THE CRUSTAL STRUCTURE BENEATH ICE STREAM C AND RIDGE BC, WEST ANTARCTICA FROM SEISMIC REFRACTION AND GRAVITY MEASUREMENTS

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Abstract: Data from a seismic refraction/wide-angle reflection and gravity profile provide information on the crustal structure beneath ice stream C and ridge BC in West Antarctica. The profile, obtained by the University of Wisconsin-Madison Geophysical and Polar Research Center in 1988, was oriented transverse to the axis of the ice stream and extended 63 km across ice stream C to ridge BC. The refraction and wide-angle reflection data were modeled using a two-dimensional ray trace forward modeling program to match travel times of refracted and reflected arrivals. Forward modeling of the gravity data was used to further define the structural model where seismic ray coverage was inadequate. These data constrain the velocity structure of the upper and middle crust (1- to 12-km depth) and provide evidence for a low-velocity zone (1.6 to 2.3 km/s) beneath the ice that varies in thickness from 100 m to 2.5 km within an apparent graben beneath ridge BC. Other major features of the structural model are (1) weak to moderate lateral variations in crustal structure, (2) a basement crustal velocity that varies from 5.65 to 5.90 km/s, (3) a sub-basement crustal velocity of 6.85 km/s at a relatively shallow depth (5–7 km), and (4) a reflective zone (12- to 14-km depth) that may indicate mafic underplating.

Key words: crustal structure, seismic refraction, gravity, West Antarctica, Siple Coast

Introduction

West Antarctica is believed to be a composite of crustal fragments or geologic terranes of various compositions that were rearranged into their present geography subsequent to the break-up of Gondwana during the Early Mesozoic (Elliot, 1985). In 1988, a seismic-refraction and gravity survey was conducted across ice stream C to ridge BC (Fig. 1) to provide a regional seismic velocity model of the crust and thereby permit a better understanding of the Mesozoic and Cenozoic tectonics of the region. The crustal-scale refraction experiment consisted of eight explosive charges, ranging from 135 to 315 kg, and two different recording arrays at opposite ends of the profile. In addition, gravity measurements were made at 1-km intervals on the same 63-km line. Further information was provided by two small-offset (720 m) refraction profiles and a ground-based radar profile of ice thickness. The purpose of this paper is to present the results of a two-dimensional forward model of the seismic refraction/wide-angle reflection and gravity data. Previous crustal seismic studies in the Ross embayment include: Rooney *et al*. (1987) on ice stream B and the Ross Ice Shelf; Robertson and Bentley (1990) on the Ross Ice Shelf; Robinson and Splettstoesser (1984) at the head of ice stream B; and McGinnis *et al*. (1985) and Cooper *et al*. (1987) in the western Ross Sea.

Regional Tectonics

Ice stream C and ridge BC overlie a portion of what has been termed by LeMasurier (1978) as the "Cenozoic West Antarctic rift system." The Cenozoic West Antarctic rift system extends roughly from the Ross Sea to the Bellingshausen Sea and is a continuation of the rifting that possibly started in the Jurassic when Africa rifted from East Antarctica (Behrendt *et al*., 1991). Evidence for rifting in-cludes (1) the large Late Cenozoic volcanoes along the west coast of the Ross Sea whose highly alkaline and bimodal volcanic rocks suggest that the volcanism in the region is rift related, (2) the widespread occurrence of Cenozoic volcanic rocks beneath the western part of the ice sheet overlying the Byrd subglacial basin inferred from aeromagnetic profiles in West Antarctica (Jankowski *et al*., 1983), and (3) the discovery from recent large-offset seismic profiles over the Ross Sea continental shelf of depths to Moho ranging from 17–21 km, which suggest an extended, rifted, continental crust (Cooper *et al*., 1987). Elliot (1985) has proposed that the Late Paleozoic-Early Mesozoic break-up of Gondwana was accompanied by block faulting and crustal thinning within the Ross embayment. Early Cenozoic subsidence of the Ross embayment resulted in the deposition of thick marine and glaciomarine sequences.

Field Experiment

During the 1988–1989 Antarctic field season eight shots were recorded along a 63-km line at two array locations (Fig. 2). The recording spread near upstream C camp (UPC) was 7.2 km in length and consisted of seven groups of geophones with each group divided into three sets of six 8-Hz geophones. The recording spread near ridge BC camp (RBC) was 690 m in length and consisted mainly of 28-Hz geophones, separated by 30 m. Eight explosive charges were fired into the two recording spreads; charge sizes increased towards the ends of the profile. Data were recorded by a high-speed digital recording system (developed at the Geophysical and Polar Research Center) with a sampling rate of 2500 samples per second. Shot and receiver locations were determined by a laser ranging system.

In addition to the crustal-scale seismic-refraction profile, two small-offset refraction profiles were made near UPC
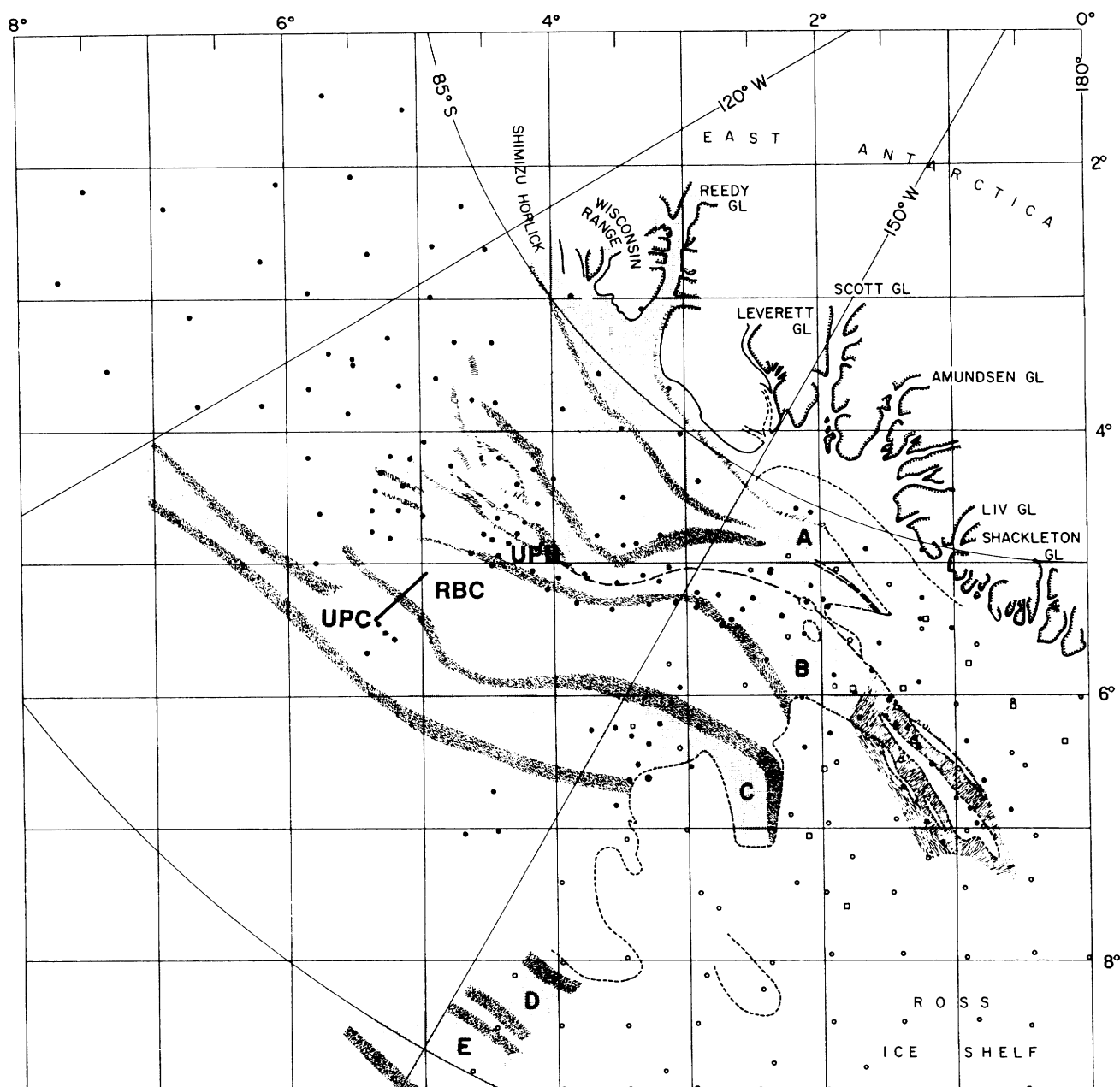
Fig. 1. Map showing the location of Ross ice streams, upstream C camp (UPC), and ridge BC camp (RBC). The location of the 1988–89 seismic, gravity, and ground-based radar profile extends 63 km grid northeast across ice stream C to ridge BC. In the rectangular grid coordinate system, 0° grid longitude lies along the Greenwich, and the grid equator passes through the geographic South Pole. One degree grid is 110 km. This map is a modified version of that from Shabtaie and Bentley (1987), q.v. for explanation of other features of the map.

and RBC to determine a velocity-depth profile in the firn (upper 50 m). The geophones were vertically oriented and placed at 2.5 m intervals out to a source-receiver separation of 720 m. Explosive charges of 0.15-kg were detonated in holes 1 m deep.

Gravity readings were made at approximately 1 km intervals on the 63-km line with a LaCoste - Romberg geodetic gravity meter (G-19). A base station reading was made both before and after to correct for any drift in the instrument. Altimeter readings were made simultaneously with each gravity reading and also at the base station throughout the

day to correct for changes in atmospheric pressure.

A SPRI Mark II 50-megahertz radar system with a digital recorder (developed in house) was used to obtain ice thickness values along the profile line. Travel times were converted to depths using an electromagnetic wave velocity of 169 m/μs and applying a correction for the low density firn. Ice thicknesses obtained by this method are accurate to approximately 10 m.

Data and Interpretation

The seismic record sections for the eight shots recorded at

Seismic Refraction & Gravity Profile

Ice Stream C

Ridge BC

upstream

grid SW

grid NE


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                     UPC                    UPC                              X-line                        RBC
                recording spread            camp                                                      recording spread
distance (km)    0      ↓                10  +        20          30          40          50   shot 7  ↓ 60
                ▽●▽▽▽▽▽●          ┤─       ●    ┤─   ●           ●    ┤─     ●          ┤─      ●    ▼    ●
                    ─                                                                          RBC
                shot 1 ▲  shot 2      shot 3     shot 4    shot 5           shot 6     camp  +   ─    shot 8
                                                                                              55.1  ▲
location (km)    0       7.2          14.2       21.4      26.5             40.9              55.1      62.3
shot size (kg)  315      270          180        135       135             180               270       315

small-offset refraction profile                                                    small-offset refraction profile
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downstream

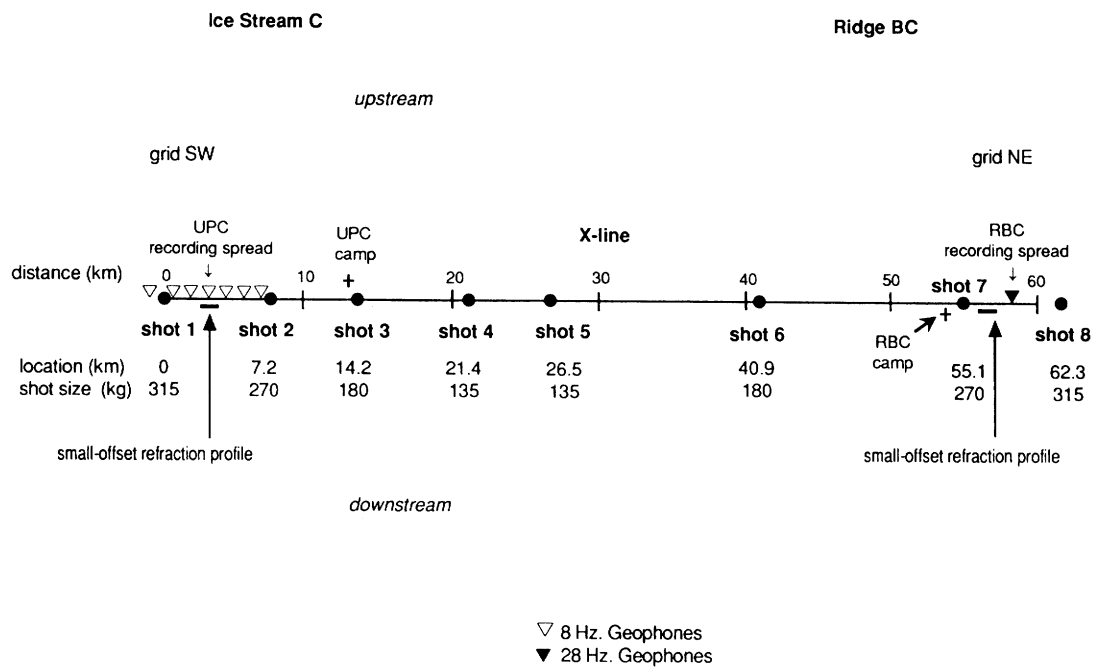▽ 8 Hz. Geophones
▼ 28 Hz. Geophones

Fig. 2. Diagram showing the recording-array locations, shot locations, and the shot sizes of the seismic refraction profile. Also shown are the two locations for the two small- offset refraction profiles.
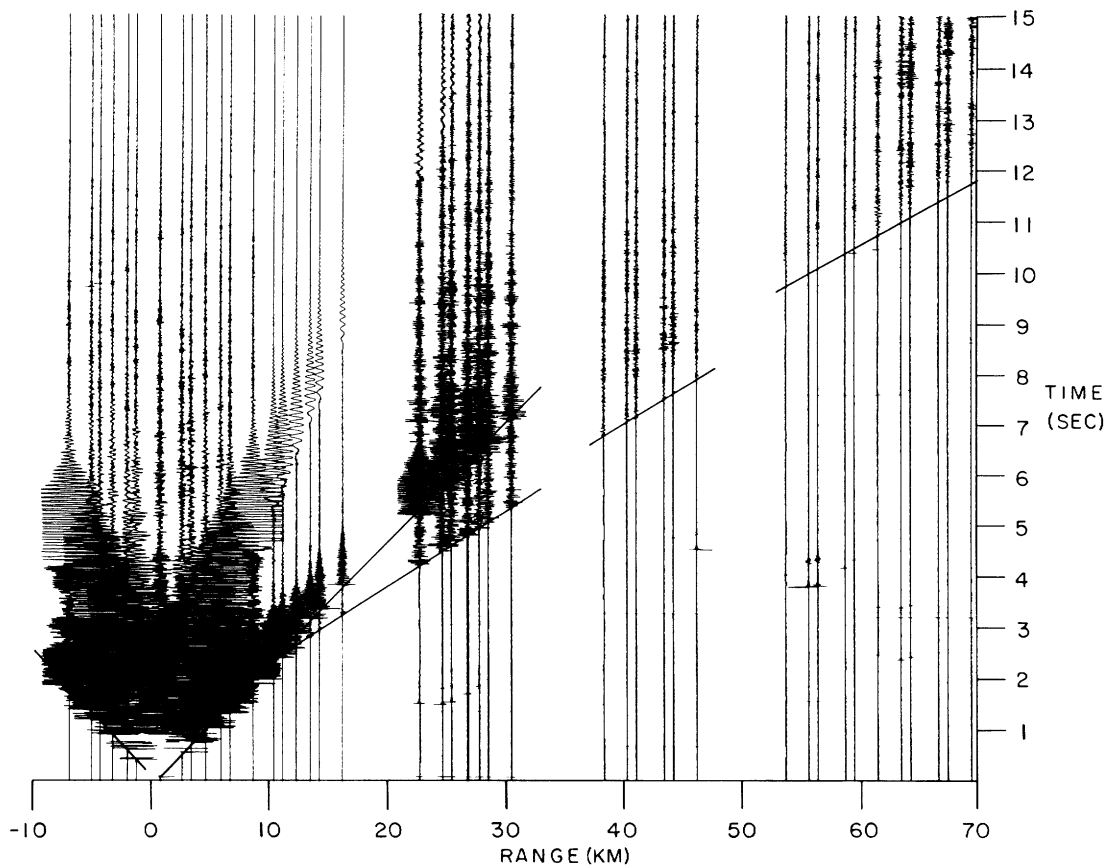

Fig. 3. Data from shot points 1–3 and 5–8 recorded at the UPC array. The high-amplitude arrivals shown from –10 to 30 km are refracted ice arrivals ($V_{ap} = 3.77$ km/s). $V_{ap} = 5.92$ km/s for the refracted arrivals from 10 to 30 km, 6.24 km/s for the refracted arrivals from 38 to 45 km, and 6.80 km/s for the refracted arrivals from 55 to 70 km. Every third trace is displayed.

UPC and RBC were used along with the gravity measurements to determine the velocity/density structure across the 63 km-long profile. Iterative forward modeling, using the two dimensional ray tracing theory of Cerveny *et al.* (1977) and software written by Luetgert (1988), was used to derive the 2D seismic velocity model that best predicts the travel times of refracted and reflected rays in a laterally varying medium. After converting seismic velocities to densities, the crustal boundaries not defined by the seismic velocity model were modeled from the gravity data using a program written by Enmark (1981).

Seismic and gravity profiles

Seismic refraction arrivals were fitted by linear segments, and the slope and intercept of each segment were used to determine the corresponding layer apparent velocities for each layer and approximate layer depths. The UPC profile (Fig. 3) shows arrivals in the ice sheet (3.77 km/s) and three groups of subglacial arrivals with apparent velocities of 5.92, 6.24, and 6.80 km/s, respectively. On the RBC profile (Fig. 4), in contrast, only the ice arrivals (3.82 km/s) and four arrivals with apparent velocities greater than 10 km/s were recorded. We have modeled the latter arrivals as wide-angle reflections.

As the absolute values of the gravity anomalies are irrelevant for the purpose of deriving a crustal model, anomalies were calculated relative to a point arbitrarily chosen to be at km 14.4 (the point of intersection of a flagged trail from camp with the profile line). The Bouguer anomalies show a regional trend from −5 to 33 mgal from grid SW to NE along the profile (Fig. 5). A relative gravity low of 20 mgal is

Fig. 4. Data from shot points 2–8 recorded at the RBC array. The high-amplitude arrivals shown from 5 to −18 km are refracted ice arrivals (V_{ap} = 3.82 km/s). V_{ap} > 10 km/s for the arrivals from − 32 to −52 km. Only two traces from each shot record are displayed.

observed over the grid NE end of the profile (40 to 55 km) and is attributed to a low density body in the upper crust.

Refraction and gravity model

The crustal model derived for ice stream C and ridge BC consists of three distinct units, which we call crustal units 1, 2 and 3, beneath the ice. Shown in Fig. 6 is our interpreted crustal model with solid lines marking interfaces derived from seismic ray-trace modeling and dashed lines indicating interfaces derived from forward modeling of the gravity data. Calculated travel-time curves and the corresponding ray diagrams from the velocity model are shown in Figs. 7a and b. The average misfit between the calculated and the observed travel times is less than 50 ms.

The following constraints were initially entered into the seismic refraction model: (1) the velocity-depth profile in the upper 50 m of firn (from the two small-offset refraction profiles), (2) the ice thickness (from the ground radar profile), and (3) the velocities in the ice (3.77 and 3.82 km/s for UPC and RBC, respectively).

The seismic velocity model was converted to a density model based on a linear relationship between seismic velocities and densities (Meissner, 1986). Iterative forward modeling of the gravity data (Fig. 8) was then used to derive the crustal boundaries not defined by the seismic velocity model (i.e. outside of ray coverage). The average misfit between the calculated Bouguer anomalies, based on the interpreted velocity model, and the observed gravity is less than 5 mgal.

Crustal Unit 1

Velocities measured for crustal unit 1 by Atre (1990) using wide-angle reflections are typical of unconsolidated sediments: 1.6 to 2.3 km/s. Assuming a compressional-wave velocity, V_p, in this crustal unit of 2.0 km/s leads to a thickness of approximately 100 m beneath the center of ice stream C. Crustal unit 1 thickens to 500 m grid northeasterly across the margin of ice stream C and, in an apparent graben beneath ridge BC, first increases in thickness to 2.5 km and then decreases again to a few hundred meters (Fig. 6). Deep-sounding reflection profiles on ice stream B have shown the existence there of at least a kilometer of unconsolidated sediments (Rooney *et al.*, 1991).

Crustal Unit 2

Refracted arrivals with apparent velocities ranging from 5.92 to 6.24 km/s from the record sections of shots 3–6, recorded at UPC, were used to model crustal unit 2 (Fig. 3). Because of the abrupt decrease in signal amplitude, the first arrivals on shot points 1 and 2 at offsets greater than 6 km were also interpreted as refracted arrivals from crustal unit 2. The resulting model of crustal unit 2 shows V_p varying from 5.65 km/s at the top of the crustal unit to 5.90 km/s at the bottom (Fig. 6). The thickness of crustal unit 2, determined mainly by gravity modeling, ranges from 5 km beneath ice stream C to 2 km beneath ridge BC. Rooney (1988), for the corresponding crustal unit beneath ice stream B, and Robinson *et al.* (1984), on an unreversed profile located at the head of ice stream B, measured somewhat lower values of V_p: 5.40 km/s and 5.30 km/s, respectively. We doubt that this difference is significant in terms of gross crustal structure.
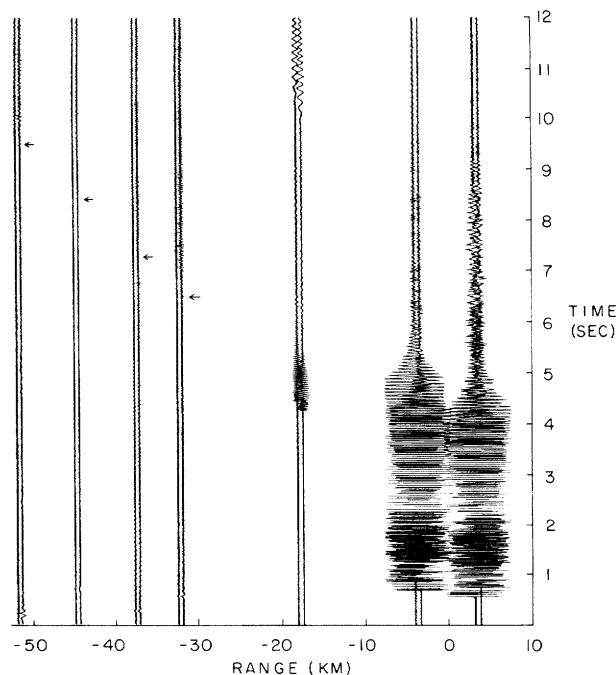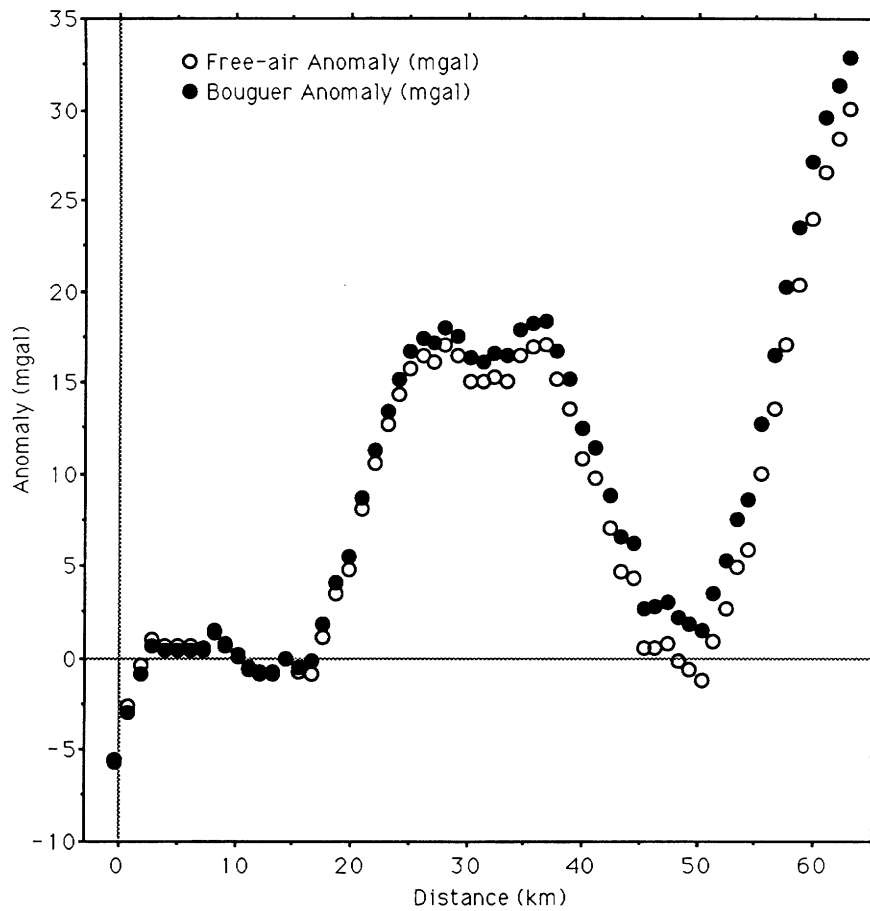
Fig. 5. Free-air and Bouguer anomalies across the 63-km long profile. All anomalies are relative to an assumed value of 0 at km 14.4. Measurements were made at 1 km intervals.
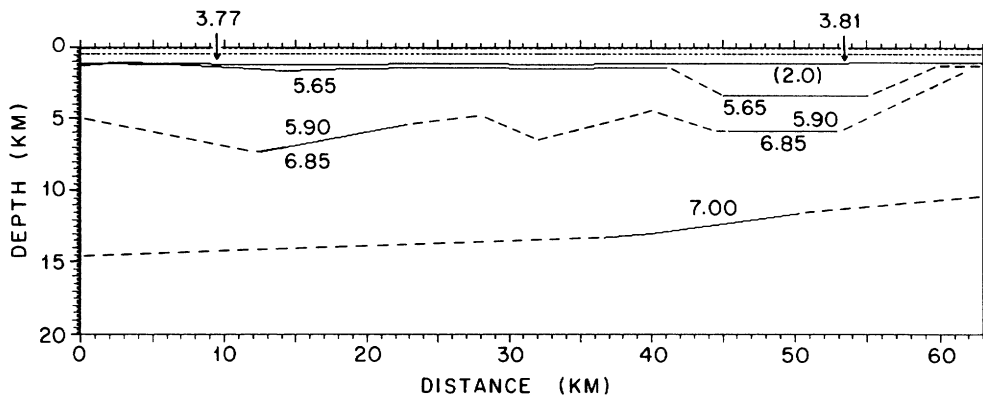

Fig. 6. P-wave velocity model derived from forward modeling of seismic refraction and gravity data. Dashed lines indicate interfaces derived from forward modeling of gravity data and solid lines indicate interfaces derived from two-dimensional ray tracing. Velocities are in km/s and the parentheses denote an assumed velocity.

Crustal Unit 3

The apparent velocity of the first arrivals observed on shots 7 and 8 at UPC, at offsets ranging from 55 to 70 km, is 6.80 km/s (Fig. 3). Matching the observed travel times for these two shots resulted in a V_p of 6.85 km/s for crustal unit 3. The thickness of unit 3, as determined by gravity modeling, varies from 5 to 10 km (Fig. 6). Forward modeling of

the presumed wide-angle reflections observed on shots 2–5 at RBC, at offsets ranging from 30 to 50 km (Figs. 4 and 7b), indicates a reflector depth between 12 and 14 km and a V_p of 7.00 km/s for the bottom of crustal unit 3. Robinson *et al.* (1984), on the unreversed profile at the head of ice stream B, recorded a similar V_p of 6.7 km/s for the corresponding crustal unit.
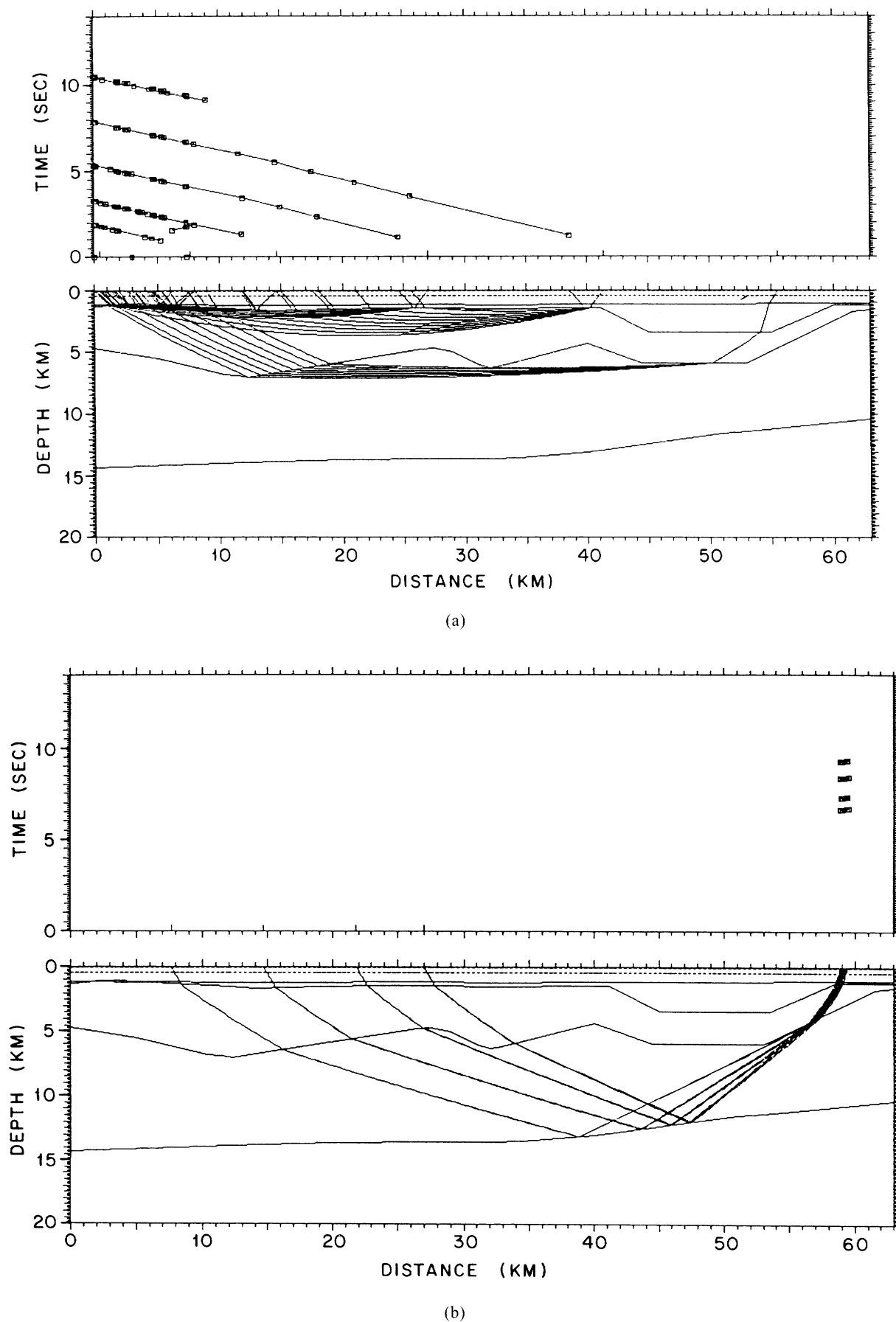
Fig. 7. Model, ray diagrams, and travel-time curves for the shots recorded at the (a) UPC array and (b) RBC array. The lines on the travel-time curves (upper diagram) are calculated travel times along the ray paths shown in the cross section (lower diagram).
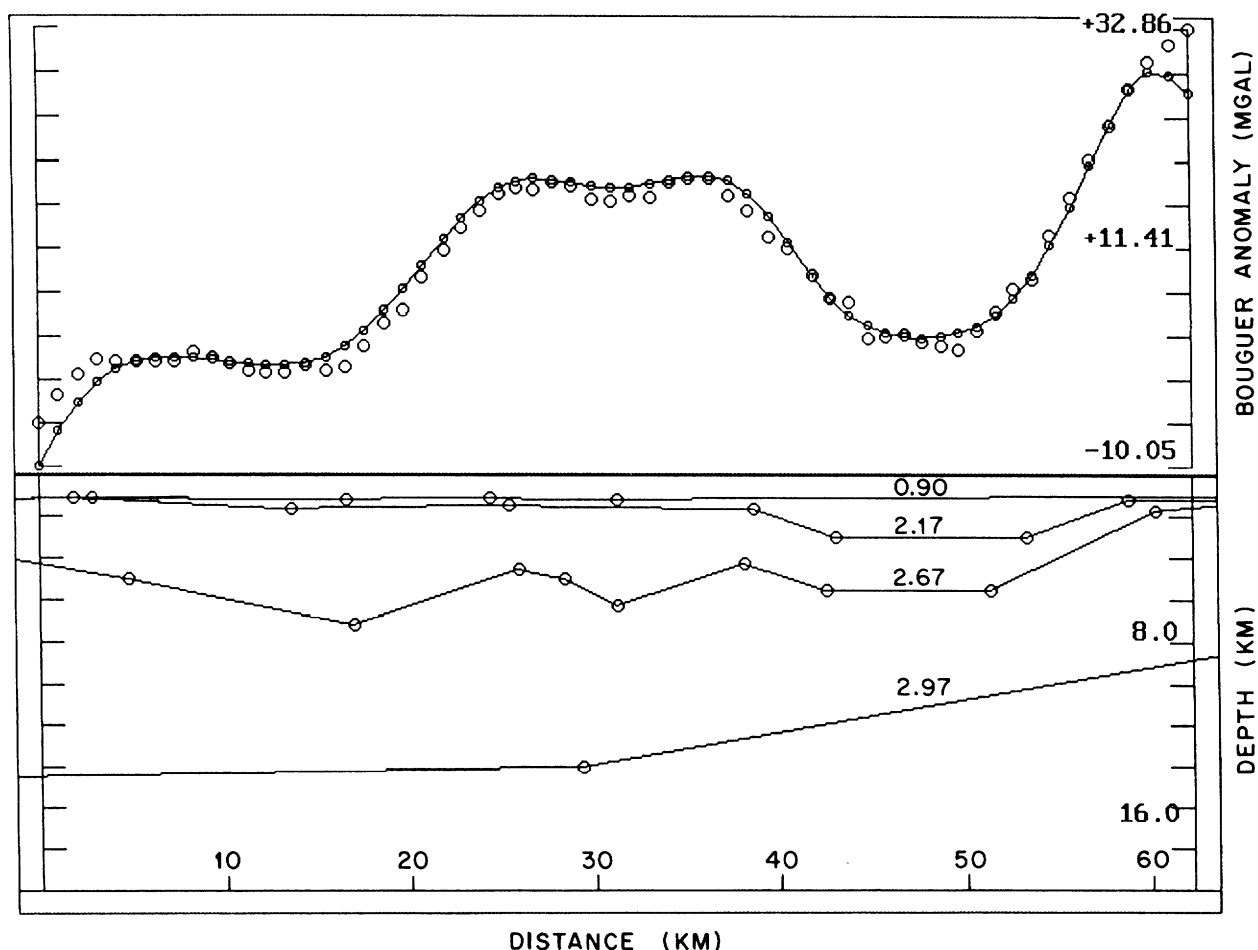
Fig. 8. Crustal density model and calculated (solid line) and observed Bouguer gravity anomaly. Densities are given in g/cm³.

Discussion and Summary

The concept of West Antarctica as having undergone crustal extension and rifting is supported by our results. Evidence for rifting from our seismic refraction and gravity profile includes (1) the full graben beneath ridge BC, (2) the presence, in the middle to upper crust (5–15 km depth), of high velocities (6.85–7.00 km/s) that are typical of a tectonic environment dominated by rifting, and (3) the presence of a reflective zone between 12 and 14 km in depth that may be due to mafic underplating.

The full graben beneath ridge BC implies that normal faulting, due to either a net horizontal extension of the rock mass that is undergoing faulting or the collapse of the rock mass as a result of removal of material from below (Suppe, 1985), has occurred in the region. Holbrook et al.(in press), in a summary of recent seismic data for the lower continental crust found that seismic P-wave velocities beneath rifts and volcanic plateaus show a major peak at 6.6–6.9 km/s and a minor peak at 7.3–7.5 km/s. Crustal unit 3, with a velocity of 6.85 km/s, is within the bounds of the major peak. Finally, the wide-angle reflections, observed on the records from shots 2–5 (Fig. 4), may have resulted from magmatic bodies or mafic underplating, although the possibility that these reflections are due to crustal layers of a different metamorphic grade or composition cannot be excluded.

The velocity/density model that we have produced (Figs. 6 and 8) is the simplest possible model that accounts for all the travel times of the interpreted seismic phases and the observed trends in the gravity data. Although the regional structure is undoubtedly more complex, the combination of the refraction/wide-angle reflection and gravity profiles provide a good estimate of the regional P-wave velocity structure.

Acknowledgements

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