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GPS evidence for a coherent Antarctic plate and for postglacial rebound in Marie Byrd Land

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Abstract

GPS measurements collected between 1999 and 2002 in Marie Byrd Land, West Antarctica indicate no significant present motion between East and West Antarctica greater than 1–2 mm/year. Low strain rates imply that the Ross Sea rift is either inactive or active at a very low rate. This result indicates that the two subcontinents are likely joined as a single coherent lithospheric plate. They could have been joined since the end of Adare Trough spreading in Oligocene time. The volcanic activity in the Ross Sea sector at present such as at Mount Erebus is most likely related to mantle upwelling and not associated with continental rifting. GPS measurements of vertical rates indicate postglacial rebound of up to 12 ± 4 mm/year in western Marie Byrd Land (wMBL). Errors are scaled 1σ. The rock uplift rates are consistent with postglacial rebound models of significant ice thinning in the eastern Ross Ice Shelf in the late Holocene.

Keywords: Antarctica; GPS; Postglacial rebound; Tectonics

1. Motion between East and West Antarctica

Measurement of crustal motions in Antarctica is key to understanding the current tectonic environment and the past- and present-day ice sheet history of the continent. In 1998, we established a GPS network of three stations in western Marie Byrd Land (wMBL) to measure rates of deformation between East and West Antarctica across the Ross Embayment and postglacial rebound in western Marie Byrd Land (Fig. 1).

The West Antarctic rift system includes the Ross Sea rift and comprises one of the largest extensional regimes on Earth. It is comparable in size to the Basin and Range province of the Western US (Tessensohn and Worner, 1991). Because the West Antarctic rift system lies under an ice sheet, it is difficult to determine the history and current activity of the rift. It is possible that extension in the Ross Sea rift ended in late Oligocene time and is not occurring today (Stock and Cande, 1999; Hamilton et al., 2001; Luyendyk et al., 2001), or happens at a very low rate. If spreading is occurring today between East and West Antarctica, this would define Antarctica as two plates with resulting impact on global plate tectonic models. Uplift of the Transantarctic Mountains is believed to be related to extension (spreading) in the Ross Em-

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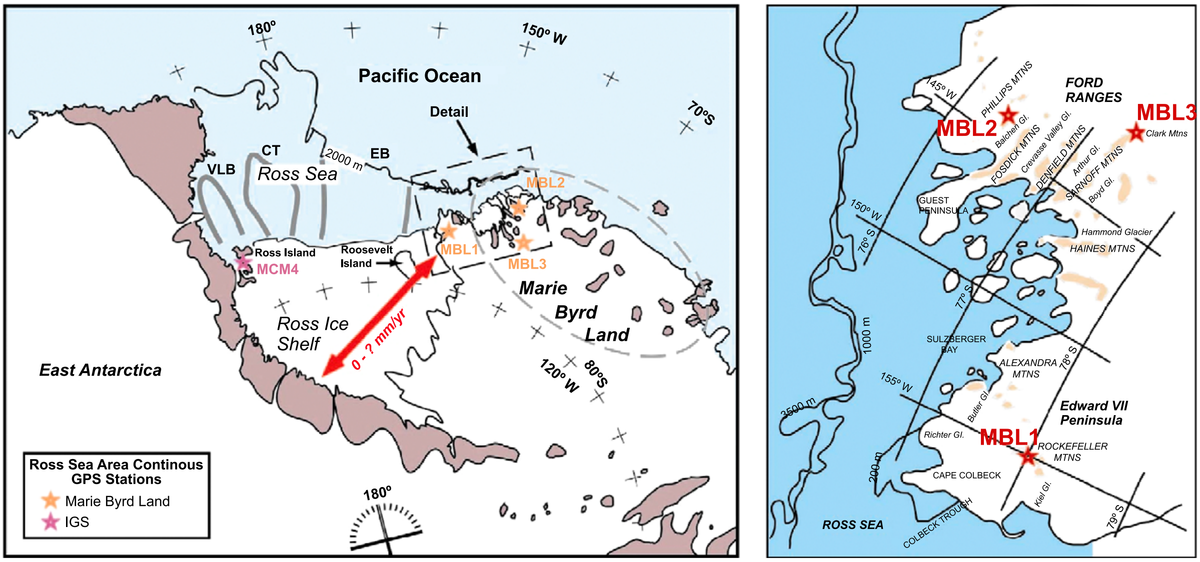

Fig. 1. General setting of the region of the GPS network, showing tectonic characteristics, the Marie Byrd Land GPS Network, and the continuous station MCM4 in McMurdo Station on Ross Island.

bayment (Behrendt and Cooper, 1991; Cande et al., 2000; Hamilton et al., 2001). Therefore, finding a significant extension rate could imply that tectonic uplift of these mountains is continuing today.

2. Postglacial rebound

There is general agreement that Antarctica was a major participant in the last glacial age within the West Antarctic Ice Sheet (WAIS), perhaps contributing more than 25 m to rising sea level during the last 21,000 years (Clark et al., 2002). The main controversy is whether or not the dominant Antarctic melt contribution to sea level rise is relatively young, perhaps related to Hypsithermal period warming events during the Holocene (10–8 to 6–4 ka), or older, corresponding to the initial collapse phase (21–14 ka) of Northern Hemispheric ice sheets (Peltier, 1998). Some glaciologists argue, based on detailed regional chronology preserved in the geological record, that Antarctica contributed very little to the last 21 ka of sea level rise (Colhoun et al., 1992). Another proposal is that the contribution was early on in global deglaciation, giving the mantle 10,000 years, or more, to re-establish gravitational equilibrium and slow vertical crustal motions to below a detectable level (Clapperton and Sugden, 1982). A recent study hypothesized late Holocene collapse of thick ice in the eastern Ross Ice Shelf in the region of Roosevelt Island (James et al., 2001). The collapse generates substantial present-day uplift in adjacent regions of wMBL. GPS determination of uplift rates presented here can help constrain different scenarios of history of the West Antarctic Ice Sheet proposed by paleoclimate modelers (e.g. Tushingham and Peltier, 1991; Huybrechts, 1992; MacAyeal, 1992). Mapping vertical rates could indicate the location of where the West Antarctic ice sheet was thickest in addition to providing constraints on the timing of ice sheet collapse. Models of the WAIS at the Last Glacial Maximum have variously indicated that the center was located anywhere from the southeastern Ross Ice Shelf to near the Transantarctic Mountains. Mapping vertical rates of rebound can distinguish between different models (e.g. Tushingham and Peltier, 1991; James and Ivins, 1995).

3. GPS array in western Marie Byrd Land

During the 1998–1999 austral summer, we deployed three autonomous and continuous GPS stations on outcrops in coastal wMBL. The systems included a Leica MC1000 GPS receiver and antenna, a Databridge high-capacity data logger, and solar panels, batteries, and wind generators for power. The stations are located in a triangle spanning Edward VII Peninsula and the Ford Ranges (Fig. 1) at the Rockefeller Mountains (MBL1), the Phillips Mountains (MBL2), and the Clark Mountains (MBL3). While engineering issues resulted in sparse data, initially the stations proved capable of generating near continuous data during the summer season. The systems were designed to shutdown if they periodically became too hot. Generation of power during the winter months proved difficult to impossible because we did not overcome problems with wind generated power systems during extreme wind events. However, the time series show nearly continuous data for the recent austral summer seasons (Figs. 2 and 3). During January of 2002, the systems were removed from the field except for the antennas, which will be used for future investigations.

4. Data processing

Data were processed using the GIPSY/OASIS software package (Zumberge et al., 1997). We used the Jet Propulsion Lab (JPL) precise GPS orbit and clock products, performed bias fixing, and transformed the solutions into the IGS00 reference frame. We processed the wMBL stations with the continu-

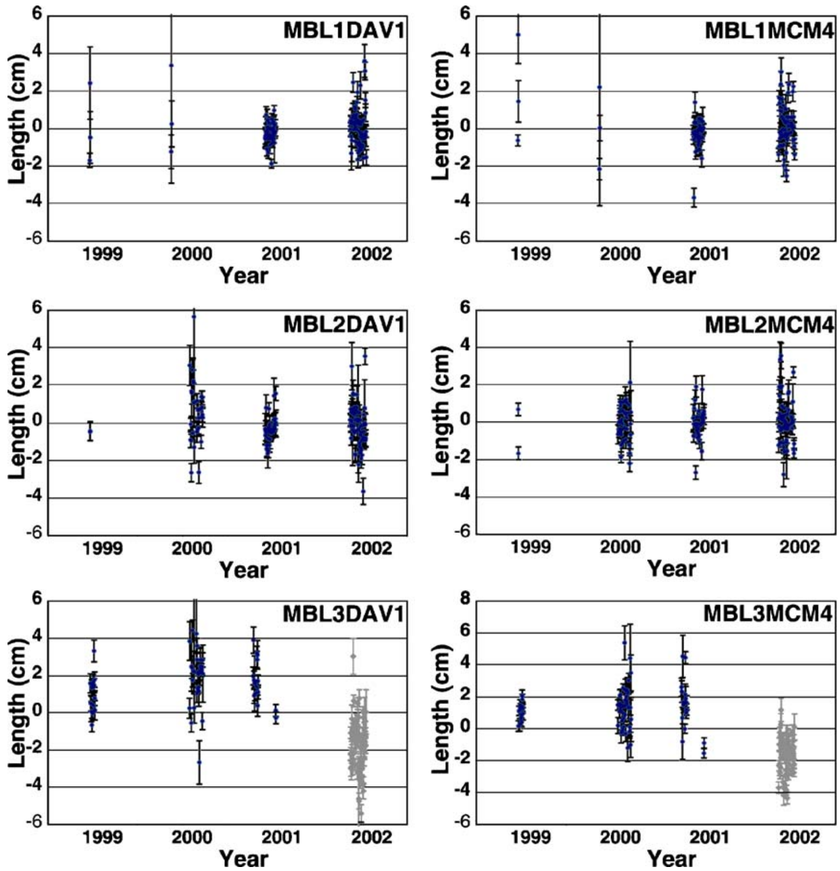

Fig. 2. Length time series for Marie Byrd Land GPS stations relative to DAV1 and MCM4. Errors are unscaled 1σ. The last season of data from MBL3 has been excluded from the solution (gray).

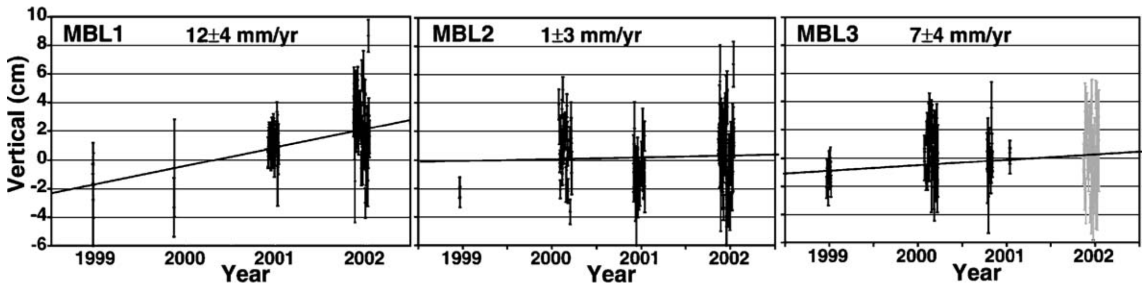

Fig. 3. Vertical time series for the Marie Byrd Land GPS stations. Errors are unscaled 1σ. Gray points during the last season at MBL3 were not used in the solution.

ous GPS stations at Casey (CAS1), Davis (DAV1), Macquarie Island (MAC1), McMurdo Station (MCM4), and O'Higgins (OHIG) (Fig. 4). CAS1 and DAV1 are on East Antarctica and MAC1 is on the Pacific Plate. The other stations are on West Antarctica, except for MCM4, which is on the western side of the Ross Sea rift zone between East and West Antarctica.

Absolute position repeatabilities for the wMBL network are 3 mm horizontal and 7 mm vertical (Figs. 2 and 3). The stability of MBL3 is questionable because of poor measurement repeatability with a bias present for the last season of data. It is possible that the outcrop is unstable or that there is a problem with an antenna element. Signal-to-noise ratios of the raw data suggest that the latter is more likely. If we remove the most recent season of data, which is inconsistent in the time series, the data repeatability for MBL3 is improved and is comparable to the other station data repeatabilities. The overall solution within the larger network is improved. The data were processed using fixed orbits and clocks in a network solution. Ambiguities were resolved.

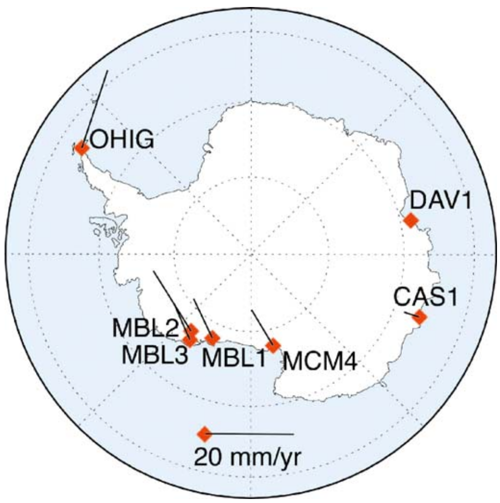

Fig. 4. Horizontal velocity vectors relative to station DAV1 (diamonds are station locations) showing the context of the wMBL GPS stations to the Antarctic continent.

5. Horizontal motions

Previous studies have dismissed MCM4 as being unstable and suggest that Antarctica is one rigid plate (Bouin and Vigny, 2000). However, these other studies did not have additional stations on west Antarctica to compare the MCM4 motions to, except for O'Higgins, on the peninsula, which has also been previously dismissed (Bouin and Vigny, 2000).

Our GPS results indicate little spreading across the Ross Embayment between McMurdo station (MCM4) and wMBL (Table 1). Our rate estimate of strain within West Antarctica (including MCM4) ranges from -0.5 ± 1.2 to 0.8 ± 1.3 mm/year, or near zero. Continued measurements are required to determine if a small amount of extension is still occurring across the Ross Sea rift. Based on these GPS results, the West Antarctic Rift system may no longer be active or is active at a very low strain level.

Our GPS results for the combined larger network suggest an overall counterclockwise rotation of the Antarctic plate of 0.22°/My around a pole of rotation

Table 1
Length change rates for Marie Byrd Land GPS stations relative to MCM4, CAS1, and DAV1

Station	Station	Length	Error	Transverse	Error
MBL1	CAS1	2.9	1.4	− 7.5	0.9
	DAV1	1.2	1.4	− 9.8	0.9
	MCM4	0.3	1.0	0.7	1.0
MBL2	CAS1	− 0.2	1.0	− 6.9	0.7
	DAV1	− 1.6	1.1	− 9.0	0.7
	MCM4	− 1.1	0.8	0.4	0.8
MBL3	CAS1	6.4	1.5	− 12.2	1.1
	DAV1	2.6	1.5	− 15.9	1.2
	MCM4	− 4.6	1.1	4.5	1.1

Errors are scaled 1σ. Plate rotation not removed (see text).

Table 2
Vertical rates for the Antarctic GPS stations

Station	Vertical	Error
MBL1	11.8	4.0
MBL2	0.8	2.7
MBL3	7.4	4.1
CAS1	6.2	1.3
DAV1	1.4	1.4
MCM4	− 1.6	2.3

Errors are 1σ, scaled by the square root of the chi-squared per degree of freedom of the solution.

located at latitude N61.6° and longitude W126.9°, relative approximately to the ITRF 2000 reference frame (IGS00) in which the GPS site velocities are estimated (Donald Argus, JPL, written communication, 2003). These results are comparable to those determined from analysis of several GPS solutions for Antarctica (Dietrich et al., 2001). We removed this rotation to determine residual relative motions between the stations on East and West Antarctica (Fig. 5). To within the 1σ errors, there is no apparent motion between East and West Antarctica. These errors are large, however, and would be reduced with longer time series, making it possible to determine if a small amount of extension is occurring between the two subcontinents.

6. Vertical crustal motions

Upward vertical motions are detected at the wMBL array (Table 2). McMurdo Station on Ross Island (MCM4) shows no significant vertical motion. Our observed vertical rates in wMBL suggest a dome of uplift centered near the Rockefeller Mountains with a peak rate of 12 ± 4 mm/year (Fig. 6, Table 2). Uplift at MBL3 is 7 ± 4 mm/year after removal of the most recent season data. Wahr et al. (1995) model uplift rates of 10 mm/year for the wMBL region assuming continuing evolution of the ice sheet. James et al. (2001) estimate an uplift rate of 10 mm/year at MBL1

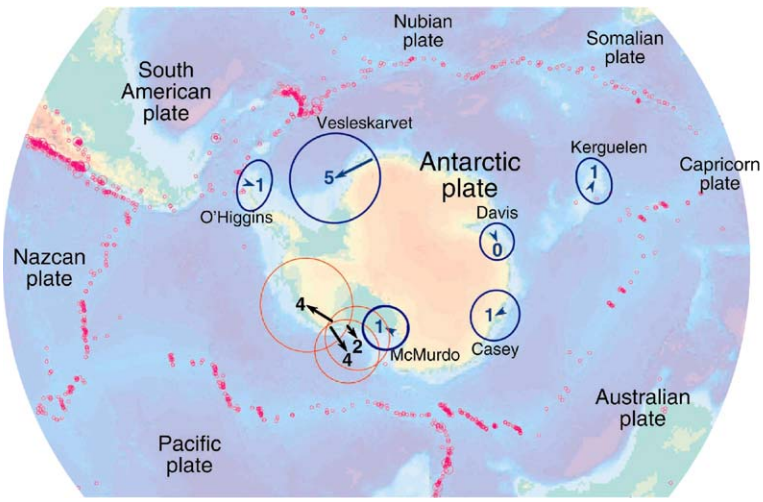

Fig. 5. Horizontal velocities after removal of clockwise rotation of the Antarctic plate. Errors are 1σ, scaled by the square root of the chi-squared per degree of freedom of the solution.

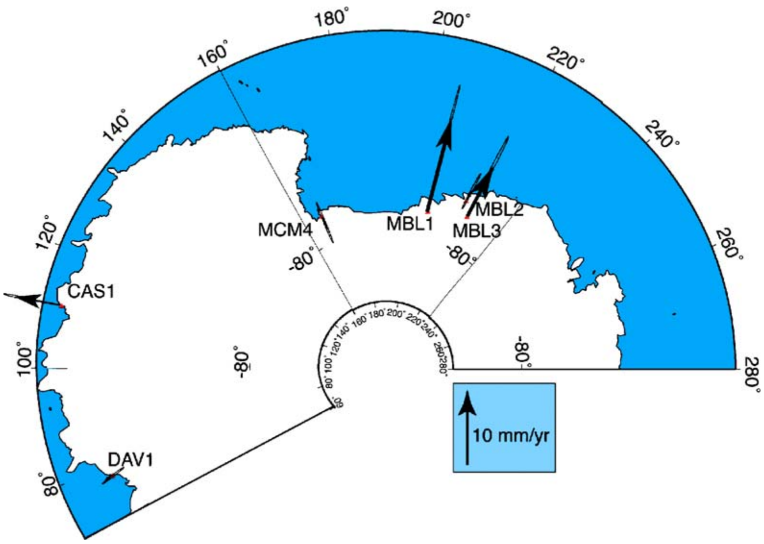

Fig. 6. Vertical absolute velocities. Errors are scaled 1σ.

based on an ice sheet reconstruction that places a dome of ice near Roosevelt Island at 4 ky that rapidly collapsed, consistent with grounding line retreat studies (Conway et al., 1999). The observed magnitude of uplift is consistent with ice thinning continuing through to the later part of the Holocene (Conway et al., 1999; Stone et al., 2003).

7. Conclusions

Taken together, currently available GPS data from the Antarctic continent, including a temporary array located in western Marie Byrd Land for the past several years, indicate that no significant horizontal strain (more than 1–2 mm/year) is occurring either within West Antarctica, between East and West Antarctica, or across the Ross Embayment. A longer time series will reduce errors so that smaller amounts of horizontal strain could be detected. It is possible that 1 mm/year of extension is occurring across the eastern Ross Sea area (Willis et al., 2003), which is consistent with these results. The last episodes of deformation between East and West Antarctica were focused in the western Ross Sea and associated with Early Tertiary uplift of the Transantarctic Mountains and with extension in the Victoria Land basin (e.g. Hamilton et al., 2001). Volcanism continuing today in the western Ross Sea apparently is not related to significant crustal strain. The Antarctic plate is now coherent and undergoing minimal strain. Upward vertical motions in wMBL are attributed to crustal rebound due to the thinning of the West Antarctic ice sheet in late Holocene time, with a load center near the eastern edge of the Ross Sea. Continued measurements in the region will reduce the errors for further comparison with postglacial rebound models.

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