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

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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 Geodic 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-12284, 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 de- 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 (Hasbly et al., 1991). 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°, 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 (McAulod and Marks, 1992).

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 NSRC 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). NSRC 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 3.1 km directly under the satellite to as large as 2.4 by 6.9 km at the edge of a 2400-km-wide swath. NSRC 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 1:500,000 scale with a standard parallel of 71°. 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-12284, 1991) and in Menounos (1989). Bands 1

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: Antarctic Image, Institute for Geophysics, University of Texas, 8701 Mapac Boulevard, Austin, TX 78759-8397.
Antarctic Plate: Tectonics from a Gravity Anomaly and Infrared Signature Image

Antarctic Plate continued from p. 117

The Antarctic Plate continues from p. 117 (vivible), 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°) 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 geologic and geophysical atlas of the circumpolar Antarctic (Hayes, 1991). The lineations on the ocean floor represent the structural fabric of the Southern Ocean as interpreted from the Geosat deflection of the vertical data (from Roeyer et al., 1990). They correspond to features such as fracture zones and spreading ridges. Although 98% to 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 lineations in the Weddell Sea region from 310° to 000°E (longitudes are given as degrees east from 000°, the Greenwich meridian), across the Pacific-Antarctic Ridge (210°E to 160°W), and the Tasman (150°E) and Balleny (153°E) fracture zones at the bottom of the image. The major-offset fracture zones of the South Pacific, the Heeman (260°W) and Tharp (255°W) 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 toward 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-Antarctic plate boundary between 200°E and 160°W and a few sections of the Australia-Antarctic plate boundary between 160°W and 150°W. Between 208° and 200°W, 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° between 193° and 196°W (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-spreadings 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°W and 180°E), causing the ridge to split 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 000°E. Only a small part of the Maud Rise rises above the bottom of the ice sheet.

TERRESTRIAL

Significant structural features on the AVHRR image of Antarctica fall into two groups: (1) mountain ranges and escarpments and (2) ice-ripped fault zones. The most prominent mountain range is the Transantarctic Mountains, which extend from North Victoria Land to 72°S and 145°E, near the bottom of the image of Antarctica to reach the South Pole in the center. The Transantarctic Mountains define the lower left side of the roughly kidney-shaped East Antarctic Peninsula shield, which is penetrated by the

- Figure 2: Geosat tracks and radiometer mosaic (paleogeostrophic projection, same area as Fig. 1).
Lambert Glacier. Amery Ice Shelf rift at 070°-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° and 33°E. This is the margin recently suggested as having been con- jucted to the late Precambrian–early Paleozoic rifted margin of western North America (Moore, 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 off" 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 (Moore, 1991; Dalziel, 1991, 1992a, 1992b; Dalla Salda et al., 1992). The Grenville orogen would have continued into Coats Land and the Heimert discussion along the eastern margin of the Weddell Sea. Noteworthy is that the Transantarctic Moun- Ats, an escarpment made up of the Heimert discussion, Kiwan Escarpment, and the Heimert discussion around Dronning Maud Land to the Sel–Ronne Mountains at 038°E. In a reconstruction of the Gondwana super- continent, this Antarctic escarpment mirrors the Lebombo monoclone of southeast Africa and reflects the pre- breakup fit of the continents (Lawver et al., 1991). The prominent north- trending Dronning Fjelldalen (Yama- to Mountains) can be seen at 72°E and 038°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 075°E com- prises the Napier complex of Archean granitic and gneiss facies metamorph- ous 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 Kappq craton exposed at Anandadotapone, and the Vestfold Hills complex appear to have controlled development of the conti- nental margin during fragmentation of Gondwana (Dalziel, 1992a).

The Lambert–Amery graben is flanked by the Prince Charles Moun- tains to the west and the very promi- nent Mount Escarpment to the east near the head of the graben. The Lamb- ert 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 lies the Gamburtsev Subglacial Mountains (80°S, 075°E). A cloud obscures this location on the image. All photographs indicate that these moun- tains, which have a sub-ice relief of over 3000 m, come close to the surface without actually being exposed (Swith- inbank, 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 ex- tends in a hoop shape from the coast. offshore, there is a definite change in trend of the outer continental margin gravity high at 100°W. West of this point, India rifted from East Antarctica during the Late Cretaceous (~135 Ma; Lawver et al., 1991), to the east, Australia rifted from East Antarctica during the Late Cretaceous (starting slowly at 96 Ma; Vevers at al., 1991). The Burger Hills, the dark area near the coast at 100°E, consist of Proterozoic and early Pale-ozoic age metamorphic and igneous rocks (Tingey, 1991). The Denman Glacier, which feeds the Shackleton Ice Shelf, is just west of the Burger Hills. To the east, there are only scattered outcrops along the coast to 155°. Between 145° and 155°E, the Vilkes Land Basin is a major feature indicated offshore by the gravity low inboard of the continental-marg i gravity high. The Vilkes Land Basin is the offshore extension of the much larger Wilkes Subglacial Basin, which lies parallel to the Transantarctic Mountains and appears to be part of a flexural downwarping extending inland beyond the South Pole (Sten and Tink, 1989). The Wilkes Subglacial basin extends northward as a feature 500 m deep by 1500 km wide and as a 1000 mb still feature to 74-S. Its greatest depth is 1500 m. To the east, between 135°E and 165°E, the Wilkes Hills on the coast and the Uspor Moun- tains inland form the western margin of the Rennick group. The Rennick Glacier can be seen as far south as 73°3.5′ at 162°E. The Bowers Mountains form a linear eastern margin to the Rennick group 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 Ant- arctica 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 1100 km from 80° to 90°E. 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. In 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 Ellis, 1982). The depression includes the Byrd Subglacial Basin, which reaches oceanic depths below the Western Antarctica Ice Sheet and appears to be part of a volcanically active rift system (Blacksheld et al., 1989). The isolated Ellsworth Mountains show up promi- nently between 77° and 80°S along 275°E. They form Earth surface the structural unit of West Antarctica that extends beneath the ice to the continental- ated at 73°7′S and 255°E, separat- ing the Weddell Sea embayment from the Ross Sea embayment. This crustal block appears to be the antithetic remnant of the Gondwana craton margin displaced from between the Transantarctic Mountains and the African craton (Dalziel, 1992a).

119

Lambert Glacier
MLB—Marie Byrd Land
MNB—McMurdo Escarpment
MN—Mühlig-Hofmannfjella
MS—Maskelyne Island
MS—Mount Spele
PM—North Victoria Land
PACANT—Pacific Antarctic
PCF—Prince Charles Mountains
PLB—Pine Island Bay
PM—Pine Mountains
QM—Queen Maud Range
RJ—Rongerfelt Range
RL—Ross Island
SM—Scott Island
SS—South Shetland Islands
TBZ—Thwaites Glacier
THZ—Thayer Fracture Zone
TI—Thurston Island
TM—Thiel Mountains
UZ—Udistenfracture Zone
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 (basins of East Antarctica), and the ~2000 m contour (Gamburtsev Subglacial Mountains). Stippled areas are major cloud groups.

Antarctic Plate continued on p. 122
Continental Margins

Unfortunately, Geoatlas do not exist for the Ross Sea or the Weddell Sea region south of 72½°S. The principal regions where there are clear-cut continental margins are the major glaciers-fed ice shelves and deep (>1000 m) continental shelves. The ice shelf is the word for the Lambert Glacier. Amery Ice Shelf—Prayde Bay region. Less spectacu-
lar on this image but possibly a larger feature is the Wilkes Land Basin off-
shore and the Wilkes Subglacial Basin offshore.

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 con-
tinent. 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 frac-
ture 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 par-
allel to the Neoproterozoic orogen of Coats Land and western Drifting Nun- gait Island, in the North Victoria Land area. Likewise, the South Tasman and Bal-
leny fracture zones, which show the northern extent of the Gondwana break-up off the west coast of Australia, trend in to the Rennick graben, which parallels the Paleozoic tectonic

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