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APPLICATIONS OF SEASAT ALTIMETER DATA IN SEISMOTECTONIC STUDIES OF THE SOUTH-CENTRAL PACIFIC

Richard V. Sailor

The Analytic Sciences Corporation, Reading, Massachusetts 01867

Emile A. Okal

Department of Geology and Geophysics, Yale University
New Haven, Connecticut 06520

Abstract. Individual tracks of SEASAT altimeter data can be used effectively to identify significant bathymetric features in remote and unsurveyed ocean areas. It is especially important, for studies of oceanic seismicity, to identify correlation (or lack of correlation) between seismicity and bathymetric features. However, in many seismically active regions, bathymetric data are sparse or nonexistent. A typical example is the south-central Pacific, an area studied by Okal et al. (1980), who identified several sites of active intraplate seismicity. The purpose of the present paper is to demonstrate how SEASAT data can be used to aid in bathymetric and seismotectonic interpretation of this remote ocean area. We present two illustrations: (1) SEASAT observations of Macdonald seamount, a volcanically active seamount representing the youngest member in the Austral Island chain, and (2) SEASAT observation of a previously undiscovered fracture zone located at approximately 21.4°S and trending east-west between 232°E and 236°E. This fracture zone is located approximately 70 km to the south of a small region of active seismicity (96 events of magnitude greater than 2.7 from 1976 to 1980). On the basis of the demonstrated ability to observe active seamounts such as Macdonald and small fracture zones, we conclude that the observed seismicity in the region near 21°S, 233°E is due to intraplate stresses but is not associated with large-scale volcanism or with an active or fossil fracture zone.

1. Introduction

The seismicity of remote oceanic areas has recently been the subject of several studies, aimed at understanding both the intraplate state of stress of the lithosphere, and the factors governing the location of individual seismic foci on the oceanic plate. Although a broad consensus now exists concerning the stresses released during intraplate events, some controversy remains as to the role played by major bathymetric features, such as seamounts and fracture zones, in the actual location of intraplate earthquakes. Sykes [1978] has proposed that seismicity is preferentially implemented in so-called zones of weakness, such as sutured fracture zones, while an on-site survey by Sverdrup and Jordan [1979] of an area of substantial seismicity in the south-central Pacific failed to identify any significant bathymetric feature. A statistical approach by Bergman and Solomon [1980] has indicated a trend toward correlation between ancient fracture zones and seismicity only in the case of substantial events.

Establishing the correlation (or lack of it) between seismicity and significant bathymetric features, such as seamounts and fracture zones, is an important aspect of our understanding of the origin of earthquakes in oceanic environments. In particular, the possible existence of unsuspected past or presently active volcanic edifices, in the vicinity of areas of substantial seismicity, could shed a totally new light on the origin of intraplate earthquakes. Although at short epicentral distances it is feasible to identify characteristics of earthquakes related to volcanism [e.g., Talandier and Kuster, 1976], this becomes difficult when operating with the high detection threshold inevitably associated with teleseismic distances. A good knowledge of the bathymetry of seismic areas is therefore desirable before any interpretation can be proposed. However, adequate bathymetric data are extremely rare in many of the world's oceans. This paper suggests the use of satellite altimeter data as an aid to tectonic interpretations in remote unsurveyed areas. We demonstrate that SEASAT altimeter data can indicate the presence and orientation of important bathymetric features. Examples will be drawn from two areas of the south-central Pacific Ocean, where a detailed study of intraplate seismicity was carried on by Okal et al. [1980].

These authors studied the seismicity of French Polynesia and the adjoining areas (5°S to 30°S; 120°W to 160°W), using a network of 15 short-period stations located on Tahiti and other islands. As discussed by Okal et al. [1980], most of their locations were determined to better than 20 km, a scale on which the bathymetric coverage is rather poor if at all available [Mammerickx et al., 1975]. Figure 1 is adapted from Figure 3 of Okal et al. [1980] and shows the foci of seismic activity identified during 1965-1979. Three areas (Regions A, B, and C on Figure 1) experienced most of the activity during this period, and, over this same period, contributed more than 90% of the total seismic energy released inside the Pacific plate (with the exception of the Hawaiian hotspot). Therefore, a good knowledge of the bathymetry

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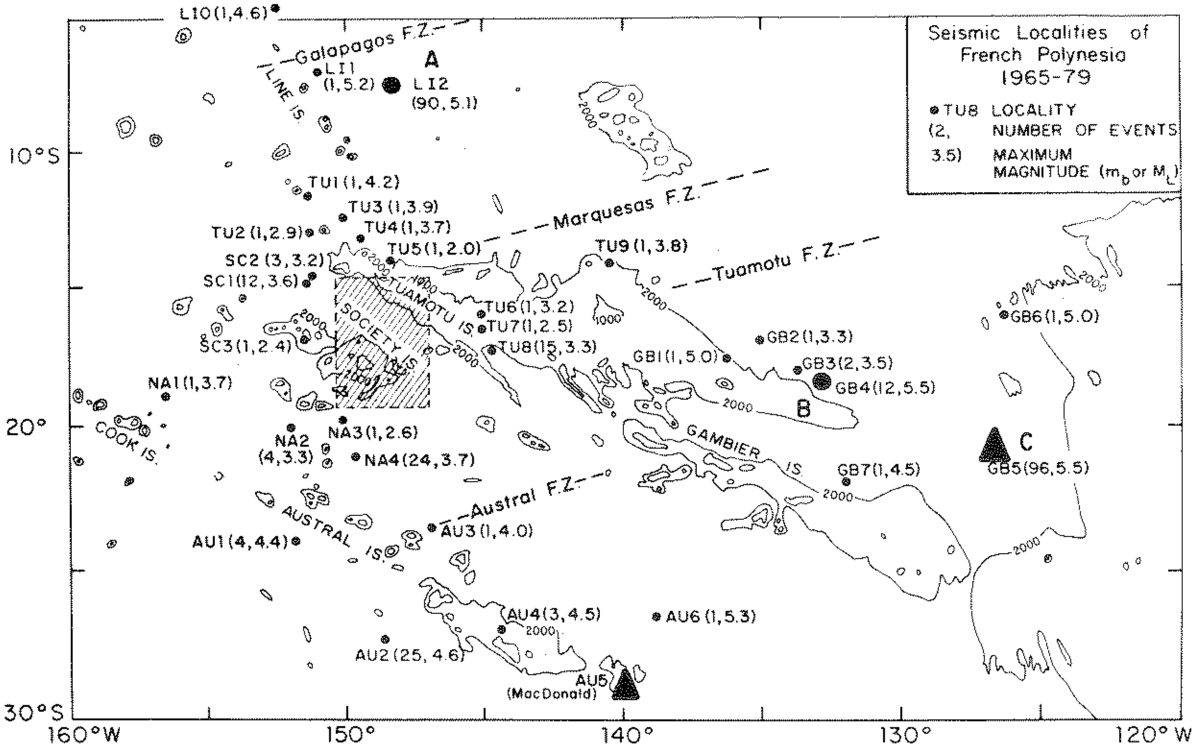

Fig. 1. Seismic localities in the south-central Pacific (adapted from Okal et al. [1980]). Epicenters in the Tahiti-Mehetia area (hatched box) have been omitted. The total number of observed events and maximum magnitude are indicated in parentheses. Solid triangles identify areas studied in the present paper.

of these three regions is warranted. Because of its proximity to the axis Tahiti-Hawaii, on which the transpacific shuttle NORPAX has been running regularly, region A was targeted for a visit by Sverdrup and Jordan [1979]. They identified geomorphological structures on the order of 10 km in dimension, but failed to reveal any large-scale bathymetric anomaly.

In this paper, we use SEASAT data over seismic locations AU5 (Macdonald Volcano) and GB5 (region C) to identify long-wavelength bathymetry (with characteristic lengths greater than 50 km) in these epicentral areas. We first verify the resolution of SEASAT data by using the case of Macdonald, whose relief is known and charted, and then proceed to explore the area of region C. We conclude that no major seamount is present in the epicentral area, but identify a small fracture zone approximately 70 km south of the epicentral area. We doubt, however, that this fracture zone plays any role in the implementation of the seismicity at GB5.

2. SEASAT Observations of Macdonald Seamount

Macdonald Seamount (Figure 2) was discovered following a seismic swarm recorded through T waves on the Pacific hydrophone network, and surveyed by R. H. Johnson in 1969, 1970, and 1973 [Johnson, 1970; Johnson and Malahoff, 1971]. Its summit was reported to be only 49 m below sea level, and Macdonald is generally interpreted as the most recent member of the Austral Island Chain, a hypothesis supported by the presence of undersaturated alkali basalts [Brousse and Richer de Forges, 1980]. Since the 1967 swarms, seven periods of intense seismic activity have been recorded by the French Polynesia network with durations as long as 1 week [Talandier and Okal, 1982]. Furthermore, two new surveys, conducted by the French Navy in June 1981 and January 1982, reported minimum depths of only 23 and 27 m, respectively. Thus, because of the several surveys conducted at Macdonald, this locality is a good candidate to use as a test case for SEASAT data analysis.

The relationships between the marine geoid and bathymetry have been discussed in many recent papers [e.g., Watts and Daly, 1981] and other papers in this issue. There are also many papers which illustrate the use of altimeter data to observe the geoid effects of features such as seamounts, fracture zones, ridges, trenches, and bathymetric swells associated with hot spots. For these applications, it is appropriate to make the simplifying assumption that the altimeter observations of sea surface height represent an approximation to the the geoid. The geoid effects due to these features have amplitudes ranging from about 1 m (for seamounts) to a few tens of meters (for trenches), while the sea surface height perturbations caused by tides and oceanographic or atmospheric effects are generally on the order of a few tens of centimeters. The altimeter orbit errors and other effects such as uncertainties in the ionospheric corrections may also be neglected for the purpose of this work.

Figure 3 is a map showing all available SEASAT

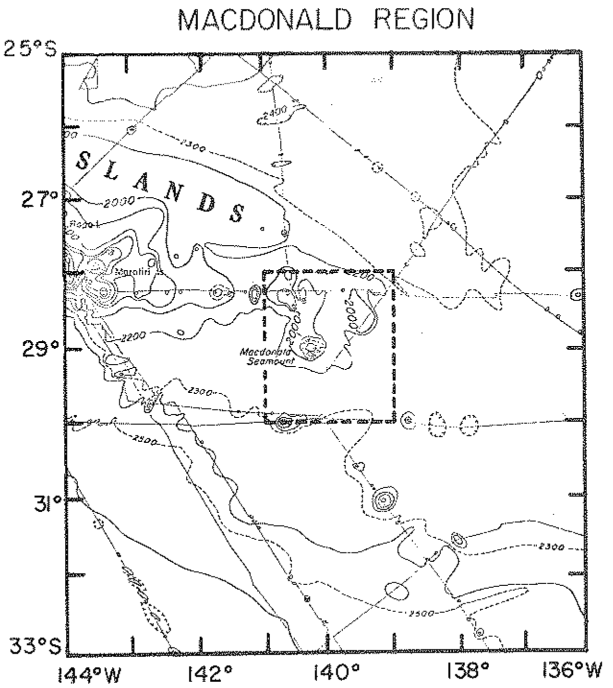

Fig. 2. Bathymetry in the area of Macdonald Seamount (soundings in fathoms). This figure is a close-up of the map by Mammerickx et al. [1975]. Dashed box delimits area shown in Figure 3.

data in a 2° by 2° square surrounding Macdonald Seamount. By good fortune, one of these SEASAT tracks, Rev 215D (a descending track), passes directly over the summit of Macdonald. Another descending track, Rev 459D, passes about 17 km to the northwest. An ascending track, Rev 481A, crosses less than 30 km to the northeast of the seamount.

Macdonald Seamount is situated atop a broad bathymetric (and geoidal) swell caused by a region of elevated temperatures associated with the Austral Island Chain (the geoid height along Rev 215D is approximately -12 m at 26°S, -7 m near Macdonald at 29°S, and -10 m at 31°S). Crough [1978] cited the Cook-Austral Chain as an example of a topographic swell caused by hotspot reheating of the lithosphere. Cochran and Talwani [1977], Watts and Daly [1981], and others provide further discussion of these long-wavelength geoid and bathymetry anomalies. For the present purpose of observing the geoid effect of Macdonald seamount itself, we are interested in much shorter wavelengths.

SEASAT data have the ability to resolve geoid features with wavelengths as short as about 30 km [Brammer and Sailor, 1980]. The geoid signature of a seamount (or any anomalous mass distribution) is directly proportional to the anomalous gravitational potential. Chapman [1979] discusses methods for computing the geoid effects of various mass distributions. Once the approximate signature of a typical seamount is known, small seamounts may be detected automatically and their sizes estimated. One method for doing this is to use matched filtering [Lazarewicz and Schank, 1982; White et al., this issue]. The matched filtering technique is a solution to the problem of detecting a known signature in a background of noise whose spectral characteristics are known.

Figure 4 shows the portions of the SEASAT-observed sea surface height profiles which are within the map area of Figure 3. These profiles consist of 350 samples of the 10 sample/s Geophysical Data Record data. The geoid feature due to Macdonald seamount is clearly visible.

To model the expected geoid height signature of a seamount, conical models are generally sufficient, since small variations in seamount shape do not significantly affect the shape of the geoid. From the bathymetry map of Johnson and Malahoff [1971], the Macdonald seamount may be approximated well by a cone having a radius of 15.7 km, a height of 3.2 km, and a base angle of 11.7°. Because this is a young seamount, implanted on Eocene lithosphere, the effects of flexure and other types of compensation are expected to be less significant than for other seamounts and were not included for the purpose of computing the theoretical geoid signatures which are shown in Figure 4 alongside the observed data. Thus, this simplified model of a conical seamount with an assumed density contrast of 1600 kg/m^3 provides a fairly good fit to the observations.

The presence of two SEASAT tracks close to the seamount allows a further test of the model signature. Both of these tracks contain very similar long wavelength components due to the large geoid swell of the Austral Island Chain. By subtracting these tracks from one another, the long wavelength component will be removed and the difference should reflect the difference between the on-axis seamount signature and the signature computed at a distance of 17 km from the axis. This is illustrated in Figure 5.

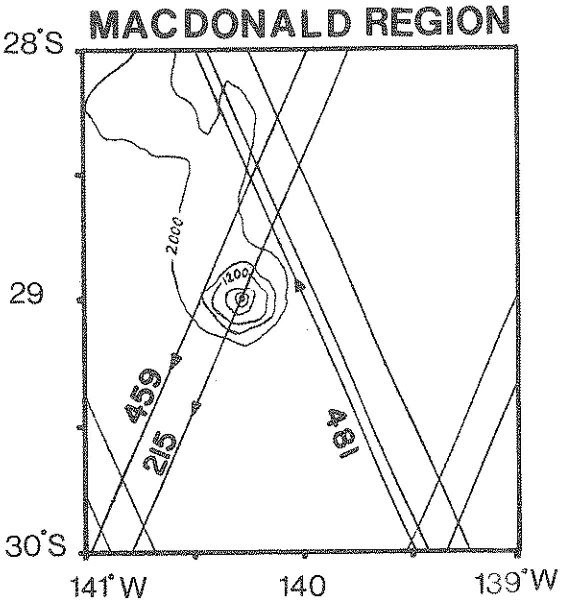

Fig. 3. SEASAT Revs crossing area of Macdonald Seamount, as defined on Figure 2. Arrows on revs indicate ascending or descending character. Bathymetry (in fathoms) is shown only in immediate vicinity of Macdonald [Mammerickx et al., 1975; Johnson and Malahoff, 1971].

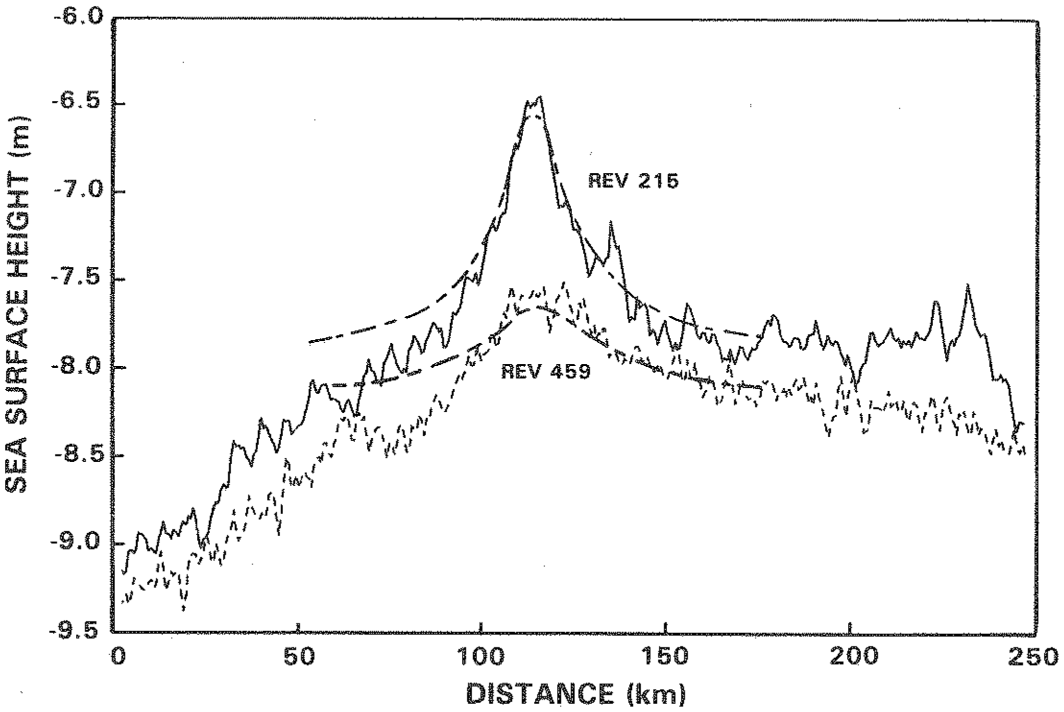

Fig. 4. Profiles of observed sea surface height along SEASAT Revs 215D and 459D compared with model geoid undulation signatures for Macdonald seamount.

3. An Unmapped Fracture Zone: SEASAT Observations in Region C

As documented on Figure 1, region C is one of the most active sites of seismicity in the Pacific plate, with 96 events recorded since 1967, all during a 'superswarm' which lasted from August 1976 to June 1979. Two focal mechanisms obtained by Okal et al. [1980] confirmed that the stress released during the events is representative of the tectonic stress built up in the plate from the gravitational sliding process known as 'ridge-push', in agreement with most current studies of intraplate seismicity [e.g., Richardson et al., 1979]. Thus, these are probably true intraplate earthquakes, in the sense of Stein [1979], unaffected in the orientation of their stress release by the potential existence of zones of previous geological activity. Furthermore, no evidence of volcanic seismicity of the type observed at Macdonald was obtained from region C. The absence of volcanic seismicity was also corroborated by the low b-values reported by Okal et al. [1980]. Region C is thus a good candidate for the investigation of the influence of bathymetric features on the location of tectonic stress release inside the oceanic plate.

Unfortunately, as shown in Figure 6, bathymetric data are practically non-existent in this portion of the Pacific, with only nine tracks covering an area of more than 10^6 km^2. [Mammerickx and Smith, 1978]. Additionally, it is not clear whether lithosphere in region C was generated at the present ridge system or at the fossil Nazca-Farallon system prior to the ridge jump and subsequent re-orientation of spreading in the Miocene [Herron, 1972]. Indeed, recent evidence [Mammmerickx et al., 1980; Bergeal and Okal, 1982] suggests that Region C may be located at the boundary line, on the present Pacific plate, separating lithosphere generated under the two regimes of spreading. Although a precise location of all events is difficult since these epicenters lie outside the Polynesian network, a variety of techniques have been used to relocate eight events (m_b = 4.7 or greater), well recorded at teleseismic distances [Okal et al., 1980; Jordan and Sverdrup, 1981; J. Talandier, personal communication, 1981]. All these efforts have indicated that the epicentral area in region C is probably not larger than 20 km. Given the scarcity of bathymetric data, SEASAT currently affords the best opportunity to determine whether there are any significant features associated with this epicentral region.

Therefore, we have examined all of the available SEASAT tracks that cross near Region C. Figure 7 shows that there are six tracks within a surrounding 2° by 2° area. Unfortunately, the closest track passes about 45 km away from this site, and it is likely that a small seamount located this far to the side of a SEASAT track would not be detected. However, a large seamount (more than 50 km in diameter and more than 2.5 km in height) would be observable. The six tracks within the area of Figure 7 do not show any indications of seamounts. However, as shown on sample data presented on Figure 8, all six of these tracks do indicate the presence of a fracture zone, about 70 km South of region C. We will call this unsuspected feature the 'Region C' Fracture Zone.

The gravity anomaly and geoid undulation effects of fracture zones are related to the fact that these features separate lithosphere

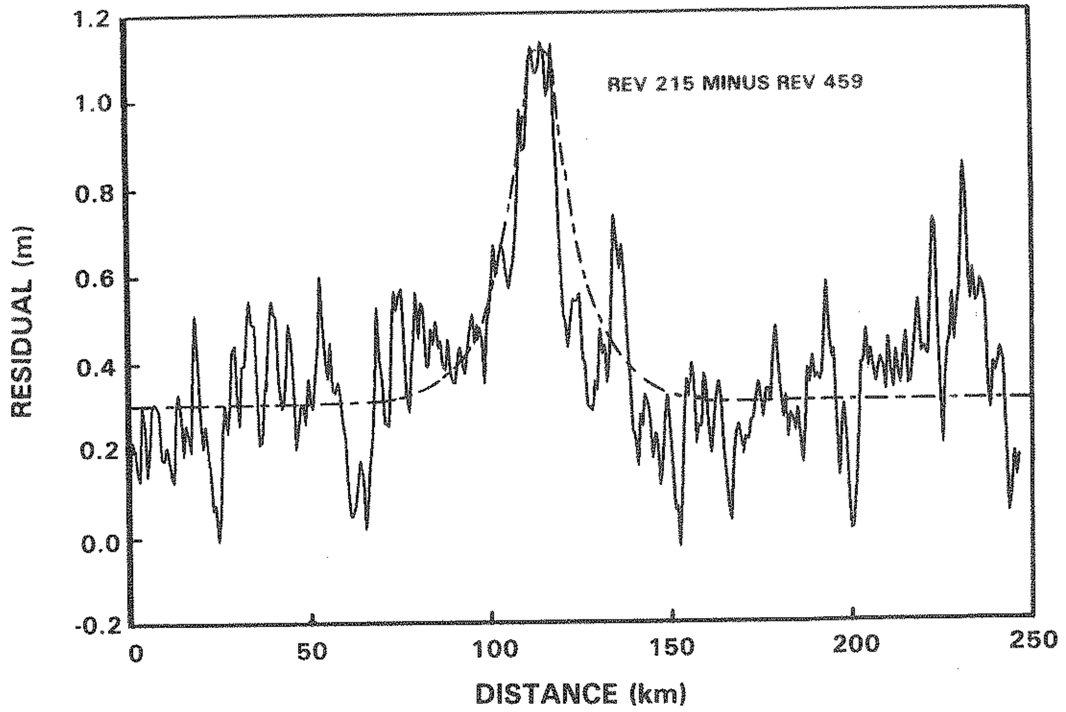

Fig. 5. Difference profile (Rev 215D - Rev 459D) compared with theoretical difference profile.

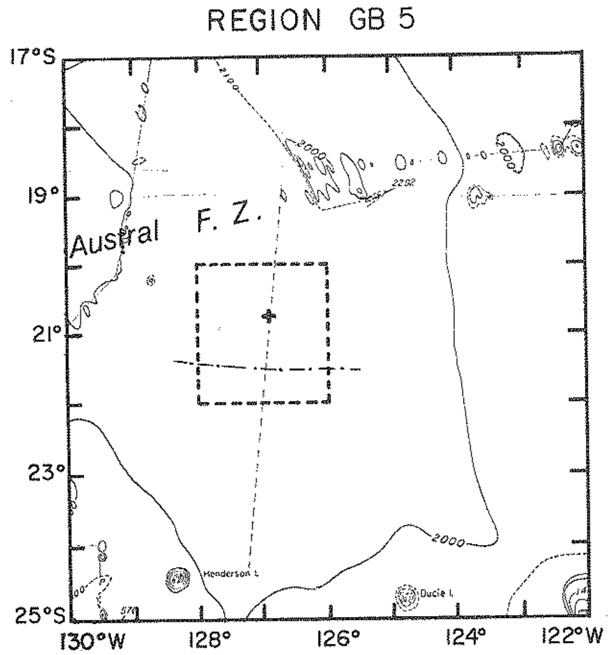

Fig. 6. Bathymetry (fathoms) for Region GB5 (data source same as that for Figure 2). Cross indicates location of seismic epicentroid [after Jordan and Sverdrup, 1981]. The dash-dot line indicates the previously unmapped fracture zone identified on SEASAT data (Region C fracture zone); the dashed line indicates the recent shiptrack whose bathymetry is plotted on Figure 9.

of differing ages, causing a gravitational edge effect [Dorman, 1975; Crough, 1979; Sandwell et al., 1980]. Because of the cooling of lithosphere with increasing age, the older lithosphere is thicker and more dense. Models using two cooling halfspaces separated by a fracture zone exhibit a geoid step which, in a profile normal to the trend of the fault, is upward as the fracture zone is crossed in the direction from older to younger lithosphere [Sandwell et al., 1980]. Schubert and Sandwell [1981] have measured this geoid step across fracture zone segments of known age offset, and have determined that the amplitude of the geoid step is approximately 0.16 m/m.y., for lithosphere approximately 20 m.y. in age, as is the case in Region C. This proportionality is in agreement with the decrease in geoid height with age across symmetric spreading ridges [Sandwell and Schubert, 1980].

The identification of possible fracture zones in SEASAT data requires recognition of the geoid step which occurs when the track crosses the fairly sharp boundary which marks a contrast in lithospheric ages. Although this boundary (fracture zone) may be quite narrow, the geoid step occurs smoothly over a distance of approximately 100 to 200 km. This feature can be seen best when the longer wavelength geoid features are removed.

Therefore, to best illustrate the consistent geoid step which we interpret as a previously uncharted fracture zone, we have plotted the geoid profiles of the tracks crossing Figure 7, with a linear trend removed (this process is a high pass operation which in this case removes wavelengths longer than about 2400 km). As shown on Figure 8, a geoid step with an

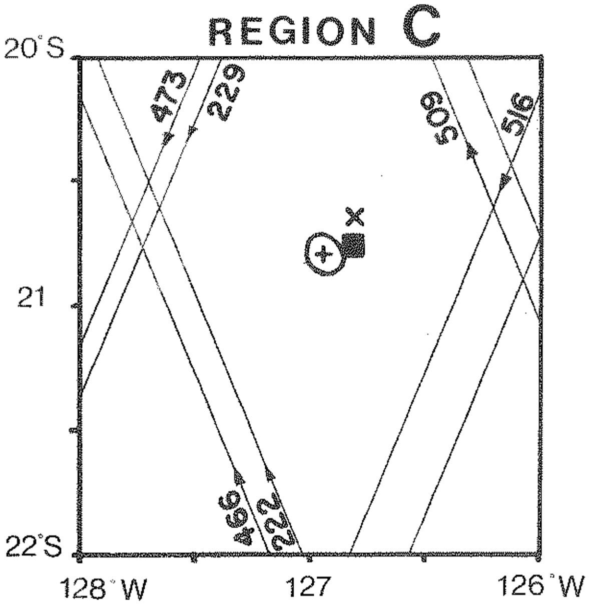

Fig. 7. SEASAT tracks crossing near region GB5. No large-scale bathymetry is available. Plus sign indicates location of seismic epicentroid [Jordan and Sverdrup, 1981], with 95% confidence ellipse; solid square indicates average epicenter as relocated by J. Talandier (personal communication, 1981); cross shows location of 400-m relief identified by J. Francheteau (personal communication, 1981).

amplitude of approximately 0.5 m is evident in all of these tracks. In all cases, the sense of the step is such that the geoid is higher to the south, indicating younger lithosphere on this side of the inferred fracture zone. These profiles also show a notchlike feature, which we interpret as the geoid effect of the local bathymetric expression of the fracture zone.

Another technique that could be used for recognizing unmapped fracture zones in altimeter data is to detect the characteristic signature in the along-track derivative of the geoid (along-track component of vertical deflection). Schubert and Sandwell [1981] have computed the expected deflection signature for half-space fracture zone models and have fit this to SEASAT deflection observations across fracture zones whose age offsets are known from magnetic lineation studies. For finding unknown fracture zones, the along-track deflection observations could be processed with a matched filter designed to detect these features [White et al., this issue]. This type of technique, using individual tracks, would probably work better than detection operations applied to geoid maps.

Our discovery of the previously unknown Region C Fracture Zone at 21.4°S, and about 70 km south of region C, is the result of the search motivated by the active seismicity of this region. Further interpretation of this result may be made: Based on the 0.16 m/m.y. relation between geoid height and age, the observed geoid step indicates an age offset of about 3 m.y. As stated previously, the inferred fracture zone trends east-west and separates younger lithosphere on the south from older (by about 3 m.y.) lithosphere to the north. We have also attempted to trace this fracture zone farther in both directions and the result is shown in Figure 6.

Independently, a small scale bathymetric survey of region C was carried out in the Summer of 1980 (J. Francheteau, personal communciation, 1980), which confirmed the absence of major relief comparable to Macdonald Seamount in this previously uncharted area, though this survey did not extend far enough south to detect the unmapped fracture zone. The maximum relief identified near region C was of the order of 400 m, comparable to the average height of seamounts identified in region A by Sverdrup [1981]. An ocean-bottom hydrophone, operated for a few hours at the site, recorded an anomalously large number of seismic events, of presumably local nature, which could not be detected by any other stations (G. Pascal, personal communication, 1981).

After concluding the present study, we obtained a chart of the original bathymetric survey along a north-south shiptrack, expected to cross both the Austral Fracture Zone (at 19.5°S) and the Region C fracture zone (at 21.4°S). As shown on Figure 9, these data support the existence of the Region C fracture zone, and suggest that its bathymetric signature may be as pronounced as that of the Austral Fracture Zone. It is difficult, however, to interpret them further, on the basis of a single ship track.

Despite our identification of a small fracture zone to the south of region C, we do not believe that this feature is responsible for the seismicity at GB5: Its distance from the epicentral locations is 70 km, a value several times larger than our epicentral uncertainty. Arguments have been presented for GB5 seismicity to be very shallow [Okal and Talandier, 1981], and no reasonable dipping of the fracture zone could account for this offset. Rather, we think that we are dealing with a situation similar to that found in region A by Sverdrup and Jordan [1979]: These authors confirmed the presence of a small fracture zone approximately 60 km south of the epicentral area of region A, and identified only geomorphological blocks of about 10 km in dimension, which they interpreted as relics of individual cycles of ridge formation, possibly controlling the size and mechanism of present-day earthquakes.

4. Discussion and Conclusion

We have shown that SEASAT data can be efficiently used in order to estimate large-scale bathymetry in uncharted areas of difficult access: In the case of Macdonald, we have successfully recognized the seamount, both in its signature and in the amplitude of the bulge it creates on the sea surface. In the case of region C, a similar exploration fails to reveal any comparable bathymetry, but identifies the presence of an unsuspected fracture zone 70 km south of the epicentral area. Although we do not think that this feature is related to the mechanism of implementation of seismicity in the GB5 area, its recognition demonstrates

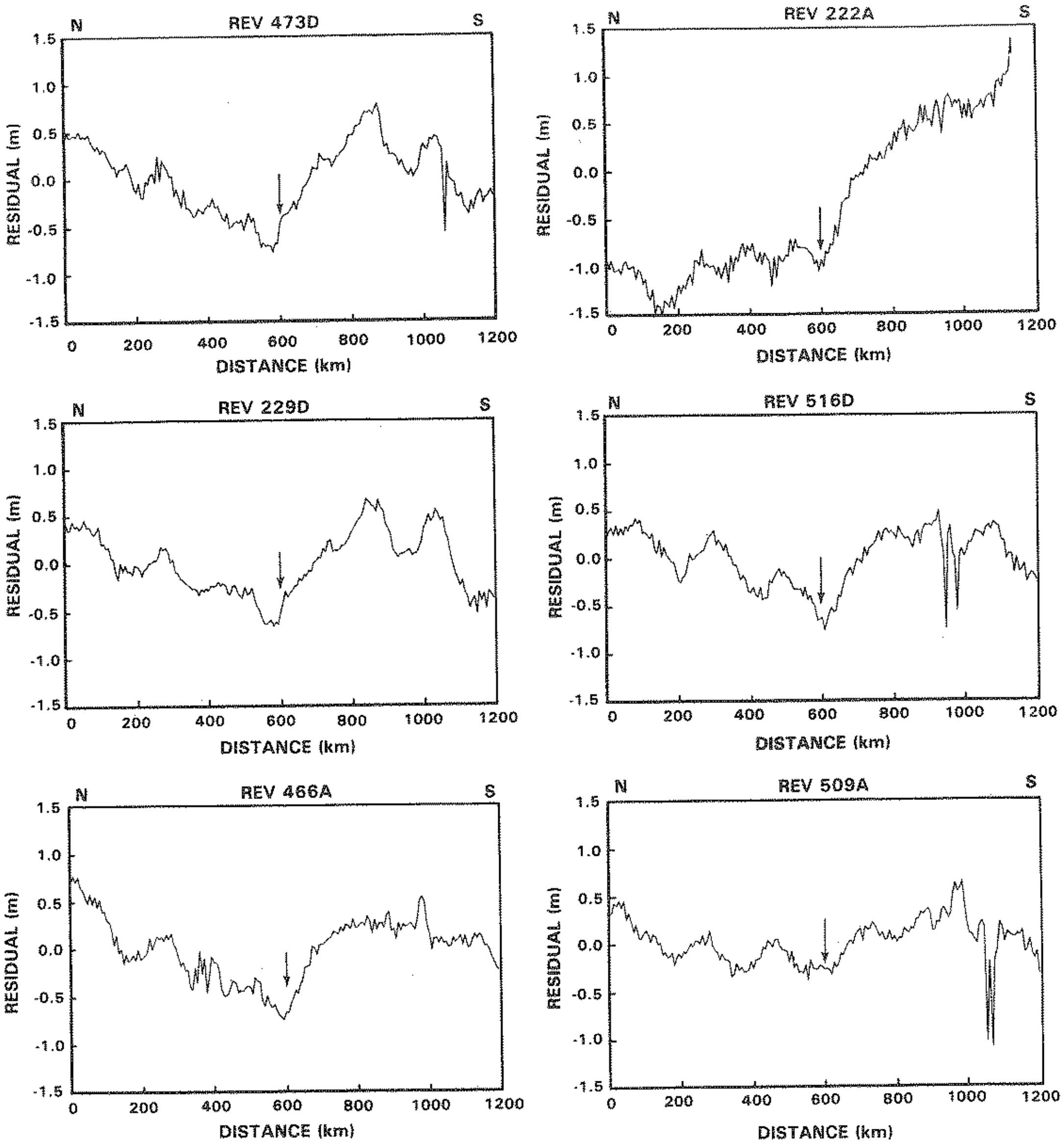

Fig. 8. SEASAT profiles (linear trend removed) for all six tracks crossing Figure 7. Profiles are centered at the location of the region C fracture zone (approximately 21.4°S). A geoid step of about 0.5 m is upward toward south, in the direction toward younger lithosphere.

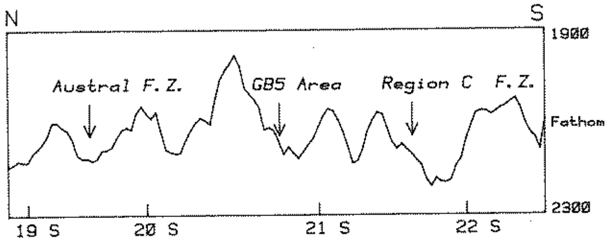

Fig. 9. Bathymetric data along the shiptrack outlined on Figure 6 (courtesy of J. Mammerickx). This is a plot of the 3-point running average of the original data from 19°S to 22°S. Note the pronounced trough at the expected location of the region C fracture zone, similar in character and size to the relief observed at the Austral Fracture Zone. Note that the horizontal axis represents individual soundings along the shiptrack and thus is not exactly linear in distance.

further the power of the method. This seemingly negative result concerning the absence of correlation between seismicity and bathymetric features is, however, in agreement with a smaller-scale survey conducted independently, and suggests a pattern reminiscent of the situation described by Sverdrup and Jordan [1979] at region A. As such, it constitutes an important result in our identification of the factors governing the location of intraplate stress release within oceanic plates.

Satellite altimeter data thus appear as a powerful tool for the systematic investigation of the bathymetric characteristics of intraplate seismic foci. Many of those fall in regions where classical bathymetric coverage is sparse or even nonexistent. For example, a number of seismological studies [e.g., Mendiguren, 1971; Forsyth, 1973; Okal, 1981] have identified well-defined areas of preferential seismicity in remote areas of the Pacific Ocean belonging to the Nazca and Antarctica plates as well as to the Pacific plate itself. It is clear that a systematic use of available SEASAT data could replace, at a fraction of the cost, shipboard expeditions to these epicentral areas and, through a study of their large-scale bathymetric patterns, provide us with much new insight into the parameters governing stress release inside oceanic plates.

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