Vol. 3, No. 5 May 1993

GSA TODAY

A Publication of the Geological Society of America

INSIDE

Antarctic Plate: Tectonics from a Gravity Anomaly and Infrared Satellite Image

Lawrence A. Lawver, Ian W. D. Dalziel
University of Texas, Institute for Geophysics,
8701 Mopac Boulevard, Austin, Texas
78759-8397

David T. Sandwell
Scripps Institution of Oceanography, La Jolla,
California 92093-0208

ABSTRACT

Two separate sets of satellite geophysical data pertaining to the structure and development of the Antarctic plate have recently become available. Altimeter profiles of sea-surface topography yield gravity anomalies over the entire Southern Ocean, and the major features of the sub-ice structure of the continent can be discerned in radiometer images. Digital combination of the two data sets has generated a composite gravity anomaly–infrared satellite image of the Earth south of 60°S as viewed from above the pole. The combined image is particularly valuable for study of the relation between the tectonic development of the continental and oceanic lithosphere.

INTRODUCTION

We have developed a composite satellite image of the Antarctic continent and surrounding ocean basins (Fig. 1). The image combines recently declassified Geosat altimeter profiles of sea-surface topography in the Southern Ocean (south of 60°S) with Advanced Very High Resolution Radiometer (AVHRR) data from Antarctica. The Geosat satellite was launched by the U.S. Navy in 1985, and the altimeter profiles were prepared and distributed by the National Geodetic Survey (Cheney et al., 1991). The gravity anomalies shown were generated from high-density (~3 km or less track spacings) altimeter profiles collected between 1985 and 1988 (Fig. 2). The AVHRR data were acquired by four NOAA satellites during the period 1980 to 1987. The digital image mosaic of the AVHRR data (Fig. 2) was assembled by the National Remote Sensing Center (NRSC) in Britain, then rectified, and finally modified to remove seasonal ice. It has been published by the U.S. Geological Survey (USGS; Miscellaneous Investigations Series Map I-2284, 1:5 000 000, 1991).

GEOSAT ALTIMETRY

The Geosat altimeter uses a pulse-limited radar along a very accurate orbit to measure the topography of the ocean surface. Because the ocean surface is nearly an equipotential surface of Earth's gravity field, repeatable variations in sea-surface topography are assumed to be caused by actual variations in marine gravity. A new method was developed (Sandwell, 1992) to combine the six million Geosat observations into a grid of gravity anomalies. To suppress the long-wavelength radial orbit error, each profile was differentiated along-track to form a sea-surface slope profile. The ascending (southeast to northwest) and descending (northeast to southwest) slope profiles (Fig. 2) were then rotated and scaled to produce grids of north and east sea-surface slope. Finally, these grids were combined to produce gravity anomalies (Haxby et al., 1983). Long-wavelength anomalies (>1000 km) were constrained by a spherical harmonic gravity model complete to degree and order 40 (Marsh et al., 1990). Variations in gravity anomaly are displayed in the image (Fig. 1) as variations in hue ranging from violet (<–35 mgal) to orange (>35 mgal). In addition, false illumination from the right side of the image was used to highlight the short-wavelength anomalies. Between 60° and 72°S, the gridded gravity anomalies have accuracies of 1 to 5 mgal, so that features as small as 10 km can be resolved. Because the Southern Ocean is sparsely surveyed by ships, these gravity anomalies reveal many previously uncharted features, particularly seamounts and fracture zones (McAdoo and Marks, 1992).

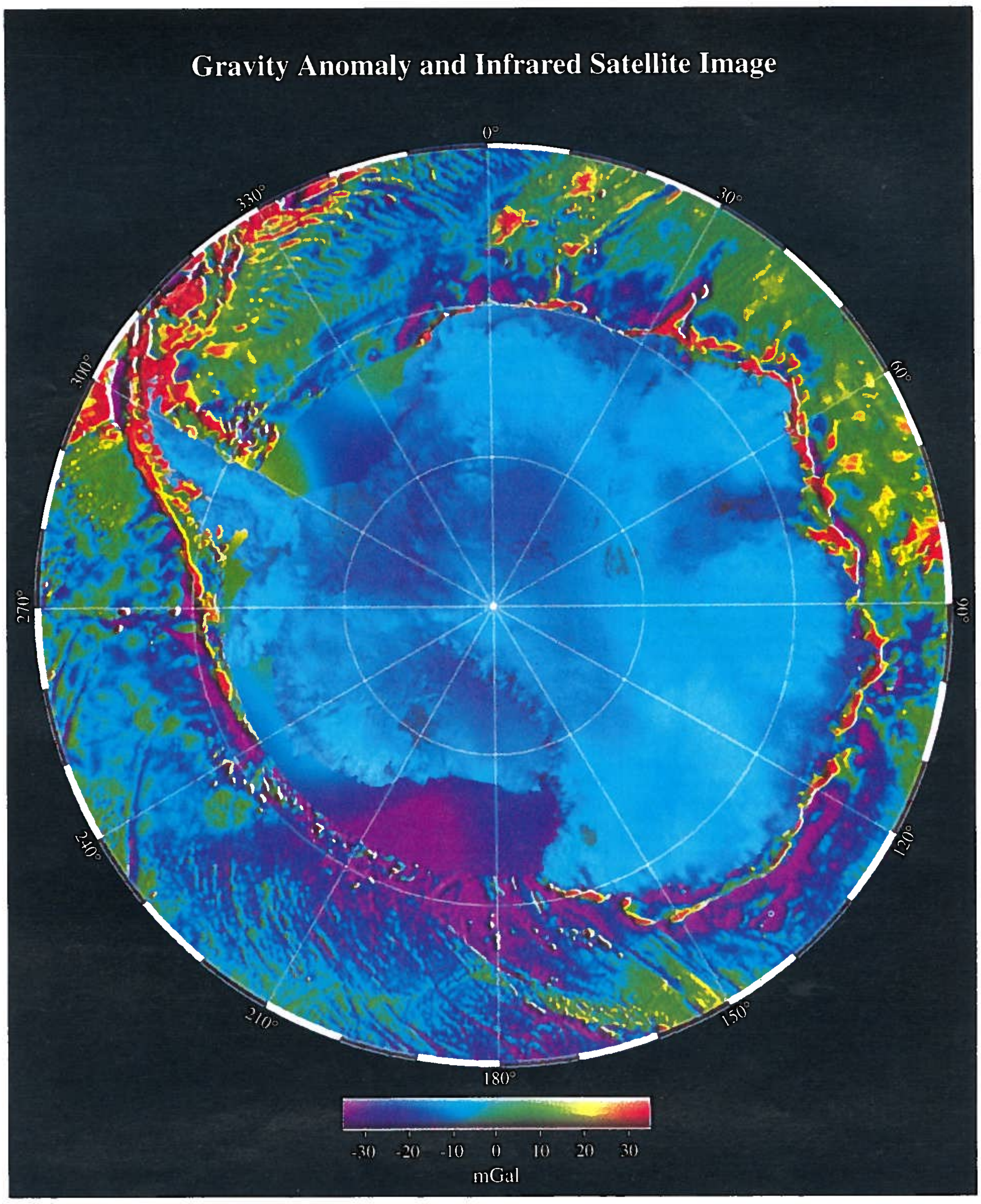


Figure 1. Composite gravity anomaly and infrared satellite image of the Antarctic continent and surrounding ocean basins south of 60°S (polar stereographic projection). Copyright 1992 by Scripps Institution of Oceanography and the Institute for Geophysics, University of Texas, Austin. To obtain a copy at a scale of 1:17 000 000, write to: Antarctic Image, Institute for Geophysics, University of Texas, 8701 Mopac Boulevard, Austin, TX 78759-8397.

RADIOMETRY

The AVHRR satellites collected images along 2400-km-wide swaths in five separate spectral bands ranging from the visible red to the far infrared. Because many of the image pixels were obscured by cloud cover, 34 sections from 25 separate image swaths were used by NOAA and NRSC to assemble the mosaic (Fig. 2). Cloud type, altitude, and position relative to the sun affect the different shapes and colors produced by the clouds and their shadows that partially obscure the ground below (Fig. 3). NRSC corrected missing or distorted lines in the AVHRR data and also corrected bands 1 and 2 for varying sun-illumination angle. The resolution of the original AVHRR data varies from 1.1 km directly under the satellite to as large as 2.4 by 6.9 km at the edge of a 2400-km-wide swath. NRSC resampled the image into a polar stereographic projection by means of ground control points, defined the edges of the mosaic sections, and then combined the sections into a consistent tone-matched image of the continent. They mapped the AVHRR mosaic to a polar stereographic graticule at 1:5 000 000 scale with a standard parallel of 71°S. The root-mean-square error in pixel location is estimated to be 2.5 km after the digital data were edited, rescaled, and processed by the USGS. Further information concerning the AVHRR image is provided on the Satellite Image Map of Antarctica (USGS Miscellaneous Investigations Series Map I-2284, 1991) and in Merson (1989). Bands 1

Antarctic Plate *continued on p. 118*

IN THIS ISSUE

GSA TODAY *May 1993*
Vol. 3, No. 5

GSA TODAY (ISSN 1052-5173) is published monthly by The Geological Society of America, Inc., with offices at 3300 Penrose Place, Boulder, Colorado. Mailing address: P.O. Box 9140, Boulder, CO 80301-9140, U.S.A. Second-class postage paid at Boulder, Colorado, and at additional mailing offices. **Postmaster:** Send address changes to *GSA Today*, Membership Services, P.O. Box 9140, Boulder, CO 80301-9140.

SUBSCRIPTIONS for 1993 calendar year: **Society Members:** *GSA Today* is provided as part of membership dues. Contact Membership Services at (800) 472-1988 or (303) 447-2020 for membership information. **Nonmembers & Institutions:** $40 for U.S., Canada, and Mexico; $50 elsewhere. Contact Subscription Services (same phones). **Single copies** may be requested from Publication Sales. Also available on an annual CD-ROM, and in an annual, hardbound, library edition; for prices and details contact Subscription Services or Membership Services. **Claims:** For nonreceipt or for damaged copies, members contact Membership Services; all others contact Subscription Services. Claims are honored for one year; please allow sufficient delivery time for overseas copies.

STAFF
Prepared from contributions from the GSA staff and membership.
Executive Director: F. Michael Wahl, Ph.D.
Science Editor: Eldridge M. Moores
Department of Geology, University of California, Davis, CA 95616
Forum Editor: Bruce F. Molnia
U.S. Geological Survey, MS 917, National Center, Reston, VA 22092
Managing Editor: Faith Rogers
Production & Marketing Manager: James R. Clark
Production Editor and Coordinator: Joan E. Manly
Graphics Production: Rochelle R. Blumenstein

ADVERTISING
Classifieds and display: contact Ann Crawford
(303) 447-2020; fax 303-447-1133

Printed with pure soy inks in the U.S.A.

Antarctic Plate *continued from p. 117*

(visible), 2 (near infrared), and 4 (far infrared) of the USGS digital AVHRR image are shown in Figure 1. The original image was filtered and resampled from a 1 km to a 2 km grid (i.e., 2.066 km pixel dimension at 90°S) prior to merging with the gravity anomaly image. The gray level of the AVHRR image was modulated by the average of bands 1 and 2, and band 4 was used to modulate the hue.

TECTONICS

Our combination of the gravity and AVHRR data allows direct examination of the relation of features in the oceanic lithosphere, the continental shelf, and the ice-covered continent (see Fig. 3 for significant features). Although not all are visible in the small-scale version of the composite image that is shown in Figure 1, those discussed in the text can be distinguished in the 1:17 000 000 version (nominal scale), which can be obtained from us (see Fig. 1 caption). This scale was chosen because it corresponds to that of the recently published marine geological and geophysical atlas of the circum-Antarctic (Hayes, 1991). The lineaments on the ocean floor represent the structural fabric of the Southern Ocean as interpreted from the Geosat deflection of the vertical data (from Royer et al., 1990). They correspond to features such as fracture zones and spreading ridges. Although 98%–99% of the Antarctic continent is covered by ice, the ice surface imaged by the AVHRR data closely reflects the sub-ice structure (Drewry, 1983; Dalziel, 1992a).

Sea Floor

Prominent sea-floor features fall into four categories; fracture zones, spreading ridges, seamounts and plateaus, and continental margins. Perhaps the most striking sea-floor features in the deep ocean are the fracture-zone lineaments in the Weddell Sea region from 310°E to 005°E (longitudes are given as degrees east from 000°, the Greenwich meridian), across the Pacific-Antarctic Ridge (210°E to 160°E), and the Tasman (150°E) and Balleny (155°E) fracture zones at the bottom of the image. The major-offset fracture zones of the South Pacific, the Heezen (260°E) and Tharp (255°E) fracture zone systems, and the Udintsev Fracture Zone at 240°E are also quite prominent. There is some hint that the Udintsev Fracture Zone may trend into the eastern coast of the Amundsen Sea at Pine Island Bay, representing a major structural boundary in West Antarctica (Dalziel and Elliot, 1982; Dalziel, 1992a).

The only active spreading center within the map area appears as a series of orthogonal ridges and transform faults along the Pacific-Antarctica plate boundary between 208° and 160°E and a few sections of the Australia-Antarctica plate boundary between 160° and 150°E. Between 208° and 200°E, the spreading center appears as a single gravity ridge superimposed on a broad gravity rise. The wake of a triangular-shaped propagating rift appears at 63°S between 193° and 196°E (see Fig. 3). Farther to the south, the spreading center appears as a gravity trough superimposed on a broad gravity rise. The change from gravity ridge to gravity trough at the spreading center may be related to the decrease in spreading rate toward the southwest (Small and Sandwell, 1992). Away from the spreading center, the conjugate bends in the fracture zones (i.e., gravity troughs) reflect changes in sea-floor-spreading direction in accordance with synthetic flowlines generated from the plate-motion models (Mayes et al., 1990). This recent change in spreading direction has resulted in extension along a major-offset transform fault (between 160° and 180°E), causing the ridge to splinter into numerous short spreading centers offset by transform faults.

Other prominent sea-floor features are submarine plateaus and numerous seamounts. Maud Rise appears as a prominent gravity high at 005°. Only a small part of the the Kerguelen Plateau extends south of 60°S at 085°E, and there is a clear gravity low (i.e., deep water) between the Kerguelen Plateau and the Antarctic margin, indicating that Kerguelen was formed after India rifted from Antarctica. However, the presence of a small alkaline volcano, Gaussberg, on the margin of the Antarctic continent (089°E, Fig. 3) indicates some structural connection between the Kerguelen Plateau and the continent. The Balleny Islands at 67°S and 165°E, Scott Island at 68°S and 180°E, and Peter I Island at 69°S and 270°E are all quite prominent features. The gravity signatures of other seamounts throughout the deep ocean areas are apparent.

Perhaps the most obvious gravity feature is the prominent high that marks the edge of the continental margin. With the exception of the Gunnerus Ridge at 032°E, there are very few anomalous seafloor features contiguous to the continental margin. The Gunnerus Ridge marks the boundary between where Africa rifted from Antarctica to the west and Sri Lanka and India rifted off to the east (Lawver et al., 1992). At two places where major ice streams drain large parts of the East Antarctic Ice Sheet, 070° to 075°E off the Amery Ice Shelf, and 115°E along the East Antarctic continental margin, major postbreakup sedimentation appears to have occurred on the continental slope, obscuring the gravity signature of the basement rocks (wide orange anomaly). There appears to be a gross 120°-angle "scallop" to the edge of the East Antarctic continent, with promontories at 000°, 055°, 080°, 100°, and 135° (see below).

Terrestrial

Significant structural features on the AVHRR image of Antarctica fall into two groups: (1) mountain ranges or escarpments and (2) ice-filled rift basins. The most prominent mountain range is the Transantarctic Mountains, which extend from North Victoria Land at 72°S and 165°E near the bottom of the image of Antarctica to near the South Pole in the center. The Transantarctic Mountains define the lower left side of the roughly kidney-shaped East Antarctic Precambrian shield, which is penetrated by the

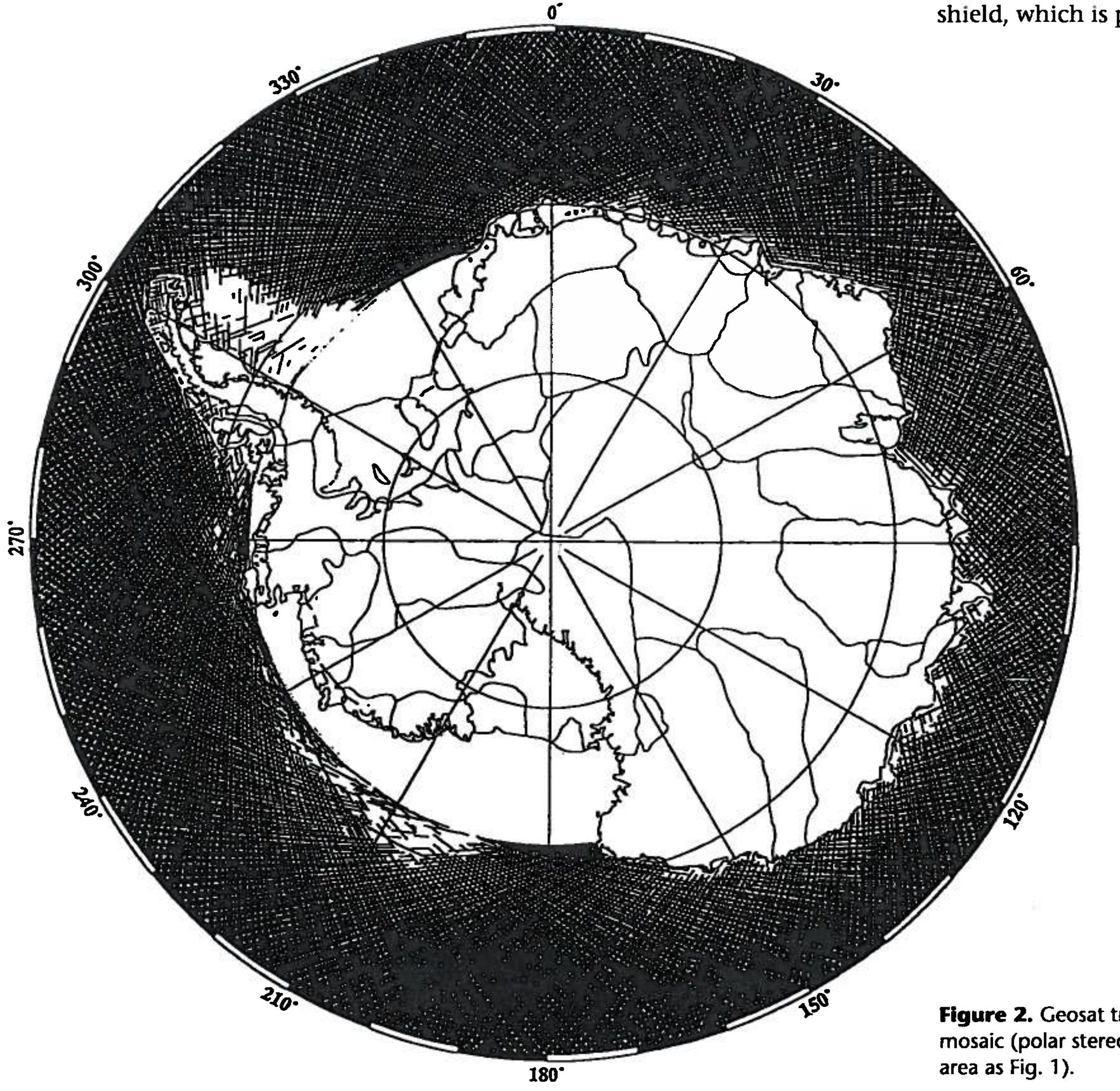
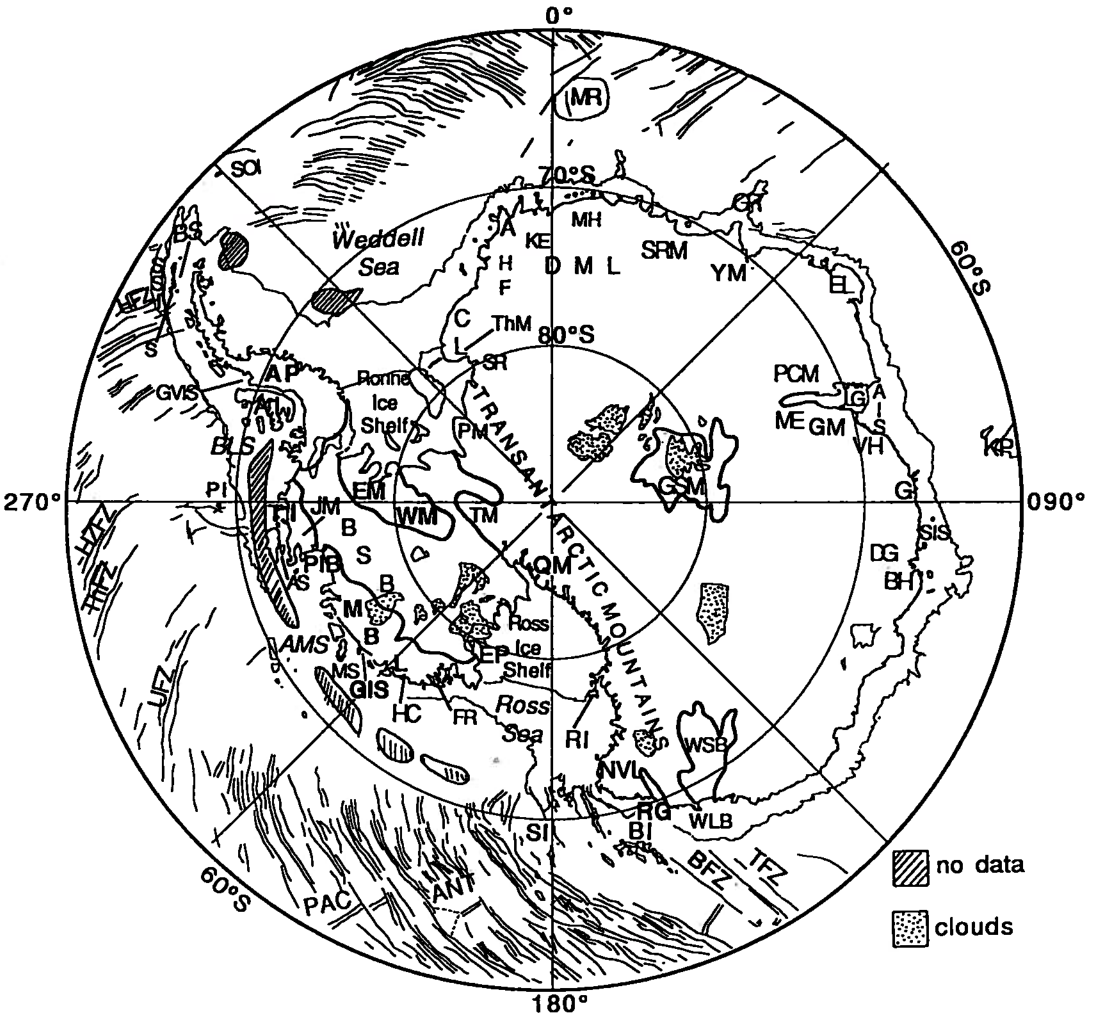


Figure 2. Geosat tracks and radiometer mosaic (polar stereographic projection, same area as Fig. 1).



A—Annandagstoppane
AI—Alexander Island
AIS—Amery Ice Shelf
AMS—Amundsen Sea
AP—Antarctic Peninsula
AS—Abbott Ice Shelf
BFZ—Balleny Fracture Zone
BH—Bunger Hills
BI—Balleny Islands
BLS—Bellingshousen Sea
BS—Bransfield Strait
BSB—Byrd Subglacial Basin
CL—Coats Land
DG—Denman Glacier
DML—Dronning Maud Land
EL—Enderby Land
EM—Ellsworth Mountains
EP—Edward VII Peninsula
FR—Ford Ranges
G—Gaussberg
GIS—Getz Ice Shelf
GM—Grove Mountains
GR—Gunnerus Ridge
GSM—Gamburtzev Subglacial Mountains
GVIS—George VI Sound
HC—Hobbs Coast
HF—Heimefrontfjella
HFZ—Hero Fracture Zone
HZFZ—Heezen Fracture Zone
JM—Jones Mountains
KE—Kirwan Escarpment
KP—Kerguelen Plateau
LG—Lambert Glacier
MBL—Marie Byrd Land
ME—Mawson Escarpment
MH—Mühlig-Hofmannfjella
MR—Maud Rise
MS—Mount Siple
NVL—North Victoria Land
PAC-ANT—Pacific-Antarctic Ridge
PCM—Prince Charles Mountains
PI—Peter I Island
PIB—Pine Island Bay
PM—Pensacola Mountains
QM—Queen Maud Range
RG—Rennick Glacier
RI—Ross Island
S—Smith Island
SI—Scott Island
SIS—Shackleton Ice Shelf
SOI—South Orkney Islands
SR—Shackleton Range
SRM—Sør Rondane Mountains
SSI—South Shetland Islands
TFZ—Tasman Fracture Zone
ThFZ—Tharp Fracture Zone
ThM—Theron Mountains
TI—Thurston Island
TM—Thiel Mountains
UFZ—Udintzev Fracture Zone
VH—Vestfold Hills
WLB—Wilkes Land Basin
WM—Whitmore Mountains
WSB—Wilkes Subglacial Basin
YM—Yamato Mountains

Figure 3. Location of features mentioned in the text (polar stereographic projection, same area as Fig. 1). The continental margin is the 2000 m bathymetric contour. Sub-ice features are delineated by the grounding line (Ross and Weddell embayments), the −500 m contour (Transantarctic Mountains front and crustal blocks of West Antarctica), the −1000 m contour (basins of East Antarctica), and the +2000 m contour (Gamburtzev Subglacial Mountains). Stippled areas are major cloud groups.

Lambert Glacier–Amery Ice Shelf rift at 070° to 075°E. The Transantarctic margin of the East Antarctic shield continues toward the top of the image and includes the Thiel and Pensacola mountains and the Theron Mountains at 79°S and 335°E. This is the margin recently suggested as having been conjugate to the late Precambrian–early Paleozoic rifted margin of western North America (Moores, 1991; Dalziel, 1991). The anomalous structural trend of the Shackleton Range at a high angle to the Transantarctic Mountains is apparent near the southeastern corner of the Weddell Sea. According to the new hypothesis suggesting that North America "broke out" from between East Antarctica–Australia and South America at the end of the Precambrian, this trend is a continuation of the Yavapai-Mazatzal and Taconic orogens of southern North America (Moores, 1991; Dalziel, 1991, 1992a, 1992b; Dalla Salda et al., 1992). The Grenville orogen would have continued into Coats Land and the Heimefrontfjella along the eastern margin of the Weddell Sea.

Northeast of the Theron Mountains, an escarpment made up of the Heimefrontfjella, Kirwan Escarpment, and Mühlig-Hofmannfjella extends around Dronning Maud Land to the Sør-Rondane Mountains at 030°E. In a reconstruction of the Gondwana supercontinent, this Antarctic escarpment mirrors the Lebombo monocline of southeast Africa and reflects the prebreakup fit of the continents (Lawver et al., 1991). The prominent north-trending Dronning Fabiolafjella (Yamato Mountains) can be seen at 72°S and 036°E. Enderby Land between 040° and 070°E can be reconstructed to India in a prebreakup fit and matches the east coast of India between 10° and 20°N. The protuberant margin of Enderby Land between 050° and 057°E comprises the Napier complex of Archean granitoid and granulite facies metamorphic rocks (Tingey, 1991). It is one of three promontories of the East Antarctic craton margin mentioned above that is underlain by a nucleus of Archean rock. The Napier complex, the ancient rocks of the Kaapval craton exposed at Annandagstoppane, and the Vestfold Hills complex appear to have controlled development of the continental margin during fragmentation of Gondwana (Dalziel, 1992a).

The Lambert-Amery graben is flanked by the Prince Charles Mountains to the west and the very prominent Mawson Escarpment to the east near the head of the graben. The Lambert Glacier, which feeds the Amery Ice Shelf, is the largest drainage system for the East Antarctic Ice Sheet (Drewry, 1983). To the south of the Lambert graben lie the Gamburtsev Subglacial Mountains (80°S, 076°E). A cloud obscures this location on the image. Air photographs indicate that these mountains, which have a sub-ice relief of over 3000 m, come close to the surface without actually being exposed (Swithinbank, 1988). The Grove Mountains appear as a dark spot at 73°S and 075°E and are one of the very few outcrops through the East Antarctic Ice Sheet.

The Shackleton Ice Shelf is the prominent feature at 097°E that extends in a hook shape from the coast. Offshore, there is a definite change in trend of the outer continental margin gravity high at 100°E. West of this point, India rifted from East Antarctica during the Neocomian Epoch of the Early Cretaceous (~135 Ma; Lawver et al., 1991); to the east, Australia rifted from East Antarctica during the Late Cretaceous (starting slowly at ca. 96 Ma; Veevers et al., 1991). The Bunger Hills, the dark area near the coast at 100°E, consist of Proterozoic and early Paleozoic age metamorphic and igneous rocks (Tingey, 1991). The Denman Glacier, which feeds the Shackleton Ice Shelf, is just west of the Bunger Hills. To the east, there are only scattered outcrops along the coast to 155°E.

Between 145° and 155°E, the Wilkes Land Basin is a major feature indicated offshore by the gravity low inboard of the continental-margin gravity high. The Wilkes Land Basin is the offshore extension of the much larger Wilkes Subglacial Basin, which lies parallel to the Transantaractic Mountains and appears to be part of a flexural downwarp extending inland beyond the South Pole (Stern and ten Brink, 1989). The Wilkes Subglacial Basin extends northward as a feature 500 m below sea level (mbsl) to 81°S and as a 1000 mbsl feature to 74°S. Its greatest depth is 1500 m. To the east, between 158°E and 160°E, the Wilson Hills on the coast and the Usarp Mountains inland form the western margin of the Rennick graben. The Rennick Glacier can be seen as far south as 73.5°S at 162°E. The Bowers Mountains form a linear eastern margin to the Rennick graben at 160°E. Tasmania rifted from the North Victoria Land margin of East Antarctica and marks the easternmost limit of the zone where Australia separated from Antarctica during Late Cretaceous time.

The western hemisphere side of the Transantarctic margin of East Antarctica is dominated by the Ross and Weddell sea embayments. The ice grounding line for the Ross Sea embayment runs roughly along 210°E from 80° to 86°S. The ice-grounding line for the Weddell Sea embayment runs from approximately 84°S and 300°E to 80°S and 285°E, and from there to 76°S and 290°E, where it connects to the base of the Antarctic Peninsula. The Ross and Weddell sea embayments are joined by a depression that lies between the Transantarctic Mountains and the Marie Byrd Land, Thurston Island, and Antarctic Peninsula crustal blocks of West Antarctica (Dalziel and Elliot, 1982). The depression includes the Byrd Subglacial Basin, which reaches oceanic depths beneath the West Antarctic Ice Sheet and appears to be part of a volcanically active rift system (Blankenship et al., 1993). The isolated Ellsworth Mountains show up prominently between 77° and 80.5°S along 275°E. They form a fourth structural unit of West Antarctica that extends beneath the ice to the Whitmore Mountains at 82°S and 255°E, separating the Weddell Sea embayment from the Ross Sea embayment. This crustal block appears to be a fragment of the Gondwana craton margin displaced from between the Transantarctic Mountains and southern Africa (Dalziel, 1992a).

Marie Byrd Land extends from 202° to 257°E and from the continental margin to 79°S. Mt. Siple is the prominent, inactive (SPRITE Group and Boyer, 1992), volcano along the continental edge at 73°S and 234°E. Between Mt. Siple and the coast of Marie Byrd Land is the Getz Ice Shelf. Inland is the Executive Committee Range parallel to the margin, and the Ford Ranges and Edward VII Peninsula forming the western end of Marie Byrd Land. Marie Byrd Land has some geologic affinities to North Victoria Land (Borg et al., 1990) and is assumed to have been closer to East Antarctica prior to Mesozoic and Cenozoic extension in the Ross Sea embayment. The Campbell Plateau and Chatham Rise, which are parts of the greater New Zealand microcontinent, rifted from Marie Byrd Land when the Pacific-Antarctic spreading center propagated between the two at around 85 Ma.

Pine Island Bay at 255°E marks the boundary between the Marie Byrd Land and Thurston Island blocks of West Antarctica. Thurston Island itself lies right along 72°S between 258° and 265°E, and is separated from the mainland by the Abbott Ice Shelf. The Jones Mountains lie to the southeast of Thurston island, and the Hudson Mountains lie due south along 76°S. Both are Tertiary volcanic centers. The Antarctic Peninsula is the prominent S-shaped peninsula that extends from 76° to 63°S between 285° and 300°E. The Thurston Island block may have originally been rotated with the Antarctic Peninsula such that they lay parallel to the Falkland Plateau prior to the breakup of Gondwana (Grunow et al., 1991). Alexander Island (69° to 72°S along 290°E) is separated from the peninsula by George VI Sound. The South Shetland Islands (63°S and 297°E to 62°S and 303°E) lie along the outer continental margin separated by the basins of Bransfield Strait. The South Shetland trench slowed or ceased subduction when spreading stopped along the remnant of the Antarctic-Aluk spreading center at 4 Ma. Volcanism and possibly active extension is occurring in Bransfield Strait.

Antarctic Plate *continued on p. 122*

Antarctic Plate *continued from p. 119*

Continental Margins

Unfortunately, Geosat data do not exist for the Ross Sea or the Weddell Sea region south of 72°S. The principal regions where there are clear-cut continuations of features across the continental margin are the major glacier-fed ice shelves and deep (>1000 m) continental shelf basins. The best example is the Lambert Glacier–Amery Ice Shelf–Prydz Bay region. Less spectacular on this image but possibly a larger feature is the Wilkes Land Basin offshore and the Wilkes Subglacial Basin onshore.

There is an obvious relation between the pattern of fracture zones that reflect the fragmentation of the Gondwana supercontinent and the internal structure of the Antarctic continent. The reason for this relation is not clear in most cases. We infer that in some way the continental structure has controlled the location of major fracture zones and/or that the onshore structures were formed at the same time and by the same mechanism as the fracture zones. The fracture zones in the eastern Weddell Sea that mark the track of Africa generally trend parallel to the Neoproterozoic orogen of Coats Land and western Dronning Maud Land (Dalziel, 1991, 1992b). Likewise, the South Tasman and Balleny fracture zones, which show the northward direction of motion of Australia, trend in to the Rennick graben, which parallels the Paleozoic tectonic fabric of North Victoria Land (Tingey, 1991). In Marie Byrd Land there seems to be a close geometric relation between the fracture zones that reflect the northwestward motion of New Zealand and the older continental basement unconformably overlain by Cenozoic volcanic rocks. A horst and graben–type topography predating the Cenozoic volcanic rocks has a west-northwest structural trend in the Ford Ranges–Fosdick Mountains area at 215°E, and a northward trend just 300 km to the east on the Hobbs Coast at 226°E. The difference reflects the change in the orientation of the fracture zones at the continental margin in the two closely spaced locations.

The Udintsev Fracture Zone, which trends toward the eastern extremity of the New Zealand microcontinent at the eastern end of the Chatham Rise, can be followed on the Geosat image nearly into the Antarctic margin in the vicinity of Pine Island Bay, as noted elsewhere (Sandwell and McAdoo, 1990). On the combined AVHRR-Geosat image, the Udintsev Fracture Zone appears to be constrained by the trends of adjacent fracture zones and to be directly aligned with the north-trending eastern margin of Pine Island Bay. However, the geologic boundary between the Marie Byrd Land and Thurston Island blocks appears to be represented by a deep trough eroded across the continental shelf by the Pine Island glacier slightly farther to the west (SPRITE Group and Boyer, 1992).

Finally, there are two striking margin-parallel features along the southern rim of the Pacific. One is the almost continuous grabenlike feature along the coast which includes the Getz Ice Shelf of Marie Byrd Land, the Abbott Ice Shelf of Thurston Island, and George VI Sound and Bransfield Strait of the Antarctic Peninsula. This may be related to the extent of Cenozoic alkaline basaltic volcanism along the margin (LeMasurier and Thomson, 1990) and to the sequential cessation of subduction along the margin during Late Cretaceous to Neogene time (Barker, 1982; Mayes et al., 1990). The second feature of note along this margin is the "mid-shelf" gravity high along the Antarctic Peninsula. This trends into Smith Island, southernmost of the South Shetland Islands, and into northern Alexander Island. These are underlain by uplifted subduction complexes that contain fossils as old as Jurassic and that were metamorphosed during Mesozoic and Cenozoic time (Barker et al., 1992; Grunow et al., 1992).

CONCLUSIONS

Combination of the radiometer and satellite gravity images of the Antarctic region reveals many interesting features of the large-scale tectonics of the region. Although the ice cover in Antarctica perhaps makes the AVHRR data more valuable there than elsewhere in the world, similar composite images, particularly from conjugate continental margins, may prove valuable in tectonic interpretation.

ACKNOWLEDGMENTS

Geosat data are from the National Geodetic Survey, National Oceanic and Atmospheric Administration. AVHRR data are from the National Oceanic and Atmospheric Administration, the National Remote Sensing Center (UK) and the U.S. Geological Survey. Funds used in preparation of the image and this article came from the National Aeronautics and Space Administration Solid Earth Sciences Program (NAG 5-1226), the National Science Foundation Division of Polar Programs (DPP 90-19247 and DPP 89-17127), Scripps Institution of Oceanography, and the Institute for Geophysics, University of Texas, Austin. Walter Smith, Mark Wiederspahn, and Lisa Gahagan gave technical assistance. Institute for Geophysics contribution 992.

REFERENCES CITED

Barker, P. F., 1982, The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: Ridge crest–trench interactions: Geological Society of London Journal, v. 139, p. 787–801.

Barker, P. F., Dalziel, I. W. D., and Storey, B. C., 1991, Tectonic development of the Scotia arc region, *in* Tingey, R. J., ed., Geology of Antarctica: Oxford, England, Oxford University Press, 680 p.

Blankenship, D. D., Bell, R. E., Hodges, S. M., Brozena, J. M., Behrendt, J. C., and Finn, C. A., 1993, Active volcanism beneath the West Antarctic ice sheet and implications for ice-sheet stability: Nature, v. 361, p. 526–529.

Borg, S. C., DePaolo, D. J., and Smith, B. M., 1990, Isotopic structure and tectonics of the central Transantarctic Mountains: Journal of Geophysical Research, v. 95, p. 6647–6667.

Cheney, R. E., Doyle, M. S., Douglas, B. C., Agreen, R. W., Miller, L., Timmerman, E. L., and McAdoo, D. C., 1991, The complete Geosat altimeter GDR handbook: Rockville, Maryland, NOAA Manual NOS NGS 7, NOAA/NOS.

Dalla Salda, L., Dalziel, I. W. D., Cingolani, C., and Varela, R., 1992, Did the Taconic Appalachians continue into southern South America?: Geology, v. 20, p. 1059–1062.

Dalziel, I. W. D., 1991, Pacific margins of Antarctica and East Antarctica–Australia as conjugate rift margins: Evidence and implications: Geology, v. 19, p. 598–601.

Dalziel, I. W. D., 1992a, Antarctica: A tale of two supercontinents?: Annual Review of Earth and Planetary Sciences, v. 20, p. 501–526.

Dalziel, I. W. D., 1992b, On the organization of American plates in the Neoproterozoic and the breakout of Laurentia: GSA Today, v. 2, p. 237–241.

Dalziel, I. W. D., and Elliot, D. H., 1982, West Antarctica: Problem child of Gondwanaland: Tectonics, v. 1, p. 3–19.

Drewry, D.,J., editor, 1983, Antarctica: Glaciological and geophysical folio: Cambridge, England, Scott Polar Research Institute.

Grunow, A. M., Kent, D. V., and Dalziel, I. W. D., 1991, New paleomagnetic data from Thurston Island: Implications for the tectonics of West Antarctica and Weddell Sea opening: Journal of Geophysical Research, v. 96, p. 17,935–17,954.

Grunow, A. M., Dalziel, I. W. D., Harrison, T. M., and Heizler, M. T., 1992, Structural geology and geochronology of subduction complexes along the margin of Gondwanaland: New data from the Antarctic Peninsula and southernmost Andes: Geological Society of America Bulletin, v. 104, p. 1497–1514.

Haxby, W. F., Karner, G. D., LaBrecque, J. L., and Weissel, J. K., 1983, Digital images of combined oceanic and continental data sets and their use in tectonic studies: Eos (Transactions, American Geophysical Union), v. 64, p. 995–1004.

Hayes, D. E., editor, 1991, Marine geological and geophysical atlas of the circum-Antarctic to 30°S: American Geophysical Union, Antarctic Research Series, v. 54.

Lawver, L. A., Sandwell, D. A., Royer, J.-Y., and Scotese, C. R., 1991, Evolution of the Antarctic continental margins, *in* Thomson, M. R. A., et al., eds., Antarctic earth science: Cambridge, England, Cambridge University Press, p. 533–539.

Lawver, L. A., Gahagan, L. M., and Coffin, M. F., 1992, The development of paleoseaways around Antarctica, *in* Kennett, J. P., and Warnke, D. A., eds., The Antarctic paleoenvironment: A perspective on global change: American Geophysical Union Antarctic Research Series, v. 56, p. 7–30.

LeMasurier, W. E., and Thomson, J. W., editors, 1990, Volcanoes of the Antarctic plate and Southern Ocean: American Geophysical Union Antarctic Research Series, v. 48.

Marsh, J. G., Koblinsky, C. J., Lerch, F., Klosko, S. M., Robbins, J. W., Williamson, R. G., and Patel, G. B., 1990, Dynamic sea surface topography, gravity and improved orbit accuracies from the direct evaluation of Seasat altimeter data: Journal of Geophysical Research, v. 95, p. 13,129–13,150.

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, v. 95, p. 8543–8567.

McAdoo, D. C. and Marks, K. M., 1992, Gravity fields of the Southern Ocean from Geosat data: Journal of Geophysical Research, v. 97, p. 3247–3260.

Merson, R. H., 1989, An AVHRR mosaic image of Antarctica, International Journal of Remote Sensing, v. 10, p. 669–674.

Moores, E. M., 1991, Southwest U.S.–East Antarctic (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425–428.

Royer, J.-Y., Gahagan, L. M., Lawver, L. A., Mayes, C. L., Nürnberg, D., Sandwell, D. T., and Scotese, C. R., 1990, A tectonic chart of the Southern Ocean derived from Geosat altimetry data, *in* St. John, B., ed., Antarctica as an exploration frontier—Hydrocarbon potential, geology, and hazards: American Association of Petroleum Geologists Studies in Geology, no. 31, p. 89–99.

Sandwell, D. T., 1992, Antarctic marine gravity field from high-density satellite altimetry: Geophysical Journal International, v. 109, p. 437–448.

Sandwell, D. T., and Mc Adoo, D. C., 1988, Marine gravity of the Southern Ocean and Antarctic Margin from GEOSAT: Tectonic implications: Journal of Geophysical Research, v. 93, p. 10,389–10,396.

Small, C., and Sandwell, D. T., 1992, An analysis of ridge axis gravity roughness and spreading rate: Journal of Geophysical Research, v. 97, p. 3235–3245.

SPRITE Group, and Boyer, C. G., 1992, The southern rim of the Pacific Ocean: Preliminary geologic report of the Amundsen Sea–Bellingshausen Sea cruise of the *Polar Sea*, 12 February–21 March 1992: Antarctic Journal of the United States, v. 27, no. 2, p. 11–14.

Stern, T. A., and ten Brink, U. S., 1989, Flexural uplift of the Transantarctic Mountains: Journal of Geophysical Research, v. 94, p. 10,315–10,330.

Swithinbank, C., 1988, Antarctica: U.S. Geological Survey Professional Paper 1386-B, 278 p.

Tingey, R. J., 1991, Commentary on schematic geological map of Antarctica: Bureau of Mineral Resources Bulletin 238, 30 p.

Veevers, J. J., Powell, C., and Rotts, S. R., 1991, Review of seafloor spreading around Australia, 1. Synthesis of the patterns of spreading: Australian Journal of Earth Sciences, v. 38, p. 373–389.

Manuscript received January 25, 1993; accepted March 11, 1993. ■