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Earth and Planetary Science Letters, 52 (1981) 397–409
Elsevier Scientific Publishing Company, Amsterdam – Printed in The Netherlands

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INTRAPLATE SEISMICITY OF ANTARCTICA AND TECTONIC IMPLICATIONS

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Received September 10, 1980
Revised version received October 23, 1980

We present a comprehensive study of the seismicity of the Antarctic plate for the period 1925–1980. The total seismic energy released during this period in the interior of the plate, 3.2×10^{22} ergs, is compared to figures for the African plate, of similar kinematics and size, and to the neighboring Nazca plate. We conclude that Antarctic seismicity is comparable to that of other plates, thus refuting the claim that a surrounding ring of spreading ridges hampers transmission of tectonic stress and leaves it stress-free, and clearly showing the importance of ridge-push as a driving mechanism for the plates. In the southeastern Pacific Basin, it is shown that the line of maximum age in the plate, which is the locus of previous positions of the triple junction, is a line of preferential stress release, along with more conventional features, e.g. fracture zones. In the Indian Ocean, we study a 1973 earthquake northeast of Kerguelen ($M_S = 5.5$): its depth (45 km), tensional mechanism, and low stress suggest that it represents a magmatic process related to the nearby hotspot, and possibly involving the pipeline structure proposed by Morgan.

1. Introduction

The study of the seismicity of Antarctica and the Southern Seas has started only about twenty years ago. Early efforts [1,2] were directed at mapping the plate's boundary around the Antarctic continent, and only more recently two intraplate earthquakes were studied in the Pacific Basin [3,4]. A systematic compilation of the intraplate seismicity of the Antarctica plate is, however, necessary to permit a reliable comparison of its state of stress with that of other plates, in order to gain a better insight on the forces driving them. Specifically, the generally low level of reported seismicity in the plate has been used as an argument (e.g. by Sykes [5]), to contend that ridges, which make up almost entirely the boundary of the Antarctic plate, are unable to transmit tectonic stresses, leaving the Antarctic plate motionless and stress-free. This would then suggest that slab-pull at subduction zones may be a prominent factor in the driving mechanism of the plates. However, a 1977 event in the Bellingshausen Sea, studied by Okal [4], gave evidence for compressional stresses generated by ridge-push, 2900 km inside the plate.

At the same time, Sykes [5] proposed in a thorough review of intraplate tectonic processes, that ancient zones of weakness, such as sutured fracture zones, may be a decisive factor in governing the implementation of seismicity, magmatism, and other forms of intraplate activity. The purpose of the present paper is then three-fold: compile the intraplate seismicity of the Antarctic plate, and compare it quantitatively to that of other plates of various kinematics; interpret the mechanisms and stresses of the events involved; and interpret their location in the context of the known tectonic structures of epicentral areas.

Our results indicate that, while seismicity is mostly concentrated in the southeastern Pacific Basin, with only one major event outside it, the seismic energy release inside the Antarctic plate is comparable to that in other intraplate areas. They also suggest that the line of maximum age inside the southeastern Pacific Basin (which represents the wake of the nearby triple junction as it moves northward) is a preferential emplacement of seismicity probably due to weakness in the plate, created by the suturing accompanying the migration process.

In the Indian Ocean, an $M_s = 5.5$ earthquake north of Kerguelen Island can be correlated to magmatic activity in the vicinity of the Kerguelen-Heard hotspot, and suggests the presence of a "pipeline" structure of the type discussed by Morgan [6].

2. Catalogue of intraplate earthquakes in Antarctica, 1925–1980

The catalogue, listed in Table 1, and mapped in Fig. 1, was obtained through a systematic search of the following sources: NOAA epicentral tape (1920–1977), ISC Bulletins (1960–1978), NEIS-PDE Monthly Bulletins (1978–February 1980) and NEIS-PDE Weekly Bulletins (February–August 1980). The intraplate character of an event was assessed by requiring that it lie at least 2° away from the plate boundary of Antarctica, which was digitized from the USGS-NOAA map of the Earth seismicity.

As always the case for any seismicity study extending back a few decades, the detection capabilities have considerably improved with time, and the detection threshold of the catalogue is strongly inhomogeneous. This becomes even more true in the case of Antarctica, for which good station coverage was achieved only during the International Geophysical Year (1957-58) and became permanent only in 1963 following installation of the WWSSN network. At that time, the teleseismic detection threshold in the Antarctica plate decreased from $M \simeq 6$ to $m_b \simeq 4.9$.

In addition, Rothé [2], quoting Lander, lists six earthquakes occurring in 1957 in the Antarctic continent and Ross Sea. No estimate of their magnitude is given; none of them was recorded by more than 6 stations or outside Antarctica; three of them are labelled "dubious". We have not incorporated these events in the catalogue, since they were most probably below the $m_b = 4.9$ threshold. For the same reason, a 1968 event ($m_b = 4.3$) reported by Kaminuma [7] in the vicinity of the Weddell Sea, has been left out.

As will be discussed more in detail in the next section, there is virtually no body-wave travel-time control on depth for most events in the catalogue. Depths listed as "33 km" are particularly meaningless in an oceanic environment. Only in the case of detailed studies of major events (e.g. [3,4], event 17 below), have estimates of epicentral depths been obtained. We have therefore chosen not to list any source depths in the catalogue.

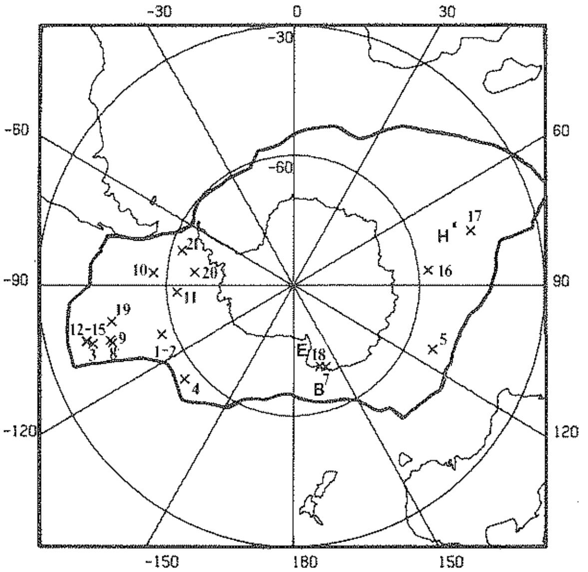

Fig. 1. Intraplate seismicity of Antarctica, 1925–1980. Crosses are individual epicenters, with numbers referring to Table 1. The thick line is the boundary of the Antarctic plate. Azimuthal equidistant projection centered on South Pole. Active intraplate volcanoes are identified by letters (*E* = Erebus, *H* = Heard, *B* = Buckle [Balleny] Island).

3. Relocations.

Relocations were carried out for all events prior to 1963, using the Jeffreys-Bullen Tables, and P arrival times listed in the ISS Bulletins. (In the case of events 1 and 2, S times were used.) In the absence of stations at close distances, these relocations are characterized by a quasi-perfect trade-off between origin time and depth, which brings in a singularity if depth is allowed to vary. Consequently, we chose to constrain the depth while carrying out relocations. An attempt was made at obtaining an estimate of the

TABLE 1

Intraplate seismicity of Antarctica, 1925–1980

Event No.	Date	Bulletin listing (NOAA-NEIS)			Magnitude	Relocation				Remarks
		origin time	lat. (°N)	long. (°E)		lat. (°N)	long. (°E)	origin time	r.m.s residual (s)	
1	27 Dec 1926	08:42:55	–57	–110	6 (PAS)	–56.8	–109.0	08:43:27		
2	27 Dec 1926	09:20:30	–57	–110	6 1/4 (PAS)	–56.8	–109.0	09:20:41		
3	12 Mar 1927	18:44:32	–41	–106	6 1/2 (PAS)	–39.4	–104.8	18:44:39.3	7.2	same as 12
4	13 Aug 1937	11:47:38	–56.5	–130	6 (PAS)	–57.4	–129.9	11:47:38.0	1.5	
5	24 Dec 1947	05:22:00	–54	114	7 (PAS)	–54.4	110.2	05:21:46.1	1.3	Indian Ocean interplate event
6	18 Jan 1949	04:43:18	–44.5	–90.5		–42.4	–90.8	04:43:33	1.8	
7	20 Apr 1952	09:37:03	–69.9	157.7		–69.8	157.9	09:37:09.0	1.0	
8	4 Dec 1956	10:07:54	–45.5	–106.6	6 1/4 (PAS)	–45.4	–107.3	10:07:55.7	0.9	normal faulting
9	28 Jan 1961	14:06:12.6	–45.1	–106.4	6 1/4 (MAT)	–45.0	–106.5	14:06:10.5	1.3	
10	17 Jan 1967	21:11:00.8	–57	–85	5.3 m_b					ISC
11	6 Jun 1970	06:14:11.9	–62.6	–93.3	4.9 m_b					
12	9 May 19171	08:25:01.7	–39.78	–104.84	6.2 m_b; 6.0 M_s					studied by Forsyth [3]
13	9 May 1971	08:53:25.9	–39.74	–104.93	5.2 m_b					aftershock of 12
14	9 May 1971	18:00:59.9	–39.84	–104.89	5.4 m_b					aftershock of 12
15	9 May 1971	18:35:09.8	–39.72	–104.98	5.4 m_b; 5.4 M_s					aftershock of 12
16	20 Mar 1973	18:13:24.8	–57.92	83.57	5.4 m_b					
17	3 May 1973	23:11:05.7	–46.14	73.20	5.5 m_b; 5.5 M_s					see section 6
18	15 Oct 1974	07:31:42.0	–70.52	161.53	4.9 m_b					
19	11 Jan 1976	23:22:40.5	–46.48	–101.07	5.6 m_b; 5.0 M_s					
20	5 Feb 1977	03:29:18.9	–66.45	–82.58	6.2 m_b; 6.4 M_s					studied by Okal [4]
21	7 Nov 1979	11:31:49.6	–62.58	–72.91	5.1 m_b					PDE

out ← 4
out Ind. ← 5
← 6
cont! ← 7

Ind. Oc. ← 16, 17
cont. ← 18

11 confirmed
2 (1926) casualties
1 < 2° 1937
3 Ind. Ocean

2 continents
1 undoc. (1967)
1 confirm. cont!

TABLE 2

Depth-constrained relocations of event 9 (28 January 1961)

Constrained depth (km)	Relocation epicenter		Origin time	r.m.s. residual (s)
	lat. (°S)	long. (°W)		
1	45.00	106.47	14:06:09.0	1.3
5	45.00	106.47	14:06:09.7	1.3
10	45.00	106.47	14.06:10.5	1.3
20	45.00	106.46	14:06:12.0	1.3
30	45.01	106.45	14:06:13.4	1.2
50	45.02	106.43	14:06:15.6	1.2
70	45.04	106.41	14:06:17.8	1.1
200	45.15	106.22	14:06:31.3	0.9
650	45.69	105.39	14:07:08.9	2.1

hypocentral depths by minimizing the root-mean-square (r.m.s.) residuals for relocations involving different values of the constrained depth, following the technique of Kanamori and Miyamura [8]. As shown in the example in Table 2, which involved 11 stations, this proved futile: The r.m.s. residual remains on the order of the precision of the reported readings (1 second) for all physically acceptable depths, and starts increasing only for the deepest solution, totally unjustified for an intraplate event. We must therefore conclude that the depth of the events in the catalogue is not constrained by the available teleseismic data. We have chosen to give origin times for relocations at a depth of 10 km (except for the continental event 7 : $d = 33$ km), which is a relatively general value reported for oceanic intraplate events [3,9,10].

In relocating events 1–6, 8 and 9, we used a number of starting epicenters, including locations on the nearest plate boundary, in order to reassess their intraplate character. In all cases, except event 6, the epicenter moved away from the boundary region. We delete event 6 from the catelogue, since the relocated epicenter lies less than 1° from a transform fault of the Chile Rise [11].

Relocations used an iterative scheme, and the program included the possibility of eliminating stations with anomalously large residuals (usually greater than 10 seconds) or with emergent arrivals. The following is a detailed discussion of the relocation results in the context of the local bathymetry [11].

Events 1 and 2, 27 December 1926. The available P data is extremely poor. Three impulsive S times were used. The relocation moves the epicenter 1° to the east, a figure probably not significant given the quality of the data. The epicentral area is about 1° north of the Eltanin fracture zone system, and the earthquakes may have been located on it.

Event 3, 12 March 1927. Although their quality was systematically less than average, all relocation efforts moved this epicenter to the area of 39°S, 105°W, where the 1971 sequence studied by Forsyth [3] occurred. As noted by Bergman and Solomon [12], this epicenter could lie on the proposed Fernandez fracture zone, although the local bathymetry is not well known. The event's surface-wave magnitude at Pasadena ($6\frac{1}{4}$) suggests that the 1971 event may be a repeat of the 1927 earthquake. The tectonic implications of this suggestion are discussed in section 4.

Event 4, 13 August 1937. Relocation of this event moves it 1° south, to a point grossly equidistant from the Udintsev and Tharp fracture zones. No other bathymetric features are known in this relatively poorly chartered area.

Event 5, 24 December 1947. This Indian Ocean event is the largest recorded inside the Antarctica plate (M = 7). A large discrepancy exists between the NOAA epicenter (54°S, 114°E) and the ISC one (55°S, 112°E). The event was relocated at 55.3°S, 112.2°E by Stover [13], who mentioned its unusual location and magnitude. By using only stations with impulsive arrivals reported to the ISS, we obtain an epicenter at 54.4°S, 110.2°E; use of a larger data set of arrivals would not move it significantly. Since this event is the only one of its type in the Indian Ocean, it is extremely important to establish its intraplate character unambiguously; despite a less-than-average quality for the relocation, all efforts to move this event to the nearby ridge failed. The bathymetry of the ridge and the magnetics in the area are well-documented (J.K. Weissel, unpublished results), and the epicenter is found to lie about 4.5° south of the Southeast Indian Ocean Ridge, in an area where the age of the lithosphere is about 15 m.y. It is located in the immediate vicinity of a major fracture zone system.

Event 6, 18 January 1949. All relocation efforts move this epicenter to a location (42.4°S; 90.8°W) in the immediate vicinity of an active transform fault part of the Chile Rise system. This event is, therefore, most probably interplate and we delete it from the catalogue.

Events 7, 20 April 1952, and 18, 15 October 1974. These are the only two events in the catalogue occurring in continental Antarctica. Since event 18 is recent, only event 7 was relocated, using a depth of 33 km. It was found that the two epicenters of events 7 and 18 are definitely distinct and separated by about 200 km. They lie in the general area of Oates Coast, on the western slope of the Antarctic Range.

Events 8, 4 December 1956, and 9, 28 January 1961. Relocation for both these events moves the epicenter to an area approximately 5° east of the East Pacific Rise, with no known major bathymetric features.

4. Energy balance of the seismicity of the Antarctica plate

The major feature of the seismicity of the Antarctica plate outlined by our results is the concentration of most epicenters in the southeastern Pacific Ocean section of the plate, where approximately 50% of the seismic energy release occurs: with the exception of the two Kerguelen-Gaussberg Plateau events of 1973, which are discussed below, seismicity is notably absent from the West Indian and South Atlantic parts of the plate, as well as from the southwestern part of the Pacific Ocean Basin. Only one major event (event 5) was reported in the East Indian Ocean part of the plate.

Using Gutenberg and Richter's [14] energy-magnitude relation, we computed the total seismic energy release in the plate over the 55 years covered by our study, to be 3.2×10^{22} ergs. Since most of the energy is contributed by older events, this figure is probably accurate to only ±50%. Still, it is interesting to compare these results with the intraplate seismicity of other plates, especially Africa, another continent-bearing plate, whose absolute motion with respect to the mantle is also very slow [15], and surrounded mostly be spreading ridges. Over the same period of time, the energy release in the African plate, estimated from Gutenberg and Richter's "Seismicity of the Earth" [16], and the data summarized in Sykes' review [5], is 7.3×10^{22} ergs. This converts into an average yearly release per unit area of 1.0×10^{13} ergs $\mathrm{yr}^{-1}\ \mathrm{km}^{-2}$ for Antarctica and 1.7×10^{13} ergs $\mathrm{yr}^{-1}\ \mathrm{km}^{-2}$ for Africa. These two figures are very comparable. Furthermore, a large part of the seismicity of the African plate is confined to the active East African Rift, and a figure of only 2.7×10^{22} ergs is obtained for the remainder of the plate. If we assume that ridge-push plays a preponderant role in creating stresses inside the plates, we can compute the yearly energy release per unit effective length of ridge bordering the plate, and we obtain values of 3.4×10^{17} ergs $\mathrm{yr}^{-1}\ \mathrm{km}^{-1}$ for Antarctica and 2.3×10^{17} ergs $\mathrm{yr}^{-1}\ \mathrm{km}^{-1}$ for Africa, using the geometrical parameters listed by Forsyth and Uyeda [17]. These figures show that, far from being aseismic, the Antarctic plate releases just about the same amount of energy per unit length of surrounding ridge, as does Africa, whose kinematics and size are similar. Comparison with the Nazca plate in which only five major events were recorded since 1925 (total energy release: 1.6×10^{21} ergs; or 0.2×10^{13} ergs $\mathrm{yr}^{-1}\ \mathrm{km}^{-2}$, or only 5×10^{15} ergs $\mathrm{yr}^{-1}\ \mathrm{km}^{-1}$ of effective surrounding spreading ridge) indicates that the Antarctic plate is substantially more seismic than this fast-moving oceanic plate, bordered both by spreading ridges and a subduction zone. We can thus refute the argument that Antarctica is stress-free because it is surrounded by ridges, or because of its slow absolute motion.

Most earthquakes in the Antarctic plate are concentrated in the southeast Pacific Basin, where spreading rates are fastest; the western Indian Ocean, and the extreme southern Atlantic Ocean Basin have no significant seismic energy release, and, significantly, these are regions where the spreading rates at nearby ridges, believed to control the state of stress in the plate, are extremely slow [15]. However, a major difference exists between the seismicity patterns in the Pacific and East Indian parts of the Antarctic plate: although the total energy release in both areas is very similar, it occurs in the form of one large earthquake (event 5) in the Indian Ocean, and several smaller events in the southeast Pacific. It is not possible to account for this different behavior on the basis of simple kinematic models involving spreading rates, since the half-spreading rate along the Southeast Indian Ocean Ridge is 3.5 cm yr^{-1} [15], almost identical to that along the Southeast Pacific Ridge in the vicinity of the Eltanin fracture zone system, which creates the stress responsible for the seismicity at epicenters 4, 8, 9, 20.

Thus, the character of intraplate seismicity appears to be governed not only by kinematic factors creating sufficient stress inside the plate, but more importantly by the ability of this stress to be released along zones of weakness, such as those defined by Sykes [5]. In this respect, it is important to realize that despite the existence of large systems of fracture zones in the southeast Indian Ocean Basin (J.K. Weissel, unpublished data), the nearby ridge has had a relatively smooth history since the Eocene, with none of the catastrophic ridge jumps and junction migrations that have characterized the southeast Pacific [24]. A detailed study in the next section will suggest that the wake of a triple junction in the southeast Pacific Basin is a zone of weakness; on the other hand, the fewer such zones in the Indian Ocean part of the plate may explain stress release through larger events, of the 1947 type, relative to the southeastern Pacific Basin, and to other plates, such as Africa, which has a long history of intraplate tectonism, and is scarred with weak zones [5].

Finally, the relocation of event 3 at the epicenter of the 1971 shocks suggests a pattern of recurrence with a period of 45 years. This provides us with a quantitative estimate of the rate at which intraplate stress is released at one particular site, and of the deformation incurred by the plate in this process. Most recent studies of oceanic intraplate earthquakes have suggested that the stresses involved are comparable to world-wide averages [4,18]; if so, using Geller's [19] scaling laws, we can estimate the displacement accompanying the 1971 event at about 10 cm. This translates into 0.15 cm yr^{-1} horizontal compression. This estimate is very small – only about 2% of the rate of increase of the width of the Antarctic plate between the Pacific and Chile Rises [15]. This important result indicates that very little deformation of the plate occurs during the process of intraplate stress release. For kinematics studies, the plate can be considered as rigid, as opposed to other situations, such as the Ninetyeast Ridge area of the Indo-Australian plate, where a much higher rate of deformation led Stein and Okal [20] to propose a two-plate model.

It remains that the seismicity of continental Antarctica is lower than that of any comparable land mass, with the exception of central and western Siberia, west of the Verkhoyansk Range. Both Antarctica and Siberia are located on slow moving plates, an argument which would corroborate Wesnousky and Scholz's [21] model, emphasizing the role of the craton in the development of continental seismicity. However, the case of Africa, whose western (tectonically stable) part is indeed seismic despite a very slow absolute velocity of the African plate, proves that other factors (potentially including weakness due to a past history of tectonism) play a crucial role in the level of seismicity inside a continental mass.

5. Tectonic interpretations of the seismicity of the southeast Pacific Basin

Events 12 and 20 have been studied in detail by Forsyth [3] and Okal [4], who attributed their compressional mechanisms to ridge-push from the nearby ridges.

Other major events in the southeastern Pacific Basin are concentrated on the flanks of the East Pacific Rise (events 1, 2, 4, 8, 9). The focal mechanism of these old events is very difficult to constrain.

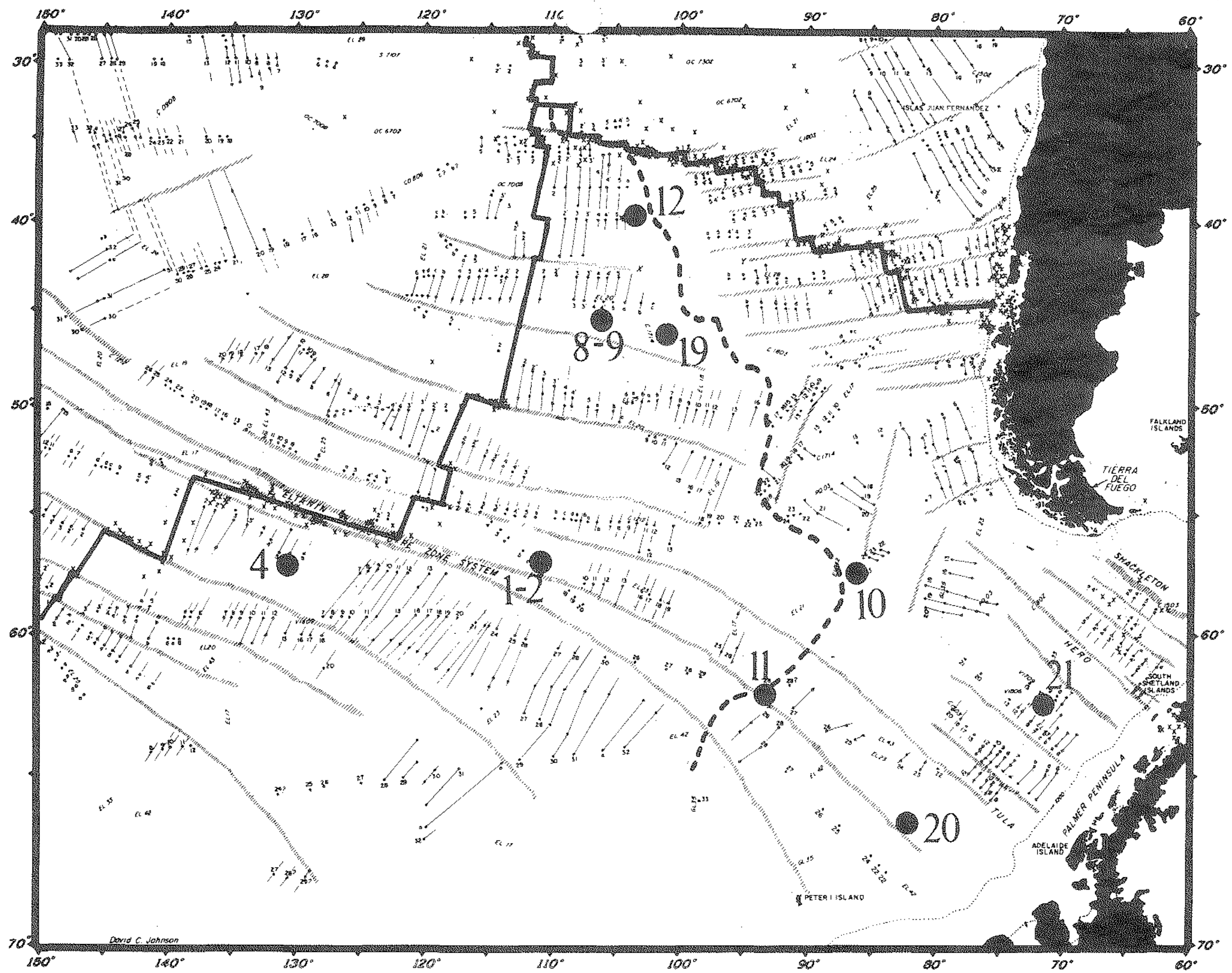

Fig. 2. Seismicity of the southeastern basin of the Pacific Ocean, plotted on the magnetic anomaly map of Weissel et al. [23]. The thick full lines are the boundaries of the plates in the basin (occasionally simplified, e.g. in the area of the Eltanin fracture zone system). The dashed line is the line of maximum age in the plate, as explained in text, obtained from the magnetic data. Individual epicenters are shown by dots, with numbers referring to Table 1; epicenter 12 also represents events 3 and 13–15. Note the correlation between epicentral locations and zones of weakness, including fracture zones and the line of maximum age.

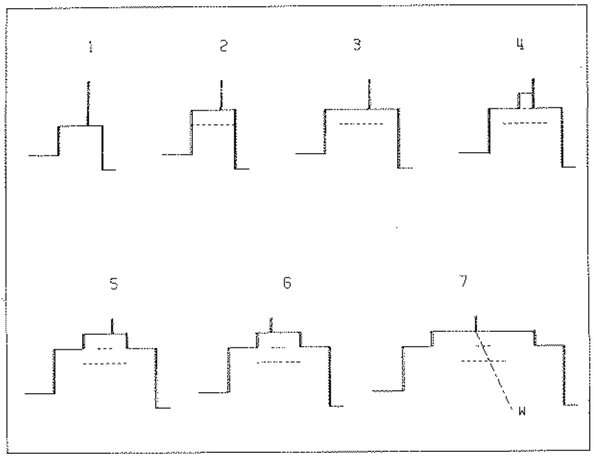

Fig. 3. Possible steps in the evolution of a RFF triple junction, leading to the development of a wake. Spreading rates are one velocity unit on the two lower ridges, and two units on the upper ridge. (1) Initial position. (2) Boundary jump northward, leaving triple fracture inactive (dashed line). (3) Spreading episode (one time unit); note scar of previous triple fracture isolated in middle of plate (dashed line). (4) Partial jump of triple fracture northward, creating unstable RRF junction. (5) Evolution into RFF junction during spreading episode (one time unit); note second scar in lower plate. (6) Ridge jump on upper ridge, with no effect on triple fracture scars in lower plate. (7) Spreading episode (two time units), note formation of wake behind the triple junction (dash-dot line "W").

One exception is event 8, for which all P-wave reports to the ISC, but two, are dilatational (one of the two compressions, surrounded by dilatations, is clearly wrong). This indicates a predominantly normal mechanism. An estimate of the age of the lithosphere from the models of Herron [22] is 8 m.y. This observation, and the compressional mechanism of the 1971 event, would indicate that the boundary between the tensional and compressional regimes in the plate runs close to the 10-m.y. isochrone, at the young end of Sykes and Sbar's [23] estimate of 10–20 m.y., obtained from observations in other ocans. Finally mechanisms for other events in the southeast Pacific Basin (events 10, 11, 19, 21) could not be obtained because of their small magnitude.

The emplacement of the older epicenters with respect to the bathymetry was discussed in the relocation section above; for more recent events, Bergman and Solomon [12] have found little correlation between epicenters 11 and 19 and the known bathymetry; no correlation is evident for event 21. Epicenter 10 lies in a small trough, which may have tectonic significance.

It is tempting, however, to associate epicenters 12, 10, 11 and 19 with the line of maximum age in the plate. In doing so, we use the map of magnetic lineations, published by Weissel et al. [24] (see Fig. 2), and draw a line of maximum age with respect to motion in a direction perpendicular to the magnetic lineations. It represents the locus of the ancient positions of the triple junction of the Pacific, Antarctic and Nazca (Farallon) plates, as it inched its way northward starting about 60 m.y. B.P. Correlations with epicenters 10 and 11 are excellent. Epicenter 12 lies in a zone of relatively quiet magnetics (anomalies 5–6) and is within 1° of the line. Epicenter 19 is somewhat off the line, as drawn from Weissel et al.'s model. However, their isochrones in this region are interpolated over as much as 20 m.y., during a time in the early Oligocene when these authors argue that a small fourth plate had to be present to account for otherwise highly asymmetric spreading patterns. This plate would have made the plate boundary in this area more complex than a simple triple junction. Furthermore, as shown in Fig. 3, the migration of an RFF-type triple junction through a series of jumps will leave a wake consisting of a number of sutured fracture zone segments, whose length in the center of the plate will be proportional to the length of time the triple junction was active at any given location (typically a few million years, or at present rates, a few hundred kilometers). This is the width which should be given to the triple junction's wake. To this degree of precision, the correlation of the line of maximum age in the plate with the emplacement of epicenters 12, 10, 11 and 19 is excellent.

Since the wake of the triple junction consists of individual fragments of fracture zones which are sutured at the time of the migration of the junction, they may retain a character of weakness for the same reason as more conventional fracture zones do [5]. However, because of their limited geographical extent, they may not be as readily identifiable in the bathymetry as the major fracture zones systems. On the basis of the evidence encountered in the Antarctic plate, we propose that the wake of the triple junction, advancing NNW, is a zone of preferential stress

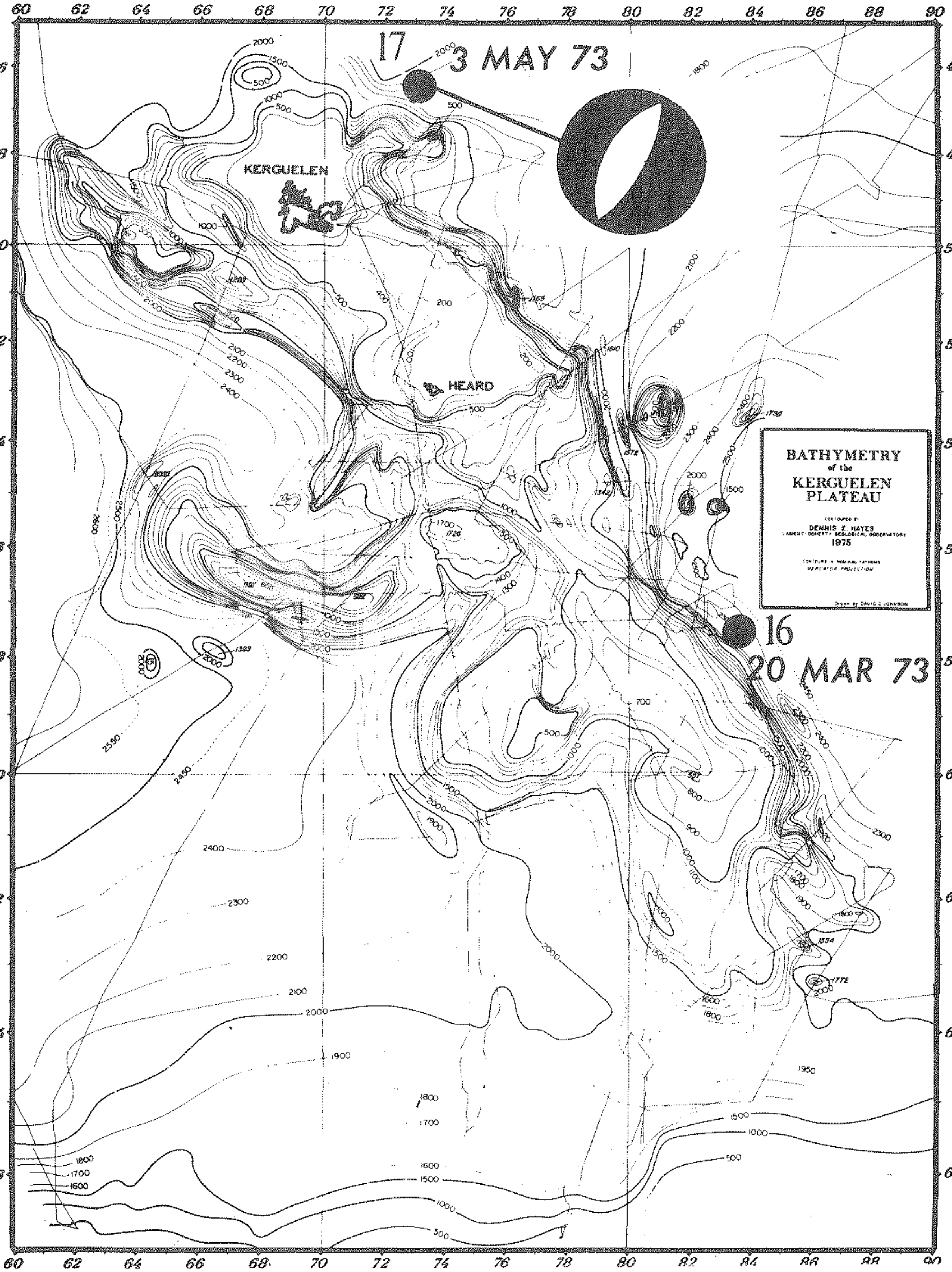

Fig. 4. Epicenters in the Kerguelen area, plotted on bathymetry map from Houtz et al. [25]. Numbers refer to Table 1. Focal mechanism of event 17 is sketched.

release, in addition to other zones of weakness, such as major fracture zones. It is interesting to note that in the Nazca plate, intraplate seismicity is emplaced either on a fossil ridge (1944, 1972) or on a line of maximum age (1965), as mapped by Herron [22]. This case, however, is somewhat different, since it involves a sharp age discontinuity across the line, but it also involves a ridge jump and a suturing process. The 1965 event studied by Mendiguren [9] occurred near the intersection (and offset) of this line by the Mendaña fracture zone, a location of double potential weakness.

6. The Kerguelen Ridge earthquakes of 1973

The only recent events in the catalogue belonging to the Indian Ocean part of the Antarctic plate (events 16 and 17) occurred in 1973, on the eastern flank of the Kerguelen-Gaussberg Plateau (see Fig. 4). The origin of this feature has long been debated, although recent studies [25–27] show that the island is oceanic in origin, with maximum isotopic ages of early Miocene/late Oligocene. The islands are interpreted as the result of large-scale magma generation, by a hotspot over which the motion of the Antarctic plate is extremely slow, and its direction ill-constrained in accordance with most plate tectonics models [15]. The only presently active volcano on the plateau is Heard Island [28]. This is probably the present location of the hotspot, in agreement with Watkins et al.'s [25] observation that volcanism on Kerguelen appears to have migrated southward with time, although Houtz et al. [26] have suggested that the hotspot moved slowly northward with respect to the plate.

Both 1973 earthquakes occurred on the eastern slope of the plateau. Despite a reported m_b of 5.4, the 20 March event (event 16) was poorly recorded, did not generate workable surface waves, and could not be significantly investigated. Only five compressional, first arrivals were obtained at selected, high-gain, WWSSN stations. On the contrary, the 3 May event ($m_b = 5.5$; $M_s = 5.5$) gave rise to substantial surface waves, and was studied using the techniques described by Okal [4]: P-wave first motions, insufficient to resolve the mechanism, are used as constraints in a computer search of focal solutions offering the best match to the amplitudes of Rayleigh and Love waves, equalized using the technique of Kanamori [29]. A summary of the data used in this study

TABLE 3

Seismic records used in the study of event 17

Code	Station	Distance (°)	Azimuth (°)	P-wave first motion	Surface waves used
KOD	Kodaikanal, India	56.37	5.1	down	
MAT	Matsushiro, Japan	101.06	48.2		L, R
GUA	Agana, Guam	87.49	67.7		L, R
MUN	Mundaring, Western Australia	35.78	82.2		R
PMG	Port Moresby, New Guinea	72.14	85.1	down	
MIR	Mirnyi, Antarctica	23.00	160.1	up	
SPA	South Pole, Antarctica	43.96	180.0		L, R
BHP	Balboa Heights, Canal Zone	136.17	220.5		R
CAR	Caracas, Venezuela	130.90	236.2		L
WIN	Windhoek, Southwest Africa	50.72	277.7	down	L, R
PRE	Pretoria, South Africa	41.01	283.9	down	
NAI	Nairobi, Kenya	54.94	313.4	down	
TAN	Antananarivo, Madagascar	34.43	313.5	down	
IST	Istanbul, Turkey	95.51	327.9		L, R
SHI	Shiraz, Iran	77.89	341.6	down	L
KEV	Kevo, Finland	120.56	343.0		R

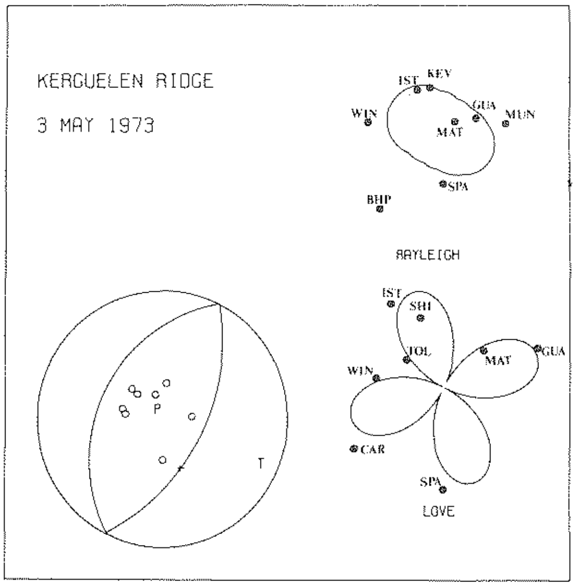

Fig. 5. Focal mechanism of event 17. Left: Lower-hemisphere stereographic projection of first motion P-wave data. Plus symbols are compressions, open circles dilatations. Faults planes obtained from surface-wave analysis. *P* and *T* are projections of compression and tension axes, respectively. Right: Theoretical radiation patterns of equalized surface waves for final mechanism. Individual dots, with station codes referring to Table 3 are observed equalized amplitude values.

is given in Table 3. Records were first low-passed filtered (excluding frequencies $\nu \geqslant 0.022$ Hz) to make the process less sensitive to lateral heterogeneity in the shallowest layers of the Earth, as discussed by Mendiguren [9] and Okal [4]. An estimate of the focal depth is then obtained by minimizing the r.m.s. residual to the fit of equalized and theoretical amplitudes. Results, shown in Fig. 5, indicate normal faulting (slip = 269°), along a plane striking 206°, and dipping 36° to the west. This solution is somewhat different from that proposed by Bergman and Solomon [12]. The difference may be due to the fact that we used only high-magnification stations (50 K or better) for our first-arrival picks. The use of stations with lower magnifications may often result in the loss of the first impetus of the wave [10]. Also, these authors could not constrain the second plane of the mechanism; in any case, their solution cannot be compatible with the equalized surface-wave radiation pattern. The surface wave moment obtained was $M_0 = (1.4 \times 10^{25} \pm 25\%)$ dyn cm, or $M_W = 6.0$ [30]. The combination of $M_s = 5.5$ and $M_W = 6.0$ indicates a relatively slow release of energy, with an apparent stress $\eta\bar{\sigma}$ of only about 3 bars [31]. This result is in agreement with the fact that this event generated observable surface waves, whereas event 16 did not, despite very similar body-wave magnitudes.

The depth of the event was obtained as 45 ± 10 km, which is compatible with the ISC's estimate of 18 ± 20 km. A shallower depth in the range of usual oceanic foci (say 15 km or less) would not be compatible with the general Love-to-Rayleigh amplitude ratio, which is seen to be adequately matched in Fig. 5. Since this ratio is obtained at relatively low frequencies (typically 0.015 Hz), its use as a depth discriminant is not affected by possible lateral heterogeneity in the source area.

The tensional nature of event 17 is also in agreement with compressional P_n arrivals recorded at seismic stations operated on Kerguelen Island at the time of the event by the Terres Australes et Antarctiques Françaises, and whose records were recently made available to us by the Laboratoire de Détection et Géophysique.

It should be noted that a rotation of the focal mechanism so as to align the direction of tension perpendicular to the tectonic direction of the Kerguelen Plateau, is impossible, since it would violate the Rayleigh-wave radiation pattern. In this respect, it is impossible to interpret this earthquake as due to glacial rebound, as Stein et al. [32] have proposed for deep normal events in the Baffin Bay.

On the other hand, we believe that the presence of a normal event, with relatively low stress, at a substantial depth below the flank of the plateau, is indicative of a zone of magmatic activity below the plate or in its deep layers. The epicenter of event 17 is about 800 km north of the hotspot's proposed location under Heard Island, and 400 km NNE from Kerguelen Island. This discrepancy may result from the "awakening" of a new volanic center northeast of Kerguelen. This would contradict the reported motion of the hotspot southward [25] but Féraud et al. [33] working in the Azores, as well as Batiza et al. [34] in the Gulf of California, have recently shown that the concept of linear progression of volcanism with age may not be valid on a small scale. Another hypothesis is that the seismic location at epicenter 17 may be part of the "pipeline" structure proposed by Morgan [6], through which the Kerguelen hotspot would feed the Indian Ocean Ridge in the vicinity of Amsterdam and Saint Paul Islands. Although Morgan's suggestion has yet to be confirmed, such a model could explain the low stress, normal mechanism and depth of event 17.

In the absence of complementary geophysical data, such as heat flow measurements, any further interpretation would be very difficult.

7. Earthquakes in Oates Land, Antarctica: events 7 and 18

Both of these events have been recorded by very few stations: seven P-wave observations were reported for event 7, and twelve for event 18. They did not generate readable surface waves, and their low magnitude prevents any focal mechanism studies. It is, however, important to try and replace them in the context of the lower-level seismicity on the Antarctic continent [7]. Apart from volcanic tremors in the area of Mount Erebus [35], small events have been identified in the Victoria Range of the Transantarctic Mountains [36], and in Adélie Land [2]. An $m_b = 4.3$ shallow event was detected in 1968 on the shore of the Weddell Sea [7]. The Ross Sea–Weddell Sea graben and the Transantarctic Mountains are remnants of the area of convergence between West and East Antarctica, about 40 m.y. ago [37]; the present seismicity indicates that tectonic processes are still active along this line, although at a very moderate level. The depth of event 18 is the only parameter of this event which could be constrained: second arrivals at South Pole and Windhoek, following P by 3.5 seconds, give a depth of 10 km, if interepreted as pP. This estimate is corroborated by the excitation of prominent Lg and Rg phases observed at faraway Antarctica stations [38]. Kaminuma [7] also reported a shallow depth for the 1968 event in the Weddell Sea area; thus, a relatively shallow depth seems to be a general characteristic of the seismicity of the Antarctic continent.

Event 18 is located in the vicinity of a line joining Mount Erebus to Balleny Islands, the only two active volcanoes in this part of the world [27]. This line has also been proposed by Morgan [6] as a pipeline feeding the Indian-Pacific Rise from the Erebus hotspot. In view of the shallow depth of event 18, any further speculation on the possible correlation between this proposed feature and the seismicity of Oates Coast is clearly unwarranted.

8. Conclusion

A compilation of intraplate seismicity in the Antarctic plate over a period of 55 years shows that this plate is as seismic as other continent-bearing, slow-moving plates, such as Africa. In this respect, it is impossible to establish a correlation between the slow motion of Antarctica and its level of seismicity. As shown previously [3,4], tectonic stress is definitely generated at the ridges along its borders, and is released at a rate comparable to that in other plates.

The emplacement of seismicity in the Pacific Ocean area suggests that, along with sutured fracture zones, the line of local maximal age in the Antarctic plate is a zone of weakness, preferential for seismic energy release.

In the Indian Ocean, a relatively deep, tensional event of $M_s = 5.5$ shows low stress, suggesting a volcanic origin. It may be associated with a magma structure of the pipeline type proposed by Morgan.

Acknowledgements

Guillaume Auquier helped in the early stages of this research. I am grateful to Bernard Minster for discussion, to Eric Bergman and Sean Solomon for a preprint of their paper, and to colleagues at Lamont-Doherty Geological Observatory for permission to use their marine maps in Figs. 2 and 4. Jeffrey Weissel kindly made available his latest work in the Indian Ocean. This paper benefited from constructive reviews by Lynn Sykes and an other reviewer. This study was supported by the Office of Naval Research, under contract N00014-79-C0292.

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