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What Caused the March 25, 1998 Antarctic Plate Earthquake ?: Inferences from Regional Stress and Strain Rate Fields

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Abstract. We investigate possible driving forces behind the occurrence of the 1998 Antarctic plate earthquake. We determine first a regional strain rate field associated with the accommodation of relative plate motion, and second, a vertically averaged minimum deviatoric stress field associated with lithospheric gravitational potential energy differences and deglaciation of the Antarctic ice cap. We find that the mechanism of this event is inconsistent with strain orientations inferred from kinematic modeling of a diffuse zone of deformation within the triple junction region. Stress perturbations associated with deglaciation cannot be ruled out as a triggering mechanism for this event.

Introduction

The March 25, 1998 Antarctic plate earthquake is an unusual event. With a moment magnitude (M_w) of 8.1 and occurring 300 km away from the nearest plate boundary, it is the largest oceanic intraplate earthquake in recorded history. Some oddities of this event become apparent when it is placed in its seismotectonic setting (Figure 1). The regional seismicity is dominated by strike-slip events on the nearby transform faults on the Southeast Indian Ridge (SEIR), which all yield a NW-SE orientation of the P-axis. The P-axis orientation of the Antarctic plate event is NE-SW. Furthermore, most of the aftershock locations (Figure 1) suggest that rupture most likely occurred on an E-W trending fault plane, which is almost perpendicular to fracture zones that delineate existing zones of weakness (Figure 1).

We investigate possible causes of this event by comparing its mechanism with local directions of principal axes determined from regional strain rate and deviatoric stress field modeling. We determine the model strain rate field to address whether the occurrence of this event is related to the accommodation of plate motions within a triple junction region that possibly involves diffuse deformation. To test a second hypothesis we determine deviatoric stresses associated with lithospheric gravitational potential energy differences, including effects of deglaciation of the Antarctic ice shelf.

Tectonic Setting

About 500 km east of the Antarctic earthquake epicenter the Antarctic (AN), Pacific (PA), and Australian (AU) plates meet at the AN-PA-AU (or Macquarie) triple junction (Figure 1). There are indications, based on seismicity [e.g., *Valenzuela and Wysession*, 1993] and inferences from plate closures [*DeMets et al.*, 1988], that the AU plate west of the Macquarie Ridge Complex (MRC) is internally deforming. This deformation may be partially responsible for the significant discrepancy that exists between the direction of AN-AU plate motion and the azimuths of the four most eastern transforms of the SEIR [*DeMets et al.*, 1988]. A possibility for the deformation in the eastern AU plate may be the proximity of the PA-AU pole of rotation. From GPS studies [e.g., *Larson et al.*, 1997] there are indications that the location of this rotation pole has changed in recent times. However this GPS result has a significant uncertainty. A change in pole location could yield large stresses in the young lithosphere within the nearby triple junction region.

Estimating a Model Strain Rate Field

To address the possible relation between the event and regional plate motions, we determine a strain rate field in the plate boundary zones associated with the accommodation of PA-AU-AN relative motion. In this approach we use a variant of the method by *Haines and Holt* [1993]. A grid is defined (Figure 2a) that mimics regional plate boundaries, using transform locations from satellite altimetry [*Spitzak and DeMets*, 1996], and that also allows us to investigate the possibility of a diffuse zone of deformation within the triple-junction region (from now on called the TJR). We apply AU-AN and PA-AN plate motion [*DeMets et al.*, 1994] at the grid boundaries that define the AU and PA plate, respectively, and determine the resulting strain rate tensor field that accommodates these velocity boundary conditions. The fixed AN plate is defined by the sourthen grid boundary (Figure 2a). Using the method of *Haines et al.* [1998] we place a priori bounds on the style of deformation within regions. For transform faults model covariances are constructed such that they constrain the principal axes of the model strain rate tensor in accordance with pure strike-slip deformation in a direction $\pm\ 2^o$ of the transform azimuths [*Spitzak and DeMets*, 1996]. Along the ridges the strain rate tensor is, within an uncertainty of $\pm\ 2^o$, constrained to pure dilation. For the MRC the style and direction of the model strain rate tensor is loosely constrained by the direction and relative magnitude of principal strains inferred from moment tensors of small and intermediate sized events. Finally, no a priori constraints are applied within the diffuse TJR and hence this region is free to deform in any direction necessary to accommodate the imposed relative motion of surrounding plates.

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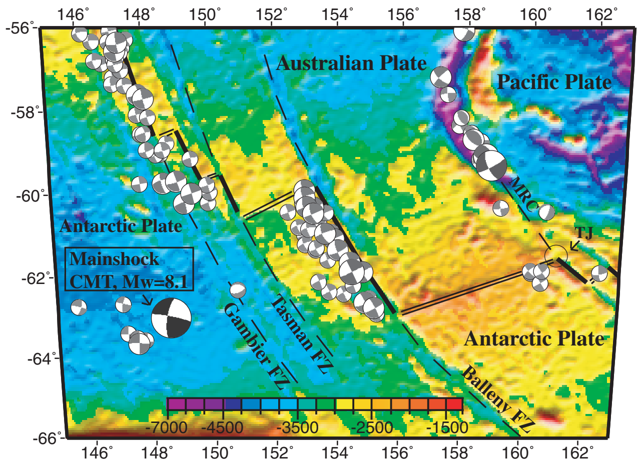

Figure 1. Focal mechanisms are from the Harvard CMT catalog (1/77-6/99). The black focal mechanisms indicate the 1998 Antarctic plate event with (some of) its aftershocks. Bathymetry is from *Smith and Sandwell* [1994]. Transform locations are derived from satellite altimetry by *Spitzak and DeMets* [1996]. MRC is the Macquarie Ridge Complex and TJ is the Australia-Pacific-Antarctica triple junction.

Estimating a Minimum Deviatoric Stress Field

Different factors contribute to the the total stress field in the region where the event occurred. Gravitational potential energy (GPE) differences have been widely recognized as an important source for intraplate stresses [e.g., *Coblentz et al.*, 1994]. These GPE differences not only reflect lateral density variations between the continent and the deep ocean basins, but also incorporate, in part, the effect of ridge push. The ridge push is suggested to be the main driving force behind previous Antarctic seismicity [*Okal*, 1980]. Other stress contributions may come from flexural effects due to sediment loading or deglaciation. However, the stress field due to sediment loading is, although large, not likely to cause seismicity; numerical calculations by *Stein et al.* [1989] show that these stresses are more likely to be relaxed through viscoelastic behavior of the lithosphere. Based on the observation that plate margin earthquakes seem to be more common on recently deglaciated margins, *Bashman* [1977] suggested that this seismicity could be due to stresses induced by glacial rebound of the lithosphere. However this may not necessarily explain the occurrence of the event. First, *Quinlan* [1984] noted that the stress due to deglaciation may trigger seismicity but could not, by itself, cause a large strike-slip component. Secondly, numerical simulations [*Stein et al.*, 1989] show that the effect of glacial loading/unloading would not extend more than a 300 km distance from the load, which is less than the distance between the epicenter of this event and the edge of (past) glacial loading. However, their result is highly dependent on assumed rheologic properties. In this study we investigate the effect of deglaciation of the Antarctic ice cap by determining the horizontal deviatoric stress field associated with lithospheric density differences before and after unloading. These stress field calculations are independent of any assumed rheology.

Using the assumption of local isostacy we calculate GPE using densities for the continental crust, mantle, and ice of, respectively, 2750, 3300, and 917 kg m^{-3}. For oceanic regimes we use a crustal thickness of 7 km and a crustal and asthenospheric density of respectively, 2960 and 3238 kg m^{-3}. We use oceanic ages from *Müller et al.* [1997] to infer the thickness of the oceanic lithosphere. For ages less than 90 Ma we adopt the half-space cooling model to calculate the lithospheric thickness, and for areas older than 90 Ma we set the thickness to 100 km, in accord with the plate-model by *Stein and Stein* [1992]. We make no assumptions about rheology, but simply solve the force balance equations for a thin sheet that relate derivatives of deviatoric stress to derivatives of the inferred potential energy values. Following the procedure described by *Flesch et al.* [2000] we assume that stress can be expressed as a vertical average over a 100 km thick column of lithosphere, and that tractions on the base of the lithosphere are negligible [e.g., *Jones et al.*, 1996]. Both assumptions are probably reasonable considering that the horizontal dimensions of the thin sheet (thousands of kilometers) are much larger than its thickness (≈100 km). *Flesch et al.* [2000] show that a minimum vertically averaged horizontal stress field associated with variations in the inferred lithospheric potential energy values can be found by minimizing the second invariant of the stress tensor while solving force-balance equations.

Results

Although we calculate a velocity gradient tensor field solution for all regional plate boundary zones (Figure 2a), we show only our estimated strain rate field for the TJR (Figure 2b). In the TJR strain rates are about an order of magni-

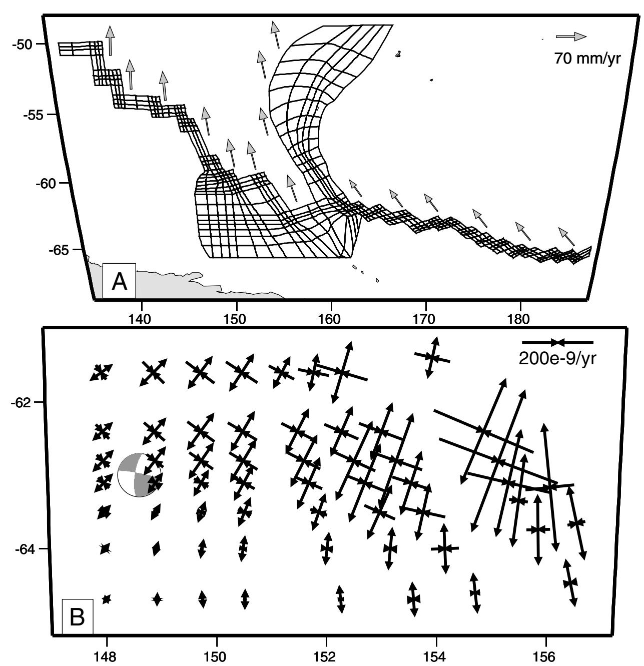

Figure 2. a) Grid in which a strain rate field is determined associated with the accommodation of relative plate motions [*DeMets et al.*, 1994]. These motions are applied as boundary velocity conditions, illustrated by the grey arrows. b) Principal axes of the strain rate field for the region where the Antarctic event occurred (indicated by CMT focal mechanism). Model strain rates in this region are one order of magnitude lower than along the surrounding ridges and transforms.

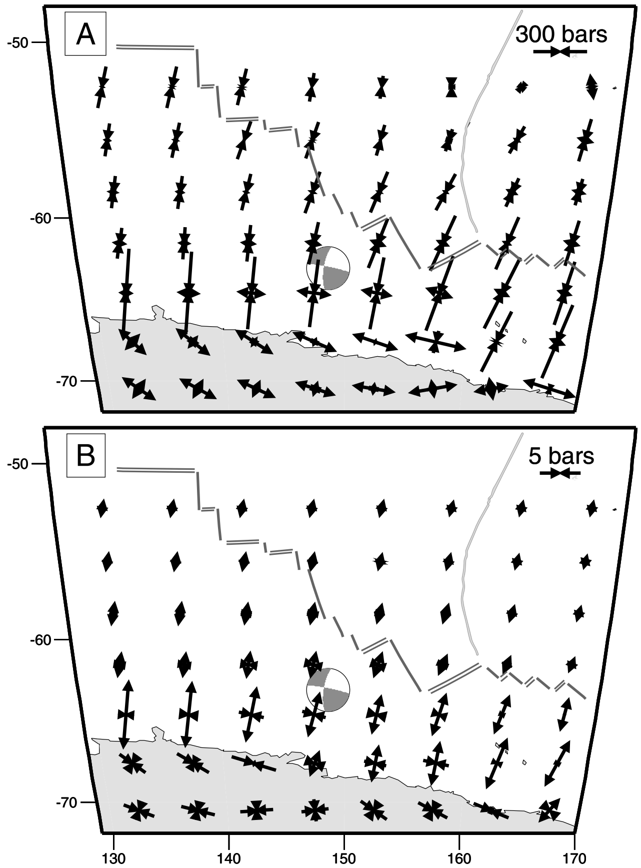

Figure 3. Principal axes of the vertically averaged minimum horizontal deviatoric stress field caused by gravitational potential energy differences within the lithosphere. CMT focal mechanism of Antarctic plate earthquake is shown. a) 'ice-age' simulation. b) change in stress tensor field from 'ice-age' to present day determined by taking the tensorial difference between the two solutions.

tude less than strains along the ridges and transforms of the surrounding plate boundaries. Principal axes near the event's epicenter indicate predominant strike slip strain, but the direction of the compressional strain axis is almost perpendicular to the P-axis of the event. This result is identical to the case where we apply plate boundary velocity conditions using Euler pole estimates by *Larson et al.* [1997].

In the dynamic calculations we investigate two models: (1) present-day, with lateral variations of land-ice thickness on Antarctica [*Bentley et al.*, 1964] , and (2) 'ice-age', with an ice cap that is 500 m thicker than present-day, a sea-level drop of 120 m, and land-ice extending up to the edge of the exposed continental shelf. A minimum vertically averaged deviatoric stress field is determined for the whole AN continent and surrounding oceanic basins, but we only show the solution for the larger TJR. The 'ice age' solution (Figure 3a) yields the expected tensional stresses over the high topography of the continent and compressional, margin normal, stress for the oceanic basins [e.g., *Jones et al.*, 1996]. Highest compressional stresses are concentrated around the continent-ocean transition. Due to the relatively large grid areas used in the inversion, expected variation in stress magnitude associated with a thinner lithosphere in the vicinity of the ridge are not resolved, and instead averages for each grid area are computed. The effect of deglaciation is shown as the tensorial difference between the present-day and 'ice-age' stress fields (Figure 3b). The differential stress is largest for the ocean-continent transition regime. At the location of the event the differential stress yields a dominating dilatational stress of 4 bars with a bearing of N14E.

Discussion and Conclusions

DeMets et al. [1988] have tested the hypothesis that the far southeast corner of the AU plate forms an independent microplate, but found that this was inconsistent with both the estimated plate velocity from plate circuit closure and seismicity on the proposed northern boundary of this plate (50^oS parallel). As a possible explanation for the occurrence of the event *Conder and Forsyth* [2000] propose that this microplate may instead exist just south of the most eastern SEIR. However, in agreement with our analysis (Figure 2b), they found that predicted motion on this fault (plate boundary?) is of opposite sense with what is indicated by the event. Our results indicate that the Antarctic Plate earthquake is not related to the accommodation of AN-AU-PA relative motion within a diffuse zone of deformation.

We find that horizontal deviatoric stresses at the event's epicenter, either in the ice-age or present-day solution, are approximately normal and parallel to the nodal planes of the event (Figure 3a), which cannot produce failure. Conditions necessary for failure to occur, i.e., a weak fault, a large vertical stress, and large associated fluid pressure, are not likely to be present; this is the first recorded seismicity in this region and the event occurred at a depth of 15 km [*Nettles et al.*, 1999]. However, it is important to note that our estimated direction of compressional stress is about 30^o away from the orientation of the fracture zones (Figure 3a). *Schwartz* [1998] suggested, based on the location of some of the aftershocks and source-history analysis, that a series of N-S trending fault planes broke during the event, consistent with possible rupture (sub-) parallel to the trends of regional fossil fracture zones.

However, we also find a tensional deviatoric stress of 4 bars about normal to the E-W nodal plane as a result of deglaciation (Figure 3b). Although this is a small difference, it may have pushed the E-W trending fault considerably closer to rupture by unloading stresses normal to the fault. This result would be consistent with rupture along the E-W trending nodal plane. Since we find that this event is unrelated to the accommodation of relative plate motions as they are presently defined, such an intraplate event of this magnitude must be extremely rare with return times perhaps in excess of 100,000 years. Therefore, it cannot be ruled out that stress changes associated with deglaciation may have played a significant role in triggering rupture. However, it remains difficult to address the specific timing of the event, especially because our present-day stress field is an estimate for any time since about 6000 yr. ago when major deglaciation came to an end. One question that still remains is why this event occurred at this location. An intriguing observation is that the epicenter is located at a place where the distance between the continent and the ridge system that encircles the AN plate is the smallest. Consequently, this region between the margin and the ridge could be relatively weak. Moreover, there may be significant interaction between unexplored local stresses related to ridge-transform processes and the stresses of the nature described in this paper.

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References

Bashman, P. W., D.A. Forsyth, and R.J. Wetmiller, The seismicity of Northern Canada, *Canadian J. Earth Sci., 14,* 1646-1667, 1977.

Bentley, C.R., R.L. Cameron, C. Bull, K. Kojima, and A.J. Gow, Physical characteristics of the Antarctic ice sheet, *Antarctic map folio series,* Am. Geograph. Soc., 1964.

Coblentz, D.D., R.M Richardson, and M. Sandiford, On the gravitational potential of the Earth's lithosphere, *Tectonics, 13,* 929-945, 1994.

Conder, J.A., and D.W. Forsyth, Do the 1998 Balleny event and its aftershocks delineate a plate boundary?, *Geophys. Res. Lett.,* this issue, 2000.

DeMets, C., R.G. Gordon, and D.F. Argus, Intraplate deformation and closure of the Australia-Antarctica-Africa plate circuit, *J. Geophys. Res., 93,* 11,877-11,897, 1988.

DeMets, C., R.G. Gordon, D.F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett., 21,* 2191-2194, 1994.

Flesch, L.M., W.E. Holt, A.J. Haines, and B. Shen-Tu, The dynamics of the Pacific - North America plate boundary zone in the western United States, *Science, 287,* 834-836, 2000.

Haines, A.J., and W.E. Holt, A procedure for obtaining the complete horizontal motions within zones of distributed deformation from the inversion of strain rate data, *J. Geophys. Res., 98,* 12,057-12,082, 1993.

Haines, A.J., J.A. Jackson, W.E. Holt, and D.C. Agnew, Representing distributed deformation by continuous velocity fields, *Sci. Rept. 98/5,* Inst. of Geol. and Nucl. Sci., Wellington, New Zealand, 1998.

Jones, C.H., J.R. Unruh, and L.J. Sonder, The role of gravitational potential energy in active deformation in the southwestern United States, *Nature, 381,* 37-41, 1996.

Larson, K.M., J.T. Freymueller, and S. Philipsen, Global plate velocities from the Global Positioning System, *J. Geophys. Res., 102,* 9961-9981, 1997.

Müller, R.D., W.R. Roest, J-Y. Royer, L.M. Gallagan, and J.G. Sclater, Digital isochrons of the world's ocean floor, *J. Geophys. Res., 102,* 3211-3214, 1997.

Nettles, M., T.C. Wallace, and S.L. Beck, The March 25, 1998 Antarctic plate earthquake, *Geophys. Res. Lett., 26,* 2097-2100, 1999.

Okal, E.A., Intraplate seismicity of Antarctica and tectonic implications, *Earth Planet. Sci. Lett., 52,* 397-409, 1980.

Quinlan, G., Postglacial rebound and the focal mechanism of eastern Canadian earthquakes, *Canadian J. Earth Sci., 21,* 1018-1023, 1984.

Schwartz, S.Y., Characteristics of the rupture process of the 1998 Antarctic earthquake from empirical green function analysis of long-period surface waves, *Eos Trans. AGU, 79*(45), Fall Meet. Suppl., F663, 1998.

Smith, W.H.F., and D.T. Sandwell, Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry, *J. Geophys. Res., 99,* 21,803-21,824, 1994.

Spitzak, S., and C. DeMets, Constraints on present-day plate motions south of 30^{o}S from satellite altimetry, *Tectonophysics, 253,* 167-208, 1996.

Stein, C., and S. Stein, A model for the global variation in oceanic depth and heat flow with lithospheric age, *Nature, 359,* 123-129, 1992.

Stein, S., S. Cloetingh, N.H. Sleep, and R. Wortel, Passive margin earthquakes, stresses, and rheology, in *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound,* pp. 231-259, Kluwer Academic Publishers, Amsterdam, The Netherlands, 1989.

Valenzuela, R.W., and M.E. Wysession, Intraplate earthquakes in the Southwest Pacific Ocean basin and the seismotectonics of the Southern Tasman Sea, *Geophys. Res. Lett., 20,* 2467-2470, 1993.

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