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Structure and Tectonic Evolution of the West Antarctic Continental Margin and Bellingshausen Sea

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ABSTRACT. New multichannel seismic (MCS) reflection and marine magnetic profiles from the Bellingshausen Sea, a remote and poorly surveyed part of the Antarctic continental margin, provide new constraints on the tectonic history of this region. These new survey data have been interpreted in combination with free-air gravity maps derived from satellite altimetry data. The free-air gravity maps show two sets of prominent linear anomalies, which we refer to as the Bellingshausen Gravity Anomaly (BGA) and De Gerlache Gravity Anomaly (DGGA). Marine magnetic data show that all of the oceanic crust in the Bellingshausen Sea west of the BGA and DGGA was formed by Late Cretaceous spreading at the Pacific-Bellingshausen ridge, and that oceanic crust east of the northern part of the DGGA was formed by early Tertiary spreading at the Antarctic-Phoenix ridge. MCS profiles reveal evidence of convergent or transpressional deformation in the vicinity of the BGA and along the continental margin directly to its west. The acoustic-stratigraphic record in these profiles also provides a relative chronology of deformation events, which we infer probably resulted from Late Cretaceous to early Tertiary plate interactions near the eastern boundary of the Bellingshausen plate. Magnetic profiles indicate an abrupt contrast in the age of oceanic crust across the northern part of the DGGA, which implies that the Antarctic-Phoenix ridge jumped to this position at about chron C27n (61 Ma). This ridge jump seems to be associated with the inception of the Antarctic-Phoenix spreading, as its timing coincides with incorporation of the Bellingshausen plate into the Antarctic plate.

Key Words: seismic reflection, magnetic, gravity, tectonic history, reconstruction

Introduction

Plate tectonic reconstructions show that the West Antarctic continental margin in the southern Bellingshausen and Amundsen seas can be divided into two parts: a western part that formed as a passive margin after the rifting of New Zealand from West Antarctica *c.* 90 Ma ago, and an eastern part where subduction continued until segments of the Antarctic-Phoenix ridge migrated into a trench at the margin during the Tertiary (Weissel *et al.*, 1977; Mayes *et al.*, 1990; McCarron & Larter, 1998). Fig. 1 shows a sequence of reconstructions spanning the interval from 105 to 45 Ma. Precise definition of the Cretaceous and Cenozoic tectonic development of this region is essential for determining the subduction history of the Antarctic Peninsula during the same interval (McCarron & Larter, 1998), and the history of relative motion between the plates of the Pacific basin and the rest of the world (Molnar *et al.*, 1975). However, many of the details of reconstructions remain uncertain because the southern Bellingshausen and Amundsen seas are remote and

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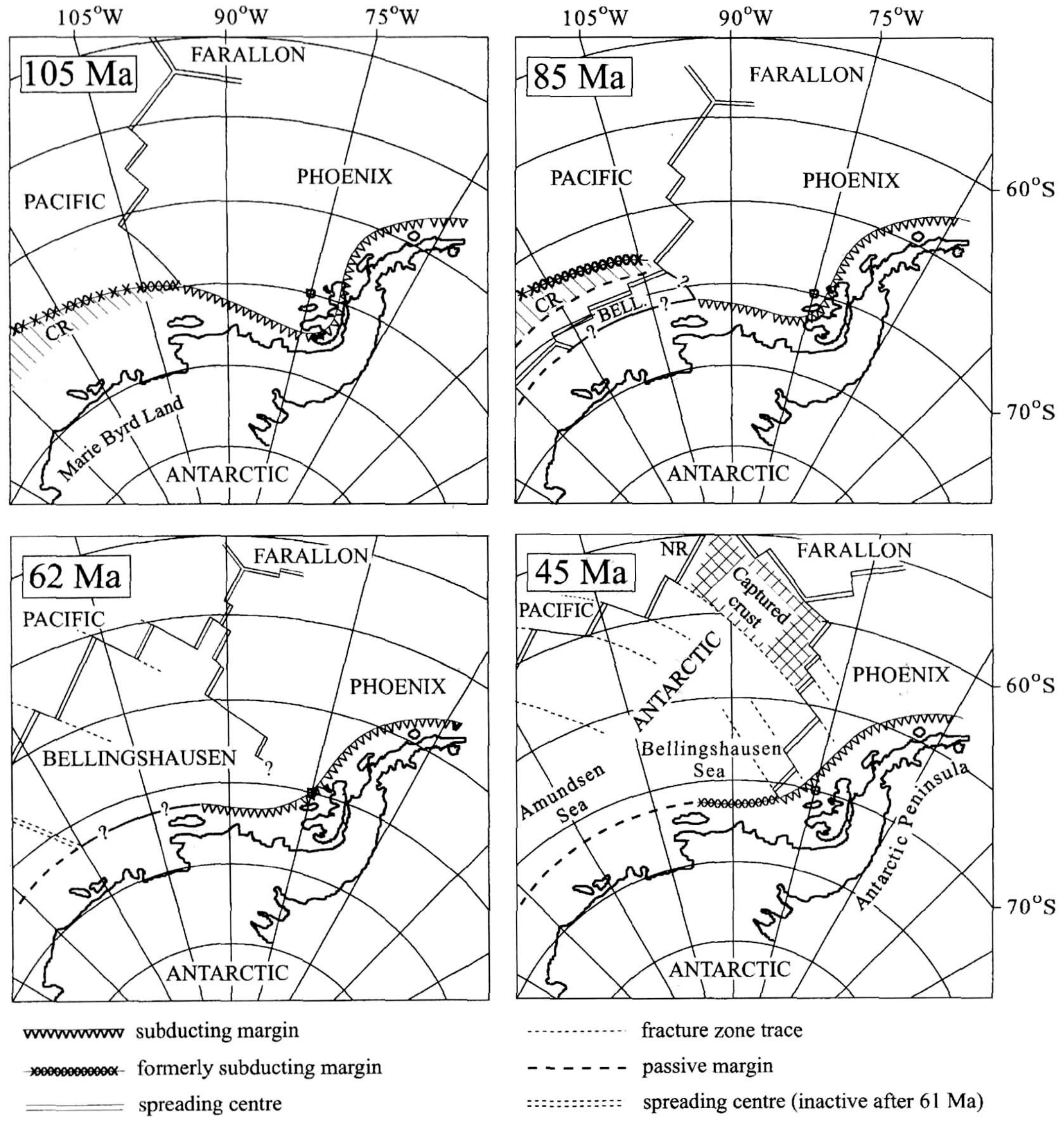

Fig. 1. Reconstructions of the South Pacific in the Antarctic reference frame, assuming no relative motion between the component blocks of West Antarctica since 105 Ma, based on data from Cande *et al.* (1982), Mayes *et al.* (1990) and Cande *et al.* (1995). The 62 Ma reconstruction approximately corresponds to the time that the Bellingshausen plate is thought to have been incorporated into the Antarctic plate (Cande *et al.*, 1995). The Phoenix plate has also been referred to by some authors as the 'Aluk' or 'Drake' plate. BELL., Bellingshausen plate; CR, Chatham Rise; NR, new ridge formed by propagation of the Pacific-Antarctic ridge at about 47 Ma. After McCarron & Larter (1998).

poorly surveyed.

Previous compilations of marine magnetic anomaly interpretations indicate that the boundary between the rifted and former subducting parts of the West Antarctic continental margin could lie anywhere between about 83°W and 105°W (Mayes *et al.*, 1990). Such compilations also appear to imply a curious tectonic event which involved the splitting of the Pacific-Phoenix ridge into separate Pacific-Antarctic and Antarctic-Phoenix ridges in the early Tertiary (Cande *et al.*, 1982). Additional uncertainties about the tectonic history of the region arise from the suggestion that an additional plate, the 'Bellingshausen' plate, existed off eastern Marie Byrd Land during the Late Cretaceous and early Tertiary (Stock & Molnar, 1987). Cande *et al.* (1995) found supporting evidence for the existence of the Bellingshausen plate prior to chron C27 (61 Ma), at which time they suggest there was a plate reorganisation and Bellingshausen-Antarctic motion ceased. The southern and eastern boundaries of the former Bellingshausen plate remain poorly defined, and it

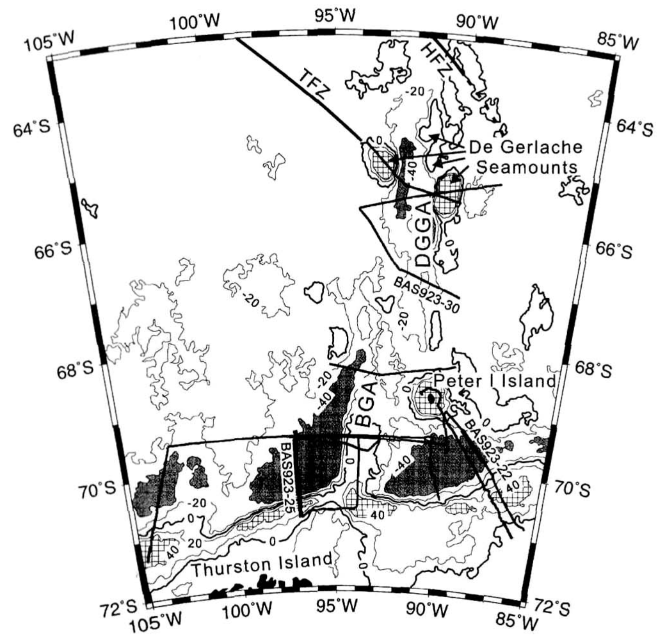

Fig. 2. Map showing location of British Antarctic Survey and Alfred Wegener Institute multichannel seismic reflection profiles (grey lines) in the Bellingshausen Sea in relation to free-air gravity anomalies. Profile BAS923-25, represented by a line drawing in Fig. 4, and the section of profile BAS923-22 displayed in Fig. 5, are shown as thicker grey lines. Free-air gravity contours from -40 to +40 mGal are drawn at 20 mGal intervals and represent the anomalies derived from satellite altimetry data by Laxon & McAdoo (1998). The 0 mGal contour is marked by a thicker line, anomalies > +40 mGal are cross-hatched, and anomalies < -40 mGal are shaded. BGA, Bellingshausen Gravity Anomaly; DGGA, De Gerlache Gravity Anomaly; HFZ, Heezen fracture zone; TFZ, Tharp fracture zone.

is not clear whether or not it included any part of the West Antarctic continental lithosphere.

In order to try and resolve some of these uncertainties the British Antarctic Survey (BAS) and the Alfred Wegener Institute for Polar and Marine Research (AWI) conducted three marine geophysical research cruises in the Bellingshausen and Amundsen Seas. In this paper we present an overview of some of the preliminary results of these cruises and discuss their implications for the tectonic history of the West Antarctic continental margin and Bellingshausen Sea.

New Marine Geophysical Data

In 1993, 1994 and 1995, BAS and AWI conducted three marine geophysical research cruises in the Bellingshausen and Amundsen seas (Fig. 2). On RRS *James Clark Ross* cruise JR04, in 1993, BAS collected c. 1500 line-km of multichannel seismic (MCS) reflection profiles using a hydrophone streamer with an active length of 2400 m and a source comprising 9 airguns with a combined chamber capacity of c. 56 l (Cunningham *et al.*, 1994). Magnetic, gravity, 10 kHz echo sounder and 3.5 kHz sub-bottom profiler data were collected simultaneously with MCS data and also along several fast reconnaissance profiles during this cruise. On RV *Polarstern* cruises ANT 11/3 (1994) and ANT 12/4 (1995) AWI collected c. 3400 line-km of MCS reflection profiles using hydrophone streamers with active lengths of either 2400 m or 600 m and an airgun source with a combined chamber capacity of c. 24 l (Miller & Grobe, 1996). Magnetic, gravity, 'Hydrosweep' multibeam bathymetry and 'Parasound' sub-bottom profiler data were collected simultaneously with MCS data and on passage tracks during these cruises.

Free-Air Gravity Data

Free-air gravity maps derived from satellite altimetry data (Sandwell & Smith, 1997; McAdoo & Laxon, 1997; Laxon & McAdoo, 1998) show two sets of prominent anomalies in the Bellingshausen Sea (Fig. 2). The Bellingshausen Gravity Anomaly (BGA) extends about 300 km NNE from the continental margin at about 94°W, and consists of an elongate gravity high bordered to the west by a deep low, the maximum contrast between the high and low being >100 mGal. The De Gerlache Gravity Anomaly (DGGA) extends northward from Peter I Island (68°50′S, 90°30′W) to 62°S. Along most of its length the DGGA consists of a central free-air high with flanking lows, the contrast locally exceeding 50 mGal.

Results

Marine Magnetic Data Interpretation

The new marine magnetic profiles were compiled

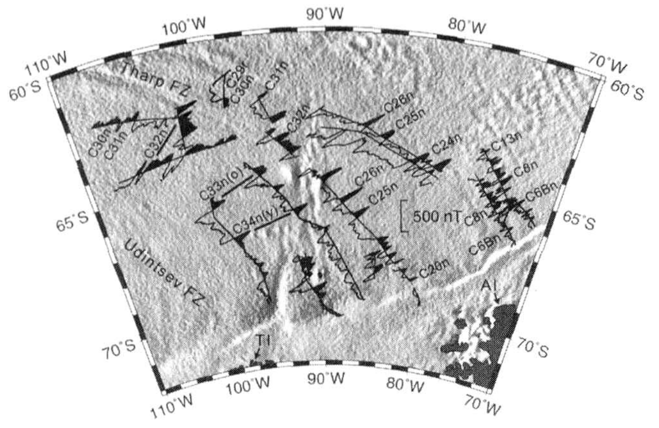

Fig. 3. Selected marine magnetic profiles plotted along ship tracks, and overlaid on a shaded-relief display of the free-air gravity field derived by Laxon & McAdoo (1998). The profiles shown are residual magnetic anomalies following removal of the International Geomagnetic Reference Field. Positive anomalies on most profiles are projected in a direction 60° clockwise from the top of the page (i.e. not a fixed geographic projection azimuth). The exceptions are the two westernmost profiles, on which positive anomalies are projected in a direction 30° clockwise from the top of the page. Positive anomalies are filled in black. Magnetic anomaly labels conform to the geomagnetic polarity timescale nomenclature used by Cande and Kent (1995). The free-air gravity field is illuminated from the west. Positive free-air anomalies and west-dipping gradients appear light, and negative free-air anomalies and east-dipping gradients appear dark. TI, Thurston Island; AI, Alexander Island.

with profiles from earlier cruises in the region. Interpretation of this magnetic data compilation reveals that all oceanic crust in the Bellingshausen Sea west of the BGA and DGGA was formed by Late Cretaceous spreading (chrons C34-C32; >83 Ma to 72 Ma) at the Pacific-Bellingshausen ridge (Fig. 3). In contrast, oceanic crust east of the northern part of the DGGA was formed by early Tertiary spreading (starting at about chron C27n; 61 Ma) at the Antarctic-Phoenix ridge.

Magnetic profiles indicate an abrupt contrast in the age of oceanic crust across the northern part of the DGGA, between chron C32n (72 Ma) to the west and chron C27n (61 Ma) to the east, with the oceanic crust on both flanks becoming younger away from the DGGA. These data imply that the Antarctic-Phoenix ridge jumped to the position of the DGGA at about chron C27n (61 Ma). This coincides with a general plate reorganisation in the South Pacific which included the incorporation of the Bellingshausen plate into the Antarctic plate (Cande *et al.*, 1995).

With the magnetic data presently available, none of the anomalies observed in the triangular area between the BGA, the De Gerlache Seamounts and a point on the continental margin at about 83° W can be unambiguously related to specific magnetic reversal chrons. Therefore the age of the oceanic crust within this triangle remains uncertain.

Multichannel Seismic Reflection Data Interpretation

MCS profiles crossing the BGA show a buried asymmetric basement trough, formed where Cretaceous oceanic crust to the west dips beneath more elevated crust to the east (Gohl *et al.*, 1997). Convergent deformation within the trough has resulted in the development of a wedge of deformed sediment more than 5 km thick coincident with the eastern flank of the BGA low. Continental rise sediments on the trough flanks provide an acoustic-stratigraphic record of vertical motion. Even the deepest sediment reflections imaged within the trough are sub-horizontal and onlap onto the eastward-dipping oceanic basement on its west flank, indicating that the basement already dipped eastward at the time they were deposited. A major unconformity with clear angular discordance between sediments above and below it occurs within the sediments overlying the oceanic crust to the east of the trough. The unconformity and reflections beneath it dip eastward, but reflections from younger sediments are sub-horizontal and onlap onto the unconformity. This indicates that the ocean floor east of the basement trough was tilted eastward after deposition of the sequence beneath the unconformity.

To the southwest, MCS profile BAS923-25 (Fig. 4) shows evidence of intense deformation beneath the continental slope, close to where the BGA extends onto the continental margin off Thurston Island. The oceanic basement beneath the continental rise on this line dips toward the margin. The overlying sediments consist of three main sequences which provide evidence of the history of vertical motion of the basement. Reflections in the deepest sequence, W3,

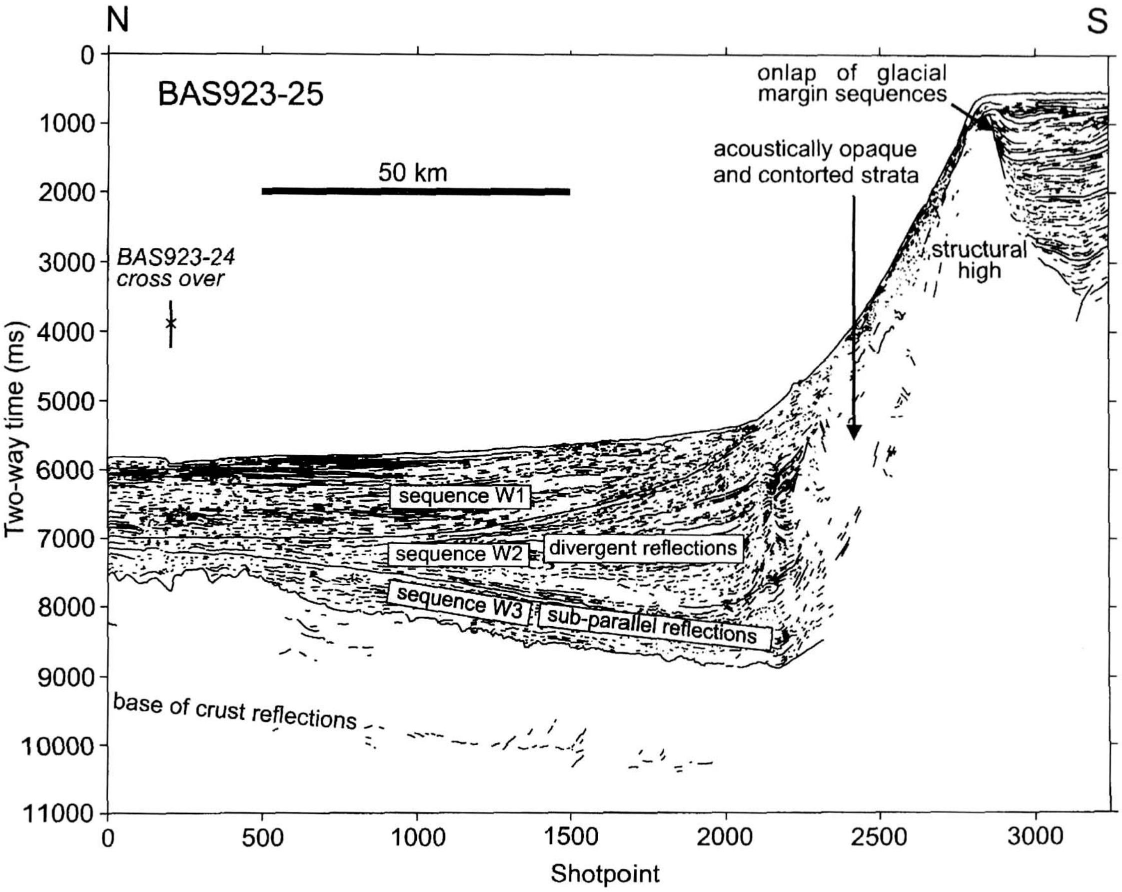

Fig. 4. Interpreted line drawing of multichannel seismic profile BAS923-25, which crosses the continental margin to the west of the Bellingshausen Gravity Anomaly (see Fig. 2 for location). Vertical exaggeration c. 15:1 in water.

are sub-parallel to and onlap onto the basement. Sequence W3 has an overall dip similar to that of the top of the basement. This contrasts with intersecting east-west profiles which cross the BGA, where reflections within W3 appear sub-horizontal and onlap onto the eastward dipping basement. Within sequence W2, which overlies W3, there is extreme divergence of reflections toward the margin, to the extent that the thickness of the sequence increases by a factor of >13 between the northern end of the line and the margin. This indicates that the oceanic basement and sequence W3 were tilted progressively down to the south during the deposition of W2. Reflections in the shallowest sequence W1 are mainly sub-parallel, although the sequence as a whole thins rapidly toward the margin. The contact zone between W2 and W1, where reflections in W1 are eliminated as it thins toward the margin, is not well imaged, but the overall geometry of the sequence suggests to us that the thinning occurs mainly by onlap of W1 sediments.

MCS profiles crossing the margin farther east, near 87°30′W, reveal an extensive, acoustically opaque high beneath the prograded continental slope (Fig. 5). Gravity data show that this area coincides with a belt of negative free-air anomalies which border the West Antarctic margin south of Peter I Island (Fig. 2), and we suspect that the high forms part of a buried accretionary prism. In contrast, MCS profiles crossing the Antarctic Peninsula margin, east of 80°W, show a steeper prograded continental slope and no evidence of an extensive, buried accretionary prism.

Multichannel seismic (MCS) profiles across the DGGA reveal that the central free-air gravity high coincides with a narrow (< 10 km wide) ridge of oceanic basement. Flanking this ridge are basement troughs filled with flat-lying, undeformed sediments which locally exceed 2 km in thickness. MCS profile BAS923-30, which crosses the DGGA at

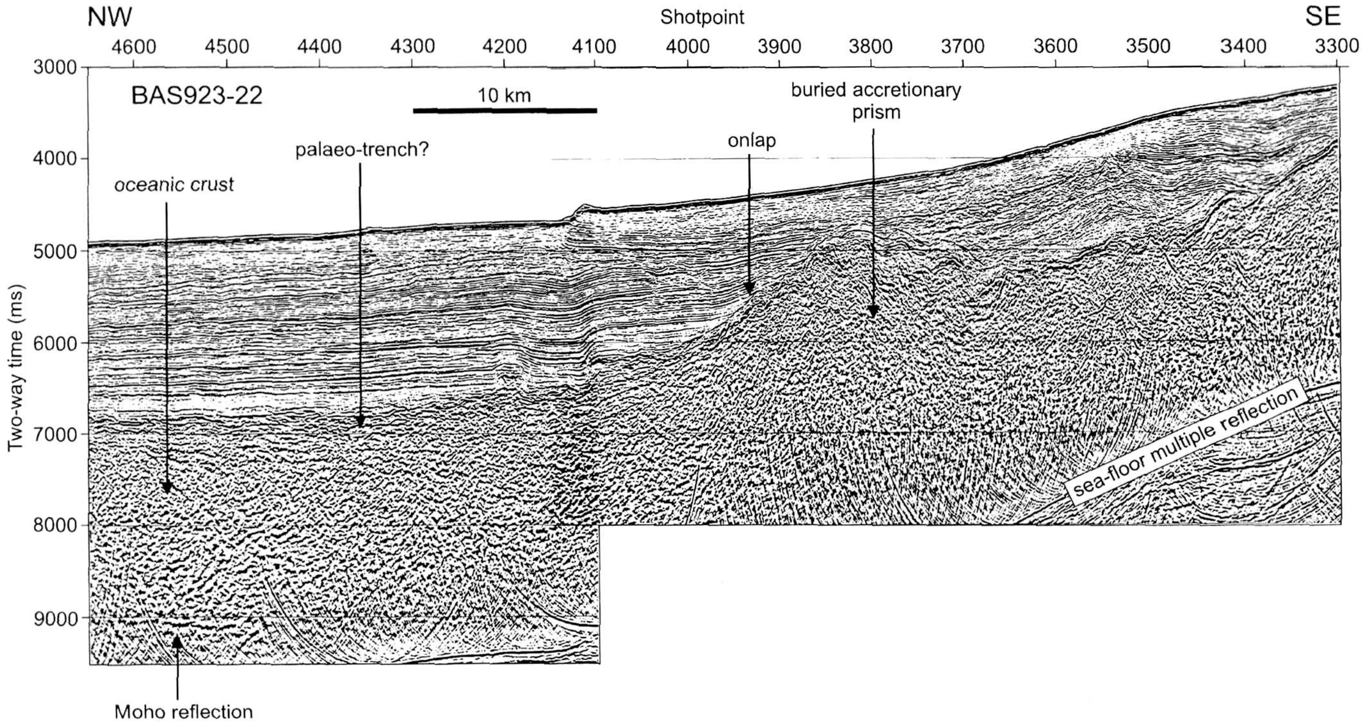

Fig. 5. The part of multichannel seismic profile BAS923-22 crossing the lower continental slope, showing an acoustic basement high interpreted as a buried accretionary prism (see Fig. 2 for location). The seismic data shown are a 24-fold common-midpoint stack which has been time-migrated using a Stolt F-K algorithm. Vertical exaggeration *c.* 7:1 in water.

about 67°S reveals a faulted boundary to the western edge of the western trough, at which the top of basement is displaced by more than 2 km. The Cretaceous oceanic crust to the west of this boundary fault exhibits flexural footwall uplift. Even the oldest sediments filling the trough onlap onto its flanks, indicating that the formation of the structure pre-dates their deposition.

Discussion

A compilation of new and previously-collected marine magnetic data reveals that all oceanic crust in the Bellingshausen Sea west of the BGA and DGGA was formed by Late Cretaceous spreading at the Pacific-Bellingshausen ridge. This implies that the part of the continental margin where subduction of the Phoenix plate continued after separation of New Zealand from West Antarctica extended no farther west than 94°W. The age and origin of oceanic crust adjacent to the margin between the BGA and about 83°W remains uncertain. However, MCS profiles crossing the margin at about 87°30′W show an acoustic basement high which we interpret as a buried accretionary prism beneath the lower continental slope. This interpretation implies that subduction has taken place along this part of the margin, although whether it stopped before or after New Zealand separated from the part of the margin farther west remains an unresolved question. Marine magnetic data show that the oceanic crust east of the northern DGGA, and east of about 83° W adjacent to the margin, was formed by early Tertiary spreading at the Antarctic-Phoenix ridge.

MCS profiles provide a relative chronology of deformation events in the vicinity of the BGA. The deepest reflections from sediments in the basement trough observed on east-west profiles across the BGA are sub-horizontal and onlap onto the eastward dipping oceanic basement, suggesting that the basement was tilted eastward soon after its formation in the Late Cretaceous. Thus it seems likely that deformation in the vicinity of the BGA may have started in the Late Cretaceous. Sub-horizontal reflections in the deep part of the trough continue into increasingly deformed reflections as they are followed eastward, indicating that convergent deformation continued during their deposition. In contrast to their sub-horizontal appearance on east-west profiles across the BGA, the correlative deep sediment reflectors (sequence W3) on the north-south profile BAS923-25 appear sub-parallel to the southward dipping basement (Fig. 4). Extreme divergence of reflections toward the margin in the overlying sequence, W2, records the southward tilting of the oceanic basement west of the BGA and sequence W3. These stratigraphic relationships clearly show that the ocean floor west of the BGA was first tilted eastward, and then later tilted southward. Thus it appears that tectonism which was initiated in the vicinity of the BGA subsequently also affected this part of the continental margin. We infer that the zone of intense deformation observed beneath the continental slope on line BAS923-25 developed at the same time as the oceanic basement was tilted southward.

Unfortunately the available MCS data do not enable reliable correlation of the sediments east and west of the BGA. Therefore the time of formation of the major unconformity within the sedimentary succession east of the BGA in relation to the tectonic events which occurred to the west remains uncertain. If the oceanic crust east of the BGA is older than that to the west, then the unconformity could have formed as a result of the initial phase of deformation which involved eastward tilting of the oceanic basement to the west. However, if the oceanic crust east of the BGA is younger than that to the west, then formation of the unconformity probably resulted from uplift associated with the later southward tilting of the oceanic basement to the west.

As we infer that deformation in the vicinity of the BGA started in the Late Cretaceous, it seems probable that it was related to plate interactions near the eastern boundary of the Bellingshausen plate. Cande *et al.* (1995) concluded that independent motion of the Bellingshausen plate stopped at about chron C27n (61 Ma), at which time it was incorporated into the Antarctic plate. Thus, if deformation in the vicinity of the BGA was related to independent motion of the Bellingshausen plate, we would expect it to have ceased at about this time.

The abrupt contrast in the age of oceanic crust across the northern part of the DGGA, interpreted from marine magnetic data, implies that the Antarctic-Phoenix ridge jumped to this position at about chron C27n (61 Ma). The time of this ridge jump coincides with the time at which Cande *et al.* (1995) estimate that independent motion of the Bellingshausen plate stopped, so if a ridge existed in this general area before 61 Ma it would have been a Bellingshausen-Phoenix ridge and must have been located farther east (Fig. 6). Therefore this event also seems to be associated with the inception of Antarctic-Phoenix spreading. However, the age and origin of the ocean floor which existed east of the DGGA prior to 61 Ma is unknown, as this ocean floor has all now been subducted beneath the Antarctic Peninsula. As the time of this ridge jump coincides with the time that the Bellingshausen plate was incorporated into the Antarctic plate, and with a wider plate reorganisation in the South Pacific (Cande *et al.*, 1995), it probably occurred as a response to a change in relative motion between the Phoenix plate and the former Bellingshausen plate.

Conclusions

1. Oceanic crust west of the BGA and DGGA was formed by Late Cretaceous spreading at the Pacific-Bellingshausen ridge, and therefore the part of the continental margin where subduction of the Phoenix plate continued after separation of New Zealand from West Antarctica extended no farther west than 94°W.

2. The age and origin of the oceanic crust adjacent to the margin between the BGA and about 83° W remains uncertain, but MCS profiles across this part of the margin show an acoustic basement high interpreted as a buried accretionary prism beneath the lower continental slope.

3. The BGA is associated with an asymmetric buried basement trough. The trough formed before

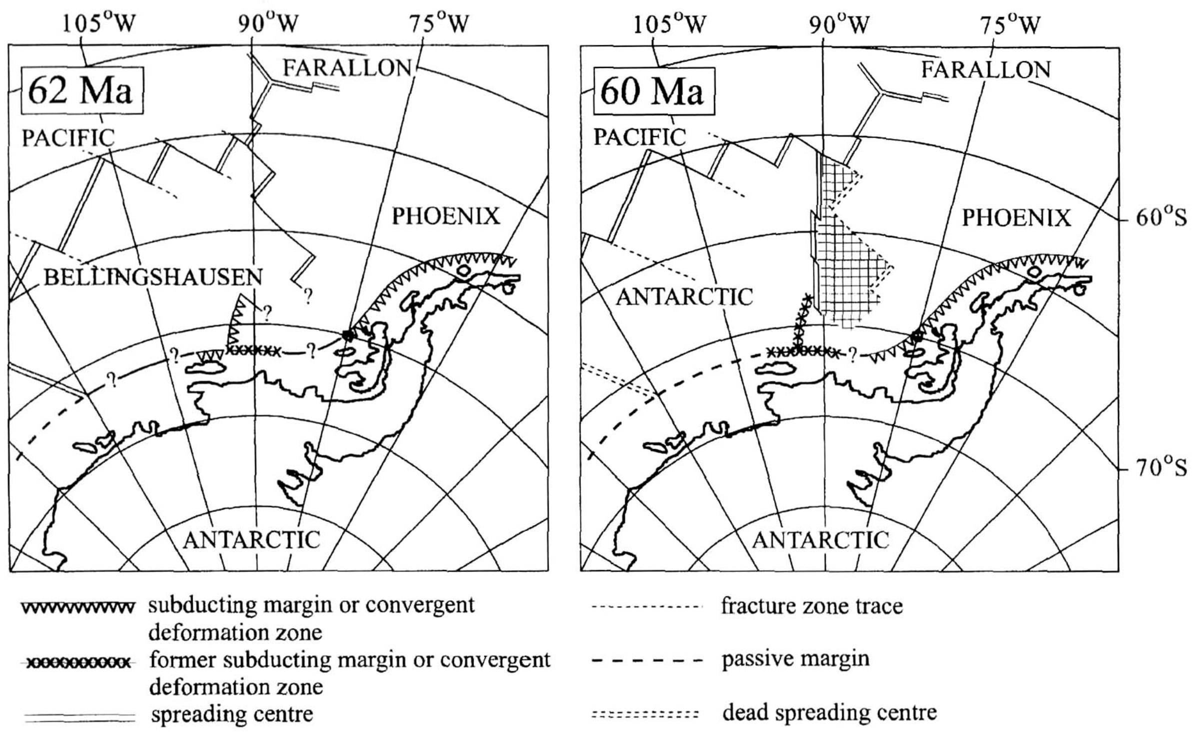

Fig. 6. Revised reconstruction for 62 Ma and new reconstruction for 60 Ma, in the Antarctic reference frame, illustrating interpretations presented in this paper. The 62 Ma reconstruction shows the important tectonic features we interpret as having been active shortly before the Bellingshausen plate was incorporated into the Antarctic plate. These include convergent deformation zones in the vicinity of the Bellingshausen Gravity Anomaly and along the part of the continental margin directly to its west, and a postulated Bellingshausen-Phoenix ridge to the northeast of the Bellingshausen Gravity Anomaly. The 60 Ma reconstruction shows the new Antarctic-Phoenix ridge, interpreted as having been produced by a ridge jump to the vicinity of the De Gerlache Gravity Anomaly about 61 Ma ago, at the same time as independent Bellingshausen plate motion ceased. The cross-hatched area of ocean floor represents part of the former Bellingshausen plate interpreted as having been captured by the Phoenix plate as a result of the ridge jump. All of the ocean floor east of the Antarctic-Phoenix ridge on this reconstruction has subsequently been subducted beneath the Antarctic Peninsula.

the oldest ocean floor sediments in the region, probably in the Late Cretaceous, but was also the locus of later convergent or transpressional deformation.

4. Later deformation also affected the continental margin directly west of the BGA, and was accompanied by southward tilting of the oceanic basement near the margin.

5. Deformation in the vicinity of the BGA and along the adjacent part of the continental margin probably resulted from Late Cretaceous to early Tertiary plate interactions near the eastern boundary of the Bellingshausen plate.

6. The Antarctic-Phoenix ridge jumped to the position of the DGGA at about chron C27n (61 Ma). This event seems to be associated with the inception of the Antarctic-Phoenix spreading, as its timing coincides with incorporation of the Bellingshausen plate into the Antarctic plate. This was also the time of a general plate reorganisation in the South Pacific and the ridge jump probably occurred in response to a change in relative motion between the Phoenix plate and the former Bellingshausen plate.

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References

Cande S.C. and Kent D.V. 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research* **100:** 6093-

6095.

Cande S.C., Herron E.M., and Hall B.R. 1982. The early Cenozoic tectonic history of the southeast Pacific. *Earth and Planetary Science Letters* **57:** 63-74.

Cande S.C., Raymond C.A., Stock J., and Haxby W.F. 1995. Geophysics of the Pitman Fracture Zone and Pacific-Antarctic plate motions during the Cenozoic. *Science* **270:** 947-953.

Cunningham A.P., Larter R.D., and Barker P.F. 1994. Glacially prograded sequences on the Bellingshausen Sea continental margin near 90°W. *Terra Antartica* **1:** 269-270.

Gohl K., Nitsche F.O., and Miller H. 1997. Seismic and gravity data reveal Tertiary interplate subduction in the Bellingshausen Sea, southeast Pacific. *Geology* **25:** 371-374.

Laxon S. and McAdoo D.C. 1998. Satellites provide new insights into polar geophysics. *Eos, Transactions, American Geophysical Union* **79:** 69 & 72-73.

Mayes C.L., Lawver L.A., and Sandwell D.T. 1990. Tectonic history and new isochron chart of the South Pacific. *Journal of Geophysical Research* **95:** 8543-8567.

McAdoo D.C. and Laxon S. 1997. Antarctic tectonics: constraints from an ERS-1 satellite marine gravity field. *Science* **276:** 556-560.

McCarron J.J. and Larter R.D. 1998. Late Cretaceous to early Tertiary subduction history of the Antarctic Peninsula. *Journal of the Geological Society, London* **155:** 255-268.

Miller H. and Grobe H. 1996. The expedition ANTARKTIS-XI/3 of RV "Polarstern" 1994. *Berichte zur Polarforschung* **188:** 115 pp.

Molnar P., Atwater T., Mammerickx J., and Smith S.M. 1975. Magnetic anomalies, bathymetry, and tectonic evolution of the South Pacific since the Late Cretaceous. *Geophysical Journal of the Royal Astronomical Society* **49:** 383-420.

Sandwell D.T. and Smith W.H.F. 1997. Marine gravity anomaly from Geosat and ERS 1 satellite altimetry. *Journal of Geophysical Research* **102:** 10039-10054.

Stock J. and Molnar P. 1987. Revised history of early Tertiary plate motion in the south-west Pacific. *Nature* **325:** 495-499.

Weissel J.K., Hayes D.E., and Herron E.M. 1977. Plate tectonic synthesis: the displacements between Australia, New Zealand and Antarctica since the Late Cretaceous. *Marine Geology* **25:** 231-277.

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