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Subduction of the Bougainville seamount (Vanuatu): mechanical and geodynamic implications

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Abstract

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New bathymetric data gathered during a Seabeam survey (SEAPSO cruise, leg 1) enable us to re-examine the flexural response of the oceanic lithosphere subducting under the New Hebrides (Vanuatu) island arc. The Bougainville seamount and Sabine bank are interpreted as immerged fossil atolls, the recent subsidence of which is related to the subduction of the oceanic lithosphere. The position and altitude of the different fossil atolls which belong to the d'Entrecasteaux or Loyalty ridges are in good agreement with predictions of elastic flexure of the lithosphere. We deduce an average effective elastic thickness of the lithosphere of about 22 km for the area under study. This value is slightly smaller than the one corresponding to the lithospheric age as given by the magnetic anomalies, but is in good agreement with the age after a correction for thermal rejuvenation. This assumption of a thermal rejuvenation of the North Loyalty basin is also supported by previously reported high heat-flow values and attenuation of S_n seismic waves. However, the location and depth of the trench in front of the North Loyalty basin do not agree with the model which fits the other data. This discrepancy is interpreted as the result of variations of the value of P_b (vertical force per unit length of trench applied at the edge of the plate) along the subduction zone. Such variations may be related to the length of the subducted slab, which is shorter in front of the d'Entrecasteaux and Loyalty ridges than in front of the North Loyalty basin, according to the hypocentral distribution of earthquakes and a tomographic image of the slab.

Introduction

The oceanic plate subducting under the New Hebrides (Vanuatu) island arc defies simple description. Much of this plate is covered by seamounts, aseismic ridges and plateaus, all of which have indeterminate age and composition. The existence of numerous seamounts on this oceanic lithosphere (Fig. 1) offers the opportunity to observe and study the bending of the Australian plate before it subducts, according to the well known approach of thin plate deformation described by Hanks (1971). Previous studies were made in this area using data from uplifted fossil atolls of the Loyalty chain and from the southern part of New Caledonia. It was observed, by an analysis of the correlation between the maximum altitude of uplifted fossil atolls and the distance to the trench, that the envelope of the upper reefs represents the bending of the oceanic lithosphere prior to subduction (Dubois et al., 1974, 1975). Indeed, the coral reefs were previously at sea level. Then, approaching the subduction zone, they were uplifted while the oceanic lithosphere bent in order to subduct under the overriding plate. Therefore, the maximum altitude of the coral reef above sea level indicates the vertical amplitude of the topographic bulge seaward of the trench axis.

According to this model, the main results previously obtained concern the following:

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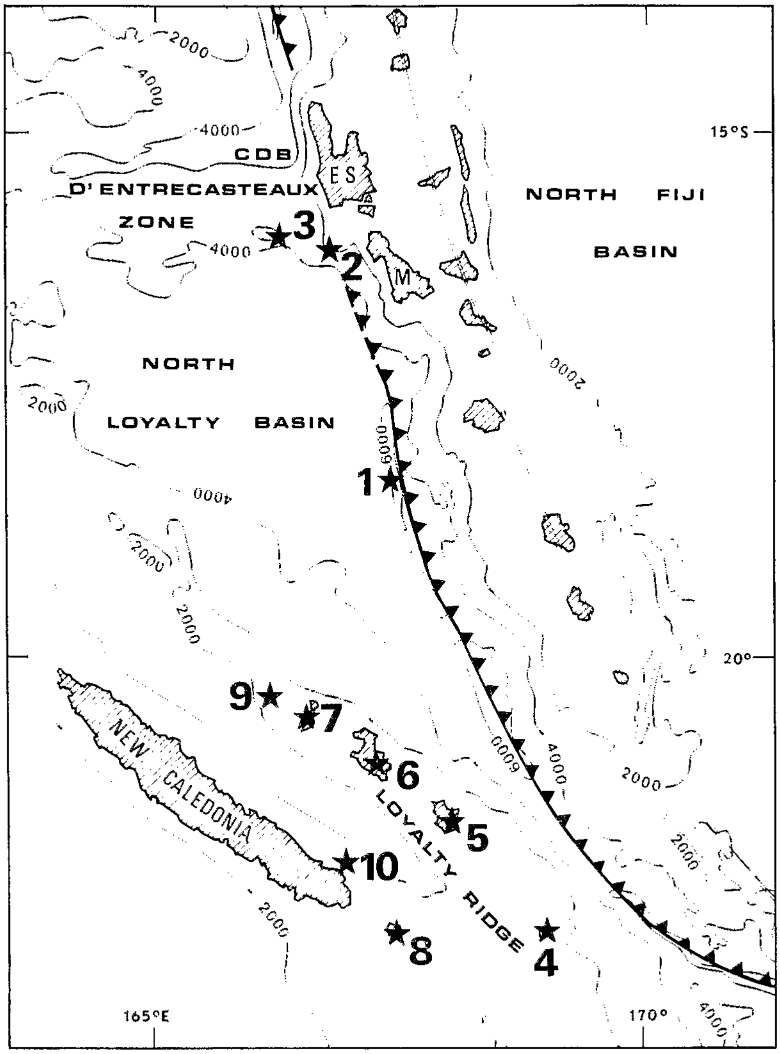

Fig. 1. Location of the uplifted or fossil atolls used in this study. *1*— Trench axis; *2*— Bougainville seamount; *3*— Sabine bank; *4*— Walpole island; *5*— Mare island; *6*— Lifu island; *7*— Uvea island; *8*— Isle of Pines; *9*— Beautemps Beaupré island; *10*— New Caledonia Reef; *ES*— Espiritu Santo island; *M*— Malekula island; *CDB*— Central d'Entrecasteaux basin. Double line represents active volcanoes. Depth contours are given in meters.

(1) The determination of the elastic thickness, about 24 km in the Loyalty islands area (Dubois et al., 1977a), which was obtained by the measurement of the horizontal extension of the topographic bulge.

(2) The subduction rate, deduced from the dating of uplifted coral samples, which is about 12 cm yr^{-1} in this area (Dubois et al., 1977b).

(3) The elasto-plastic behaviour of the lithosphere when the bending stresses are more than 4 kbar in the proximity of the trench. The elasto-plastic model was used with both an analytical formulation approach (e.g. Turcotte et al., 1978) and a finite element method (Carey and Dubois, 1981).

A recent survey was performed using the Seabeam echo-sounder of *N/O Jean Charcot* (SEAPSO cruise, leg 1). This leg was devoted to the study of the subduction/collision of the Loyalty and d'Entrecasteaux ridges. In the surveyed area, a reef-capped submerged seamount, formerly called Bougainville spur, was carefully mapped and renamed the Bougainville seamount (Daniel et al., 1986). In the same area stands a

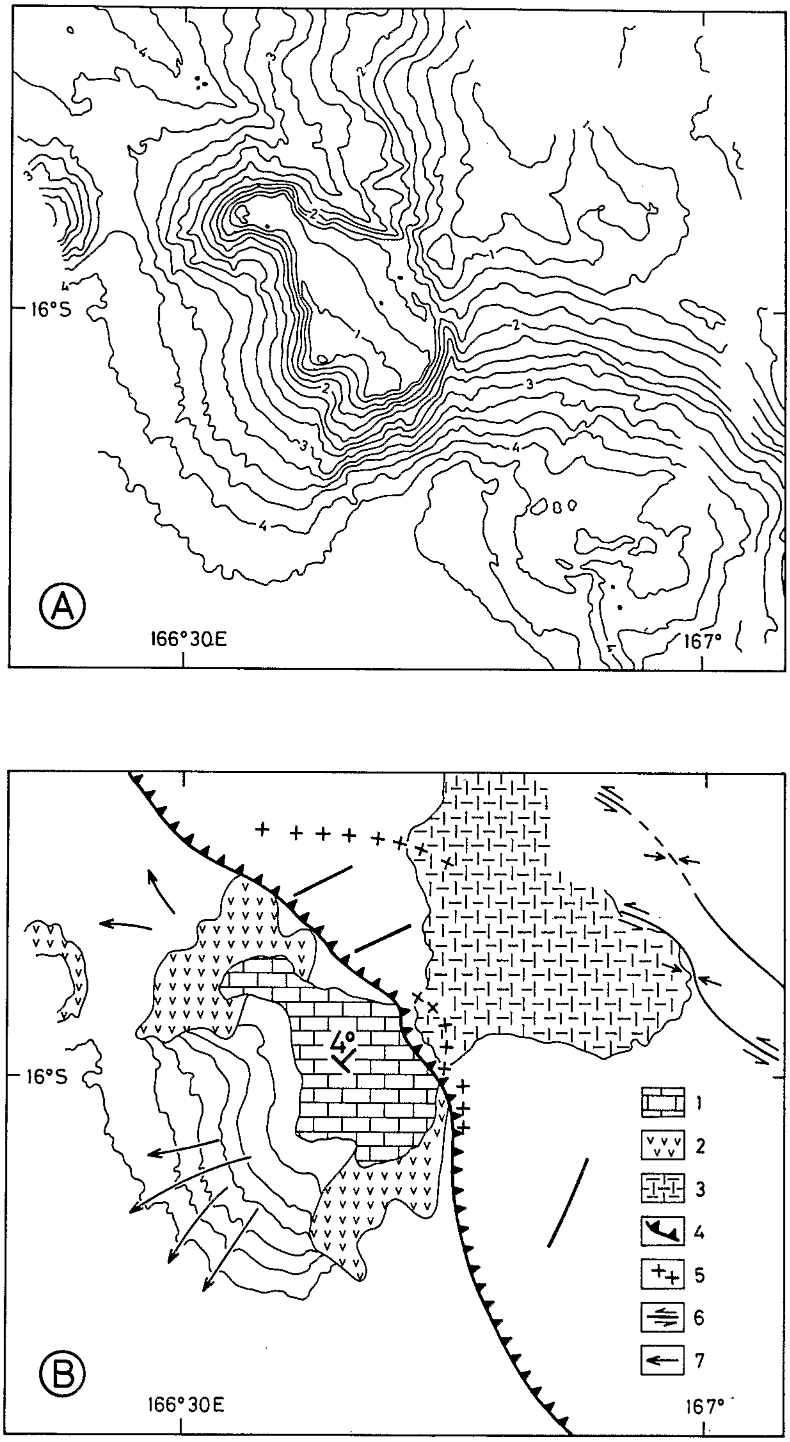

Fig. 2. Contact between the Bougainville seamount and the New Hebrides arc. (A) Seabeam map (equidistance 250 m). (B) Morphostructural sketch map: *1*— coral platform; *2*— volcanic flows; *3*— south Santo island arc framework; *4*— front of deformation; *5*— ridge; *6*— fault; *7*— slumps.

second pre-emergent coral reef-capped seamount. the Sabine bank, the top of which is about 7 m below sea level. Coral reef limestone samples were obtained by dredging on the flanks of the Bougainville seamount, and single-channel seismic profiles were taken across the seamount.

In this paper we analyse the new data on the Bougainville seamount and Sabine bank. These data improve the accuracy of the geometry of the bending of the lithospheric plate, in order to study the mechanical behaviour of the oceanic lithosphere in this area. Our results concerning the average flexural response of the North Loyalty basin are then discussed in the framework of other geodynamic studies.

Data and modelling

On the Seabeam map (Fig. 2) the Bougainville seamount has gentle basal slopes, then steep lateral slopes, and a flat top at a water depth of 1000 m which is slightly tilted towards the northeast (4°). A seismic reflection profile (SEAPSO 1087, Fig. 3) shows a sedimentary layer of about 1 s (two-way travel time) affected by a normal fault with a small throw. The fault must trend northwest perpendicularly to the general tilting of the seamount. Under the layer (probably limestone) an unstratified formation is visible. The rock samples obtained by dredging show, in the preliminary interpretation, a volcanic basement capped by coral limestone. This seamount may previously have approached the sea surface, as the Sabine bank now does, before subsiding to its present position. Combining these new data with previous data concerning the New Hebrides subduction zone, we can define a flexural curve of the oceanic lithosphere seaward of the trench axis with nine data points: southeast New Caledonia uplifted reefs, Beautemps Beaupré, the isle of Pines, Uvea, Lifu, Mare, Walpole islands and then the Sabine bank and Bougainville seamount (see Table 1 and Fig. 4).

The problem of a possible error on the uplift due to the erosion of coral reefs has been discussed by McNutt and Menard (1978, 1979) and Jarrard and Turner (1979). According to McNutt and Menard (1978), the effect of erosion would, in any case, produce a non-systematic error since the amount of erosion for each atoll would vary as a function of rainfall, elevation and length of exposure. Such an error should be reflected in large misfits of the theory to the data. Since the misfit is remarkably low, they concluded that erosion does not alter their results. This argument can also be applied to the uplifted atolls of the Loyalty islands, since the time of exposure to atmospheric erosion (which lies between 0 m.y. for Beautemps Beaupré to 1.5 m.y. for Walpole) and the altitudes are different for each atoll, and we do not observe any misfit. On the other hand, Jarrard and Turner (1979) pointed out that "Makateas" (coral terraces around high volcanic island) can be locally eroded by rainwater run-off from the central

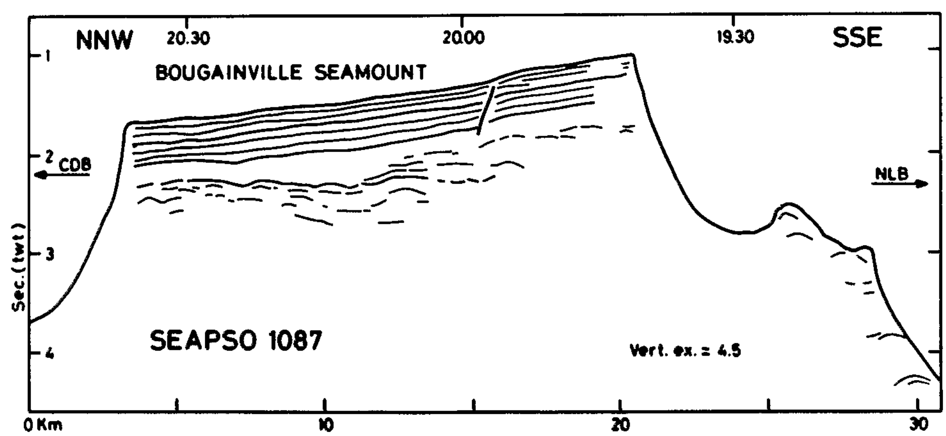

Fig. 3. Single-channel seismic reflection profile over the Bougainville seamount: *CDB*— central d'Entrecasteaux basin: *NLB*— North Loyalty basin.

TABLE 1

Location and altitude of the uplifted or fossil atolls used in this study

Observed data	Distance to the active volcanoes line (km)	Vertical elevation (m)
1 Trench line	140	−2500
2 Bougainville seamount	151	−1000
3 Sabine bank	203	−7
4 Walpole island	219	+71
5 Mare island	240	+138
6 Lifu island	282	+104
7 Uvea island	325	+46
8 Isle of Pines	348	+20
9 Beautemps Beaupré	354	+4
10 New Caledonia reef	372	+10

volcanic hill. But, since the Loyalty islands are flat, without central volcanic hills, such an effect cannot act here. So, we can conclude, as McNutt and Menard (1978) did, that the effect of erosion on coral reefs can be neglected for the interval of accuracy needed (2–3 m).

On Fig. 4 we plotted the coral reef maximum altitude versus the distance to the volcanic line considered as a reference line. In previous works (Dubois et al., 1974, 1975), the reference was the axis of the trench but, in the area studied here, the volcanic line is a better reference since the trench disappears in front of the d'Entrecasteaux zone, and we know (Karig and Sharman, 1975) that the distance between the trench axis and the active volcanic line generally remains constant along the same island arc; for example, in the New Hebrides island arc this distance is 143 ± 3 km. Therefore, the accuracy of the distance to the reference line is about 5 km. On the same graph, we give the position of the trench axis and its relative depth, defined as trench depth minus depth of abyssal plain, according to Grellet and Dubois (1982). A value of 2500 m is obtained for the relative depth of the New Hebrides trench between the Loyalty and d'Entrecasteaux ridges, in the North Loyalty basin.

Thus we obtain an observed deflection curve of the oceanic lithosphere which is controlled by ten

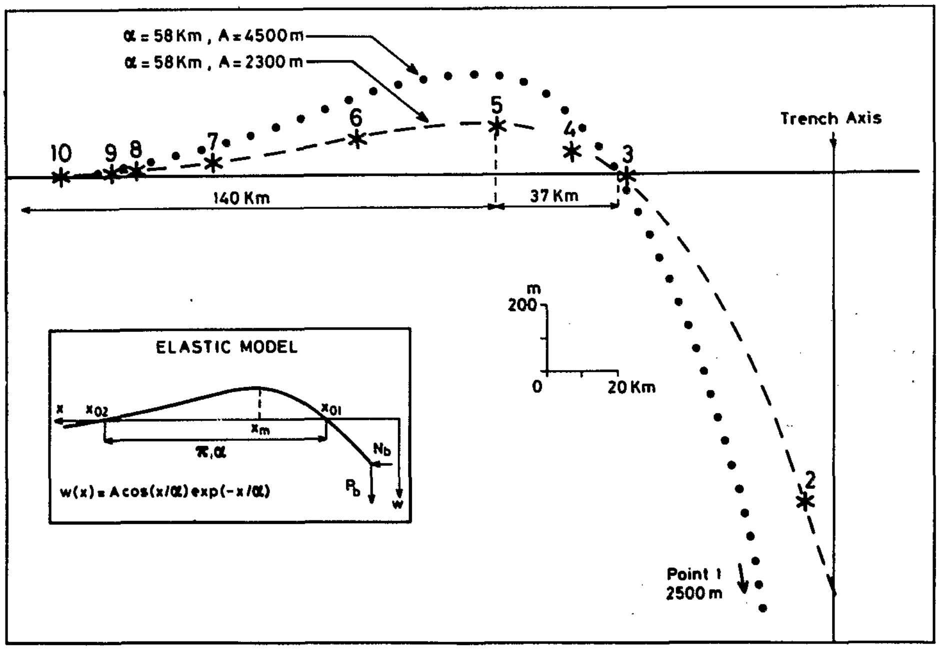

Fig. 4. Deflection of the oceanic lithosphere prior to subduction. Uplifted and fossil atolls are shown with asterisks. The size of the asterisks corresponds to the accuracy of the data. The dashed line is the theoretical elastic curve ($\alpha = 58$ km, $A = 2300$ m) which best fits the observed data, except in the trench depth. To fit this point with an elastic model, the amplitude of the bulge would have to be doubled (dotted line).

data points (Fig. 4). These data can be modelled in different ways:

(1) These observed values except point 1 (trench axis) are in good agreement with an elastic model. Using the approximation of thin plates deformation (Hanks, 1971) and neglecting the horizontal compression N_b (Caldwell et al., 1976), the deflection of an elastic plate overlying a fluid substratum under free edge loading is (see Fig. 4):

$$w(x) = A \exp(-x/\alpha) \cos(x/\alpha)$$

with $A = 2\, P_b/k\alpha$

where $\alpha = (4D/k)^{1/4}$ is the flexural parameter; $D = EH^3/12(1-\nu^2)$ is the flexural rigidity; H is the effective elastic thickness; E is the Young's modulus ($= 6.5 \times 10^{10}$ N m^{-2}); ν is the Poisson's ratio ($= 0.25$); P_b is the vertical force per unit length of trench; and $k = (\rho_m - \rho_w)g = 23\,000$ kg m^{-2} s^{-2}, where ρ_m and ρ_w are densities below and above the plate respectively. The best-fit values of parameters in our study are:

$\alpha = 58 \pm 2$ km
$A = 2300 \pm 10$ m

Thus the corresponding value of the elastic thickness is:

$H = 22 \pm 2$ km

(2) Assuming the same elastic thickness, it is possible to fit point 1 and points x_{01}, x_{02} (see Fig. 4) using another value of A. In such case we obtain $A = 4500$ m, but we can observe on Fig. 4 that the amplitude of the bulge would be twice as large under the North Loyalty basin; yet, unfortunately, no precise data are available in this area (see Fig. 1). On the other hand, the depth of the trench in front of the Loyalty ridge cannot be estimated because the ridge has already entered the subduction zone.

Coming back to the map (see Fig. 1), it appears that the flexural response of the oceanic lithosphere is not the same all along the New Hebrides island arc. Deflections are smaller for points that belong to the d'Entrecasteaux or Loyalty ridges (points 2–8) than for point 1 which is in front of North Loyalty Basin. This must now be discussed.

Discussion and interpretation

The value of 22 km for the effective elastic thickness is smaller than the one which can be computed (e.g. Bodine et al., 1981) from the age of the lithosphere. Interpretation of the magnetic anomalies (Lapouille, 1982; Weissel et al., 1982, Collot et al., 1985) shows that the lithospheric age in the North Loyalty basin increases from 42 m.y. in the south to 55 m.y. in the north. Using a mean lithospheric age of about 48 m.y., the theoretical effective elastic thickness would be around 28 km. Indeed, our value corresponds to the effective elastic thickness of a lithosphere supporting seamounts on top of well developed ridges. Therefore, it is much more likely that these seamounts were emplaced on a lithosphere which was subjected to a thermal rejuvenation, as proposed by Menard and McNutt (1982) or McNutt (1984). Indeed, the mean depth (4200 m) in the ridges area yields an effective thermal age (McNutt, 1984) of 25 m.y., which agrees with the computed elastic thickness (22 km). The hypothesis of a thermal rejuvenation of the North Loyalty basin is also supported by abnormally high heat-flow values (McDonald et al., 1973) south of the d'Entrecasteaux ridge (2.81 cal cm^{-2} s^{-1}), while north of this ridge the mean value is around 1.32 cal cm^{-2} s^{-1}. These high values can be related to recent volcanic activity which occurred 10 m.y. ago on Mare island (Baudron et al., 1976). Furthermore, important attenuation of S_n seismic waves has been noticed by Molnar and Oliver (1969) south of d'Entrecasteaux ridge. Dubois (1971) also pointed out a P-wave travel time anomaly in the upper mantle beneath the North Loyalty basin. All these data agree with our assumption of a thermal rejuvenation of the North Loyalty basin.

Assuming the same elastic thickness H all along the subduction zone, we propose that the observed variations in lithospheric flexure between the North Loyalty basin and the d'Entrecasteaux and Loyalty ridges are only related to the value of A. Different values of A indeed correspond to different values of P_b. Our result shows that the value of P_b under North Loyalty Basin is twice the value of P_b under d'Entrecasteaux and Loyalty ridges. In the model, P_b is the vertical force per unit length of trench applied at the edge of the plate (see Fig. 4), and is related to the weight of the subducted slab. We can interpret these different values of P_b with reference to the shape of the subducted slab given by seismological data under the New Hebrides island arc. Two gaps in the hypocentral distribution of earthquakes are observed in the prolongation of the d'Entrecasteaux and Loyalty ridges (see Fig. 5) at a depth ranging from 150 to 300 km (Louat et al., 1982). Furthermore, a three-dimensional inversion (Goula and Pascal, 1979) shows the existence of two low-velocity zones for S waves in the slab. The locations of these zones correspond to the previously mentioned seismicity gaps. These results support our shorter slab explanation in front of the d'Entrecasteaux and Loyalty ridges, and are in good agreement with small values of P_b in both areas.

In previous papers (Dubois et al., 1977a, Carey and Dubois, 1981) we observed that it was impossible to fit point 1 (trench axis) with an elastic model. Therefore, we used an elasto-plastic behaviour, arguing that the yield stress of plasticity is reached in the proximity of point x_{01} (Turcotte et al., 1978). This general observation in various subduction zones enabled us to compute an effective yield strength, the mean value of which is about 3.8–4.8 kbar.

In the present study, we use an elastic model for the data observed on the d'Entrecasteaux and Loyalty ridges ($\alpha = 58$ km, $A = 2300$ m). The maximum extensive stress is:

$$\sigma_{xx} = \frac{-EH}{2(1-\nu^2)} \frac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

which corresponds to $(\sigma_{xx})_{\max} = 3.3$ kbar for $x = \alpha\pi/4$. Using the Von Mises criterion of plasticity ($\sigma_c = \sigma_{xx}\ (1-\nu+\nu^2)^{1/2}$ for thin plate deformation), we have $(\sigma_c)_{\max} = 3$ kbar, which is smaller than the average yield strength. Therefore an elastic model is adequate for approximating the lithospheric flexure under the d'Entrecasteaux and Loyalty ridges.

Under the North Loyalty basin, the elastic model ($A = 4500$ m) best fitting the position and depth of the trench implies large stresses ($(\sigma_{xx})_{\max} = 6.5$ kbar, $(\sigma_c)_{\max} = 5.8$ kbar). Thus the bending of the lithosphere must be in better agreement with an elasto-plastic model in this area. With this model, the amplitude of the bulge will be smaller than with the elastic one fitting point 1. Note that we did not consider the three-dimensional formulation of the problem due to lateral variations of the values of parameters (i.e. P_b) for the North Loyalty basin, since the distance between the two ridges is larger than 500 km.

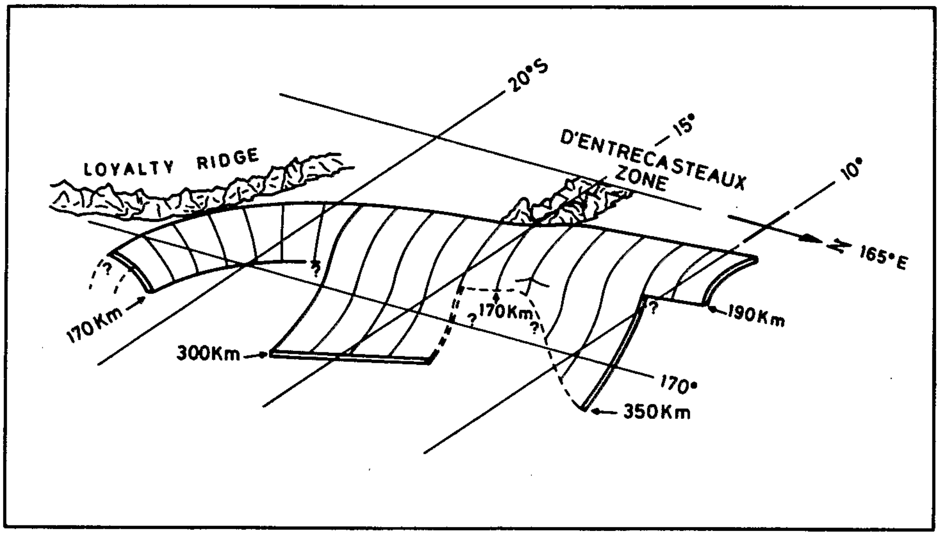

Fig. 5. Schematic three-dimensional representation of the subducting slab in the New Hebrides trench, deduced from a study of seismicity (from Louat et al., 1982).

It is also possible to correlate the flexural shape and rheological behaviour of the oceanic plate with the recent uplift of the overriding plate in the Espiritu Santo island and Malekula island area.

Quaternary uplift of the frontal arc region is widely distributed troughout the New Hebrides. and evidenced by the existence of uplifted coral reef terraces. However. the maximum uplift is observed on Santo and Malekula islands (Taylor et al., 1980; Jouannic et al., 1982). Furthermore. whereas the Quaternary uplift rate is constant on some islands, such as the Torres islands. there is. on Santo and Malekula, an uplift rate acceleration during the Holocene (Taylor et al., 1985). Therefore, that acceleration is probably related to the subduction of the d'Entrecasteaux ridge.

Taylor et al. infer that the uplifted areas were previously occupied by the inner slope of the trench, and it is possible that some sediments from the d'Entrecasteaux ridge could have been accreted to the inner slope and then uplifted.

Three possible interpretations of that uplift can be proposed:

(a) The effect of buoyancy of the underthrusted part of the d'Entrecasteaux ridge (Moretti, 1983; Moretti and Ngokwey, 1985).

(b) The vertical component of the effect of the collision of the d'Entrecasteaux ridge with the overriding plate (Collot et al., 1985).

(c) The shorter length of the subducting slab in front of the d'Entrecasteaux ridge (this paper).

In fact, effects (a) and (c) both tend to diminish the value of P_b, which may explain the elastic behaviour of the oceanic lithosphere under the d'Entrecasteaux ridge.

Conclusion

To summarize, we interpret the Bougainville seamount and the Sabine bank as immerged fossil atolls, the recent subsidence of which is related to the subduction of the oceanic lithosphere under the New Hebrides island arc. The positions and altitudes of the different fossil atolls are in good agreement with the predictions of the elastic model. This gives an average elastic thickness for the lithosphere of 22 km, for the area under study. This value is smaller than the one (Bodine et al., 1981) corresponding to the lithospheric age given by magnetic anomalies in this area, but corresponds to the effective thermal age (McNutt, 1984) deduced from the mean depth of the North Loyalty basin. A thermal rejuvenation of the North Loyalty basin is also supported by previously reported high heat-flow values and attenuation of seismic waves.

The discrepancy of the position and depth of the trench in front of the North Loyalty basin is interpreted as the result of variations in the value of P_b along the subduction zone. We relate these variations to the length of the subducted slab, which is shorter in front of the d'Entrecasteaux and Loyalty ridges than in front of the North Loyalty Basin.

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