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GEOPHYSICAL RESEARCH LETTERS, VOL. 14, NO. 2, PAGES 147-150, FEBRUARY 1987

THE 1942 SOUTHWEST INDIAN OCEAN RIDGE EARTHQUAKE: LARGEST EVER RECORDED ON AN OCEANIC TRANSFORM

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Abstract. The 1942 Southwest Indian Ocean earthquake is the largest ever recorded on an oceanic transform. Its mechanism has essentially the expected pure strike-slip geometry. Using long-period surface wave techniques, the seismic moment is found to be 1.3×10^{28} dyn-cm; directivity suggests southwestward rupture propagation over approximately 130 km. This shock is then much smaller than previously reported on the basis of its high unified Richter magnitude ($M = 8.3$). It does not show the slow energy release occasionally found in large transform fault events. Scaling laws and thermal modeling suggest that seismic slip extended at least to the 600 ° C isotherm.

Introduction. Oceanic transform fault [TF] earthquakes, whose magnitudes rarely reach 7, are generally smaller than the largest shocks at or near subduction zones such as the Chilean (1960) or Alaskan (1964) events. A clear exception is the Southwest Indian Ocean Ridge [SWIOR] shock of November 10, 1942 ($M = 7.9$ [Gutenberg and Richter, 1954]; $M = 8.3$ [Richter, 1958]). As the largest known oceanic TF event, it played a key role in Burr and Solomon's [1977] analysis of the variation in magnitudes and moments among oceanic transforms. As a result, we studied this event, despite the difficulties inherent in dealing with older events [Stein et al., 1986].

The 1942 event is shown by a large dot on Figure 1, with the recent (post-1963) seismicity along the relevant segment of the SWIOR. Norton [1976] noted a seismic gap from about 49° to 53°S and suggested that it might be related to the infrequent release of energy in large shocks such as the 1942 event. The more recent epicentral data restrict this gap to a length of about 180 km, southwest from the 1942 epicenter.

The location plotted (49.4°S, 30.6°E) is that given by the International Seismic Summary [ISS], to which relocations using ISS data indeed converged. It is clearly aligned with post-1963 seismicity defining the plate boundary between Africa and Antarctica. A somewhat different location, 150 km to the east and off the plate boundary (49.5°S, 32°E), is given by Gutenberg and Richter [1954], on the basis of Gutenberg's personal relocation [Seismological Society of America, 1980]. This inconsistency is puzzling, since Gutenberg used the ISS dataset. The location of the 1942 epicenter is along the northern part of the "Q" Transform Fault (D. Abbott, pers. comm., 1986), also called "Andrew Bain Transform Fault" [Wald and Wallace, 1986]. From 49°S to 53°S, it could involve a single transform about 440 km long, or several slightly offset shorter segments. These authors identified a number of anomalous events with substantial dip-slip components southwest of the 1942 epicenter on the Bain TF. They suggested a component of "leaking" in the transform, due to a slight bend in its azimuth.

Magnitude. The magnitude of the 1942 event was given as $M = 7.7$ [Gutenberg, 1945], $M = 7.9$ [Gutenberg and Richter, 1954], and $M = 8.3$ [Richter, 1958]. Geller and Kanamori [1977] have shown that the Gutenberg and Richter magnitude is close to the present-day 20-s M_s value. Using long period records, we have determined $M_s = 8.1 \pm 0.4$ (Table 1). Brune and King [1967] measured the 100-s spectrum of a single record of R_3, and found an equalized amplitude (2.5 mm at $\Delta = 90°$) comparable to that of the largest subduction zone shocks. Burr and Solomon [1977] then derived their moment estimate, 2.8×10^{28} dyn-cm, through a relation proposed by Brune [1968].

Little is known about the depth of the event: most stations were at great distances, and the trade-off between depth and origin time remained largely unconstrained. The NOAA epicentral tape gives 25 km, and the ISS 28 km. Since we obtained no record suitable for body wave modeling, we use the latter value for focal mechanism and surface wave calculations.

Focal Mechanism. Only 11 stations reported first motions to the ISS, 10 of them at distances greater than 78°. The two PKP dilatational readings at Pasadena and Mount Wilson, checked on the original records by the authors, indicate a minute but discernible component of normal faulting. The resulting mechanism (strike 196°; dip 84°; rake 192°), shown on Figure 1, is consistent with strike-slip along the TF. It also fits the surface waves, as shown in the next section. Only the reported compression at Tananarive (not available for verification) is violated. Moving this station into a compressional quadrant would increase the strike of the fault by 20°, and make the mechanism incompatible with the bathymetry, the recent earthquake mechanisms and the strong amplitude of Love waves at Uppsala and Copenhagen. The resulting mechanism does not show the large anomalous dip-slip components found further to the southwest by Wald and Wallace [1986]; this difference in behavior is consistent with their model of a bend in the transform.

Surface Wave Analysis and Seismic Moment. We analyzed the records listed in Table 1, using the methods of Kanamori [1970]. We digitized at 2-s intervals, and filtered for periods greater than 70 s, thus largely eliminating the influence of hypocentral depth. In view of the large G_2 amplitude at Uppsala (azimuth $\simeq 21°$ from the fault strike), we conducted a directivity analysis at this station [Ben-Menahem and Toksöz, 1962]. Figure 2 shows the spectral ratio $|G_1(\omega)/G_2(\omega)|$ after equalization to a common distance. Assuming that the rupture propagated in the azimuth of the fault strike, this suggests southwestward rupture over 130 km, at 3.5 km/s. Although the agreement between observed and theoretical values is not perfect, these figures give the best fit to the

Paper number 6L7079.
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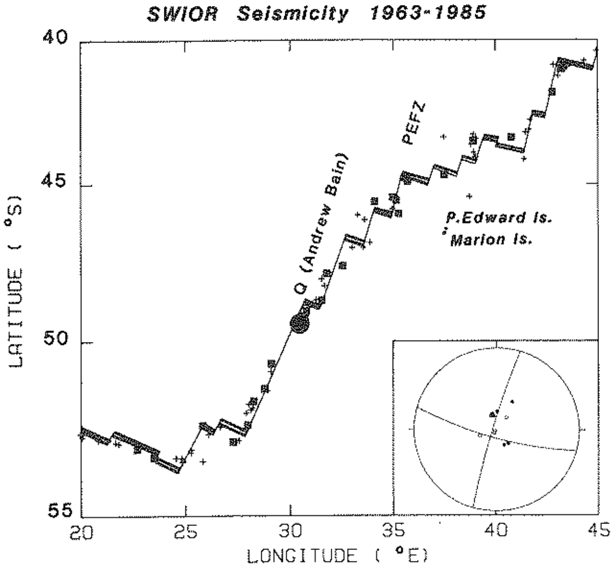

Fig. 1. Post-1963 seismicity along the SWIOR in the vicinity of the 1942 epicenter (large dot). Crosses show events with $m_b \geq 5.0$, squares events with at least one reported magnitude ≥ 5.5 . *Inset:* Focal mechanism of the 1942 event, as obtained from first motions (solid: up; open: down), and surface waves.

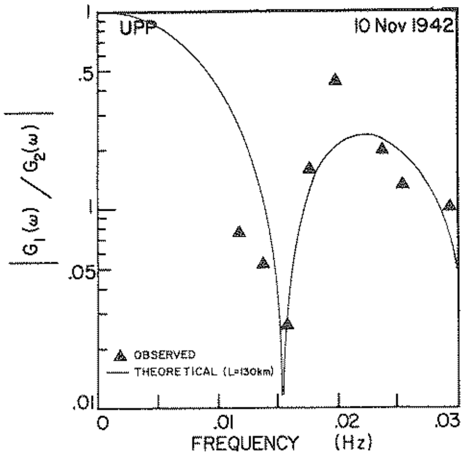

Fig. 2. Directivity function vs. frequency at UPP. The solid line is the theoretical curve for $L = 130$ km, $v = 3.5$ km/s; the symbols are observed values; note minimum in G_1 around 0.016 Hz ($T = 65$ s).

minimum around 65 s and the maximum around 47 s. This length of rupture coincides remarkably with the area of quiescence of the recent seismicity (Figure 1), suggesting that most of the seismic slip on this TF occurs in very large events.

Using this rupture mechanism, we matched normal mode synthetics with the observed records to determine the seismic moment (Figure 3 and Table 1). The good agreement between values obtained for different azimuths confirms the accuracy of the focal mechanism. The average value $M_0 = (1.3 \pm 0.5)\ 10^{28}$ dyn-cm or $M_w = 8.0$ [Kanamori, 1977], is less than half that suggested by Burr and Solomon [1977], from Brune and King's [1967] investigation. However, Brune and King used the single R_3 record at Victoria [VIC], only $\phi = 10°$ away from a Rayleigh node. In this geometry, the Rayleigh amplitude is $\cot^2 2\phi = 7.5$ times more sensitive than its Love counterpart to uncertainty in the fault strike. Also, VIC was at a distance $\Delta = 162°$ (or 522° for R_3), in a region where Brune and King's distance correction factor varies extremely rapidly with distance. Their moment estimate is thus prone to a large systematic error, which they put at possibly a factor of 5. Since we used stations at distances closer to 90°, and located in radiation lobes, we feel that our results are more accurate.

Discussion and Conclusion. Since this event is the largest ever recorded on an oceanic TF, it is natural to explore its relation to the slip process on such faults. Given the limited data available and the resulting uncertainties, the discussion must be somewhat schematic. We infer the range of possible source parameters using relationships between the seismic moment M_0, fault length L, width W, average dislocation D, rigidity μ, and stress drop $\Delta\sigma$ for strike-slip cracks: $M_0 = \mu WLD = \pi\, \Delta\sigma\, W^2 L/2$ and $\Delta\sigma = 2\mu D/\pi W$ [Kanamori and Anderson, 1975].

Figure 4*a* shows the range of fault dimensions con-

TABLE 1. Seismic Records Used in This Study

Code	Station	Distance (°)	Azimuth (°)	Instrument	Phase	Measured m_b	M_s	M_0 (10^{28}dyn-cm)
LPB	La Paz	83.1	353	Short-Period EW	Body	7.7		
CHR	Christchurch	81.4	153	Galitzin NS-EW	R_1		8.13	
AUC	Auckland	88.2	152	Milne-Shaw	R_1		7.89	
DBN	De Bilt	103.7	344	Galitzin NS-EW	R_1		8.5	
COP	Copenhagen	106.1	349	Galitzin NS-EW	R_1		7.7	
UPP	Uppsala	109.7	353	Wiechert EW	G_1			
	"	109.7	353	Wiechert EW	G_2			0.94
	"	109.7	353	Wiechert NS	R_1		8.3	1.58
OTT	Ottawa	131.9	294	Milne Shaw NS-EW	G_1		7.8	1.85
	"	131.9	294	Milne Shaw NS-EW	G_2			1.30
SCO	Scoresbysund	125.7	341	Galitzin Z	R_1			1.21
					average values:	7.7	8.1 ± 0.4	1.35 ± 0.45

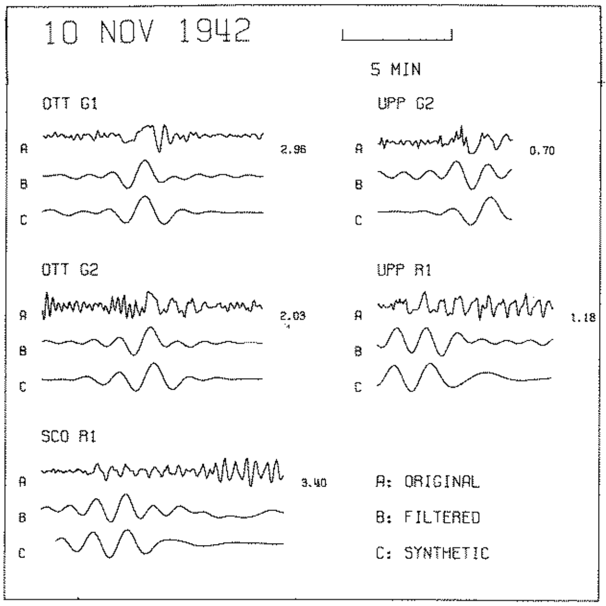

Fig. 3. Long-period surface wave data and synthetics. (A) Data (with peak-to-peak amplitudes in cm); (B) observed records filtered for $T \geq 70$ s; (C) synthetics for the proposed focal and rupture mechanisms.

sistent with $M_0 = 1.3 \times 10^{28}$ dyne-cm, for a range of stress drops. Larger stress drops correspond to smaller fault dimensions and larger displacements. We consider two limiting values for L: 130 km, as suggested by the surface waves, and 440 km corresponding to failure of the entire TF. In the first case, the average W would range from 35 to 20 km, with corresponding slips from 7 to 12 m. The longer fault value implies widths from 20 to 11 km, and slips from 4 to 7 m. These numbers are not easy to interpret because of the lack of comparable oceanic transform events. One possible comparison might be with continental TF earthquakes. For the 1906 San Francisco event ($M_s = 8.3$), the observed slip ($\simeq 4$ m) and fault length (300 km), and geodetic estimates of a fault width less than 12 km, yield $M_0 = 2$—7×10^{27} dyn-cm, consistent with surface wave estimates (4×10^{27} [Thatcher, 1975]), suggesting an average $\Delta\sigma =$ 40 bar. For the smaller 1940 Imperial Valley event ($M_s = 7.1$), Geller [1976] suggests 2 m of slip on a fault 70 km long and 11 km wide, corresponding to $M_0 = 4.8 \times 10^{26}$ dyne-cm and $\Delta\sigma = 55$ bar. Okal [1976] estimated $L = 270$ km for the 1957 Gobi-Altai event (mostly strike-slip; 1.8×10^{28} dyn-cm). In this context, a length of only 130 km for the 1942 event seems short, since its moment is comparable to that of the Gobi-Altai event, and as much as 5 times larger than for the 1906 earthquake.

Since faulting extends only to such depths where the lithosphere retains the necessary strength, W should be related to the rheology and thermal structure of the transform, which in general differ in oceans and continents. The maximum depth of oceanic intraplate events is bounded by about the 750 ° C isotherm [Wiens and Stein, 1983, 1984; Chen and Molnar, 1983; Bergman and Solomon, 1984]. The situation for oceanic transforms is less clear due to the difficulty in estimating thermal structure. The simplest thermal model is one in which the temperature at any point on a transform is the average of that expected on the two flanks for a cooling halfspace, closely approximating a more accurate numerical solution by Forsyth and Wilson [1984]. Using this model, Engeln et al. [1986] found that centroid depths for Atlantic TFs were above the 400 ° C isotherm, and suggested that slip in such events generally did not extend below the 600 ° C isotherm. Burr and Solomon [1977] noted, using the 1942 event as an important datum, that the maximum moment and magnitude of oceanic transform earthquakes is proportional to transform length and inversely proportional to spreading rate, as expected from thermal models.

Figure 4*b* shows a thermal model for the Bain TF, assuming a 440 km offset and a half spreading rate of 8 mm/yr. For this model, most possible geometries imply seismic slip to depths below the 600 ° C isotherm. At one extreme, $L = 130$ km and $\Delta\sigma = 50$ bar require faulting deeper than the 800 ° C isotherm. In contrast, if $L = 440$ km, most of the slip can occur above the 600 ° C isotherm. Even in this case, some slip must take place below the 400 ° C isotherm unless the stress drop was quite high, at least 150 bar.

We thus are left with several possibilities. The 130 km rupture length, favored by the surface wave study and the presently quiet seismic zone, requires either high stress drops, or rupturing below the 600 ° C isotherm. Alternatively, the thermal model, which simply assumes that a transform offsets two cooling halfspaces, may be inappropriate. It should work well for a transform offsetting a pair of long ridge segments, but clearly overestimates the temperatures for the present situation, where a series of short ridge segments are separated by long transforms. A 440 km rupture can be reconciled with faulting constrained above the 600 ° C isotherm, even in the model of Figure 4*b*; however, it disagrees with both the seismicity pattern and directivity studies. In either case, it is likely that slip

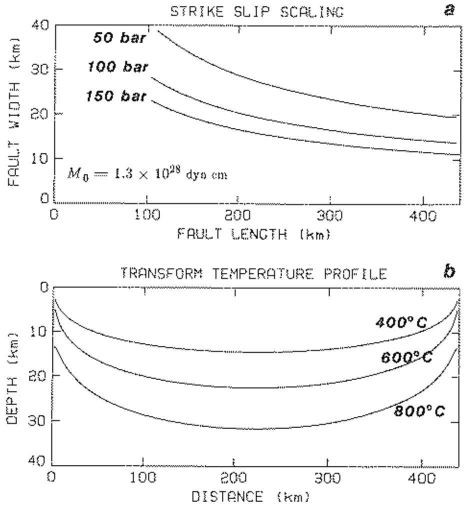

Fig. 4. *a*: Fault width vs. fault length, computed for the 1942 event, using the scaling relations of Kanamori and Anderson [1975]. *b*: Temperature profiles along a TF, in the simple model of Engeln et al. [1986], with numerical values adequate for the Bain TF (Length: 440 km; half spreading rate: 8 mm/yr).

extended down to at least the 600°C isotherm, and that slip in such a large transform event extended deeper than in smaller ones.

Finally, we can compare our results to those for large shocks on the Gibbs TF [Kanamori and Stewart, 1976], and along other selected transforms [Okal and Stewart, 1982], which had M_s much larger than expected from m_b, and still higher M_w, reflecting a slow rupture in which energy release increases with period. In contrast, the 1942 earthquake ($m_b = 7.7$; $M_s = 8.1$; $M_w = 8.0$) does not show this effect (m_b may not be significant, since at $T = 3$ s, it saturates around 7.5 [Geller, 1976]). We conclude that the slow energy release noted for the Gibbs TF is not a general feature of the largest oceanic transform shocks.

Acknowledgments. We are indebted to Ian Norton and Dallas Abbott for providing unpublished bathymetry, and to the many seismologists who sent us records. This research was supported by the Office of Naval Research, under Contract N00014-84-C-0616 (EAO), and the National Science Foundation under grants EAR-84-05040 (EAO) and EAR-84-07510 (SS).

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(Received October 31, 1986;
accepted December 3, 1986.)