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Slow earthquakes along oceanic fracture zones: evidence for asthenospheric flow away from hotspots?

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The regime of strain release along transform faults of the Mid-Oceanic Ridge system is studied. It is shown that earthquakes along certain fracture zones exhibit systematic discrepancies between values of their magnitudes measured at short and long periods, implying a regime of slower strain release, also observed in a pattern of complex body waveshapes. These "slow" fracture zones do not correlate with simple geographic or kinematic properties, but usually occur in the neighborhood of hotspot volcanism, frequently also characterized by gravity and bathymetry anomalies. We propose that regimes of slow strain release may be due to a partial lubrication of the fault along these fracture zones, which may itself be due to asthenospheric flow from the nearby hotspots, along the pattern of pipelines described by Vogt and Johnson and by Morgan.

1. Introduction

The problem of the origin of volcanism on oceanic islands is particularly complex in the case of islands located on, or in the immediate vicinity of, the Mid-Oceanic Ridge (MOR) system. Whereas in the case of intraplate hotspots, Crough [1] has shown that bathymetry and gravity are compatible with compensation at shallow depth (within the lithospheric plate), it has been recognized for almost a decade that swells and gravity anomalies along the MOR require deeper compensation [2,3], a feature suggesting that the origin of the swells on which most MOR hotspots are located, lies in a deep convective pattern below the plates. Even in cases when individual hotspots (such as Iceland or Azores) may be compensated at shallow depths, deeper anomalies are necessary to account for the overall elevation of the MOR [4].

In this general framework, Vogt and others (e.g. [5]) proposed that "pipelines" of asthenospheric flow may extend along the MOR system, away from hotspots, in particular in the area located between Iceland and the Gibbs Fracture Zone. Geophysical and geochemical evidence is indeed available to support the existence of such a longitudinal pipeline [6,7]. Later, Morgan [8] extended this concept to the case of an intra-plate hotspot (e.g. Galapagos or Reunion), where the pipeline structure is then transverse to the MOR system. Specifically, he interpreted both the spatial progression of the age of volcanism in the Galapagos area and the geochemical gradient pattern among the islands to propose a second kind of hotspot island, generated at the MOR, at the mouth of a pipeline feeding it from a nearby hotspot: because the azimuth of the volcanic chain involved is not compatible with absolute plate motions, it is not possible to account for the formation of oceanic islands such as Darwin or Rodriguez by a stationary hotspot model, while the geochemical evidence requires generation from an undepleted reservoir. As pointed out by Morgan himself, his "pipeline" model is hypothetical, and additional geophysical and geochemical data are needed to confirm or infirm its validity. Recently, Vink and Morgan [9] have used paleomagnetic evidence for a ridge jump in the northern Atlantic, to propose that such a pipeline was involved in the generation of the Iceland-Faeroe Plateau, at a time when Iceland was an intra-plate hotspot, and before it managed to trap the MOR to itself.

Most of the features proposed by Vogt and Johnson or Morgan are located in areas of strong bathymetry and gravity anomalies (e.g. Iceland, Azores, Bouvet, Rodriguez, Kerguelen). However, it is worth pointing out that no estimate of either the depth or the horizontal dimensions of the flows involved in the transverse pipeline model has been given by Morgan, although Vogt and Johnson have proposed estimates of 25–50 km for both variables in the longitudinal case.

In this paper, we report early results from a world-wide study of the conditions of strain release along fracture zones of the MOR system. They suggest that those fracture zones located at the mouths of the individual pipelines proposed by Morgan [8, p. 5359], in areas which also are in general the site of highs in bathymetry and gravity, are characterized by anomalously slow earthquakes; these events are reminiscent of the earthquakes studied by Kanamori and G.S. Stewart [10] on the Gibbs Fracture Zone (FZ) in the North Atlantic, a feature interpreted by Vogt and Johnson [5] as damming the longitudinal asthenospheric flow down the Reykjanes Ridge. Additionally, we report evidence for intra-plate seismicity along the proposed Kerguelen-Amsterdam pipeline, a pattern also present in the area of the Bouvet Island–Conrad FZ system, and compile petrological and geochemical data in this area which support Morgan's model. Although this does not constitute firm evidence for the structures proposed by Vogt and Johnson [5] or Morgan [8], it suggests that a pattern of lubrication of the faults, possibly created by the presence of an excess of magma, exists along these particular fracture zones. Such a pattern could be expected from the proposed models, due to a contamination of the MOR system by the pipe flow from the nearby plume. Details of our seismic investigations will be presented in full in another paper.

2. Slow earthquakes along the MOR system

Following Kanamori and G.S. Stewart's [10] observation of slow earthquakes along the Gibbs FZ, we addressed the question of the universality of this behavior [11]. Fig. 1 and Table 1 are an updated although still preliminary version of our global results. We have investigated post-1963 earthquakes with at least one reported magnitude larger than 6, along a series of long transform faults, and are currently in the process of extending this investigation to the entire MOR system. Specifically, we have identified the following eight fracture zone systems, along which earthquakes are characterized by slow release of energy, leading to M_s values as much as 1.4 units larger than m_b: Gibbs FZ (North Atlantic), Romanche FZ (Equatorial Atlantic), Conrad FZ, Bullard FZ and Bouvet FZ (South Atlantic), Rodriguez FZ and "Beta" FZ (in the nomenclature of J.K. Weissel, personal communication, 1980) (south-central Indian Ocean), and Balleny Islands ("Mu") FZ (Indian-Pacific Passage). On the opposite, earthquakes along most fracture zone systems exhibit comparable m_b and M_s values, indicating that strain release is taking place faster; typical examples of this behavior are the Challenger FZ (Pacific Ocean), the long fracture zone immediately to the west of the Prince Edward Island FZ, and a few other fracture zones in the southwest Indian Ocean, the "Epsilon" FZ (southeastern Indian Ocean), and the Kangaroo ("Iota") FZ in the extreme southeastern Indian Ocean. In some instances, such as the Doldrums FZ (Equatorial Atlantic), or the "Kappa" and "Lambda" FZ's (south of Australia), an intermediate trend was identified, with M_s slightly larger than m_b. Finally, the Eltanin FZ system in the southern Pacific, exhibits only small earthquakes, with either slow or fast characteristics. Values of the magnitudes reported in Table 1 were checked by the authors from individual records, and in the case of M_w, obtained from equalization of very-long-period multiple surface waves observed on WWSSN or IDA records following the technique of Kanamori [12]. In selecting symbols for Fig. 1, we have defined a regular (or fast) earthquake as one for which m_b, M_s and M_w differ by not more than 0.5 unit, and a slow earthquake

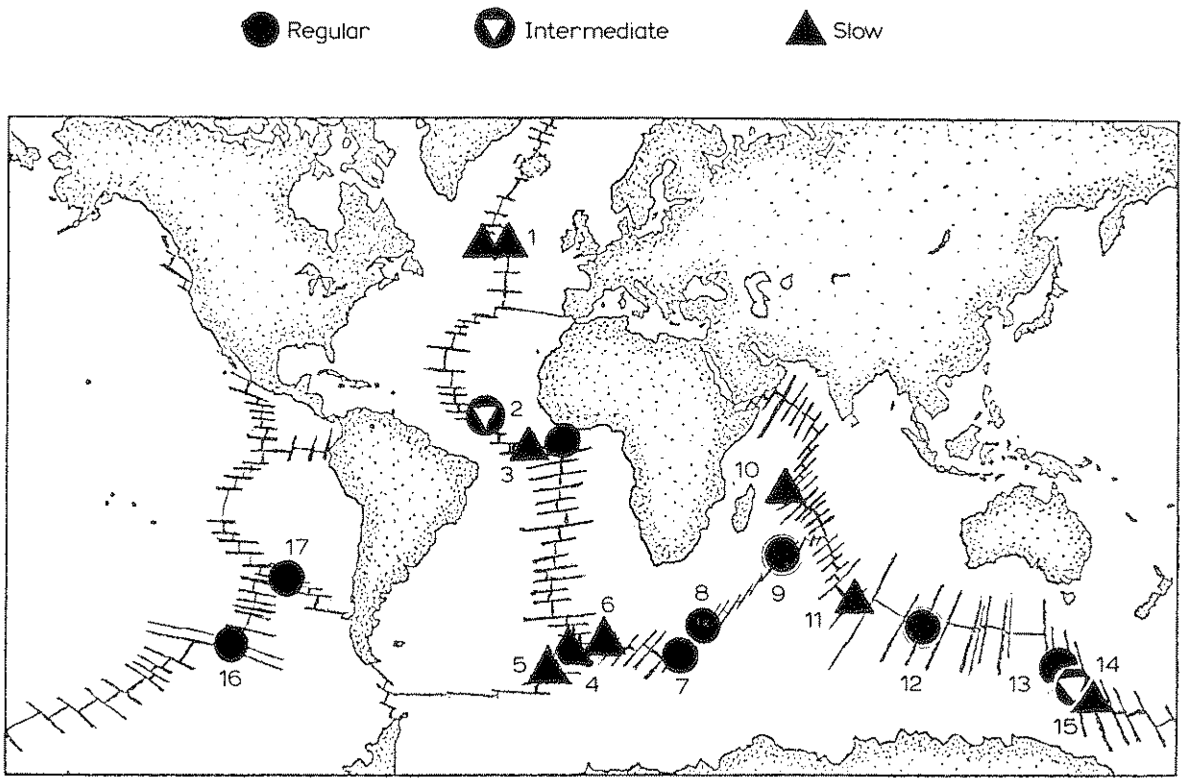

Fig. 1. Schematic Mercator projection map of the MOR system, with fracture zone earthquakes listed in Table 1. Symbols identify regular (fast), intermediate and slow events. Events described in text, but occurring outside transform faults, or not connected with plate motion (e.g. Azores, 1980), are not included. Numbers along fracture zones refer to Table 1.

as one for which they differ by 0.9 unit or more. However, in interpreting magnitude values in Table 1, it is important to keep in mind that due to finite rupture propagation along the source fault [13], the m_b scale, representing one-second energy, saturates around 6.2, whereas M_s, measured at 20 seconds, saturates around 8.2. The slow character of the events exhibiting $m_b : M_s : M_w$ disparities was confirmed by an analysis of body-wave shapes. Fig. 2 is a comparison of long-period P waves for slow and fast (regular) strain release; slow fracture zones exhibit complex wave shapes, with total strain release lasting as much as 60 seconds, while fast events have much simpler wave shapes. This difference in behavior is further demonstrated by the deconvolution results presented in Fig. 2B.

The geometric and kinematic data included in Table 1 preclude any correlation of the behavior of strain release with simple geometric or kinematic parameters, such as rate of spreading, length of transform fault, absolute velocity of the plates involved, or age gap across the fracture zone (this last parameter being a combination of the first two). Also, as shown in the last column of Table 1, the possibility that transform faults exhibiting slow earthquakes be "leaky", that is show a difference between their azimuth and that of the vector of relative motion of the plates, can also be excluded: no correlation is found between the regime of strain release, and the residuals between the relevant azimuths, as computed from Minster and Jordan's [14] model RM2. Thus, the regime of strain release appears to be controlled by local factors, rather than by the geometry or kinematics of the particular plate boundary involved. It is interesting, at this stage, to note that a similar

TABLE 1

Fracture zone and earthquake data

Transform fault	Date	Reference	Epicenter (°N, °E)	Magnitudes m_b	M_s	M_w	Transform fault length (km)	Total rate (cm/yr)	Azimuth residual (°) [14]
1. Gibbs	13 Feb 67	[10]	52.7, −34.1	5.5	6.5	6.9	350	2.2	1.5
	16 Oct 74	[10]	52.6, −32.1	5.9	6.9	7.0	350	2.2	1.5
2. Guinea	4 Apr 77		7.4, −34.9	5.8	6.0	6.5	350	3.4	
3. Romanche	5 Aug 71		−0.9, −22.1	6.0	7.0	6.9	800	3.8	4.9
	16 Aug 65		−0.5, −19.9	6.1	6.0		800	3.8	4.9
	15 Nov 65		−0.2, −18.6	5.8	6.3		800	3.8	4.9
	24 Jan 67		−0.8, −20.8	5.2	6.5		800	3.8	4.9
	28 Aug 73		−0.9, −22.1	5.8	6.8		800	3.8	4.9
4. Conrad	3 Jan 71		−55.9, −2.4	5.7	7,1	7.0	175	1.9	2
5. Bullard	7 Apr 73		−58.5, −13.6	5.5	6.7	6.8	450	1.9	4
6. Bouvet	18 Dec 78	[32]	−54.6, 2.1	5.4	6.5	6.9	175	1.6	2
7. SWIOR (23°E)	26 Oct 69		−53.4, 23.5	5.8	6.1				
8. P. Edward West	10 Nov 42		−50, 30	7.7 *	7.9	8.0	400+	1.6	1
	11 Nov 80		−52, 29	6.2	6.7	6.6 **	400+	1.6	1
9. SWIOR (60°E)	23 Jan 81		−30, 60	6.0	6.7		250	1.8	1
10. Rodriguez	28 May 73		−17.8, 65.6	5.0	5.9	6.4	280	4.7	
11. Beta	4 May 70		−41.6, 79.7	5.3	6.2	6.3	120	7.2	
	21 Nov 76		−41.6, 80.2	5.3	6.2		120	7.2	
	19 Feb 77		−41.3, 80.5	5.8	6.0	6.3	120	7.2	
12. Epsilon	1 Jun 73		−47.9, 99.7	5.9	6.1	6.3	100	7.5	
13. Kangaroo	11 May 76		−51.6, 139.8	5.8	6.2		230	6.8	
14. Kappa	25 Sep 73		−55.8, 146.5	5.9	6.3		90	6.7	
15. Balleny	18 May 76		−60.4, 154.2	5.3	6.2	6.2 **	330	6.3	6
16. Eltanin	4 Apr 71		−56.2, −122.5	6.2	6.6		950	8.9	0.5
17. Challenger	14 Apr 79		−36.0, −102.4	6.3	6.6	6.9	970	7.0	4–12

SWIOR = Southwest Indian Ocean Ridge.

* Long-period body-wave magnitude.

** Preliminary value.

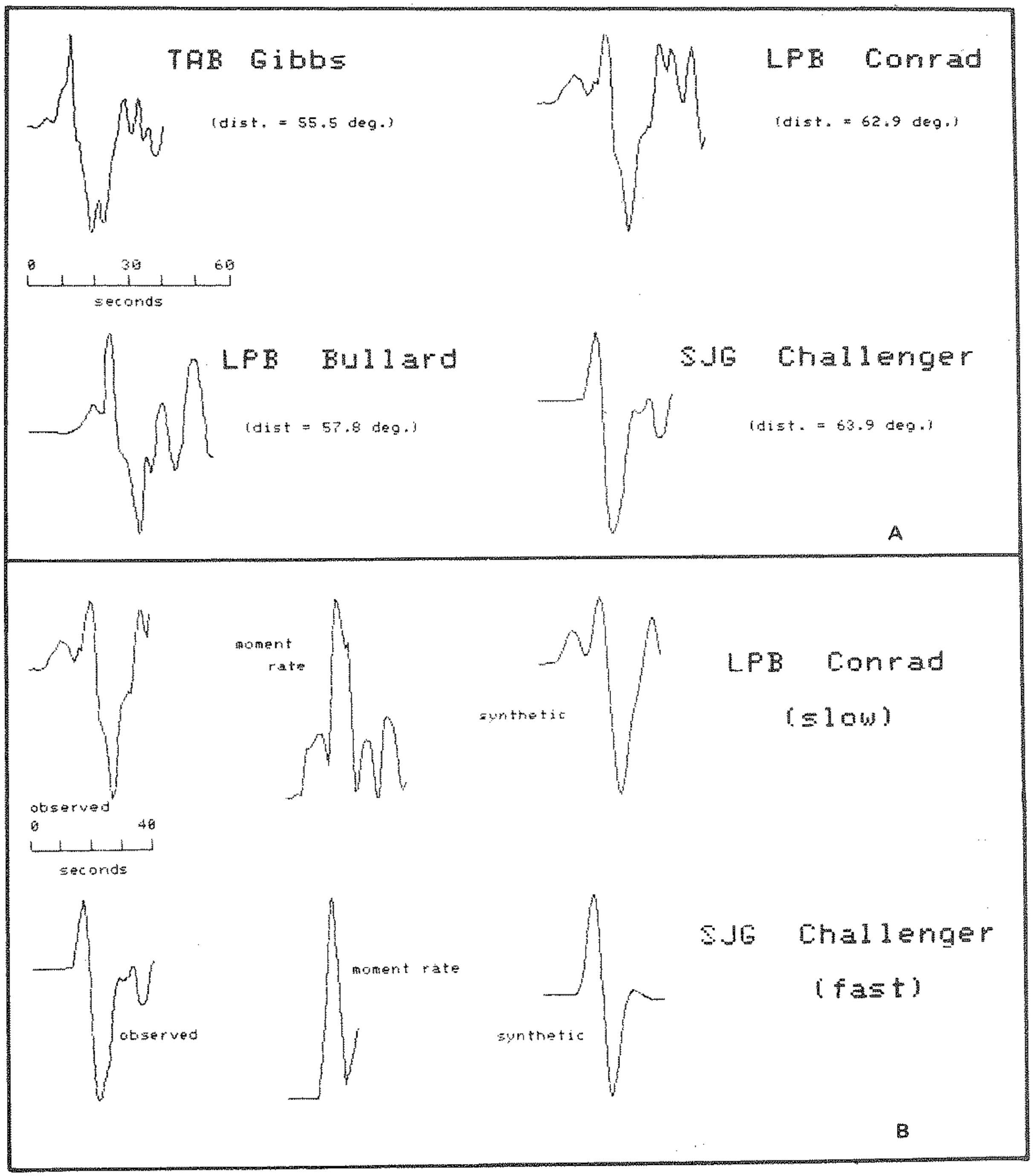

Fig. 2. A. Long-period P waves registered at selected WWSSN stations following earthquakes along the Gibbs (1967), the Conrad (1971), the Bullard (1973), and the Challenger (1979) Fracture Zones. Epicentral details given in Table I. Note that the first three events (all of the slow type) are characterized by complex waveshapes, whereas the fourth one (of the fast type) gives rise to a very simple waveshape. B. Examples of source deconvolution for two long-period P waves. Left: original seismogram; center: deconvolved moment rate; right: resulting synthetic. Note that an excellent fit is obtained for the Challenger event with a source lasting only about 15 seconds, whereas the Conrad event, clearly a multiple event, requires a source lasting at least 25 seconds.

conclusion was attained by Anderson et al. [2] in their investigation of bathymetry and gravity anomalies along ridge crests.

3. A case study: the southeast Indian Ocean Ridge

Fig. 3 is a map of the northern and southeastern sections of the Indian Ocean Ridge system, south of 15°S, based on bathymetry and magnetics by McKenzie and Sclater [15], the Geological Atlas of the World [16], and J.K. Weissel (personal communication, 1980). We have plotted on this map all earthquakes along these two branches of the MOR system, with at least one magnitude (m_b or M_s) larger than 5, for the period 1963–1977. Regular earthquakes, characterized by comparable values of m_b and M_s, and simple waveshapes, are plotted as solid circles. Only four events, plotted as solid triangles, were found to exhibit $m_b : M_s$ discrepancies; they are clearly clustered at two localities: one 1973 event occurred on a fracture zone east of Rodriguez Island (which we will call the Rodriguez FZ), and had $m_b = 5.0$, $M_s = 5.8$, $M_w = 6.4$; two events occurred in 1970 ($m_b = 5.3$, $M_s = 6.2$, $M_w = 6.3$) and 1976 ($m_b = 5.3$, $M_s = 6.2$) southeast of St. Paul and Amsterdam Islands, on the Beta FZ. A regular event ($m_b = 5.8$, $M_s = 6.0$, $M_w = 6.2$) also occurred in 1977 on the Beta FZ. Additionally, a major event, with dip-slip focal mechanism and slow behavior ($m_b = 5.6$, $M_s = 6.5$), occurred in 1975 on the ridge segment separating the Alpha and Beta FZ's. This is the only event to occur on a ridge segment of the MOR system in the southern Indian Ocean during 1963–1977 with an M_s greater than 5. The two clusters where slow earthquakes occur correspond exactly with the mouths of the pipelines proposed by Morgan [8] to explain the formation of secondary-type hotspots at the MOR: the Reunion to Rodriguez and Heard-Kerguelen to Amsterdam pipes. In proposing his pipe model, Morgan has argued that the strike of the Rodriguez Ridge extending from the southern tip of the Mascarene Plateau to the MOR could not be reconciled with the absolute motion of the African plate over a hotspot fixed with respect to the mantle, but rather represented the wake on the African plate of the extremity of a structure linking the Reunion hotspot (moving slowly southwest in a frame fixed to the African plate) and its closest point on the MOR system (moving relatively rapidly northeast in the same frame, due to ridge accretion). This area also corresponds to a significant bathymetric anomaly in the immediate vicinity of the MOR system. Morgan went on to speculate that a similar situation could exist in the Amsterdam-St. Paul area: Amsterdam would be the terminus of a pipe extending to the MOR system from the Heard-Kerguelen hotspot. Although no strong bathymetric anomaly is known in the relatively poorly chartered waters separating Amsterdam and Kerguelen, a strong positive gravity anomaly is well documented in this area [17], and we will review a variety of arguments which give strong support to Morgan's hypothesis: Amsterdam's age has been identified as belonging to the Brunhes period, and tentatively given as 0.2–0.4 m.y., whereas St. Paul is a younger island, where volcanism may be as recent as 0.04 m.y., with residual geothermal activity lasting to the present

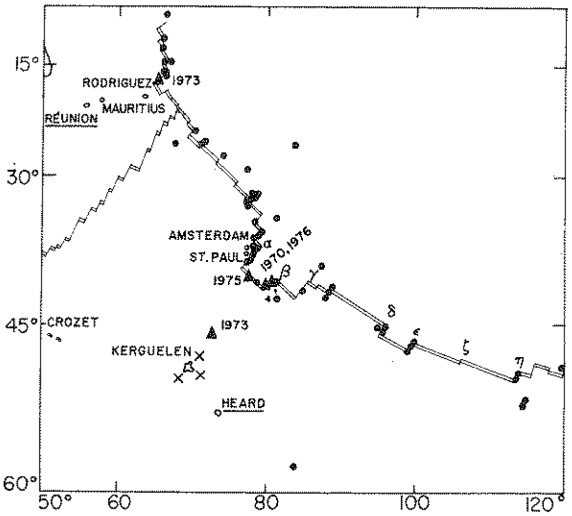

Fig. 3. Schematic map of the south-central Indian Ocean. The MOR is shown with fracture zones labeled according to J.K. Weissel's nomenclature (personal communication). Solid circles identify earthquakes which occurred along, or in the vicinity of, the northern and southeastern branches of the ridge during 1963–1977. Slow events, with year of occurrence, are identified by solid triangles. The name of islands with active volcanism is underlined. Crosses indicate local seismic foci detected by the Kerguelen network.

[18]. After some controversy in the early 1970's, the oceanic origin of the Kerguelen basalts is now well established [19], and the Kerguelen-Heard structure is interpreted as an oceanic hotspot. The petrology and chemistry of lavas from Amsterdam and St. Paul has been described by Girod et al. [20], Gunn et al. [21], and Hedge et al. [22]. St. Paul is characterized by tholeiites of various Al contents, enriched in Fe and Ti. Amsterdam has both high-Al lavas, similar in composition to basalts from the nearby MOR, and low-Al, high-Ti tholeiites, similar to Hawaiian tholeiites, and to basalts from the Galapagos Ridge [23]. Furthermore, $^{87}Sr/^{86}Sr$ ratios have been found to be anomalously high for MORB material: 0.7038–0.7040 on Amsterdam [22], and 0.7035–0.7068 on St. Paul [20,22]. These values are comparable to ratios characteristic of hotspot islands, and are higher than values obtained along the Southeast Indian Ridge (0.7034 [24]), and comparable to those on Kerguelen (0.7043–0.7058 [22]). This geochemical pattern is similar to that observed along the Reunion-Rodriguez feature [25], and indicates that Amsterdam and St. Paul basalts cannot share their origin with the local MORB, but rather must have a deep, undepleted, "hotspot-type" origin, consistent with Morgan's model. In addition to being the only sea-level volcanoes close to the MOR system in the region mapped in Fig. 3, Rodriguez and St. Paul and Amsterdam sit next to the only major indentations of the Indian plate into the African and Antarctic plates, characterized by a reversal of the offset of the ridge segment at major fracture zones, from left-lateral in the south to right-lateral in the north. Morgan has suggested that this reversal near Rodriguez may be the expression of ridge jumps, illustrating the reluctance of the MOR to being pushed away from its feeder hotspot by the expansion of the African plate. This pattern would be similar to the mechanism proposed for Iceland by Vink and Morgan [9]. However, a detailed magnetic profile by Schlich and Patriat [26] in the area located between Amsterdam and Kerguelen does not exhibit any major ridge jumps, and indicates that the indentation must be at least 32 m.y. old; although a comparison of the spreading rate obtained by these authors in the Antarctic plate and Minster and Jordan's [14] RM2 rate for the total spreading strongly suggests asymmetric spreading (an infinitesimal form of the ridge-jumping process [27]), this property is clearly present along most segments of the Southeast Indian Ocean MOR, and does not make the area between the Alpha and Beta FZ's peculiar along this section of the MOR. We must therefore conclude that even though the origin of the St. Paul indentation into the Antarctic plate may have been related to the Heard hotspot, it is now a passive feature. It is in this framework that we propose to interpret the clusters of slow earthquakes in the vicinity of Rodriguez and St. Paul as linked to the probable existence of the Morgan pipes. In section 5, we give a preliminary discussion of the mechanism which may lead to slow strain release in the presence of magmatic material.

Additionally, Okal [28] has identified and studied a 1973 intra-plate earthquake, located approximately 400 km northeast of Kerguelen. This earthquake similarly shows an increase in magnitude with period ($m_b = 5.5$, $M_s = 5.5$, $M_w = 6.0$), and is characterized by normal faulting, with the tensional axis directed along the strike of the Kerguelen-Gaussberg Plateau (Fig. 3). Although its depth was poorly constrained, this event could be substantially deeper than the foci of typical oceanic intra-plate earthquakes. More importantly, in terms of strain release regimes, this event differs fundamentally from the only other intra-plate earthquake detected teleseismically in the vicinity of the Kerguelen-Gaussberg Plateau, which had a comparable m_b, but practically no surface waves [28]. This slow earthquake, occurring in a portion of the plate aged approximately 25 m.y. [26], cannot be related to the major tectonic stress field in the plate, which most studies of intra-plate seismicity have found to be compressional and due to ridge-push in lithosphere of that age (e.g. [29]). Similarly, it cannot be due to a loading phenomenon, or to glacial rebound, because of the orientation of its tension axis. Low-level, local seismicity has also been detected by a four-station network of short-period vertical seismometers, operated on Kerguelen Island during 1973–1977 by the Terres Australes et Antarctiques Françaises. Preliminary results from this network indicate the presence of an area of repeated seismicity, about 100 km southeast of the island. Another seismic focus is also present at a similar distance to the northeast. A third, weaker, seismic center is located to the southwest of Kerguelen (see Fig. 3). We interpret the intra-plate seismicity in this area as the expression of a regional tectonic stress, unexplained in the framework of rigid plate tectonics, and propose that the $M_w = 6.0$ event of 1973 is associated with the asthenospheric process involved in the pattern suggested by the high-gravity, active island volcanism, and geochemical differentiation present in the Kerguelen-Amsterdam region. We believe that all these phenomena could be expressions of the "pipeline" structure proposed in this area by Morgan [8]. The low-level seismicity northeast and southeast of Kerguelen may also be related to this feature.

4. Other areas

In this section, we generalize our results to other MOR's, and show that those fracture zones which we have identified as exhibiting slow earthquakes are located in the vicinity of hotspots, do in general correlate well with strong bathymetric or gravity anomalies, and could be associated with pipelines of asthenospheric flow, either longitudinal [5], or transverse [8].

Gibbs Fracture Zone. This has been proposed as the terminus damming a longitudinal flow extending down from Iceland along the Reykjanes Ridge [5]. This ridge is located along one of the major bathymetry and gravity highs along the MOR system [2].

Romanche Fracture Zone, Equatorial Atlantic. Submarine active volcanism is known in the area of the Romanche FZ [30]; seamounts, active historically, are documented along a path linking this fracture zone to Fogo, Cape Verde, an active intraplate hotspot [31]. A transverse pipeline could exist in this area. However, as in the case of the shorter Beta FZ in the Indian Ocean, we have identified both slow events (1967, 1971, 1973) and fast sequences (August, November, 1965) along this very long fracture zone system.

Conrad, Bullard and Bouvet Fracture Zones, South Atlantic. This region, which shows a pronounced bathymetry anomaly, is particularly rich in slow earthquakes along fracture zones [11,32]. A geochemical and petrological study in this area [33] has revealed fractionated basalts, with higher-than-MORB Sr isotopic ratios, the chemistry and petrology of the ridge basalts evolving gradually from contaminated material in the immediate vicinity of Bouvet Island, to normal MORB's on the ridge segment immediately east of the Conrad FZ. The similarity of this pattern with the case of the Reykjanes Ridge, where a geochemical gradient extends down from the Iceland plume [5], with normal MORB's found just north of the Gibbs FZ, itself characterized by slow strain release, is striking. Additionally, Creaven et al. [34] have identified a large, slow, intra-plate earthquake northwest of the Conrad FZ, whose mechanism is not simply understood in the context of rigid plate tectonics. However, a seismicity study over a period of 60 years [11] has revealed a perfect balance between seismic slip and plate motion, precluding the possibility of creep along the fracture zone. Bouvet Island is one of the sites which Morgan has proposed for possible pipes. We propose to associate the slow earthquakes in the area with such a structure.

Balleny Island area. Balleny Islands and Mount Erebus, Antarctica are the only two active volcanoes in this part of the Antarctic plate [30]. Morgan [8] has proposed the Erebus-Balleny system as a possible pipeline. A number of difficulties arise, since Balleny Island is clearly an intra-plate feature, 400 km away from the ridge, and furthermore, in a region showing a negative gravity anomaly. Nevertheless, it is interesting to note that if such a feature exists, its mouth at the ridge would locate precisely along the "Mu" FZ, where earthquakes do exhibit slow characteristics.

Conversely, we would expect all of Morgan's proposed pipelines to produce slow earthquakes at their mouths, and we must examine the following two remaining areas:

Galapagos. We have not identified any particularly slow behavior for earthquakes in the Galapagos area. However, west of the mouth of Morgan's proposed pipe at Darwin Island, this could be explained by the fact that fracture zones are relatively short, and therefore cannot sustain large earthquakes. East of the Galapagos Islands, and along the plate boundary, we have identified only one major transform fault event (1969), with fast behavior, at longitude 85°W. On the other hand, no earthquakes with any magnitude greater than 5 were identified along the 170-km-long Ecuador transform fault, at 84°W longitude, during the period 1920–1977, possibly suggesting a creeping boundary. Additionally, intra-plate seismicity is present north of the plate boundary, inside the Cocos plate, particularly at 3.9°N and 85.9°W, with a 1976 shock of intermediate strain release behavior ($m_b = 5.9$; $M_s = 6.5$; complex waveshapes) featuring a strike-slip focal mechanism. This intra-plate seismicity is reminiscent of the situation in the South Atlantic.

Azores. Morgan [8] also included the Azores, a region with positive gravity and depth residual anomalies, as a location for a possible pipeline structure. This would be in line with Féraud et al.'s [35] observations of a violation of the linear progression of volcanic age with distance. Also, a recent study by Hirn et al. [36] suggests that the major 1980 earthquake in the area was not displacement-controlled in the framework of rigid plate motion, but rather represented a local stress regime. We have analyzed IDA records from this event, and obtained a moment of 2.0×10^{26} dyn-cm, which in the fault geometry of Hirn et al., suggests a low stress drop of only 11 bars. Wave shapes for this event are found to be relatively complex.

Eltanin Fracture Zone. Additionally, we address the case of the Eltanin FZ system. We have compiled the seismicity of the Eltanin FZ system for the period 1920–1977 [37]. Despite its length (1000 km), no earthquakes greater than $M_s = 6.6$ are documented along the Eltanin FZ system. An estimated cumulative moment for 1920–1977 of 1.65×10^{27} dyn-cm was obtained, or 2.9×10^{25} dyn-cm/yr. Despite the poor control on the events' magnitude for the early years of this survey, this estimate was found to vary little with time: If we restrict ourselves to the period 1961–1977, for which the quality of the data is more homogeneous, we find figures of 4.75×10^{26} dyn-cm, and 2.8×10^{25} dyn-cm/yr, respectively. These figures can be compared to the cumulative moment expected from the geometry of the fracture zone and the kinematics of the plates involved. Using Minster and Jordan's [14] model RM2, a transform length of 1000 km, a (conservative) width of the fault of 20 km, and a rigidity of 300 kbar, we obtain a figure of 5×10^{26} dyn-cm/yr, 15 times greater than observed in the seismicity. Although one explanation for this discrepancy may be extremely long recurrence times along this particular fracture zone system, it is more likely that a substantial part of the motion along the Eltanin FZ is taken up aseismically, by creep. This behavior is fundamentally different from the pattern observed along the "slow" Gibbs and Conrad FZ's. Both Kanamori and G.S. Stewart [10], and L.M. Stewart and Okal [11] have concluded that seismicity accounted for the entire motion predicted along these features. Detailed bathymetry along the Eltanin FZ system has identified two main fracture zones [38]: the Heezen FZ to the north, and the Tharp FZ to the south, separated by approximately 120 km. Given this morphology, and by analogy with other areas featuring slow earthquakes, we hypothesize that the Eltanin FZ system may be the location of a trapped hotspot, in the fashion proposed by Vogt and Johnson [5, p. 1401]. The absence of island volcanism could be due to a relatively minor flow of magmatic material, sufficient however to lubricate the faults to the point of inducing creep, and preventing the occurrence of large earthquakes. Additionally, this feature could explain the existence of the Louisville Ridge, whose empirical correlation with the Eltanin FZ system has been recognized [39], but never satisfactorily explained. This hypothesis could be tested by a number of means, including geochemical studies along the Louisville Ridge–Eltanin FZ system.

Southwest Indian Ocean Ridge. Finally, we will concentrate on the Southwest Indian Ocean Ridge. This is an area where a very large anomaly exists, both in residual bathymetry and free air gravity. Its topographic expression consists of the Crozet and Prince Edward Plateaus in the Antarctic plate, and of the Madagascar Plateau in the African plate. Although very little is known about the petrology and the chemistry of the islands, their volcanism is thought to have been active during the Brunhes epoch [40], and the Crozet islands are known to be of undepleted origin [22]; Marion erupted in 1980 [41]. The seismicity along this branch of the MOR system was partially investigated by Norton [42]. The fracture zone immediately to the west of the Prince Edward FZ (which we will call the Prince Edward West FZ) was the site of a gigantic earthquake in 1942 ($M_s = 7.9$, $M_w = 8.0$). This event, however, does not feature a slow mechanism. Activity on the Prince Edward West FZ occurred also in 1968, 1978 and 1980, again in the "fast" mode. In the area corresponding to the swell and the gravity anomaly (roughly 30–50°E), few substantial earthquakes (with at least one magnitude greater than 6) have occurred outside of the Prince Edward West FZ since the start of the WWSSN network in 1963; none of them exhibited slow behavior. However, Gutenberg and Richter [43] list a number of large events all throughout this area for the period 1920–1951. In the absence of a critical evaluation of the magnitude of these old events, it is impossible to distinguish between the possibility of the area east of the Prince Edward West FZ undergoing creep and of it being just a seismic gap, with a recurrence time of earthquakes greater than 50 years. The mere size of the 1942 event on the Prince Edward West FZ ($M_w = 8.0$) requires extremely long recurrence times, on the order of 200 years for a transform 400 km long. Elsewhere along the Southwest Indian Ocean Ridge, earthquakes are found to have fast characteristics between the Prince Edward West FZ and the Bouvet area, and northeast of 50°E. In summary, the Prince Edward West FZ is of the "fast" type; in the area associated with the plateau anomalies, no conclusion can be reached, as to the pattern of strain release, since a history of old events might be related to locked faults with very long recurrence times.

5. Discussion

The absence of correlation between strain release regimes and simple kinematic parameters precludes the interpretation of the various degrees of decoupling along the fracture zones through global models such as shear heating [44], and requires the influence of an additional, local, agent. On the other hand, the good correlation between slow earthquakes and areas of bathymetric and gravity anomalies, and undepleted island volcanism, indicates that slow regimes of strain release are probably governed by the presence of asthenospheric activity of hotspot type origin. Although the present data cannot be taken as a proof of the existence of the pipes proposed by Vogt and Johnson [5] and Morgan [8], it clearly points out to an additional anomalous phenomenon in the areas previously outlined by these and other authors. Furthermore, we believe that the various regimes of strain release, identified in the present study along fracture zones of the MOR system, are representative of degrees of decoupling of the two plates in contact along the transform fault, and we propose that they are an expression of the intensity of magmatic activity along the walls of the fracture zone. This activity may be controlled by the flow from the proposed longitudinal or transverse pipes. (Volcanic structures due to the infusion of asthenospheric magma at the dammed extremity of a pipeline structure has been documented along the Gibbs FZ [5], and Hey and Vogt [45] have proposed that it may result in ridge migration in the Galapagos area.) In the absence of intense asthenospheric flow (Challenger FZ, Prince Edward West FZ, Epsilon FZ), the two sides of the fault are strongly coupled, stress drop during earthquakes is large, and strain release fast. With the infusion of some magma, the fault becomes lubricated, the coupling decreases, leading to a pattern of discrete asperities [46]. Their rupture through a triggering process increases the duration of the source (Gibbs FZ, Rodriguez FZ, Beta FZ), and leads to complex waveshapes. Finally, in the presence of substantial lubrication, the fault becomes strongly decoupled, resulting in creep, and occasionally in the rupture of isolated, small asperities, leading to small earthquakes, with the regime of strain release controlled by the actual number of asperities failing (possibly fast in the case of a single asperity). This pattern may apply to the Eltanin FZ system.

In several cases, we have noticed that the geographic correlation between slow fracture zone events and other anomalous properties such as isotope geochemistry or residual gravity, is not carried to a small scale (e.g. along the Conrad FZ, see section 4): anomalously slow earthquakes keep occurring at a distance from the parental hotspot greater than the limit of both geochemical contamination and the associated bathymetry and gravity highs. We interpret this apparent problem with our proposed model simply as illustrating different geographic scales involved in different geophysical or geochemical processes: in particular, a long transform fault is needed to dam longitudinal asthenospheric flow efficiently and create the conditions for the existence of a major slow earthquake. In this respect, it would be futile for example to try to correlate slow earthquakes along the North Atlantic MOR with the small-scale geochemical and bathymetry structures recently described by le Douaran and Francheteau [47], since not enough long transform faults exist along most of it to provide a homogeneous "sampling" of the regime of strain release.

Finally, we addressed the question of a possible difference in aftershock patterns between fast and slow events; however, we were not able to investigate this conclusively, due to lack of data: all the events we study are in oceanic areas and detection capabilities for their aftershocks, expected in the magnitude range $m_b = 4$–5, are poor.

6. Conclusion

We have shown that slow regimes of strain release along fracture zones of the MOR system are not controlled by geometric or kinematic factors. Rather, a good correlation exists with the presence of asthenospheric flow from nearby hotspots, located either on the ridge, in the pattern suggested by Vogt and Johnson [5], or inside the plate, as proposed by Morgan [8]. In this respect, and although additional evidence of the validity of Morgan's concept is undoubtedly necessary before it can be widely accepted, our study gives evidence of anomalous geophysical properties at the mouths of at least four of the specific "pipelines" proposed by Morgan in his 1978 paper. The different regimes of strain release can be interpreted in the framework of the asperity model [46] by involving a reduction of the coupling between the two walls of the fault under lubrication by the asthenospheric flow. In the case of the Eltanin FZ system, the absence of major earthquakes show that part of the plate motion must be taken up by creep. We propose that a hotspot may be trapped inside the fracture zone system. This hypothesis could be tested by geochemical studies along the Louisville Ridge–Eltanin FZ system.

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