Fig. 8.24 Velocity profiles from Precambrian crustal regions worldwide.





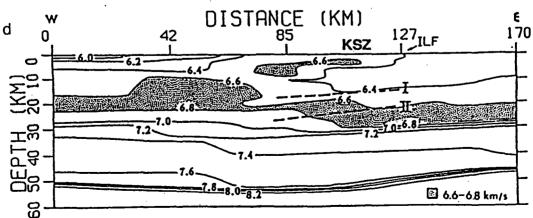


Fig. 8.25 Comparison of BABEL Line 1 with 2D velocity models from other Precambrian regions.

- a) BABEL Line 1 Model A
- b) Kalahari Craton (Baier et al. 1983)
- c) SE Grenville Province (Hughes and Leutgert, 1992)
- d) Kapuskasing Structural Zone, Superior Province (Clowes, 19)

Between 18 and 25 km depth there is generally either a velocity step or a change in gradient, the velocity below exceeding 6.5 km s⁻¹ in all cases except the North Australian Craton where a lower mid-crustal velocity is recorded.

Most of the profiles show a relatively featureless interval of low velocity gradient below this. The thickness of this zone varies from less than 10 km (N. Australian Craton profile TCMI 2, Turanian Platform) to more than 20 km (Kalahari Craton, Churchill Province of N. America). In BABEL Line 1 the zone is approximately 18 km thick.

A high velocity ($V_p > 7 \text{ km s}^{-1}$) is present in all the profiles except for the Churchill Province and Kalahari Craton and even in the latter profile there is a transition layer to the Moho. Only at the Grenville-Superior front is a low velocity layer observed in the lower crust. The depth to the Moho is slightly greater for BABEL Line 1 than for most of the other profiles but shows a reasonable correlation with the North Australian Craton, Kalahari Craton and Superior Province.

In Fig 8.25, BABEL Line 1 Model A is compared with three other 2D models from Precambrian shield areas: the Kalahari Craton in southwest Africa (b), the southeastern Grenville Province (c) and the Kapuskasing Structural Zone in the Superior Province of North America (d). All three show strong lateral variations in velocity, including laterally limited high velocity layers in both North American profiles. The high velocity body at 20 km depth in the Grenville profile is interpreted as mafic cumulates, the remnant of magmatic intrusions. That in the Kapuskasing profile is thought to be due to a low angle thrust fault along which midcrustal rocks have been brought to the surface.

Moho topography is observed beneath the Kalahari Craton and Kapuskasing Structural Zone. In the first case this is associated with a lateral change in the crust while in the second it is associated with the Proterozoic age thrust fault mentioned above which extends down to the middle crust. This is further evidence that Moho topography can survive for long periods of geological time.

8.8 Conclusions

A large volume of high quality, high resolution seismic data was acquired in and around the Sea of Bothnia in the BABEL experiment of 1989 using marine airgun shots and land recording stations. The use of digital PDAS recording equipment proved partially successful, with the loss of a certain amount of data near the beginning, and thereafter requiring constant supervision. Once recorded, the data were much faster to process, by-passing the lengthy digitisation process necessary for the analogue Geostore data. The Geostores, on the other hand, allowed unsupervised recording of up to two days' worth of data in the field between tape changes. This enabled many stations to be operated by a small number of people.

Reversed 2D modelling of Line 1 was carried out for the incomplete in-line dataset, and unreversed modelling for two of the off-line datasets. These were combined to give an approximate three dimensional interpretation, gravity modelling providing an additional constraint to the inline model. A number of interesting features were found, including a significant increase in crustal thickness extending for over 100 km in the central and northern part of the line. This is in agreement with Heikkinen

and Luosto's model derived from an independent dataset and can be tied in with the negative gravity anomaly at the northern end of the Bothnian Sea. A high velocity, high density upper crustal body interpreted as a dioritic pluton accounts for the small gravity high to the south of this.

Also notable are the non-smooth nature of the boundaries in the lower crust and the fragmented reflectors in the mid-crust. The mid-upper crust is found to be laterally inhomogeneous, with high and low velocity zones in certain areas. The major reflected phases are generally found to arise from relatively short boundary segments (<50 km) most of which can be tied in with short reflectors in the normal incidence data. This brings into doubt the existence of continuous boundaries over large areas, given the lack of evidence for them from the normal incidence data.

The models may provide evidence for the presence of a major tectonic shear zone (the Baltic-Bothnian Megashear), a crustal scale thrust fault, or both, in the central/northern part of the line. Although the evidence for either of these is not conclusive, there is clearly a crustal scale structure here.

The major drawbacks of the dataset, apart from the data loss at station 101P, were the lack of near surface information due to the large minimum offset between shot and receiver (>20 km), and the poor coverage towards the centre of the line due to its length. Both of these disadvantages could have been avoided by the deployment of one or more ocean bottom seismographs (OBS) along the line. This, however, would have necessitated the use of a second ship to deploy and recover the instruments, which funds did not allow. Nevertheless, it is a point to be borne in mind when planning future experiments.

8.9 Further work

There is a large quantity of data yet to be processed and studied from the off-line stations situated around the Swedish coast of the Sea of Bothnia. This could be used to find the limits and dimensions of the Moho depression more accurately. There is no obvious way in which to display and interpret this fan-spread data, although Heikkinen and Luosto (1992) have attempted to use normal moveout corrections to look at the Moho reflected arrival. The way forward must inevitably be integrated three dimensional modelling of all the relevant wide angle and normal incidence datasets. Perhaps a new way of defining the model should be used in which short length, isolated reflectors can be defined in a more or less smooth velocity gradient.

The data also contain much information from converted S-wave phases, mostly converted at the sea bed (Matthews, 1993). This information must also be included in the modelling process to provide valuable additional constraints.

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APPENDIX A

Appendix A: Computer programs

Contents:

1.	BPFILT	Apply band pass frequency filter to specified traces (choice of box-car, trapezoidal or Hanning window).
2.	COMBINE9	Combine up to 9 separate datasets by sequentially appending them to a new file.
3.	EXTR	Extract a given time interval from the specified traces and write to a new file, with optional resampling in time.
4.	F-K	Perform a 2D Fourier transform on a dataset consisting of 512 samples by 512 traces, plot the resultant f-k spectrum and apply a pie-slice velocity filter, writing the result to a new file.
5.	F-T	Perform a 1D Fourier transform on each trace and write out the frequency series to a new file.
6.	NORMALISE	Normalise a dataset by scaling so that the maximum value in each trace is equal to a specified constant.
7.	PANEL	Take a small panel of traces and apply a range of band pass frequency filters, each time writing the results to a file.
8.	RMDC	Remove the DC compenent from each trace.
9.	STACK	Stack up to 50 traces in a rolling window with a linear moveout correction of given velocity.
10.	STATICS	Apply a static correction to each trace based on the water depth recorded at the shotpoint.
11.	TRACEBIN	Bin traces by distance.
12.	TRANSFORM	Deskew and scale coordinates from digitising table, de-reducing travel-time curves if required.
13.	WATERD	Extract a list of shotpoints and corresponding water depths from a dataset.

1. BPFILT

```
program bpfilt
c accepts trace file sequence and band pass filters
   include "/home/kanga/dave/Flib/include/rhicom.h"
   include "/home/kanga/dave/Flib/include/segytc.h"
   include "/home/kanga/dave/Flib/include/functions.h"
   include "/home/kanga/dave/Flib/include/dls.h"
   integer*4 ierr, ihand, ohand, recsz
   integer*4 param
   integer*4 itrace, ifirst, ilast, nrec
   integer*4 iwopt,nsampl
   real*4 work(16384), srate, f1, f2, f3, f4
   character iname*20, oname*24, ipath*25, opath*25
   call dlsini()
c defaults
   ipath = './
    opath = './
   iname = '1 160bs5
    oname = '
С
    window is hanning
    iwopt = 2
    f1 = 3.0
   f2 = 4.0
    f3 = 30.0
    f4 = 40.0
```

A-3

```
c ifirst is trace no. at start of loop, ilast is
c trace no. at end, and nrec is step size
    ifirst = 1
    ilast = 9999
    nrec = 1
С
c get parameter values from user via menu
        call menu(ipath,opath,iname,iwopt,f1,f2,f3,f4,ifirst,ilast)
        print*
        print 4
        read*,param
        print*
        if (param.EQ.99) goto 9
        if (param.EQ.1) then
                 print*,'enter new input pathname:'
                 read 5, ipath
        elseif (param.EQ.2) then
                 print*,'enter new output pathname:'
                 read 5, opath
        elseif (param.EQ.3) then
                 print*,'enter new filename:'
                 read 5, iname
        elseif (param.EQ.4) then
                 print*,'enter window type:'
                 read 6, iwopt
        elseif (param.EQ.5) then
                 print*, 'enter low-cut frequency (bottom):'
                 read 7.f1
        elseif (param.EQ.6) then
                 print*, 'enter low-cut frequency (top):'
```

	read 7,f2	& 'Cannot find all dataset files')
	elseif (param.EQ.7) then	call exit(1)
	print*,'enter high-cut frequency (top):'	endif
	read 7,f3	c
	elseif (param.EQ.8) then	call optdat (opath,oname, 1, recsz, ohand, ierr)
	print*,'enter high-cut frequency (bottom):'	C
	read 7,f4	if(ierr.LT.0) then
	elseif (param.EQ.9) then	call report('segy','dataset','F',
	print*, enter first trace number:	& 'Unable to create dataset - space? or exists?')
	read 8,ifirst	call exit(1)
	elseif (param.EQ.10) then	endif
	print*,'enter last trace number:'	c
	read 8,ilast	ccccccccccccccccccccccccccccccccccccccc
	endif	c read segy header
	go to 1	c
c		call rhead(ihand,0,ierr)
4	format (2X, Enter number of parameter to alter (99 to continue): ',\$)	c
5 🗒	format (A)	if (ierr.LT.0) then
6	format (I)	call report('segy','dataset','F',
7	format (F5.0)	& 'Unable to read reel header file')
8	format (I4)	call exit(1)
С		endif
9	continue	С
С	•	nsampl = rhinsm
	oname = iname(1:lnb(iname))//_bpf	if (rhisr.NE.0) srate = $1.0E6/rhisr$
С		С
ccccc	222222222222222222222222222222222222222	000000000000000000000000000000000000000
c oper	input and output files	c
С		do 10 itrace=ifirst,ilast,nrec
	call optdat (ipath,iname,0,recsz,ihand,ierr)	print 1000, itrace
c		1000 format(1X,'Filtering trace:',15)
	if(ierr.LT.0) then	C
	call report('segy','dataset','F',	c

```
c read in trace header to common block
С
          call rtdh(ihand,itrace,ierr)
          if (ierr.LT.0) then
           call report('segy','dataset','F',
   & 'Unable to read trace header file')
           call exit(1)
          endif
c check for end of file
          if (ierr.GT.0) then
           call report('segy','dataset','I',
   & 'End of file reached')
            goto 11
           endif
           if (unsamp.NE.0) nsampl = unsamp
           if (wsr.NE.0) srate = 1.0E6/wsr
c read in data, apply filter + write to new file
           call rtrd (ihand,itrace,work,nsampl,ierr)
           if (ierr.LT.0) then
            call report('segy','dataset','F',
    & 'Unable to read trace data file')
            call exit(1)
           endif
С
      call bpass(nsampl,work,f1,f2,f3,f4,srate,iwopt)
С
           call wtrd (ohand, itrace, work, nsampl, ierr)
```

```
С
         if (ierr.LT.0) then
          call report('segy','trace data','F',
  & 'Unable to write to file')
          call cltdat(ohand)
          call exit(1)
         endif
c put filter values to common block variables
c and write to new header file
         ulofrq = f1
        uhifrq = f4
c fill in some other variables required by plot programe
         if (ufldfn.EQ.0) ufldfn = ufldtn
         if (utrace.EQ.0) utrace = 1
С
         ushot = 0
         call wtdh(ohand,itrace,ierr)
         if (ierr.LT.0) then
          call report('segy','trace data','F',
  & 'Unable to write to file')
          call cltdat(ohand)
          call exit(1)
         endif
10 continue
 11 continue
```

```
A-6
```

```
c print last trace header common block values
   print 100, ushot ,utrc ,ufldfn,ufldtn,usrcpn,ucdp,
        utrace, utrtyp, unsum, unstk, uduse,
        wrange,wrcvge,wsrcse,wsrcdp,wrcvde,wsrcde,
  &
                wsrcwd,wrcvwd,
  &
                wsrcx ,wsrcy ,wrcvx ,wrcvy ,ucunit,
  &
                wvelw ,wvelsw,usrcut,urcvut,usrcst,urcvst,
                utotst,ulaga ,ulagb ,udelt ,umutst,umutfn,
  &
                unsamp,wsr ,ugntyp,wgain ,wgnst ,
                ucorr ,ufrqst,ufrqfn,uslen ,ustyp ,ustlen,
                uetlen,utptyp,ualfrq,ualslp,unofrq,unoslp,
   &
                ulofrq,uhifrq,uloslp,uhislp,uyear,uday,
   &
                uhour ,umin ,usec ,utctyp,xmsec ,
              xeyear, xeday, xehour, xemin, xesec, xemsec,
   &
        xdelt ,xrvel,xrtoff ,xstncd,xevecd
   &
100 format(6(I10),/,5(I10),/,6(F10.2),/,2(F10.2),/,4(F10.2),I10,/,
        2(F10.2),4(I10),/,6(I10),/,I10,F10.2,I10,2(F10.2),/,
        3(6(I10),/),5(I10),/,6(I10),/,3(I10),2(6X,A4),/)
c write out file header with extended name
    call whead(ohand,0,ierr)
   if (ierr.LT.0) then
          call report('segy','dataset','F',
   & 'Unable to write reel header file')
          call exit(1)
    endif
c dump common block rhicom + extras
```

```
С
       print*,'\n Rhicom common block'
       print 101, rhintr, rhinax, rhisr, rhisrf,
         rhinsm,rhinsf,ifmt ,rhirli,rhilni, rhimes
 101 format(1X,3(I8),/,1X,6(I8))
call cltdat(ihand)
   call cltdat(ohand)
   stop
   end
subroutine menu(pathi,patho,name,iwopt,f1,f2,f3,f4,ifirst,ilast)
С
       character*(*) pathi, patho, name
       integer iwopt, ifirst, ilast
       real f1,f2,f3,f4
       print 200
       print 201, pathi
       print 202, patho
       print 203, name
       print 204, iwopt
       print 205,f1
       print 206,f2
       print 207,f3
       print 208,f4
       print 209, ifirst
```

print 210, ilast

```
print 299
С
       format(10X,'*****************,',
200
  &
         10X,'* BAND PASS FILTER *',/,
         10X,'*************************
  &
 201
       format(2X,'1. Input pathname:',T55,A25)
       format(2X,'2. Output pathname:',T55,A25)
 202
 203
       format(2X,'3. Filename:',T55,A20)
       format(2X,'4. Window type (0=box,1=trapezoid,2=hanning)
 204
:',T58,I1)
 205
       format(2X,'5. Low-cut frequency - bottom
                                                      :',T55,F5.1)
 206
       format(2X,'6. Low-cut frequency - top {not used for} :',T55,F5.1)
        format(2X,'7. High-cut frequency - top { box window } :',T55,F5.1)
 207
        format(2X,'8. High-cut frequency - bottom
 208
                                                      :',T55,F5.1)
        format(2X,'9. First trace number :', T55,I4)
 209
 210
        format(1X,'10. Last trace number :',T55,I4)
 299
       format(1X,'99.
                             Run')
С
        return
        end
```

2. COMBINE9

```
program combine9
С
c combines up to 9 data and header files
   include "/home/kanga/dave/Flib/include/rhicom.h"
   include "/home/kanga/dave/Flib/include/segytc.h"
   include "/home/kanga/dave/Flib/include/functions.h"
   include "/home/kanga/dave/Flib/include/dls.h"
С
   integer*4 ierr, ihand(9), ohand, recsz
   integer*4 param, nsampl, filenum, maxnum
   integer*4 itrace, ifirst, ilast, nrec, otrace
   character*24 iname(9), oname, ipath
   real*4 work(16384)
С
   call dlsini()
С
c defaults
    ipath = './
    iname(1) = '1 161bs2
    iname(2) = '2 161bs2
    iname(3) = '3 161bs2
    iname(4) = '4 161bs2
    iname(5) = '5 161bs2
    iname(6) = '6 161bs2
    iname(7) = '7_161bs2
    iname(8) = '8 161bs2
    iname(9) = '9 161bs2
    oname = 161bs2
С
```

```
c ifirst is trace no. at start of loop, ilast is
c trace no. at end, and nrec is step size
   otrace = 1
   ifirst = 1
   ilast = 9999
   nrec = 1
   filenum= 1
   maxnum = 2
c get parameter values from user via menu
        call menu(ipath,iname,maxnum,oname)
        print*
        print 4
        read*,param
        print*
        if (param.EQ.99) goto 9
        if (param.EQ.1) then
                print*,'enter new pathname:'
                read 5, ipath
        elseif (param.EQ.2) then
                print*, 'enter number of files to combine :'
                read 6.maxnum
        elseif (param.EQ.3) then
                print*,'enter 1st filename:'
                read 5, iname(1)
        elseif (param.EQ.4) then
                print*, 'enter 2nd filename :'
                read 5,iname(2)
        elseif (param.EQ.5) then
                print*,'enter 3rd filename:'
```

read 5, iname(3)

C

	elseif (param.EQ.6) then	c open input file, read segy header
	print*,'enter 4th filename :'	call optdat (ipath,iname(filenum),0,recsz,ihand(filenum),ierr)
	read 5,iname(4)	C
-	elseif (param.EQ.7) then	if(ierr.LT.0) then
	print*,'enter 5th filename :'	call report('segy','dataset','F',
	read 5,iname(5)	& 'Cannot find all dataset files')
	elseif (param.EQ.8) then	call exit(1)
	print*,'enter 6th filename :'	endif
	read 5,iname(6)	C
	elseif (param.EQ.9) then	call rhead(ihand(filenum),0,ierr)
	print*,'enter 7th filename:'	C
	read 5,iname(7)	if (ierr.LT.0) then
	elseif (param.EQ.10) then	call report('segy','dataset','F',
	print*,'enter 8th filename :'	& 'Unable to read reel header file')
	read 5,iname(8)	call exit(1)
	elseif (param.EQ.11) then	endif
	print*,'enter 9th filename :'	C
	read 5,iname(9)	nsampl = rhinsm
	elseif (param.EQ.12) then	С
	print*,'enter output filename :'	000000000000000000000000000000000000000
	read 5,oname	c open output files 1st time round
	endif	c
	go to 1	if (filenum.eq.1) then
С	80	call optdat (ipath,oname, 1, recsz, ohand, ierr)
4	format (2X, Enter number of parameter to alter (99 to continue): ',\$)	if(ierr.LT.0) then
5	format (A)	call report('segy','dataset','F',
6	format (I1)	& 'Unable to create dataset - space? or exists?')
С	(-1)	call exit(1)
9	continue	endif
c		endif
	000000000000000000000000000000000000000	C
10	continue	000000000000000000000000000000000000000
С		C
-		

```
do 100 itrace=ifirst.ilast.nrec
         print 1000, itrace, otrace
c
c read in trace header to common block
         call rtdh(ihand(filenum),itrace,ierr)
         if (ierr.LT.0) then
          call report('segy','dataset','F',
  & 'Unable to read trace header file')
          call exit(1)
         endif
c check for end of file
         if (ierr.GT.0) then
          call report('segy','dataset','I',
  & 'End of file reached')
      call cltdat(ihand(filenum))
          filenum=filenum+1
       if (filenum, LE. maxnum) then
                 goto 10
          else
                goto 101
          endif
         endif
c read in data and write to new file
        call rtrd(ihand(filenum),itrace,work,nsampl,ierr)
        call wtrd(ohand,otrace,work,nsampl,ierr)
c edit header
         ufldfn=otrace
         ufldtn=otrace
```

```
if (xrvel.eq.0) xrvel=10000
С
С
      call wtdh(ohand,otrace,ierr)
      if (ierr.LT.0) then
       call report('segy','trace data','F',
  & 'Unable to write to file')
       call cltdat(ohand)
       call exit(1)
      endif
otrace=otrace+1
100 continue
101 continue
c write out file header with extended name
  call whead(ohand,0,ierr)
  if (ierr.LT.0) then
       call report('segy','dataset','F',
  & 'Unable to write reel header file')
       call exit(1)
  endif
С
call cltdat(ohand)
С
```

1000 format(1X,' trace: ',I5,' ->',I5)

```
C
   stop
   end
С
       subroutine menu(path,iname,maxnum,oname)
С
       integer maxnum
       character*(*) path, iname(maxnum), oname
С
       print 200
       print 201,path
       print 202,maxnum
       do i=1,maxnum
        print 203,i+2,i,iname(i)
        enddo
       print 204, oname
       print 299
       format(10X,'*************,/,
 200
        10X,'* COMBINE FILES *',/, 10X,'**************
  &
  &
        format(2X,'1. Input pathname:',T45,A25)
 201
 202
        format(2X,'2. Number of files:',T45,I1)
        format(2X,I1,'. Filename ',I1,' :',T45,A20)
 203
        format(2X,'12. Output filename:',T45,A20)
 204
       format(1X,'99.
 299
                           Run')
        return
        end
```

3. EXTR

program extr	itrace = 1
c	otrace = 0
c accepts trace file sequence and extracts portion with optional resampling	resmp = .false.
c	new_srate=100.0
include "/home/kanga/dave/Flib/include/rhicom.h"	c
include "/home/kanga/dave/Flib/include/segytc.h"	ccccccccccccccccccccccccccccccccccccccc
include "/home/kanga/dave/Flib/include/functions.h"	c get parameter values from user via menu
include "/home/kanga/dave/Flib/include/dls.h"	c
c	do while (param.ne.99)
integer*4 ierr, ihand, recsz, nsampl, itrace	call menu(ipath,iname,oname,ifirst,ilast,nrec,tfirst,tlast,
integer*4 ohand, new_recsz, new_nsampl, otrace	& resmp,new_srate)
integer*4 ifirst, ilast, nrec, tfirst, tlast	print*
integer*4 param	print 4
character iname*32, oname*32, ipath*32	read*,param
real*4 intrace(16384), work(16384), outtrace(16384)	print*
real*4 srate,new_srate	if (param.EQ.1) then
logical resmp	<pre>print*,'enter new pathname :'</pre>
c	read 5,ipath
call dlsini()	elseif (param.EQ.2) then
c	print*,'enter new input filename:'
ccccccccccccccccccccccccccccccccccccccc	read 5,iname
c defaults	elseif (param.EQ.3) then
ipath = './'	print*, enter new output filename:
iname = '17bs4'	read 5,oname
oname = 'extract'	elseif (param.EQ.4) then
C	print*,'enter first trace number :'
c ifirst is trace no. at start of loop, ilast is	read 8,ifirst
c trace no. at end	elseif (param.EQ.5) then
ifirst = 1	print*,'enter last trace number:'
ilast = 9999	read 8,ilast
nrec = 1	elseif (param.EQ.6) then
tfirst = 1	print*,'enter trace step:'
tlast = 4000	read 8,nrec

```
elseif (param.EQ.7) then
                                                                                        call optdat (ipath,iname,0,recsz,ihand,ierr)
                print*, 'enter first sample number:'
                                                                                        if(ierr.LT.0) then
                                                                                           call report('extract', 'dataset', 'F',
                read 8,tfirst
        elseif (param.EQ.8) then
                                                                                   & 'Cannot find all dataset files')
                print*,'enter last sample number:'
                                                                                          call exit(1)
                read 8,tlast
                                                                                         endif
        elseif (param.EQ.9) then
                                                                                        call rhead(ihand,0,ierr)
                if (resmp) then
                 resmp=.false.
                                                                                        if (ierr.LT.0) then
                                                                                           call report('extract','dataset','F',
                else
                                                                                   & 'Unable to read reel header file')
                 resmp=.true.
                                                                                           call exit(1)
                endif
        elseif ((param.EQ.10).and.(resmp)) then
                                                                                        endif
                print*,'enter new sample rate:'
                read 6, new srate
                                                                                        nsampl = rhinsm
        elseif (param.EQ.90) then
                                                                                        if (rhisr.NE.0) srate = 1.0E6/rhisr
                call report('extract', 'menu', 'I',
                                                                                c output
                'user requested abort')
  &
                                                                                        call optdat (ipath,oname, 1, new recsz, ohand, ierr)
                call exit(1)
                                                                                        if(ierr.LT.0) then
                                                                                           call report('extract', 'dataset', 'F',
        endif
                                                                                   & 'Cannot find all dataset files')
   enddo
                                                                                           call exit(1)
С
        new nsampl=tlast-tfirst+1
                                                                                         endif
        new recsz = new nsampl*4
                                                                                 С
        format (2X, Enter number of parameter to alter (99 to continue): ',$)
                                                                                c MAIN LOOP
  5
        format (A)
        format (F5.0)
                                                                                    do 10 itrace=ifirst,ilast,nrec
        format (I4)
                                                                                          otrace=otrace+1
                                                                                          call razout('Trace: ',itrace)
call flush(6)
c open files and read segy header
c input
```

c read	l in trace header to common block
	call rtdh(ihand,itrace,ierr)
	if (ierr.LT.0) then
	call report('extract','dataset','F',
&	'Unable to read trace header file')
	call exit(1)
	endif
С	
c che	ck for end of file
	if (ierr.GT.0) then
	call report('extract', 'dataset', 'I',
&	' End of file reached')
	goto 11
	endif
С	
c che	ck for correct sample no. and rate
	if (unsamp.NE.0) nsampl = unsamp
	if (wsr.NE.0) srate = $1.0E6/wsr$
С	
c read	d in data
	call rtrd (ihand,itrace,intrace,nsampl,ierr)
С	
	if (ierr.LT.0) then
	call report('extract','dataset','F',
&	' Unable to read trace data file ')
	call exit(1)
	endif
С	
cccc	222222222222222222222222222222222222222
С	
	if (resmp) then
	<pre>call taper(nsampl,intrace,int(0.25*srate))</pre>
	call resamp(16384,intrace, 16384, work, srate, new_srate, 6)

```
wsr=1.0E6/new_srate
         call aacopy(work,tfirst,tlast,outtrace,1,new nsampl)
        else
         call aacopy(intrace,tfirst,tlast,outtrace,1,new nsampl)
        endif
С
        unsamp=new_nsampl
c write to file
        ufldfn=otrace
        ufldtn=otrace
        xrtoff=xrtoff+real(tfirst-1)*wsr/1.0E3
С
        call wtdh(ohand,otrace,ierr)
         if (ierr.LT.0) then
         call report('extract','dataset','F',
  & 'Unable to write to trace header file')
          call exit(1)
         endif
         call wtrd (ohand, otrace, outtrace, unsamp, ierr)
         if (ierr.LT.0) then
         call report('extract','trace data','F',
  & 'Unable to write to file')
          call cltdat(ihand)
         call exit(1)
         endif
10 continue
c END OF MAIN LOOP
```

11 continue	print 201,pathi
c	print 202, iname
c write new file header, updating appropriate variables	print 203, oname
rhinsf=rhinsm	print 204, ifirst
rhinsm=unsamp	print 205, ilast
rhisrf=rhisr	print 206,nrec
rhisr=int(wsr)	print 207,tfirst
,	print 208,tlast
call whead(ohand,0,ierr)	print 209, resmp
if (ierr.LT.0) then	if(resmp) then
call report('extract','dataset','F',	print 210, new srate
& 'Unable to write to trace header file')	endif
call exit(1)	print 290
endif	print 299
C	c
call cltdat(ihand)	200 format(9X,'*************,',
call cltdat(ohand)	& 9X,'* EXTRACT DATA *',/,
c	& 9X,'**********')
stop	format(2X,'1. Input pathname:',T45,A25)
end	202 format(2X,'2. Input filename :',T45,A20)
c	format(2X,'3. Output filename:',T45,A20)
000000000000000000000000000000000000000	format(2X,'4. First trace number :',T45,I4)
C	format(2X,'5. Last trace number :',T45,I4)
subroutine menu(pathi,iname,oname,ifirst,ilast,nrec,tfirst,tlast,	206 format(2X,'6. Trace step :',T45,I4)
& resmp,new_srate)	format(2X,'7. First sample number :',T45,I4)
c	208 format(2X,'8. Last sample number :',T45,I4)
character*(*) pathi, iname, oname	209 format(2X,'9. Resample? :',T47,L1)
integer ifirst, ilast, nrec, tfirst, tlast	format(1X,'10. New sample rate (Hz) :',T43,F6.
real*4 new_srate	290 format(1X,\n',1X,'90 ABORT')
logical resmp	299 format(1X,'\n',1X,'99. RUN')
c	c
print*,\f	return
print 200	end

APPENDIX A

4. F-K

F-K.H

С		
С		common block for variables in f-k program
С		
		integer*4 param
		integer*4 ifirst, toff, pltype, nclass
С		
		real*4 trsep, class(20), f_filt(4), v_filt(4), redvel
С		
		character iname*32, oname*32, ipath*48
		character driver*16, title*24, vflag*4, fflag*4
С		
		logical reversed, war
С		
		common /fkcom/
	&	param, ifirst, toff, pltype, nclass, class, f_file
	&	v filt, redvel, trsep, iname, oname, ipath,
	&	driver, title, vflag, fflag, reversed, war
		save /fkcom/
С		
-		

p	rogram f_k
С	
c f-k	spectrum and velocity filtering
С	
	nclude "/home/kanga/dave/Flib/include/rhicom.h"
	nclude "/home/kanga/dave/Flib/include/segytc.h"
	nclude "/home/kanga/dave/Flib/include/functions.h"
i	nclude "/home/kanga/dave/Flib/include/dls.h"
С	
i	nclude "/home/kanga/dgl3dpg/fortran/include/f-k.h"
С	
	integer*4 ihand, ohand, ierr, recsz, length
	integer*4 itrace, otrace, nsampl, size
C SIZE	e = data array dimensions - must be a power of 2
	parameter(size=512)
	real*4 buffer(16384), srate, signi,dc,timint,scale
	real*4 xstart,xend,tstart,tend, rtoff
	real*4 rdat(size,size), idat(size,size), ampl(size,size)
	character*40 info(5)
•	logical ok
С	call dlsini()
	call fkini()
С	our Runo
•	ufldfn= 1
	itrace= 1
	redvel= 0.0
	rtoff = 0.0
С	
cccc	000000000000000000000000000000000000000
С	
	call fkdef(0)
1	call fkget(size)

```
call fkdef(1)
С
       call addsuff(iname,' fk',oname,length)
c open input file
       call optdat (ipath,iname,0,recsz,ihand,ierr)
       if(ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Cannot find all dataset files')
         call exit(1)
       endif
С
c read segy header
       call rhead(ihand,0,ierr)
       if (ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Unable to read reel header file')
         call exit(1)
       endif
С
       nsampl = rhinsm
       if (rhisr.NE.0) srate = 1.0E6/rhisr
c find first trace
       do while (ufldfn.lt.ifirst)
        call rtdh(ihand,itrace,ierr)
        if (ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Unable to read trace header file')
```

call exit(1)	goto 110
endif	endif
if (ierr.EQ.1) then	c
call report('segy','dataset','F',	c check for correct sample no. and rate
& 'shot point range doesn"t exist')	if (unsamp. $NE.0$) nsampl = unsamp
call exit(1)	if (wsr.NE.0) srate = $1.0E6/wsr$
endif	if $(xrtoff.NE.0)$ rtoff = real $(xrtoff)$
itrace=itrace+1	if (xstart.EQ.0.0) xstart=wrange/1000.0
end do	xend=wrange/1000.0
itrace=itrace-1	c
xstart=wrange/1000.0	c get reduction velocity if necessary
c	if ((war).and.(xrvel.ne.0.0)) then
000000000000000000000000000000000000000	redvel = real(xrvel)/1000.0
c READ IN DATA TO REAL ARRAY	endif
c	c
do 100 while (.true.)	c read in data
if (ufldfn.GE.(ifirst+size-1)) goto 110	call rtrd (ihand, itrace, buffer, nsampl, ierr)
itrace=itrace+1	if (ierr.LT.0) then
call razout('Reading trace: ',itrace)	call report('segy','dataset','F',
call flush(6)	& 'Unable to read trace data file')
c	call exit(1)
c read in trace header to common block	endif
call rtdh(ihand,itrace,ierr)	c
if (ierr.LT.0) then	c copy data to array rdat
call report('segy', 'dataset', 'F',	k=itrace-ifirst+1
& 'Unable to read trace header file')	call azero(size,rdat(1,k))
call exit(1)	call aacopy(buffer,toff,toff+size,rdat(1,k),1,size)
endif	call mean(size,rdat(1,k),dc)
c	call azero(size,idat(1,k))
c check for end of file	c
if (ierr.GT.0) then	202222222222222222222222222222222222222
call report('segy','dataset','I',	c
& 'End of file reached')	100 continue

110	continue	enddo
С	,	endif
c calcu	late start+end times	c
	tstart=(rtoff/1000.0)+toff/srate	c reverse in x if necessary
	tend=(rtoff/1000.0)+(toff+size-1)/srate	if (.not.reversed) then
С		call reverse2d(rdat,size,size)
c data	info	endif
	info(1)="	c
	write(info(1),'(a14,f6.1,a2,f6.1,a3)'),	c do 2D fft and reorder wavenumber information
&	'offset range ',xstart,' -',xend,' km'	signi=1.0
	info(2)="	call fft2d(rdat,idat,size,size,signi)
	write(info(2),'(a15,f6.2,a2,f6.2,a2)'),	call kord2d(rdat,size,size)
&	'time interval ',tstart,' -',tend,' s'	call kord2d(idat,size,size)
	info(3)="	timint=1.0/srate
	write(info(3),'(a16,f6.2,a3)'), 'sample rate', 'srate,' /s'	c
	info(4)="	c ask whether to plot unfiltered data
	if(war) then	call usrmes('plot unfiltered f-k data - ',1)
	write(info(4),'(a15,f4.1,a5)'), 'data reduced at',redvel,' km/s'	call askok(6,5,ok)
	endif	if (ok) then
С		c
c fill i	n any spaces at end of array	c get amplitude information
	if (k.lt.size) then	do j=1,size
	do j=k+1,size	do i=1,size
	call azero(size,rdat(1,j))	ampl(i,j)=sqrt(rdat(i,j)**2+idat(i,j)**2
	call azero(size,idat(1,j))	enddo
	enddo	enddo
	endif	c
С		c transpose f and k axes
c tape	r edges (20 samples)	call transpose(ampl,size)
	call taper2d(size,k,rdat,20,20)	C
	if ((nsampl-toff).lt.size) then	c normalise
	do j=1,k	call norm(ampl,size*(size/2+1),1.0,scale)
	call taper 2(psampl-toff rdat(1 i) 1.20)	info(5)="

write(info(5),'(a24,e10.3)'),'amplitude normalised to ',1.0/scale	
C	
c plot f-k data	
c NB only plot data below nyquist frequency	
if (pltype.eq.2) then	
call fkplot(ampl,size,(size/2)+1,trsep,timint,	
& nclass,class,driver,title,info)	
elseif (pltype.eq.3) then	
call fkplot3d(ampl,ampl,size,(size/2)+1,trsep,timint,	
& nclass,class,driver,title,info)	
endif	
c	
endif	
c	
ccccccccccccccccccccccccccccccccccccccc	
c apply velocity/frequency filter	
c	
call fkfilter(rdat,idat,size,size,trsep,timint,f_filt,v_filt,	
& fflag,vflag,redvel)	
c	
ccccccccccccccccccccccccccccccccccccccc	
c plot filtered data?	
c	
call usrmes('plot filtered f-k data - ',1)	
call askok(6,5,ok)	
if(ok) then	
C	
c get amplitude information	
do j=1,size	
do i=1,size	
ampl(i,j)=sqrt(rdat(i,j)**2+idat(i,j)**2)	
ampi(i,j)=sqri(idai(i,j) · · · 2 + idai(i,j) · · · 2) enddo	
	
enddo	

```
c transpose f and k axes
        call transpose(ampl,size)
С
c normalise
        call norm(ampl,size*(size/2+1),1.0,scale)
        info(5)="
        write(info(5),'(a24,e10.3)'),'amplitude normalised to ',1.0/scale
С
         if (pltype.eq.2) then
         call fkplot(ampl,size,(size/2)+1,trsep,timint,
                nclass, class, driver, title, info)
  &
         elseif (pltype.eq.3) then
         call fkplot3d(ampl,ampl,size,(size/2)+1,trsep,timint,
  &
                nclass, class, driver, title, info)
         endif
С
        endif
c write out filtered data to file
        call usrmes('write filtered data - ',1)
        call askok(6,5,ok)
        if(ok) then
c inverse transform
        call kord2d(rdat,size,size)
        call kord2d(idat,size,size)
        signi=-1.0
        call fft2d(rdat,idat,size,size,signi)
        if (.not.reversed) then
         call reverse2d(rdat,size,size)
```

call reverse2d(idat,size,size)	& 'Unable to read trace header file')
endif	call exit(1)
C	endif
call optdat (ipath,oname,1,recsz/decifact,ohand,ierr)	c
if(ierr.LT.0) then	if (ierr.GT.0) then
call report('segy','dataset','F',	call report('segy','dataset','I',
& 'Cannot create output files - exist?')	& 'End of file reached')
call exit(1)	goto 210
endif	endif
C	C
itrace=1	c copy data to buffer
otrace=1	c nb pad traces with non-zero constant so agc in 'razzle' can cope
ufldfn=0	call pad(buffer,1,16384,0.001)
C C	call aacopy(rdat(1,otrace),1,size,buffer,toff,toff+size)
do while (ufldfn.lt.ifirst)	C
call rtdh(ihand,itrace,ierr)	call wtrd (ohand, otrace, buffer, nsampl/decifact, ierr)
if (ierr.LT.0) then	if (ierr.LT.0) then
call report('segy','dataset','F',	call report('segy','dataset','F',
& 'Unable to read trace header file')	& 'Unable to write to trace data file')
call exit(1)	call exit(1)
endif	endif
itrace=itrace+1	C
end do	unsamp=unsamp/decifact
itrace=itrace-1	wsr=wsr*real(decifact)
C	C C
do 200 while (.true.)	call wtdh(ohand,otrace,ierr)
if (ufldfn.GE.(ifirst+size-1)) goto 210	if (ierr.LT.0) then
call razout('Writing trace: ',otrace)	call report('segy','dataset','F',
call flush(6)	& 'Unable to write to trace header file')
Can Hush(o)	call exit(1)
call rtdh(ihand,itrace,ierr)	endif
if (ierr.LT.0) then	C
call report('segy','dataset','F',	itrace=itrace+1
can report seg, dataset, i,	111100 111100 1

```
otrace=otrace+1
                                                                      c character
200
       continue
                                                                              ipath = './'
210
       continue
                                                                              iname = '11g128 8'
                                                                              driver='mx11'
С
        rhinsm=rhinsm/decifact
                                                                              title= 'F-K spectrum'
        rhinsf=rhinsf/decifact
                                                                              vflag = 'YES'
        rhisr =rhisr *decifact
                                                                              fflag = 'NO '
        rhisrf=rhisrf*decifact
                                                                      c logical
                                                                              reversed= false.
С
        call whead(ohand,0,ierr)
                                                                              war =.tme.
        if (ierr.LT.0) then
                                                                      c numerical
         call report('segy','dataset','F',
                                                                              ifirst= 1
  & 'Unable to write reel header file')
                                                                              toff = 600
         call exit(1)
                                                                              trsep = 75.0
        endif
                                                                              nclass= 14
                                                                              pltype= 2
С
    call cltdat(ohand)
                                                                      С
       endif
                                                                      c filter parameters
                                                                              data f filt / 2.0, 4.0,
                                                                                                           50.0 /,
С
                                                                                                   40.0.
                                                                                v filt / 4.0, 6.0,
                                                                                                           11.0 /
                                                                         &
                                                                                                   8.0,
С
   call cltdat(ihand)
                                                                      c class limits
                                                                              data class /0.005.
                                                                                                   0.010,
   stop
                                                                                                                  0.05,
                                                                                     0.10,
                                                                                                    0.15,
                                                                                                                  0.20,
                                                                         &
   end
                                                                                     0.25,
                                                                         &
                                                                                                    0.30,
                                                                                                                  0.35,
                                                                         &
                                                                                     0.40,
                                                                                                   0.45,
                                                                                                                  0.50,
&
                                                                                     0.55,
                                                                                                   0.60.
                                                                                                                  0.65,
       subroutine fkini()
                                                                                     0.70,
                                                                                                   0.75,
                                                                         &
                                                                                                                  0.80,
                                                                         &
                                                                                     0.85,
                                                                                                   0.90 /
С
c menu default settings for f-k
                                                                              return
       include "/home/kanga/dgl3dpg/fortran/include/f-k.h"
                                                                              end
С
```

	subrouti	ne fkdef(mode)
С		
c mod	ie = 0	read default values from file fk.dat if it exists
С		else generate defaults
С	1 -	write menu values to file fk.dat
С		
		"/home/kanga/dave/Flib/include/functions.h" "/home/kanga/dgl3dpg/fortran/include/f-k.h"
С		
	integer*	4 mode, iunit
	characte	er*6 filename
С		
	iunit=ig	
	filenam	e='fk.dat'
С		
c chec	k if file exi	
		s(filename)) then
c oper	as OLD fi	
	open(unit=iunit, file=filename, status='old',
&		form='formatted', iostat=ierr)
С		
c else	open as NI	
		node.ne.0) then
	open(unit=iunit, file=filename, status='new',
&		form='formatted', iostat=ierr)
	else	
		reec(iunit)
	return	
	endif	
c		
		w(iunit,mode)
	close(u	nit=iunit)

```
call ifreec(iunit)
С
       return
       end
С
subroutine fkget(size)
c get parameter values for f-k from user via menu
       include "/home/kanga/dgl3dpg/fortran/include/f-k.h"
       integer*4 size
   do while (param.NE.99)
       call fkmenu(size)
       print*
       print 4
       read*,param
       print*
       if (param.EQ.1) then
               print*,'enter new input pathname:'
               read 5, ipath
       elseif (param.EQ.2) then
               print*,'enter new input filename:'
               read 5, iname
        elseif (param.EQ.3) then
               if(war) then
                war = .false.
               else
                war = .true.
               endif
       elseif (param.EQ.4) then
```

print*,'enter first trace number:'
read 8, if irst
elseif (param.EQ.5) then
print*,'enter first sample number:'
read 8,toff
elseif (param.EQ.6) then
print*,'enter trace separation :'
read 7,trsep
elseif (param.EQ.7) then
print*,'enter number of classes :'
read 8,nclass
elseif (param.EQ.8) then
call classdef(nclass,class)
elseif (param.EQ.9) then
if(pltype.eq.2) then
pltype=3
else
pltype=2
endif
elseif (param.EQ.10) then
print*,'enter device name :'
read 5,driver
elseif (param.EQ.11) then
if(vflag(1:1).eq.'Y'.or.vflag(1:1).eq.'y') then
vflag='NO '
elseif(vflag(1:1).eq.'N'.or.vflag(1:1).eq.'n') then
print*,'enter velocity filter parameters:'
read 9,v_filt
vflag='YES'
endif
elseif (param.EQ.12) then
if(fflag(1:1).eq.'Y'.or.fflag(1:1).eq.'y') then
fflag='NO '

```
elseif(fflag(1:1).eq.'N'.or.fflag(1:1).eq.'n') then
                 print*, 'enter frequency filter parameters:'
                 read 9.f filt
                fflag='YES'
                endif
       elseif (param.EQ.13) then
               if (reversed) then
                reversed=.false.
                else
                reversed=.true.
                endif
        elseif (param.EQ.14) then
                print*, 'enter title for plot : '
                read 5, title
        elseif (param.EQ.90) then
                call report('f-k transform', 'menu', 'I',
  &
                'user requested abort')
                call exit(1)
        endif
   end do
С
        format (2X, 'Enter number of parameter to alter (99 to continue): ',$)
        format (A)
       format (F8.0)
       format (I4)
        format (4f5.0)
        return
        end
```

subroutine classdef(nclass, class)		subroutine ikplot(data,nk,nt,dx,dt,ncl,acl,		
c		& driver,title,info)		
	integer*4 nclass	c		
	real*4 class(20),tclass	c adapted from UNIRAS AGL/CONTOURS example programs		
С		$c \qquad \qquad con 007 + con 002$		
	if(nclass.ge.0) then	c		
	iclass=1	c nk,nf: grid dimensions		
	do while (iclass.ne.0)	c ncl : no. class limits (-ve = percentiles) c ncol : colour scale		
	print 300			
	do i=1,nclass	c dx : distance sample interval in m		
	print 301,i,class(i)	c dt : time sample interval in sec		
	enddo	c data(nk,nf):f-k data array		
	print 302	c		
	read 303,iclass,tclass	parameter (ncol=1,iundef=9999)		
	if(iclass.ge.1.and.iclass.le.nclass) then	parameter (fundef=999.999)		
	class(iclass)=tclass	С		
	endif	real*4 data(nk,nf), acl(20), dt,dx		
	enddo	real*4 kmin,kmax,fmin,fmax,height,h		
	else	integer*4 lenar1(4), lenar2(3), plotnum /1/		
	print 400	character txtar1(4)*10, txtar2(3)*5		
	call delay(5.)	character driver*(*),driver_str*30		
	endif .	character title*(*),info(5)*(40),uni_str*12		
С		c		
300	format(1x,'\f',4x,'class value')	save plotnum		
301	format(1x,t7,i2,t15,f10.3)	c user coord limits		
302	format(2x, 'enter class number, value (return to exit):')	fmin=0.0		
303	format(i,f11.0)	fmax=1.0/(2.0*dt)		
400	format(1x,'\f',5x,'class boundaries calculated as percentiles')	kmin=-1.0/(2.0*dx)		
С		kmax = 1.0/(2.0*dx)		
	return	call minmax(nk*nf,data,amin,amax)		
	end	C .		
С		c character string lengths of axis texts and axis text strings		
ccccc	000000000000000000000000000000000000000	data lenar1 / 10,2,9,2 /		

	data txtar1 / 'wavenumber','/m','frequency','Hz' /
С	
•	ag between numeric labels on k and f axes are 3 tickmarks between each label nticks = 4 dblf=5.0 dblk=0.5E-3
С	•
c charac	cter string lengths and character strings for colour scale data lenar2 /5,5,3/ data txtar2 /'below','above','???'/
c	
c open l	UNIRAS
	driver_str='sel '//driver//';exit' write(uni_str,'("UNIPICT.",I1)') plotnum plotnum=plotnum+1 call gbegin (driver_str, ' ', uni_str)
С	ouii googiii (uiivoi_bu; , uiii_bu)
c set lin	nits and viewport call grpsiz(xsi,ysi) xm=min(xsi,ysi) xsize = 0.6*xm ysize = xsize xoff = 0.25*(xsi-xsize) yoff = 0.5*(ysi-ysize) call glimit(kmin,kmax,fmin,fmax,amin,amax) call gyport(xoff,yoff,xsize,ysize)
	call gwbox(1.0,1.0,0.0)
С	-
c set cla	ass levels if (ncl.gt.0) then call rclass(acl,ncl,0)
	else

```
c percentiles
          call rclass(0.0,-ncl,4)
         endif
c use colours from colour scale ncol
         call rshade(ncol,0)
c plot the 2d contour map (quick contour for large datasets)
         if (nk*nf.le.512*512) then
           call gcnr2s(data,nk,nf)
         else
           call grsz2q(0,0.5,0.5)
           call gcnr2q(data,nk,nf)
         endif
С
         height = 0.03*min(xsize,ysize)
c plot 4 axes
         call gscale
         call raxtef(4,'cenb',1)
         call raxsti(nticks)
         call raxdis(3,1,iundef)
c plot k-axes
          call raxtex(6,lenar1(1),txtar1(1),fundef,fundef,height)
          call raxtex(5,lenar1(2),txtar1(2),fundef,fundef,0.8*height)
          call raxlfo(2,-3,iundef,iundef)
          call raxbti(iundef,fundef,fundef,dblk)
c bottom
          call raxdis(6,1,iundef)
          call raxdis(5,1,iundef)
          call raxis(1,fmin,height,1)
```

c top

	call raxdis(6,0,iundef)	c
	call raxdis(5,0,iundef)	c give plot a title
	call raxdis(4,0,iundef)	tpf=fmax+0.2*(fmax-fmin)
	call raxis(1,fmax,height,2)	tpk=0.5*(kmin+kmax)
С	······································	call rtxjus(1,3)
	lot f-axes	call rtxhei(5.0)
·P	call raxtex(6,lenar1(3),txtar1(3),fundef,fundef,height)	call rtx(-1,title,tpk,tpf)
	call raxtex(5,lenar1(4),txtar1(4),fundef,fundef,0.8*height)	C
	call raxlfo(0,0,iundef,0)	c add additional info
	call raxbti(iundef,fundef,fundef,dblf)	call rtxjus(0,0)
c le		call rtxhei(3.0)
CR	call raxdis(6,1,iundef)	do i=1,5
	call raxdis(5,1,iundef)	call rtx(-1,info(i),
	call raxdis(4,1,iunder)	& (kmax+0.05*(kmax-kmin)),(tpf-real(i)*h))
	call raxis(4,1,1tinder) call raxis(2,kmin,height,1)	enddo
٠.	· · · · · · · · · · · · · · · · · · ·	C
CI	right call raxdis(6,0,iundef)	c close UNIRAS
	call raxdis(5,0,iundef)	call gend ()
	call raxdis(4,0,iundef)	return
	call raxis(2,kmax,height,2)	end
С	1.1 1.1 2	C
c plot legend showing correspondence between colour & amplitude if (ncl.ge.15) then		CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
	height=0.7*ysize/real(iabs(ncl))	subroutine fkplot3d(ante3d,ante4d,nk,nf,dx,dt,ncl,
	h=0.8*(fmax-fmin)/real(iabs(ncl))	& acl,driver,title,info)
	else	c
height=0.7*ysize/15.0		c adapted from UNIRAS AGL/CONTOURS example program con00
	h=0.8*(fmax-fmin)/15.0	c
endif		c np : no. samples
	call rtxfon('cenb',1)	c nk,nf: grid dimensions
	call gclopt(lenar2,txtar2,height,	c ncl : no. class limits (-ve = percentiles)
	& 3,0.0,1)	c ncol: colour scale
	call gcoscl(kmax+0.1*(kmax-kmin),fmin)	c dx : distance sample interval in m

```
fmin,fmax,kmin,kmax
                     real*4
                     integer*4 lenar1(6), lenar2(3), iplane(3), plotnum/1/
                     character txtar1(6)*10, txtar2(3)*5
                     character driver*(*),driver str*30
                     character title*(*),info(5)*40,uni str*12
             С
                     save plotnum
A-30
            c user coord limits
                     fmin=0.0
                     fmax=1.0/(2.0*dt)
                     kmin=-1.0/(2.0*dx)
                     kmax = 1.0/(2.0*dx)
             С
                     call minmax(nk*nf,ante3d,zmin,zmax)
                     zmin=0.0
                      zmax=1.0
             С
```

c contour line widths

&

data wid / 0.3 /

c character string lengths of axis texts and axis text strings data lenar1 / -2, -2, -2, -2, -2, -2 /

'','amplitude'/

data txtar1 / '/m', 'wavenumber', 'Hz', 'frequency',

: time sample interval in sec

parameter (ncol=1.iundef=9999)

parameter (fundef=999.999)

c ante4d(nk.nf): data for 4th dimension (colour contours)

real*4 ante3d(nk,nf), ante4d(nk,nf), acl(20),dx,dt

c ante3d(nk,nf): data for 3rd dimension (z)

c dt

С

```
c spacing between numeric labels on x, y and z axes
c there are 4 tickmarks between each label
        nticks = 4
        db1f=5.0
        dblk=0.5E-3
        dblz=0.25
С
c planes for axis annotation
        data iplane /1.1.1/
c character string lengths and character strings for colour scale
         data lenar2 /5,5,0/
         data txtar2 /'below ','above',' '/
c open UNIRAS
         driver str='sel '//driver//':exit'
        write(uni str,'("UNIPICT.",I1)') plotnum
         plotnum=plotnum+1
         call gbegin (driver str, '', uni str)
c set limits and viewport
         call grpsiz(xsi,ysi)
        xm=min(xsi,ysi)
         xsize = 0.8*xm
         vsize = xsize
         xoff = 0.25*(xsi-xsize)
         yoff = 0.25*(ysi-ysize)
         call glimit(kmin,kmax,fmin,fmax,zmin,zmax)
         call gvport(xoff,yoff,xsize,ysize)
c set 3d viewing parameters
```

call gwbox(1.0,1.0,0.5)

```
call geve(-3.0,-4.0,3.5)
c plot 3d axis system - x, y and z axes plotted separately because
c axis attributes differ
         call gvproj(2)
         height = 0.035*min(xsize, ysize)
С
c text for labels and axis texts
         call raxtef(4,'cenb',1)
         call raxtef(6,'cenb',1)
c turn plotting of minor tickmarks, axis texts and tick lines on.
c and set attributes to get integer type labels
         call raxdis(3,1,iundef)
         call raxdis(6.1.iundef)
         call raxdis(7,1,iundef)
c number of minor tickmarks
         call raxsti(nticks)
c plot the x
         call raxlfo(2,-3,iundef,iundef)
          call raxbti(iundef,fundef,fundef,dblk)
          call raxis3(1.height,iplane,lenar1,txtar1)
С
c plot the y axis
          call raxlfo(0,0,iundef,0)
          call raxbti(iundef,fundef,fundef,dblf)
          call raxis3(2,height,iplane,lenar1,txtar1)
С
c plot z axis
          call raxlfo(2,0,iundef,0)
          call raxbti(iundef,fundef,fundef,dblz)
```

```
call raxis3(3,height,iplane,lenar1,txtar1)
c set class levels
         if (ncl.gt.0) then
          call rclass(acl.ncl.0)
         else
c percentiles
          call rclass(0.0,-ncl,4)
         endif
c use colours from colour scale ncol
         call rshade(ncol.0)
c define contour line widths
c when only one width defined - applies to all contour lines
         call gconwi(wid,1)
c set fishnet attributes
c every 5th gridline is plotted in anti-background colour
         call gconli(0,0.0,0,5.0,5.0,0.2,1)
c switch off the plotting of walls
         call gwall(9999)
c plot the 4d contour map
         call gconr4(ante3d,ante4d,nk,nf)
c plot legend showing correspondence between colour & signal strength
         if (ncl.ge.15) then
          height=0.55*vsize/real(iabs(ncl))
          else
          height=0.55*ysize/15.0
          endif
```

```
call rtxfon('cenb',1)
                                                                                            with Hanning windows
                                                                                   С
        call gclopt(lenar2,txtar2,height,
  &
                 3,0.0,1)
                                                                                   c NB if fsize or psize = 0 then corresponding filter not applied
        call gcoscl(xoff+1.15*xsize,yoff+0.05*ysize)
                                                                                       include "/home/kanga/dave/Flib/include/functions.h"
                                                                                       include "/home/kanga/dave/Flib/include/dls.h"
c give plot a title
        tpf=yoff+1.1*ysize
                                                                                   С
        tpk=xoff+0.6*xsize
                                                                                            integer*4 nk, nf, fsize, psize, fs, ps
        call rtxfon('swim',1)
                                                                                   c fsize,psize = no. points defining half of window
        call rtxjus(1,3)
                                                                                            parameter(fsize=20,psize=20)
                                                                                            real*4 rdat(nk,nf), idat(nk,nf), dx, dt
        call rtxhei(5.0)
        call rtx(-1,title,tpk,tpf)
                                                                                            real*4 fvals(16000), kvals(16000)
                                                                                            real*4 f filt(4), v_filt(4),rp_filt(4), redvel
С
        additional info
                                                                                            real*4 f(2*fsize), fa(2*fsize), p(2*psize), pa(2*psize)
c add
        call rtxfon('cenb',1)
                                                                                            real*4 pi, arg
        call rtxius(0,0)
                                                                                            parameter(pi=3.1415967)
                                                                                            character*4 fflag,vflag
        call rtxhei(3.5)
         do i=1.5
         call rtx(-1,info(i),
                                                                                   c calculate (reduced) slownesses
         (xoff+0.9*xsize),(0.9*tpf-real(i)*5.0))
                                                                                            doi=1.4
                                                                                             if (redvel.eq.0.0) then
         enddo
                                                                                              rp filt(5-i)=1.0/v filt(i)
c close UNIRAS
                                                                                              else
                                                                                              rp_filt(5-i)=1.0/v_filt(i)-1.0/redvel
         call gend ()
                                                                                             endif
         return
         end
                                                                                            enddo
                                                                                    c calculate freq. ordinates (Hz)
do j=1,nf/2
         subroutine fkfilter(rdat,idat,nk,nf,dx,dt,f filt,v filt,
                                                                                             a=real(i)
                          fflag,vflag,redvel)
                                                                                              b=real(nf)
   &
                                                                                             fvals(j)=(a-1.0)/(b*dt)
С
         Design and apply frequency and velocity (slowness) filters
                                                                                             fvals(nf-j+1)=-a/(b*dt)
С
```

```
enddo
С
c calculate wavenumber ordinates in (1/km)
         do j=1,nk
          a=real(i)
          b=real(nk)
          kvals(j)=1000.0*((a-1.0)/(b*dx)-0.5/dx)
         enddo
С
c check whether frequency filter is required
         if(fflag(1:1).eq.'Y'.or.fflag(1:1).eq.'y') then
          fs=fsize
         else
          fs=0
          goto 100
         endif
c design frequency filter window
         call azero(f,2*fsize)
         fa(1)=fvals(1)
         fa(2*fsize)=fvals(nf/2)
         do i=2,fsize
            fa(i)=f filt(1)+
                  real(i-2)*(f filt(2)-f_filt(1))/real(fsize-2)
   &
            arg=pi*real(i-2)/real(fsize-2)
            f(i)=0.5*(1.0-\cos(arg))
С
            fa(i+fsize-1)=f filt(3)+
                  real(i-2)*(f filt(4)-f filt(3))/real(fsize-2)
            f(i+fsize-1)=0.5*(1.0+cos(arg))
         enddo
c check whether velocity filter is required
```

```
100
       if(vflag(1:1).eq.'Y'.or.vflag(1:1).eq.'y') then
        ps=psize
        else
        ps=0
        goto 200
       endif
c design slowness filter window
       call azero(p,2*psize)
        pa(1)=kvals(1)/fvals(1)
       pa(2*psize)=kvals(nk)/fvals(1)
       do i=2,psize
          pa(i)=rp filt(1)+
  &
                real(i-2)*(rp_filt(2)-rp_filt(1))/real(psize-2)
          arg=pi*real(i-2)/real(psize-2)
          p(i)=0.5*(1.0-cos(arg))
С
          pa(i+psize-1)=rp_filt(3)+
                real(i-2)*(rp_filt(4)-rp_filt(3))/real(psize-2)
          p(i+psize-1)=0.5*(1.0+cos(arg))
        enddo
c apply filter
200
        call fk filt(fvals,kvals,rdat,idat,nf,nk,
  &
                  pa,p,2*ps,fa,f,2*fs)
С
        return
        end
```

	subroutine fkrw(iunit,mode)
С	
c read/v	write f-k defaults file fk.dat
С	
	include "/home/kanga/dgl3dpg/fortran/include/f-k.h"
С	
	integer*4 iunit, mode
С	
c MOD	DE=0 - read
	if (mode.eq.0) then
	read (iunit,100) ifirst, toff, pltype,
&	nclass
	read (iunit,101) trsep
	read (iunit,102) class
	read (iunit,103) v_filt, f_filt
	read (iunit,104) iname, ipath, driver,
&	title, vflag, fflag
	read (iunit,105) reversed, war
C	
c MOI	DE=1 - write
	elseif (mode.eq.1) then
&	write (iunit,100) ifirst, toff, pltype, nclass
	write (iunit, 101) trsep
	write (iunit, 102) class
	write (iunit, 103) v_filt, f_filt
	write (iunit, 104) iname, ipath, driver,
&	title, vflag, fflag
	write (iunit, 105) reversed, war
С	
	endif
С	
100	format(4i4)

```
101
       format(f7.2)
102
       format(20f6.3)
103
       format(8f5.2)
       format(a20,a40,a15,a24,2a3)
104
105
       format(211)
C
       return
       end
subroutine fkmenu(size)
С
       display f-k menu on screen
С
С
       include "/home/kanga/dgl3dpg/fortran/include/f-k.h"
       integer*4 size
       character*10 type
С
       type='???'
       if (pltype.eq.2) type='2-D'
       if (pltype.eq.3) type='3-D'
С
       print 199
       print 200, size, size
       print 201, ipath
       print 202, iname
       print 203,war
       print 204, if irst
       print 205,toff
       print 206,trsep
       print 207,nclass
       print 208
```

	print 209,type	c
	print 210,driver	000000000000000000000000000000000000000
	print 211,v_filt,vflag	
	print 212,f filt,fflag	subroutine fk filt(xf,xk,x,y,lxf,lxk,pa,p,np,fa,f,nf)
	print 213,reversed	C
	print 214,title	c slowness-frequency filtering in the f-k domain
	print 290	c
	print 299	c dls 87c
С	•	c adapted - dpg 91
199	format(1X,'\f\n',	c
&	t18,'***************//,	c x(lxf,lxk) 2d data array of real part
&	t18,'* F-K transform *')	c y(lxf,lxk) 2d data array of imaginary part
200	format(t18,'* ',i4,' x',i4,' *',/,	c xf(lxf),xk(lxk) arrays containing ordinates
&	t18.'***************	c p(np),pa(np) slowness filter values and ordinates
201	format(2X,'1. Input pathname ',T48,A32)	c if np=0 then no filter is applied
202	format(2X,'2. Filename ',T48,A32)	c f(nf), fa(nf) angular frequency filter values and ordinates
203	format(2X,'3. Use WAR reduction info ',T53,L1)	c if nf=0 then the nyquist is assumed
204	format(2X,'4. First trace number ',T50,I4)	c
205	format(2X,'5. Time offset in samples ',T50,I4)	c the filters are interpolated linearly to obtain coefficients
206	format(2X,'6. Trace separation ',T50,F6.1)	c at the requred velocity and frequency values
207	format(2X, '7. No. contour classes ', T50, I4)	c frequency filters are assumed symmetric about f=0.0
208	format(2X,'8. Alter contour classes')	c
209	format(2X,'9. Plot type (2-D or 3-D) ',T52,A3)	parameter(maxlen=2048)
210	format(1X,'10. Device name ',T46,A10)	real*4 x(lxf,lxk),xf(lxf),xk(lxk),p(np),pa(np),f(nf),fa(nf)
211	format(1X,'11. Velocity filter(',4F5.1,')',T52,A3)	real*4 y(lxf,lxk)
212	format(1X,'12. Frequency filter(',4F5.1,')',T52,A3)	real*4 ffilt(maxlen), slowness
213	format(1X,'13. Reversed data',T53,L1)	C
214	format(1X,'14. Title ',T48,A24)	c store frequency filter coefficients to save time
290	format(1X,\n',1X,'90. ABORT')	if(nf.gt.0) then
299	format(1X,\n',1X,'99. RUN')	do 100 jf=1,lxf
С		call linint(fa,f,nf,abs(xf(jf)),ffilt(jf))
	return	100 continue
	end	else

```
call pad(ffilt,1,lxf,1.0)
              endif
           С
           c now execute the filter
               do 300 jk=1,lxk
                do 200 jf=1,lxf
           С
           c calc velocity filter
                  if(np.gt.0.and.xf(jf).ne.0.0) then
                    slowness=xk(jk)/xf(jf)
                    call linint(pa,p,np,slowness,pfcoff)
                  else
                    pfcoff=1.0
                  endif
           С
A-36
           c apply filter
                  x(jf,jk)=x(jf,jk)*ffilt(jf)*pfcoff
                  y(jf,jk)=y(jf,jk)*ffilt(jf)*pfcoff
           С
           200
                  continue
           300 continue
               return
               end
```

5. F-T

```
program f t
c accepts trace file sequence and outputs frequency amplitude
c spectrum trace sequence
   include "/home/kanga/dave/Flib/include/rhicom.h"
   include "/home/kanga/dave/Flib/include/segytc.h"
   include "/home/kanga/dave/Flib/include/functions.h"
   include "/home/kanga/dave/Flib/include/dls.h"
   integer*4 ierr, ihand, ohand, recsz, new recsz
   integer*4 param
   integer*4 itrace, otrace, ifirst, ilast, nrec
   integer*4 len,11,12,nsampl
   real*4 work(16384),x(16384),y(16384),srate,df
    character iname*20, oname*24, ipath*25, opath*25
   call dlsini()
c defaults
    ipath = './
    opath = './
    iname = '1 160bs5
   oname = '
c ifirst is trace no. at start of loop, ilast is
c trace no. at end, and nrec is step size
    ifirst = 1
    ilast = 9999
    nrec = 1
    otrace = 0
```

```
С
c get parameter values from user via menu
        call menu(ipath,opath,iname,ifirst,ilast,nrec)
        print*
        print 4
        read*,param
        print*
        if (param.EQ.99) goto 9
        if (param.EQ.1) then
                print*,'enter new input pathname:'
                read 5, ipath
        elseif (param.EQ.2) then
                print*,'enter new output pathname:'
                read 5,opath
        elseif (param.EQ.3) then
                print*,'enter new filename:'
                read 5.iname
        elseif (param.EQ.4) then
                print*, 'enter first trace number:'
                read 6, if irst
        elseif (param.EQ.5) then
                print*,'enter last trace number :'
                read 6, ilast
        elseif (param.EQ.6) then
                print*, 'enter trace step:'
                read 6.nrec
        endif
        go to 1
С
        format (2X, Enter number of parameter to alter (99 to continue): '.$)
```

nsampl = rhinsm

len = nsampl

do 90 i=1.13

len=2**(i+1)

if (rhisr.NE.0) srate = 1.0E6/rhisr

if(nsampl.gt.(2**i).and.nsampl.le.(2**(i+1))) then

oname = iname(1:lnb(iname))//_ft'

format (A)

format (I4)

continue

```
endif
90 continue
  11 = len / 2 + 1
  12 = 11 + 1
c open output files
       new recsz=11*4
    call optdat (opath,oname,1,new recsz,ohand,ierr)
С
       if(ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Unable to create dataset - space? or exists?')
         call exit(1)
       endif
do 10 itrace=ifirst.ilast.nrec
        call razout('Transforming trace', itrace)
        call flush(6)
        otrace=otrace+1
c read in trace header to common block
        call rtdh(ihand,itrace,ierr)
        if (ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Unable to read trace header file')
         call exit(1)
        endif
```

U	
c chec	k for end of file
	if (ierr.GT.0) then
	call report('segy','dataset','I',
&	'End of file reached')
	goto 11
	endif
С	Circui
C	if (unsamp.NE.0) nsampl = unsamp
	if (wsr.NE.0) srate = 1.0E6/wsr
	11 (WS1.14E.0) State - 1.0E0/WS1
C road	in data + write to new file
C read	call rtrd (ihand,itrace,work,nsampl,ierr)
	• • • • • • • • • • • • • • • • • • • •
	if (ierr.LT.0) then
	call report('segy','dataset','F',
&	'Unable to read trace data file')
	call exit(1)
	endif
C	
c cosii	ne taper both ends of array to zero over 0.5 seconds
_	call taper(nsampl,work,int(0.5*srate))
C	
	to working array
1	call azero(16384,x)
	call aacopy(work,1,nsampl,x,1,nsampl)
C	
	nsform the time series
	call azero(len,y)
	signi = -1.0
	call ffta(len, x, y, signi)
С	
_	amplitude
	do i=1 len

```
work(j) = sqrt(x(j)**2+y(j)**2)
          enddo
c calc the frequency interval
      df = srate / dfloat(len)
c write out 1st half of frequency series
          call wtrd (ohand, otrace, work, 11, ierr)
          if (ierr.LT.0) then
            call report('segy','trace data','F',
   & 'Unable to write to file')
            call cltdat(ohand)
            call exit(1)
           endif
С
c amend trace header
          ufldfn=otrace
           ufldtn=ufldfn
           unsamp=11
           wsr=df*1.0E6
c fill in some other variables required by plot program
           if (ufldfn.EQ.0) ufldfn = ufldtn
           if (utrace.EQ.0) utrace = 1
           ushot = 0
С
           call wtdh(ohand,otrace,ierr)
           if (ierr.LT.0) then
            call report('segy','trace data','F',
   & 'Unable to write to file')
            call cltdat(ohand)
            call exit(1)
           endif
```

c	rhinsf rhinsm
ccccccccccccccccccccccccccccccccccccccc	c
c	call whead(ohand,0,ierr)
10 continue	if (ierr.LT.0) then
11 continue	call report('segy', 'dataset', 'F',
С	& 'Unable to write reel header file')
ccccccccccccccccccccccccccccccccccccccc	call exit(1)
С	endif
print 100, ushot, utrc, ufldfn, ufldtn, usrcpn, ucdp,	С
& utrace, utrtyp, unsum, unstk, uduse,	000000000000000000000000000000000000000
& wrange,wrcvge,wsrcse,wsrcdp,wrcvde,wsrcde,	c dump common block rhicom + extras
& wsrcwd,wrcvwd,	c
& wsrcx ,wsrcy ,wrcvx ,wrcvy ,ucunit,	print*,'\n Rhicom common block'
& wvelw ,wvelsw,usrcut,urcvut,usrcst,urcvst,	print 101,rhintr,rhinax,rhisr,rhisrf,
& utotst,ulaga ,ulagb ,udelt ,umutst,umutfn,	& rhinsm,rhinsf,ifmt ,rhirli,rhilni, rhimes
& unsamp,wsr ,ugntyp,wgain ,wgnst ,	101 format(1X,3(I8),/,1X,6(I8))
& ucorr ,ufrqst,ufrqfn,uslen ,ustyp ,ustlen,	c
& uetlen,utptyp,ualfrq,ualslp,unofrq,unoslp,	000000000000000000000000000000000000000
& ulofrq,uhifrq,uloslp,uhislp,uyear,uday,	c
& uhour, umin, usec, utctyp, xmsec,	call cltdat(ihand)
& xeyear, xeday, xehour, xemin, xesec, xemsec,	call cltdat(ohand)
& xdelt,xrvel,xrtoff,xstncd,xevecd	С
c	stop
100 format(6(I10),/,5(I10),/,6(F10.2),/,2(F10.2),/,4(F10.2),I10,/,	end
& 2(F10.2),4(I10),/,6(I10),/,I10,F10.2,I10,2(F10.2),/,	c ·
& 3(6(I10),/),5(I10),/,6(I10),/,3(I10),2(6X,A4),/)	000000000000000000000000000000000000000
c	c
ccccccccccccccccccccccccccccccccccccccc	subroutine menu(pathi,patho,name,ifirst,ilast,nrec)
c amend and write out new file header	c
c	character*(*) pathi, patho, name
rhisr=int(df*1.0E6)	integer ifirst, ilast, nrec
rhisrf=rhisr	c
rhinsm=11	print 200

```
print 201, pathi
        print 202, patho
        print 203,name
        print 204, if irst
        print 205, ilast
        print 206,nrec
        print 299
        format(10X,'****************************,/,
200
         10X,'* Frequency Transform *',',
10X,'*************************
  &
  &
        format(2X,'1. Input pathname:',T55,A25)
201
        format(2X,'2. Output pathname:',T55,A25)
202
        format(2X,'3. Filename :',T55,A20)
203
        format(2X,'4. First trace number :', T55,I4)
204
        format(2X,'5. Last trace number :',T55,I4)
205
206
        format(2X,'6. Step
                                      :',T55,I4)
299
        format(1X,'99.
                               Run')
С
        return
        end
```

6. NORMALISE

```
program normalise
c accepts trace file sequence and normalises data to +/- lim
   include "/home/kanga/dave/Flib/include/rhicom.h"
   include "/home/kanga/dave/Flib/include/segytc.h"
   include "/home/kanga/dave/Flib/include/functions.h"
   include "/home/kanga/dave/Flib/include/dls.h"
   integer*4 ierr, ihand, recsz, nsampl
   integer*4 param
   integer*4 itrace, ifirst, ilast
   character name*25, ipath*25
       real*4 intrace(16000), srate, lim, scale
С
   call dlsini()
c defaults
С
   ipath = './
   name = '1 16bs2
   lim=100.0
c ifirst is trace no. at start of loop, ilast is trace no. at end
   ifirst = 1
   ilast = 9999
   itrace = 1
c get parameter values from user via menu
   do while (param.ne.99)
```

```
call menu(ipath,name,ifirst,ilast,lim)
      print*
     print 4
     read*,param
      print*
     if (param.EQ.1) then
               print*,'enter new pathname:'
               read 5, ipath
      elseif (param.EQ.2) then
               print*,'enter new filename:'
               read 5,name
      elseif (param.EQ.3) then
               print*,'enter first trace number:'
               read 8, if irst
      elseif (param.EQ.4) then
               print*,'enter last trace number:'
               read 8, ilast
      elseif (param.EQ.5) then
               print*,'enter limit:'
               read 6.lim
      elseif (param.EQ.90) then
               call report('normalisation','menu','I',
               'user requested abort')
&
               call exit(1)
      endif
 enddo
      format (2X, Enter number of parameter to alter (99 to continue): ',$)
      format (A)
      format (F5.2)
      format (I4)
```

С

c open	files and read segy header
С	
	call optdat (ipath,name,0,recsz,ihand,ierr)
С	
	if(ierr.LT.0) then
	call report('normalise','dataset','F',
&	Cannot find all dataset files')
	call exit(1)
	endif
С	
	call rhead(ihand,0,ierr)
С	
	if (ierr.LT.0) then
	call report('normalise','dataset','F',
&	'Unable to read reel header file')
	call exit(1)
	endif
С	
	nsampl = rhinsm
	if (rhisr.NE.0) srate = 1.0E6/rhisr
c	
ccccc	222222222222222222222222222222222222222
c find	first trace
c .	
	do while (ufldfn.lt.ifirst)
	call rtdh(ihand,itrace,ierr)
	if (ierr.LT.0) then
	call report('normalise', 'dataset', 'F',
&	' Unable to read trace header file')
	call exit(1)
	endif
	if (ierr.EQ.1) then
	call report('normalise' 'dataset' 'F'

```
& 'shot point range doesn"t exist')
          call exit(1)
         endif
         itrace=itrace+1
С
         call razclk()
         call flush(6)
С
        end do
        itrace=itrace-2
c MAIN LOOP
С
    do 10 while (.true.)
         if (ufldfn.GE.ilast) goto 11
         itrace=itrace+1
         print 1000, itrace
С
         call razout('Trace: ',itrace)
         call flush(6)
c read in trace header to common block
         call rtdh(ihand,itrace,ierr)
         if (ierr.LT.0) then
          call report('normalise','dataset','F',
   & 'Unable to read trace header file')
          call exit(1)
         endif
c check for end of file
         if (ierr.GT.0) then
          call report('normalise','dataset','I',
  & 'End of file reached')
```

```
c read in data
                call rtrd (ihand, itrace, intrace, nsampl, ierr)
        С
                if (ierr.LT.0) then
                 call report('normalise','dataset','F',
           & 'Unable to read trace data file')
                 call exit(1)
                endif
A-46
        c remove dc
                call norm(intrace,nsampl,lim,scale)
        c write to file
                 call wtdh(ihand,itrace,ierr)
                 if (ierr.LT.0) then
                  call report('statics','dataset','F',
              'Unable to write to trace header file')
                  call exit(1)
```

call wtrd (ihand, itrace, intrace, nsampl, ierr)

call report('segy','trace data','F',

goto 11

c check for correct sample no. and rate

if (unsamp.NE.0) nsampl = unsamp if (wsr.NE.0) srate = 1.0E6/wsr

endif

endif

if (ierr.LT.0) then

C

```
'Unable to write to file')
         call cltdat(ihand)
         call exit(1)
        endif
10 continue
 11 continue
   call cltdat(ihand)
С
1000 format(1X,'Trace:',I5)
   stop
   end
С
      subroutine menu(pathi,name,ifirst,ilast,lim)
C
      character*(*) pathi, name
      integer ifirst, ilast
С
      print*,'\f'
      print 200
      print 201, pathi
      print 202,name
      print 203, if irst
      print 204, ilast
      print 205,lim
      print 290
      print 299
      print 300
```

```
200
       format(9X,'****************,/,
        9X,'* NORMALISATION *',/,
  &
        9X,'************
 &
 201
       format(2X,'1. Input pathname:',T45,A25)
202
       format(2X,'2. Filename :',T45,A20)
       format(2X,'3. First trace number
 203
                                          :', T45,I4)
       format(2X,'4. Last trace number
 204
                                          :',T45,I4)
       format(2X,'5. Maximum data value required:',T45,F5.1)
 205
 290
       format(1X,\n',1X,'90
                                  ABORT')
 299
       format(1X,\n',1X,'99.
                                  RUN')
С
 300
       format(1X,\n',1X,'Warning: original data will be overwritten')
¢
       return
       end
```

7. PANEL

wlen=5.0

```
gap = 1.0
       slp = 2.0
С
c if irst is trace no. at start of loop, panlen is
c no. traces in panel, and nrec is step size
        ifirst = 1
        panlen = 18
        nrec = 1
С
c get parameter values from user via menu
   do while (param.NE.99)
        call menu(ipath,opath,iname,ifirst,lowf,hif,wlen,gap)
        print*
        print 4
        read*,param
        print*
        if (param.EQ.1) then
                print*, 'enter new input pathname :'
                read 5, ipath
        elseif (param.EQ.2) then
                print*, 'enter new output pathname:'
                read 5, opath
       elseif (param.EQ.3) then
                print*,'enter new filename:'
                read 5, iname
        elseif (param.EQ.4) then
                print*, 'enter first trace number :'
                read 6, if irst
        elseif (param.EQ.5) then
                print*, 'enter low frequency limit (>1.0):'
```

```
read 7,lowf
                                                                                С
                if(lowf.le.1.0) then
                                                                                        call rhead(ihand,0,ierr)
                 print*,'must be > 1.0 :'
                                                                                        if (ierr.LT.0) then
                read 7,lowf
                                                                                          call report('segy','dataset','F',
                endif
                                                                                          'Unable to read reel header file')
                                                                                   &
        elseif (param.EQ.6) then
                                                                                          call exit(1)
                print*, 'enter high frequency limit:'
                                                                                        endif
                read 7.hif
                                                                                С
        elseif (param.EQ.7) then
                                                                                        nsampl = rhinsm
                print*, 'enter frequency window length:'
                                                                                        if (rhisr.NE.0) srate = 1.0E6/rhisr
                read 7, wlen
                                                                                С
        elseif (param.EQ.8) then
                                                                                        call optdat (opath,oname, 1, recsz, ohand, ierr)
                print*, 'enter interval between start of successive windows:'
                                                                                        if(ierr.LT.0) then
                                                                                                call report('segy','dataset','F',
                read 7,gap
                                                                                               'Unable to create dataset - space? or exists?')
        endif
                                                                                   &
                                                                                                call exit(1)
    enddo
                                                                                        endif
C
        format (2X, 'Enter number of parameter to alter (99 to continue): ')
        format (A)
                                                                                format (I)
                                                                                С
        format (F5.1)
                                                                                    newtrace = 0
                                                                                    do 20 panel = 1,int((hif-wlen-lowf)/gap+1)
С
        oname = iname(1:lnb(iname))// pan'
                                                                                С
                                                                                        freq=lowf+(panel-1)*gap
                                                                                        slpl = sqrt(freq)
slph = sqrt(freq+wlen)
c open input files, read segy header and open output files
                                                                                С
        call optdat (ipath,iname,0,recsz,ihand,ierr)
                                                                                        f1=freq-slpl
        if(ierr.LT.0) then
                                                                                        f2=freq
          call report('segy','dataset','F',
                                                                                        f3=freq+wlen
  & 'Cannot find all dataset files')
                                                                                        f4=freq+wlen+slph
          call exit(1)
                                                                                        if (f2.GT.f3) then
                                                                                         f2 = (f2+f3)/2
        endif
```

```
f3 = f2
        endif
С
        print 1000, panel, f1, f2, f3, f4
    do 10 i=1, panlen, nrec
          itrace = i + ifirst - 1
          newtrace = newtrace+1
          print 1001, itrace, newtrace
С
c read in trace header to common block
          call rtdh(ihand,itrace,ierr)
          if (ierr.LT.0) then
           call report('segy','dataset','F',
   & 'Unable to read trace header file')
           call exit(1)
          endif
С
          if (nsampl.EQ.0) nsampl = unsamp
          if (srate.EO.0.AND.wsr.NE.0) srate = 1.0E6/wsr
c read in data, apply filter + write to new file
          call rtrd (ihand, itrace, work, nsampl, ierr)
          if (ierr.LT.0) then
           call report('segy','dataset','F',
   & 'Unable to read trace data file')
           call exit(1)
          endif
          call bpass(nsampl,work,f1,f2,f3,f4,srate,iwopt)
С
          call wtrd (ohand,newtrace,work,nsampl,ierr)
          if (ierr.LT.0) then
```

```
call report('segy','trace data','F',
  & 'Unable to write to file')
          call cltdat(ohand)
          call exit(1)
         endif
c put filter values to common block variables and write to new header file
        ulofrq = int(f1)
         uhifrq = int(f4)
С
         ufldtn = newtrace
         ufldfn = newtrace
С
        call wtdh(ohand,newtrace,ierr)
         if (ierr.LT.0) then
          call report('segy','trace data','F',
   & 'Unable to write to file')
          call cltdat(ohand)
          call exit(1)
         endif
С
10 continue
c put in a couple of blank traces
   do 16 j=1,2
        newtrace=newtrace+1
         ufldtn = newtrace
         ufldfn = newtrace
         utrtyp = 3
     call wtrd(ohand,newtrace,work,nsample,ierr)
        call wtdh(ohand,newtrace,ierr)
```

```
print 1002, newtrace
                                                                        С
 16 continue
                                                                               character*(*) pathi, patho, name
 20 continue
                                                                               integer*4 ifirst
                                                                               real*4 lowf,hif,wlen,gap
C
       print*,"total number of traces = ",newtrace
                                                                               print 200
                                                                               print 201, pathi
print 202, patho
c write out file header with extended name
                                                                               print 203, name
       rhintr = newtrace
                                                                               print 204, ifirst
                                                                               print 205,lowf
С
   call whead(ohand,0,ierr)
                                                                               print 206,hif
   if (ierr.LT.0) then
                                                                               print 207, wlen
         call report('segy','dataset','F',
                                                                               print 208, gap
  & 'Unable to write reel header file')
                                                                               print 209
         call exit(1)
                                                                               format(10X,'****************************/
                                                                         200
   endif
                                                                                 10X,'* BAND PASS FILTER PANELS*',/,
                                                                                 10X.'*****************
                                                                          &
201
                                                                               format(2X,'1. Input pathname
                                                                                                                   :',T55,A25)
   call cltdat(ihand)
                                                                         202
                                                                               format(2X,'2. Output pathname
                                                                                                                    :',T55,A25)
   call cltdat(ohand)
                                                                               format(2X,'3. Filename
                                                                         203
                                                                                                                 :',T55,A20)
                                                                         204
                                                                               format(2X,'4. First trace number
                                                                                                                   :',T55,I5)
1000 format(1X,"Panel ",I3,5X,"low-cut =",2F6.1,5X,"high-cut =",2F6.1)
                                                                         205
                                                                               format(2X,'5. Low frequency limit
                                                                                                                    :',T55,F5.1)
1001 format(1X,"Filtering trace: ",I5,"->",I5)
                                                                         206
                                                                               format(2X,'6. High frequency limit
                                                                                                                    :',T55,F5.1)
1002 format(1X,"Blank trace : ",5X "->",15)
                                                                               format(2X,'7. Frequency window length
                                                                         207
                                                                                                                       :',T55,F5.1)
                                                                               format(2X, '8. Interval between successive windows:', T55, F5.1)
С
                                                                         209
                                                                               format(2X,'9.
                                                                                                 RUN')
   stop
   end
                                                                                return
                                                                                end
```

subroutine menu(pathi,patho,name,ifirst,lowf,hif,wlen,gap)

8. RMDC

```
program rmdc
c accepts trace file sequence and removes dc component
   include "/home/kanga/dave/Flib/include/rhicom.h"
   include "/home/kanga/dave/Flib/include/segytc.h"
   include "/home/kanga/dave/Flib/include/functions.h"
   include "/home/kanga/dave/Flib/include/dls.h"
   integer*4 ierr, ihand, recsz, nsampl
   integer*4 param
   integer*4 itrace, ifirst, ilast
   character name*25, ipath*25
       real*4 intrace(16000), srate, dc
   call dlsini()
c defaults
С
   ipath = './
   name = '1_16bs2
c ifirst is trace no. at start of loop, ilast is
c trace no. at end
   ifirst = 1
   ilast = 9999
   itrace = 1
c get parameter values from user via menu
   do while (param.ne.99)
```

```
call menu(ipath,name,ifirst,ilast)
       print*
       print 4
       read*,param
       print*
       if (param.EQ.1) then
                print*,'enter new pathname:'
               read 5, ipath
        elseif (param.EQ.2) then
                print*,'enter new filename:'
                read 5.name
        elseif (param.EQ.3) then
                print*, 'enter first trace number:'
                read 8.ifirst
        elseif (param.EQ.4) then
                print*,'enter last trace number :'
                read 8, ilast
        elseif (param.EQ.90) then
                call report('dc correction','menu','I',
  &
                'user requested abort')
                call exit(1)
       endif
   enddo
       format (2X, Enter number of parameter to alter (99 to continue): ',$)
        format (A)
       format (F5.2)
        format (I4)
c open files and read segy header
        call optdat (ipath,name,0,recsz,ihand,ierr)
```

if(ierr.LT.0) then	call razclk()
call report('rmdc','dataset','F',	call flush(6)
& 'Cannot find all dataset files')	c
call exit(1)	end do
endif	itrace=itrace-2
С	С
call rhead(ihand,0,ierr)	000000000000000000000000000000000000000
if (ierr.LT.0) then	c MAIN LOOP
call report('rmdc','dataset','F',	c
& 'Unable to read reel header file')	do 10 while (.true.)
call exit(1)	if (ufldfn.GE.ilast) goto 11
endif	itrace=itrace+1
c	call razout('Trace: ',itrace)
nsampl = rhinsm	call flush(6)
if (rhisr.NE.0) srate = 1.0E6/rhisr	c
C	c read in trace header to common block
000000000000000000000000000000000000000	call rtdh(ihand,itrace,ierr)
c find first trace	if (ierr.LT.0) then
c	call report('rmdc','dataset','F',
do while (ufldfn.lt.ifirst)	& 'Unable to read trace header file')
call rtdh(ihand,itrace,ierr)	call exit(1)
if (ierr.LT.0) then	endif
call report('rmdc','dataset','F',	c .
& 'Unable to read trace header file')	c check for end of file
call exit(1)	if (ierr.GT.0) then
endif	call report('rmdc','dataset','I',
if (ierr.EQ.1) then	& 'End of file reached')
call report('rmdc','dataset','F',	goto 11
& 'shot point range doesn't exist')	endif
call exit(1)	c
endif	c check for correct sample no. and rate **
itrace=itrace+1	if (unsamp.NE.0) nsampl = unsamp
С	if (wsr.NE.0) srate = $1.0E6/wsr$

С	
c read i	in data
	call rtrd (ihand,itrace,intrace,nsampl,ierr)
	if (ierr.LT.0) then
	call report('rmdc','dataset','F',
&	'Unable to read trace data file')
•	call exit(1)
	endif
С	chuii
-	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
	000000000000000000000000000000000000000
c remo	· · · - ·
_	call mean(nsampl,intrace,dc)
C	
	000000000000000000000000000000000000000
	to file
С	
	call wtdh(ihand,itrace,ierr)
	if (ierr.LT.0) then
	call report('statics','dataset','F',
&	'Unable to write to trace header file')
	call exit(1)
	endif
С	
	call wtrd (ihand,itrace,intrace,nsampl,ierr)
	if (ierr.LT.0) then
	call report('segy','trace data','F',
&	'Unable to write to file')
	call cltdat(ihand)
	call exit(1)
	endif
С	
_	000000000000000000000000000000000000000
С	

```
10 continue
 11 continue
   call cltdat(ihand)
1000 format(1X,'Trace: ',I5)
   stop
   end
С
       subroutine menu(pathi,name,ifirst,ilast)
С
       character*(*) pathi, name
       integer ifirst, ilast
С
       print*,'\f'
       print 200
       print 201, pathi
       print 202,name
       print 203, if irst
       print 204, ilast
       print 290
       print 299
       print 300
 200
       format(9X,'*************/,
  &
        9X,'*D.C. CORRECTION*',/,
        9X,'************
  &
 201
       format(2X,'1. Input pathname:',T45,A25)
       format(2X,'2. Filename :',T45,A20)
 202
 203
       format(2X,'3. First trace number
                                         :', T45,I4)
 204
       format(2X,'4. Last trace number
                                         :',T45,I4)
```

```
290 format(1X,'\n',1X,'90 ABORT')
299 format(1X,\n',1X,'99. RUN')
c
300 format(1X,\n',1X,'Warning: original data will be overwritten')
c
return
end
```

9. STACK

STACK.H

```
С
         common block for variables in stacking program
С
С
         integer*4 maxstack
         parameter(maxstack=11)
С
        integer*4 stackpos(maxstack), id(maxstack)
С
        real*4
                 stackdat(16000,maxstack), x(maxstack),
                 array(maxstack)
   &
С
        common /stackcom/
   &
                 stackpos,id,stackdat,x,array
        save /stackcom/
c
```

STACK MENU.H

```
С
С
         common block for menu variables in stacking program
         integer*4 param
         integer*4 ifirst, ilast, channel
         integer*4 stacksiz, trorig
С
         real*4 stackvel, trsep, xorig
С
         character iname*20, oname*24, ipath*25, opath*25
         character war*3, flag*3
С
         common /menucom/
   &
                  param, ifirst, ilast, channel, stacksiz, trorig,
                  stackvel, trsep, xorig, iname, oname, ipath, opath,
  &
  &
                  war, flag
         save /menucom/
С
```

```
program stack
c accepts trace file sequence and stacks with linear moveout
   include "/home/kanga/dave/Flib/include/rhicom.h"
   include "/home/kanga/dave/Flib/include/segytc.h"
   include "/home/kanga/dave/Flib/include/functions.h"
   include "/home/kanga/dave/Flib/include/dls.h"
   include "../include/stack menu.h"
   include "../include/stack.h"
       integer*4 ihand, ohand, ierr, recsz
       integer*4 itrace, otrace, nsampl
       real*4 trace(16000), srate
    call dlsini()
ufldfn=1
       itrace= 1
       otrace= 1
С
       call menu default()
       call menu()
c initialise stack parameters
       call stackini(stacksiz)
c open input and output files
```

```
call optdat (ipath,iname,0,recsz,ihand,ierr)
       if(ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Cannot find all dataset files')
         call exit(1)
       endif
    call optdat (opath,oname, 1, recsz, ohand, ierr)
       if(ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Unable to create dataset - space? or exists?')
         call exit(1)
       endif
c read segy header
       call rhead(ihand,0,ierr)
С
       if (ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Unable to read reel header file')
         call exit(1)
       endif
       nsampl = rhinsm
       if (rhisr.NE.0) srate = 1.0E6/rhisr
c find first trace
```

do while (ufldfn.lt.ifirst)

call rtdh(ihand,itrace,ierr)	
if (ierr.LT.0) then	
call report('segy','dataset','F',	
& 'Unable to read trace header file')	
call exit(1)	
endif	
if (ierr.EQ.1) then	
call report('segy','dataset','F',	
& 'shot point range doesn"t exist')	
call exit(1)	
endif	
itrace=itrace+1	
end do	
itrace=itrace-1	
C .	
000000000000000000000000000000000000000	
c MAIN LOOP	
C	
do 100 while (.true.)	
if (ufldfn.GE.ilast) goto 110	
itrace=itrace+1	
print 1000, itrace, otrace	
C	
c read in trace header to common block	
call rtdh(ihand,itrace,ierr)	
if (ierr.LT.0) then	
call report('segy','dataset','F',	
& 'Unable to read trace header file')	
call exit(1)	
endif	
c	
c check for end of file	
if (ierr.GT.0) then	

```
& 'End of file reached')
         goto 110
        endif
c check for correct channel no., sample no. and rate
        if ((channel.NE.0).AND.(channel.NE.utrace)) goto 100
        if (nsampl.EQ.0) nsampl = unsamp
        if (srate.EQ.0.AND.wsr.NE.0) srate = 1.0E6/wsr
С
c read in data
        call rtrd (ihand, itrace, trace, nsampl, ierr)
С
        if (ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Unable to read trace data file')
         call exit(1)
        endif
С
       call stk(trace, srate, nsampl)
c write to new file
         call wtrd (ohand, otrace, trace, nsampl, ierr)
         if (ierr.LT.0) then
          call report('segy','trace data','F',
  & 'Unable to write to file')
          call cltdat(ohand)
          call exit(1)
```

call report('segy','dataset','I',

endif

call cltdat(ihand)

call cltdat(ohand)

С

```
С
    stop
    end
subroutine menu()
c get parameter values from user via menu
С
        include "/home/kanga/dgl3dpg/fortran/include/stack_menu.h"
    do while (param.NE.99)
        call display menu()
        print*
        print 4
        read*,param
        print*
        if (param.EQ.1) then
                print*, 'enter new input pathname :'
                read 5, ipath
        elseif (param.EQ.2) then
                print*, 'enter new output pathname:'
                read 5, opath
        elseif (param.EQ.3) then
                print*,'enter new filename:'
                read 5, iname
        elseif (param.EQ.4) then
                print*, 'enter no. traces per stack (max 50):'
                read 6, stacksiz
        elseif (param.EQ.5) then
                print*, 'enter reduction velocity to stack:'
                read 7, stackvel
```

	eiseif (param.EQ.6) then	0	iormat (1)
	print*,'is data already reduced?:'	7	format (F8.2)
	read 5,war	8	format (I4)
	elseif (param.EQ.7) then	c	
	print*,'enter first trace number:'		oname = iname(1:lnb(iname))//' stk'
	read 8,ifirst	С	
	elseif (param.EQ.8) then		return
	print*,'enter last trace number :'		end
	read 8,ilast	С	
	elseif (param.EQ.9) then	cccc	ccccccccccccccccccccccccccccccccccccccc
	print*,'enter channel number (0 to ignore):'	С	
	read 6,channel		subroutine menu_default()
	elseif (param.EQ.10) then	С	
	print*,'is trace separation constant?'		include "/home/kanga/dgl3dpg/fortran/include/stack_menu.h"
	read 5,flag	С	,-
	elseif (param.EQ.11) then		ipath = './
	if ((flag(1:1).EQ.'Y').OR.(flag(1:1).EQ.'y')) then		opath = './
	print*,'enter trace separation:'		iname = 'l1101_bpf '
	read 7,trsep		oname = '
	endif	С	
	elseif (param.EQ.12) then		stacksiz = 5
	if ((flag(1:1).EQ.'Y').OR.(flag(1:1).EQ.'y')) then		stackvel = 6.0
	print*,'enter trace number of reduction origin'	С	w ====01
	read 8,trorig		war = 'YES'
	else		rst is trace no. at start of loop, ilast is
	print*,'enter positon of reduction origin (km)'		ice no. at end
	read 7,xorig		ifirst = 1
	endif		ilast = 9999
	endif	С	
enc	l do		channel = 0
c .	C + (OX II) + 1 C	С	fire and of
4	format (2X, Enter number of parameter to alter (99 to continue): ',\$)		flag = 'NO'
5	format (A)		trsep = 50.0

	trorig = 1	&	12X,'* STACKING *',/,
	xorig = 0.0	&	12X,'**********')
С		201	format(2X,'1. Input pathname:',T35,A25)
	return	202	format(2X,'2. Output pathname:',T35,A25)
	end	203	format(2X,'3. Filename :',T35,A20)
ccccc	222222222222222222222222222222222222222	204	format(2X,'4. Stack size :',T37,I2)
С		205	format(2X,'5. Stack velocity:',T33,F8.2)
	subroutine display_menu()	206	format(2X,'6. Use WAR reduction info:',T37,A3)
С	· · · -	207	format(2X,'7. First trace number :',T35,I4)
	include "/home/kanga/dgl3dpg/fortran/include/stack_menu.h"	208	format(2X,'8. Last trace number :',T35,I4)
С		209	format(2X,'9. Channel no.(0 to ignore):',T38,I1)
	print*,\f	210	format(1X,'10. Constant trace spacing:',T37,A3)
	print 200	211	format(1X,'11. Trace separation :',T35,F6.3)
	print 201, ipath	212	format(1X,'12. Origin (trace number):',T35,I4)
	print 202,opath	213	format(1X,'11')
	print 203, iname	214	format(1X,'12. Origin (km) :',T35,F6.3)
	print 204,stacksiz	299	format(1X,\n',1X,'99. RUN')
	print 205,stackvel	С	,
	print 206,war		return
	print 207,ifirst		end
	print 208,ilast	С	
	print 209,channel	cccccc	222222222222222222222222222222222222222
	print 210,flag	c	
	if ((flag(1:1).EQ.'Y').OR.(flag(1:1).EQ.'y')) then		subroutine stackini(stacksiz)
	print 211,trsep	c	
	print 212,trorig	inc	clude "/home/kanga/dgl3dpg/fortran/include/stack.h"
	else	С	
	print 213		integer*4 stacksiz
	print 214,xorig	Ċ	
	endif		do 10 I=1,stacksiz
	print 299		stackpos(I)=I
С			id(I)=3
200	format(12X,'************//,	10	continue

```
endif
С
        return
                                                                                  c check fold
        end
                                                                                             fold=0
                                                                                             do 20 J=1, stacksiz
if (id(stackpos(J)).EQ.1) fold=fold+1
C
        subroutine stk(work, srate, nsampl)
                                                                                    20
                                                                                             continue
                                                                                             if (fold.EQ.0) then
С
    include "/home/kanga/dave/Flib/include/segytc.h"
                                                                                              idout=3
                                                                                              goto 99
С
        include "/home/kanga/dgl3dpg/fortran/include/stack.h"
                                                                                             else
        include "/home/kanga/dg13dpg/fortran/include/stack menu.h"
                                                                                              idout=1
                                                                                             endif
С
        integer*4 fold, idout, isamp, shift, nsampl
        real*4 work(16000), sum, slow, srate
                                                                                  c shift & sum samples
                                                                                             do 90 isamp=1,nsampl
С
c copy new trace to stack
                                                                                             sum=0.0
        call aacopy(work,1,nsampl,stackdat(1,stackpos(1)),1,nsampl)
                                                                                              do 80 J=1, stacksiz
                                                                                               if (id(stackpos(J)).NE.1) goto 80
                                                                                               shift=int((x(stackpos(1))-x(stackpos(J)))*srate*slow)
c extract useful info from trace header common block
          if ((flag(1:1).EQ.'Y').OR.(flag(1:1).EQ.'y')) then
                                                                                               if ((isamp+shift.LE.0).OR.(isamp+shift.GE.nsampl).OR.
                 x(stackpos(1)) = (ufldfn-trorig)*trsep
                                                                                      &
                                                                                                    (stackdat(isamp+shift,stackpos(J)).EO.999.999)) then
                                                                                                     work(isamp)=0.0
          else
                 x(\text{stackpos}(1)) = \text{wrange-}(\text{xorig}*1000.0)
                                                                                                     goto 90
                                                                                               endif
          endif
                                                                                               sum=sum+stackdat(isamp+shift,stackpos(J))
          id(stackpos(1))=utrtyp
                                                                                     80
                                                                                              continue
c calculate (1/velocity), correcting for wide angle data
                                                                                               work(isamp)=sum/fold
                                                                                    90
                                                                                             continue
С
        slow = 1.0/(\text{stackvel*}1000.0)
                                                                                  c move traces along one place in stack
С .
          if ((war(1:1).EQ.'y').OR.(war(1:1).EQ.'Y')) then
                                                                                            do 95 J=1, stacksiz
           if (xrvel.NE.0.) slow = (1.0/xrvel)-(1.0/(stackvel*1000.0))
                                                                                            stackpos(J)=stackpos(J)+1
```

```
if (stackpos(J).gt.(stacksiz)) stackpos(J)=1
95 continue
c
c amend trace header values
99 unstk=fold
utrtyp=idout
c
return
end
```

10. STATICS

program statics

A-67

С

wvel = 1.4

```
svel = 5.8
        rvel = 5.8
        trvel = 6.5
        sdatum = 150.0
        rdatum = 0.0
       wdepth = 50.0
       srcdepth=7.5
       rcvelev=10.0
c get parameter values from user via menu
   do while (param.ne.99)
        call menu(ipath,name,ifirst,ilast,wvel,svel,trvel,
                sdatum,rdatum,rvel)
  &
        print*
        print 4
        read*,param
        print*
        if (param.EQ.1) then
                print*,'enter new pathname:'
                read 5, ipath
        elseif (param.EQ.2) then
                print*,'enter new filename:'
                read 5,name
        elseif (param.EO.3) then
                print*, 'enter first trace number :'
                read 8, if irst
        elseif (param.EQ.4) then
                print*, 'enter last trace number :'
                read 8, ilast
        elseif (param.EO.5) then
                print*, 'enter water layer velocity:'
```

	read 6, wvel	if(ierr,LT.0) then
	elseif (param.EQ.6) then	call report('statics','dataset','F',
	print*,'enter sea bed velocity:'	& 'Cannot find all dataset files')
	read 6,svel	call exit(1)
	elseif (param.EQ.7) then	endif
	print*,'enter target arrival velocity:'	c
	read 6,trvel	call rhead(ihand,0,ierr)
	elseif (param.EQ.8) then	c
	print*,'enter source datum depth:'	if (ierr.LT.0) then
	read 6,sdatum	call report('statics','dataset','F',
	elseif (param.EQ.9) then	& 'Unable to read reel header file')
	print*,'enter receiver datum elevation:'	call exit(1)
	read 6,rdatum	endif
	elseif (param.EQ.10) then	c
	print*,'enter receiver rock velocity:'	nsampl = rhinsm
	read 6,rvel	if (rhisr.NE.0) srate = 1.0E6/rhisr
	elseif (param.EQ.90) then	c
	call report('static correction', 'menu', 'I',	CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
&	'user requested abort')	c find first trace
	call exit(1)	c
	endif	do while (ufldfn.lt.ifirst)
en	addo	call rtdh(ihand,itrace,ierr)
С		if (ierr.LT.0) then
4	format (2X, Enter number of parameter to alter (99 to continue): ',\$)	call report('statics','dataset','F',
5	format (A)	& 'Unable to read trace header file')
6	format (F5.2)	call exit(1)
8	format (I4)	endif
С		if (ierr.EQ.1) then
ccccccccccccccccccccccccccccccccccccccc		call report('statics','dataset','F',
c open files and read segy header		& 'shot point range doesn"t exist')
С		call exit(1)
	call optdat (ipath,name,0,recsz,ihand,ierr)	endif
С	•	itrace=itrace+1

'End of file reached')

c check for correct sample no. and rate

goto 11

endif

С

С

call razclk()

call flush(6)

itrace=itrace-2

end do

```
if (unsamp.NE.0) nsampl = unsamp
         if (wsr.NE.0) srate = 1.0E6/wsr
c read in data
         call rtrd (ihand, itrace, intrace, nsampl, ierr)
         if (ierr.LT.0) then
          call report('statics','dataset','F',
   & 'Unable to read trace data file')
          call exit(1)
          endif
c do static shift
c if water depth defined in trace header then set new water depth
c otherwise keep same waterdepth as before
          if (wsrcwd.ne.0.0) then
          wdepth = wsrcwd
          endif
c do same with source depth and receiver elevation
c NB source depth seems to be 10 times too large in PDAS data
          if (wsrcdp.ne.0.0) then
          srcdepth=wsrcdp
          endif
          if (wrcvge.ne.0.0) then
          rcvelev=wrcvge
          endif
С
          wshift=statshift(wdepth-srcdepth,sdatum-srcdepth,wvel,svel,trvel)
          rshift=statshift(0.0,rcvelev-rdatum,wvel,rvel,trvel)
          tshift = int(srate*(wshift+rshift))
          call aacopy(intrace,tshift,nsampl,outtrace,1,
        (nsampl-tshift+1))
```

c pad out with blanks	call clidat(thand)		
do i=(nsampl-tshift+1),nsampl	c		
outtrace(i)=0.0	1000 format(1X, 'Trace: ',15)		
enddo	C		
C	stop		
000000000000000000000000000000000000000	end		
c amend trace header	c		
c	222222222222222222222222222222222222222		
wrcvde=rdatum	C		
wsrcde=sdatum	subroutine menu(pathi,name,ifirst,ilast,wvel,svel,trvel,		
c	& sdatum,rdatum,rvel)		
000000000000000000000000000000000000000	c		
c write to file	character*(*) pathi, name		
c	integer ifirst, ilast		
call wtdh(ihand,itrace,ierr)	real*4 wvel,svel,trvel,sdatum,rdatum,rvel		
if (ierr.LT.0) then	c		
call report('statics','dataset','F',	print*,^f		
& 'Unable to write to trace header file')	print 200		
call exit(1)	print 201,pathi		
endif	print 202,name		
c	print 203, ifirst		
call wtrd (ihand,itrace,outtrace,nsampl,ierr)	print 204,ilast		
if (ierr.LT.0) then	print 205, wvel		
call report('segy','trace data','F',	print 206,svel		
& 'Unable to write to file')	print 207,trvel		
call cltdat(ihand)	print 208,sdatum		
call exit(1)	print 209,rdatum		
endif	print 210,rvel		
c	print 290		
ccccccccccccccccccccccccccccccccccccccc	print 299		
c	print 300		
10 continue	c		
11 continue	200 format(5X,'*****************************/,		

```
&
        5X,'*BATHYMETRIC STATIC CORRECTION*',/,
  &
 201
       format(2X,'1. Input pathname:',T45,A25)
 202
       format(2X,'2. Filename
                                 :',T45,A20)
       format(2X,'3. First trace number
                                            :', T45,I4)
 204
       format(2X,'4. Last trace number
                                            :',T45,I4)
 205
       format(2X,'5. Water velocity (km/s)
                                             :',T44,F5.2)
       format(2X,'6. Sea bed velocity (km/s)
                                             :',T44,F5.2)
 206
       format(2X,'7. Target arrival velocity (km/s):',T44,F5.2)
 207
                                               :',T43,F6.2)
       format(2X,'8. Source datum depth (m)
 208
       format(2X,'9. Receiver datum elevation (m):',T43,F6.2)
 209
       format(1X,'10. Receiver rock velocity (km/s):',T44,F5.2)
 210
       format(1X,\n',1X,'90
                                   ABORT')
 290
                                   RUN')
 299
       format(1X,\n',1X,'99.
 300
        format(1X,\n',1X,'Warning: original data will be overwritten')
С
        return
        end
С
        function statshift(depth,datum,vel1,vel2,trvel)
С
        returns static correction (s) to datum level at or below
        non-uniform interface
        depth = depth to interface
        datum = depth to datum level
        vel1 = constant velocity above interface
        vel2 = constant velocity below
        trvel = target arrival apparent velocity
```

```
real*4 depth,datum,vel1,vel2,trvel
real*4 shift1, shift2

shift1=depth*sqrt(trvel**2-vel1**2)/vel1
shift2=(datum-depth)*sqrt(trvel**2-vel2**2)/vel2
statshift=(shift1+shift2)/(trvel*1000.0)

return
end
```

C

С

11. TRACEBIN

```
program tracebin
                                                                                       read 5, ipath
                                                                                       write(*,'(A,$)') 'name of dataset to bin:'
С
    reads in a trace file sequence, bins it and writes it out to
                                                                                       read 5.iname
        a binned dataset, stacking with any trace already present
                                                                                        write(*,'(A,$)') 'output pathname: '
С
                                                                                        read 5, opath
   include "/home/kanga/dave/Flib/include/rhicom.h"
                                                                                        write(*,'(A,$)') 'name of binned dataset:'
   include "/home/kanga/dave/Flib/include/segytc.h"
                                                                                        read 5, oname
    include "/home/kanga/dave/Flib/include/functions.h"
    include "/home/kanga/dave/Flib/include/dls.h"
                                                                                        format (A)
С
        integer*4 ihand, ohand, ierr, irecsz, orecsz
                                                                                integer*4 redvel, tstart, id
        integer*4 itrace, otrace, nsampl, isamp
                                                                               c open input files
        character*32 iname, oname, ipath, opath, filnam
        real*4 newtrace(16000), srate, bintrace(16000)
                                                                                        call optdat (ipath,iname,0,irecsz,ihand,ierr)
        real*4 minoff, binlen, wdist, delay, sintval
                                                                                        if(ierr.LT.0) then
                                                                                          print *, iname
          minoff=offset of centre of nearest bin
                                                                                          call report('trace bin','dataset','F',
С
          binlen=length of bin
                                                                                   & 'Cannot find all dataset files')
С
          wdist =distance to centre of bin(integer multiple of binlen)
                                                                                          call exit(1)
С
                                                                                        endif
c
    call dlsini()
                                                                                c read file header
С
call rhead(ihand,0,ierr)
                                                                                        if (ierr.LT.0) then
c default and initial values
                                                                                          call report('trace bin', 'dataset', 'F',
С
                                                                                   & 'Unable to read reel header file')
        ipath ='./
        opath ='./
                                                                                          call exit(1)
                                                                                        endif
С
                                                                                        nsampl = rhinsm
         itrace= 0
                                                                                        if (rhisr.NE.0) srate = 1.0E6/rhisr
С
        write(*,'(A,$)') 'input pathname: '
```

```
С
         ******
        ** main loop **
         *****
    do 100 while (.true.)
         itrace=itrace+1
         call razout('binning trace ',itrace)
         call flush(6)
С
c read in trace header to common block
С
          call rtdh(ihand,itrace,ierr)
          if (ierr.LT.0) then
           call report('trace bin','dataset','F',
   & 'Unable to read trace header file[3]')
           call exit(1)
          endif
c check for end of file
          if (ierr.GT.0) then
           call report('trace bin','dataset','I',
      ' End of file reached')
           goto 110
          endif
c check for non-seismic traces
          if (utrtyp.ne.1) then
           goto 100
          endif
С
          otrace=int((wrange-minoff)/binlen +1.5)
```

```
if (otrace.le.0) then
          goto 100
         endif
         wdist=minoff+binlen*(otrace-1)
         delay=wdist/xrvel - (xrtoff/1000)
         id=utrtyp
         sintval=wsr
         redvel=xrvel
         tstart=xrtoff
c check for correct sample no. and rate **
         if (nsampl.EQ.0) nsampl = unsamp
         if (srate.EQ.0.AND.wsr.NE.0) srate = 1.0E6/wsr
С
c read in corresponding bin trace header, clearing common block first
С
         call cltdh()
         call rtdh(ohand,otrace,ierr)
         if (ierr.LT.0) then
          call report('trace_bin','dataset','F',
         'Unable to read trace header file[4]')
          call exit(1)
         endif
С
c read in data
         call rtrd (ihand,itrace,newtrace,nsampl,ierr)
         if (ierr.LT.0) then
          call report('trace_bin','dataset','F',
   & 'Unable to read trace data file')
```

```
c check that all trace headers in bin file have been written to
         i=0
         do while(.true.)
          i=i+1
          call rtdh(ohand,i,ierr)
          if (ierr.LT.0) then
           call report('trace bin','dataset','F',
   & 'Unable to read trace header file[5]')
           call exit(1)
          endif
С
          if (ierr.GT.0) then
           call report('trace bin','dataset','I',
        'End of file reached')
           goto 120
           endif
С
           if (ufldfn.eq.0.and.ufldtn.eq.0) then
           ufldfn=i
           ufldtn=i
           wrange=minoff+(i-1)*binlen
С
           call wtdh(ohand,i,ierr)
           if (ierr.LT.0) then
             call report('segy','trace data','F',
       'Unable to write to file')
             call cltdat(ohand)
             call exit(1)
            endif
           endif
С
         enddo
```

12. TRANSFORM

```
program transform
С
        Rotation, translation and scaling of coordinates from
        digitising table for use with beam87.
С
        N.B. 1st 3 coord pairs in input file must be bottom left,
С
        bottom right, and top left corners respectively.
С
         include '/home/kanga/dave/Flib/include/functions.h'
         include '/home/kanga/dave/Flib/include/dls.h'
С
         real t0, t1, d0, d1, t, d
         real a(3), b(3), x, y, vel
         real angle, dscale, tscale, SINA, COSA
         integer idummy, ierr
         character iname*20, oname*20, path*25, ifn*45, ofn*45, join
С
         call dlsini()
         call getparam(path,iname,oname,d0,d1,t0,t1,vel)
С
         ioin='/'
         if (path(1:1).eq.'') join=''
         ifn=path(1:lnb(path))//join(1:lnb(join))//iname
         ofn=path(1:lnb(path))//join(1:lnb(join))//oname
С
         open(unit=10,file=ifn(1:lnb(ifn)),status='OLD')
          open(unit=11,file=ofn(1:lnb(ofn)),status='NEW')
С
          do i=1.3
          read(10,100),a(i),b(i),dummy
          end do
 С
          angle=atan(((b(1)-b(2))/(a(2)-a(1))+(a(1)-a(3))/(b(1)-b(3)))/2)
```

SINA=sin(angle)

```
COSA=cos(angle)
        dscale=(d1-d0)/((a(2)-a(1))*cos(angle)-(b(2)-b(1))*sin(angle))
        tscale=(t1-t0)/((a(3)-a(1))*sin(angle)+(b(3)-b(1))*cos(angle))
        do while (.true.)
         doi=1.4
          read(10,100,iostat=ierr),x,y,idummy
          if (ierr.lt.0) then
           print*,'end of file reached'
            goto 50
          endif
          d=dscale*((x-a(1))*COSA-(y-b(1))*SINA)+d0
          t=tscale*((x-a(1))*SINA+(y-b(1))*COSA)+t0
c unreduce data if necessary
          if (vel.ne.0) t=t+d/vel
          write(11,110) d,t
          end do
         write(11,*)''
        end do
С
        close(unit=11)
 50
        close(unit=10)
C
        format(f8.3,1x,f8.3,1x,i2)
 100
        format(f10.5,f10.5,$)
 110
С
         end
```

```
С
        subroutine getparam(path,iname,oname,d0,d1,t0,t1,vel)
С
        real t0, d0, t1, d1, vel
         character iname*20, oname*20, path*25, red*3
С
         print*,\f** Transformation of coordinates **\n'
         print 10
         read(*,'(A25)'),path
         print 20
         read(*,'(A20)'),iname
         print 30
         read(*,'(A20)'),oname
         print 40
         read(*,'(F8.0)'),d0
         print 50
         read(*,'(F8.0)'),d1
         print 60
         read(*,'(F5.0)'),t0
         print 70
         read(*,'(F5.0)'),t1
         print 80
         read(*,'(A3)'),red
         if ((red(1:1).eq.'y').or.(red(1:1).eq.'Y')) then
           print 90
           read(*,'(F5.2)'),vel
          else
           vel=0.0
          endif
 С
          format(' path name: ',$)
  10
          format('input filename:',$)
  20
          format('output filename: ',$)
  30
```

```
format(' left side offset:',$)
format(' right side offset:',$)
format(' bottom time:',$)
format(' top time:',$)
format(' is data already reduced?',$)
format(' reduction velocity used:',$)

return
end
```

APPENDIX A

13. WATERD

```
program waterd
c reads header file and writes out the water depth to screen,
c distance etc for every nrecth trace.
   include "/home/kanga/dave/Flib/include/rhicom.h"
   include "/home/kanga/dave/Flib/include/segytc.h"
   include "/home/kanga/dave/Flib/include/functions.h"
   include "/home/kanga/dave/Flib/include/dls.h"
   integer*4 ierr, ihand, recsz
   integer*4 itrace, ifirst, ilast, nrec, otrace
   integer*4 nsampl
   real*4 srate
   character iname*20, oname*24, ipath*25, opath*25
   call dlsini()
c defaults
   ipath = '.
   opath = '.
c ifirst is trace no. at start of loop, ilast is
c trace no. at end, and nrec is step size
    otrace = 1
   ifirst = 1
   ilast = 4000
   nrec = 100
c get parameter values from user via menu
С
       print*,'enter trace step:'
```

A-82

```
read 5,nrec
       format (i5)
       print *, 'enter filename'
       read 6, iname
       iname = '16bs5 bpf'
 6 format (a)
       oname = iname(1:lnb(iname))//' hdat'
c open input and output files
       call optdat (ipath,iname,0,recsz,ihand,ierr)
       if(ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Cannot find all dataset files')
         call exit(1)
       endif
c read segy header
       call rhead(ihand,0,ierr)
       if (ierr.LT.0) then
         call report('segy','dataset','F',
  & 'Unable to read reel header file')
         call exit(1)
       endif
       nsampl = rhinsm
       if (rhisr.NE.0) srate = 1.0E6/rhisr
```

```
do 10 itrace=ifirst,ilast,nrec
c read in trace header to common block
        call rtdh(ihand,itrace,ierr)
        if (ierr.LT.0) then
          call report('segy','dataset','F',
  & 'Unable to read trace header file')
          call exit(1)
         endif
С
c check for end of file
         if (ierr.GT.0) then
          call report('segy','dataset','I',
  & 'End of file reached')
          goto 11
         endif
С
         if (nsampl.EQ.0) nsampl = unsamp
         if (srate.EQ.0.AND.wsr.NE.0) srate = 1.0E6/wsr
C
        print 1001, ufldfn,wrange/1000,wsrcwd
10 continue
 11 continue
 1001 format(i6,2x,2(f10.3,1x))
    stop
    end
```

A-83

Appendix B : Routines used in above programs

Contents:

- 1. ADDSUFF Append a suffix to a filename by string concatenation.
- 2. NORM Scale a real array so that the maximum value is equal to a specified constant, returning the scaling factor applied.
- 3. REVERSE2D Reverse the columns of a 2 dimensional real array.
- 4. TAPER Apply a cosine taper of given lengths to each end of a real array.
- 5. TAPER_2 Apply a cosine taper of different given lengths to either end of a real array.
- 6. TAPER2D Apply a cosine taper of given length to either side of a 2 dimensional real array.
- 7. TRANSPOSE Transpose a 2 dimensional array about the leading diagonal.

```
ADDSUFF
                                                                 call minmax(lx,x,amin,amax)
c create filename by adding suffix to user-defined
                                                                 if((amax-amin).eq.0.0) then
c name (padded with ''s) and giving length of new
                                                                  scale=0.0
c filename (without ''s)
                                                                 else
                                                                  scale=lim/max(abs(amax),abs(amin))
С
      subroutine addsuff(name,suffix,newname,length)
                                                                 endif
                                                                 call avmul(lx,x,scale)
С
      character*(*) name,suffix,newname
                                                                 return
      integer m,length
                                                                 end
С
                                                               newname=name
      m=index(newname,'')
      newname(m:)=suffix//'
                                                              TAPER
      length=index(newname,'') - 1
      if (length.EQ.-1) length=len(newname)
                                                               subroutine taper(lx1,data,l1)
С
      return
                                                               c perform cosine taper on both ends of real array over 11 samples
      end
data(lx1) = data array
                                                               С
                                                                            = taper length
                                                                     11
                                                               С
NORM
                                                                     integer*4 lx1,11
                                                                     real*4 data(lx1)
real*4 pi,d1,f1,arg
  subroutine norm(x,lx,lim,scale)
                                                                     parameter(pi=3.1415927)
  normallization to +,- lim for real*4 data,
                                                               С
                                                                     d1=pi/real(11)
  scaling factor returned
  real*4 x(lx),lim,scale
                                                                      do 20 i=1,1x1
                                                                       if (i.le.11) then
                                                                        arg=d1*real(i-1)
c determine max
```

B-2

```
elseif (i.ge.(lx1-l1)) then
                                                                        do\ 20\ i=1,lx1
         arg=d1*real(lx1-i+1)
                                                                         if (i.le.11) then
        else
                                                                          arg=d1*real(i-1)
         arg=pi
                                                                         elseif (i.ge.(lx1-l2)) then
        endif
                                                                          arg=d2*real(lx1-i+1)
        f1=0.5*(1-(\cos(\arg)))
                                                                          else
С
        data(i)=data(i)*f1
                                                                          arg=pi
                                                                          endif
С
                                                                         f=0.5*(1-(\cos(\arg)))
20
       continue
                                                                          data(i)=data(i)*f
                                                                 20
                                                                         continue
      return
      end
return
                                                                        end '
                                                                 TAPER 2
TAPER2D
       subroutine taper_2(lx1,data,l1,l2)
                                                                 С
                                                                        subroutine taper2d(lx1,lx2,data,l1,l2)
c perform cosine taper on both ends of real array
       data(lx1) = data array
              = taper length at start of array
                                                                 c perform cosine taper on 2d real array
       11
С
              = taper length at end of array
       12
                                                                        integer*4 lx1,lx2,l1,l2
С
                                                                        real*4 data(lx1,lx2)
       integer*4 lx1,11,12
       real*4 data(lx1)
                                                                 С
                                                                        real*4 pi,d1,d2,f1,f2,arg
       real*4 pi,d1,d2,f,arg
                                                                        parameter(pi=3.1415927)
       parameter(pi=3.1415927)
С
                                                                        d1=pi/real(l1)
       d1=pi/real(l1)
                                                                        d2=pi/real(12)
       d2=pi/real(12)
```

B-3

```
B-4
```

```
С
       do 10 j=1,lx2
        if (j.le.12) then
         arg=d2*real(j)
        elseif (j.ge.(lx2-l2)) then
         arg=d2*real(lx2-j)
        else
         arg=pi
        endif
        f2=0.5*(1-(cos(arg)))
        do 20 i=1,1x1
         if (i.le.11) then
          arg=d1*real(i)
         elseif (i.ge.(lx1-l1)) then
          arg=d1*real(lx1-i)
         else
           arg=pi
         endif
         f1=0.5*(1-(\cos(arg)))
          data(i,j)=data(i,j)*f1*f2
 С
         continue
20
        continue
 10
 С
        return
        end
```

REVERSE2D

```
subroutine reverse2d(data,11,12)
С
c reverse real*4 array in 2nd dimension
      <----12---->
     2 2 0 1 1
                       1 1 0 2 2
     2 2 0 1 1
                       1 1 0 2 2
 11 2 2 0 1 1 ----> 1 1 0 2 2
                       1 1 0 2 2
     2 2 0 1 1
                       1 1 0 2 2
     2 2 0 1 1
      integer*4 11,12
      real*4 data(11,12), dummy
С
      do j=1,12/2
       do i=1,11
        dummy=data(i,j)
        data(i,j)=data(i,12-j+1)
       data(i,12-j+1)=dummy
       enddo
      enddo
      return
      end
```

```
TRANSPOSE
```

B-5

```
subroutine transpose(data,l)
c transpose real*4 square array along principle diagonal
                      0 2 2 2 2
     0 1 1 1 1
                      10222
     20111
     2 2 0 1 1 ----> 1 1 0 2 2
                      1 1 1 0 2
     2 2 2 0 1
                      1 1 1 1 0
     2 2 2 2 0
     integer*4 l
     real*4 data(l,l), dummy
      do j=1,1
      do i=j,l
       dummy=data(i,j)
       data(i,j)=data(j,i)
       data(j,i)=dummy
      enddo
      enddo
      return
      end
```

Appendix C: Routines from other sources

D.L.Stephenson:

AACOPY Real array copy routine

ASKOK Ask for YES/NO confirmation from user

AZERO Zero a real array

BPASS Band pass filter routine (variable window, freq domain)

CLTDAT Close ISEGY dataset files

DLSINI Initialise DLS subroutine library

EXISTS Test whether a file exists

FFTA Fast Fourier Transform (Cooley-Tukey)

FFT2D 2D Fast Fourier Transform

GBEGIN Open UNIRAS file + segment

GEND Close UNIRAS file

KORD2D Reorder 2D f-k array for increasing k (or vice versa)

LININT Linear interpolation between points in an array

LNB Determine last non blank character in a string

MEAN Calculate mean and remove from a real array

OPTDAT Open ISEGY dataset files

PAD Fill a real array with a constant

REPORT Error report subroutine

RESAMP Time domain resampling subroutine using sin(x)/x

RHEAD Read ISEGY reel header file

RTDH Read ISEGY trace data header from file

RTRD Read ISEGY trace data from file

USRMES Print a string on the terminal WHEAD Write ISEGY reel header file

WTDH Write ISEGY trace data header to file

WTRD Write ISEGY trace data to file

C. Prescott:

RAZCLK Write rotating bar to screen without scrolling

RAZOUT Write string and integer to screen without scrolling

APPENDIX D

Appendix D: Programs from other sources

C. Peirce / C.Prescott:

DAZZLE Seismic data plotting program (UNIRAS graphics)

P. A. Matthews:

CONVERT Convert PDAS-type seismic data files (IBM format) to

ISEGY format (SUN format)

V. Cerveny:

BEAM87 Forward modelling package using Gaussian Beam

approximation for wide angle seismic data (adapted for UNIRAS graphics by C. Prescott and P. A. Matthews;

adapted for normal incidence by P. A. Matthews)

D. L. Stephenson:

SEGY Ready SEGY reel data and store in ISEGY format.

M.H.P.Bott

GRAV Two dimensional gravity modelling program

GLOBAL LAB

GLOBAL LAB Digitisation and data display package (Macros written

by R. E. Long)

APPENDIX E

Appendix E: Large scale data record sections (1:400000)

- 1: Station 101P Band pass filtered Stacked @ 6.5 km s⁻¹ (5 trace)
- 2: Station F01A Band pass filtered
- 3: Station 1A Band pass filtered
- 4: Station 5A Band pass filtered Binned (bin width 75 m)

