New Hebrides trench: subduction rate from associated lithospheric bulge[1]

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We present new data on the lithospheric bulge in the vicinity of the Loyalty and New Hebrides Islands, and attempt to interpret the difference of the topographic profile of the outer wall of the New Hebrides trench from a theoretical profile. The free edge of the lithospheric plate appears to correspond to a line of maximum seismic strain release. The uplift rate and consequently the subduction rate have been calculated from studies of the dynamic aspect of the bulge and from $^{230}Th/^{234}U$ ages of raised coral terraces.

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Introduction

Considerable indications of vertical movements and relative sea level changes exist in New Caledonia and the Loyalty Islands. Some of these, such as the peneplanation of the ultramafic massifs on New Caledonia, indicate older movements, whereas others, such as drowned river valleys on the continental shelf of New Caledonia (Launay 1972), indicate more recent movements. On the east coast of New Caledonia and on the Isle of Pines, coral terraces have been recently uplifted. The Loyalty Islands are uplifted atolls, the tops of which lie more than 100 m above present sea level on Maré and Lifou. By separating eustatism from other possible causes of level changes Dubois *et al.* (1974, 1975) interpreted uplift of the Loyalty Islands group as the result of an upward bulge of the lithosphere in front of its underthrusting beneath the New Hebrides island arc. This is modelled by a thin elastic plate resting on a fluid of negligible viscosity. Models of lithospheric flexure have been discussed previously by Gunn (1943), Lliboutry (1969), Walcott (1970), Hanks (1971), and Watts and Talwani (1974).

In this paper the topography of the bulge is discussed together with problems involved in reconciling parts of it with the model. Finally the dynamic aspect of the lithospheric bulge and new $^{230}Th/^{234}U$ dates are analysed so that the subduction velocity of the Indian plate beneath the Pacific plate at the New Hebrides trench may be computed.

Topography

By measuring the maximum elevation for each island of the Loyalty Archipelago and the distance of each island from the New Hebrides trench, Dubois *et al.* (1974) found that the top of the flexure appears to be located near Maré while the zero value is located somewhere to the northwest of Yate (Figs. 1 and 2).

By applying Hank's (1971) equation

$$[1] \quad \xi = \frac{-P_b}{\beta(\rho_m - \rho_w)g}\frac{2\lambda^2}{3\alpha^2 - \beta^2} \times e^{-\alpha x}[2\alpha\beta\cos\beta x + (\alpha^2 - \beta^2)\sin\beta x]$$

in which

$$[2] \quad \lambda = [(\rho_m - \rho_w)g/4\Gamma]^{1/4}$$

$$[3] \quad \Gamma = EH^3/12(1-\sigma^2)$$

$$[4] \quad \alpha = (\lambda^2 + N_b/4\Gamma)^{1/2}$$

$$[5] \quad \beta = (\lambda^2 - N_b/4\Gamma)^{1/2}$$

where σ = Poisson's ratio; E = Young's modulus; H = thickness of lithospheric plate; ρ_m, ρ_w = densities above and below the plate respectively; P_b, N_b = vertical and horizontal forces on the edge of the plate respectively; Γ = flexural rigidity; and g = average gravity.

Dubois *et al.* (1975) calculated from fitting the topography that the flexural parameter (I/λ) is

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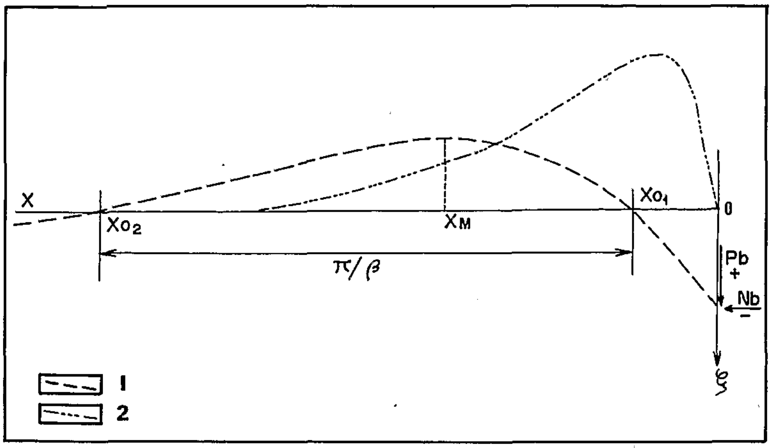

FIG. 1. Theoretical deflection curve (1) and relative strain (2) across a thin plate. X01 and X02 are the first and second zeros.

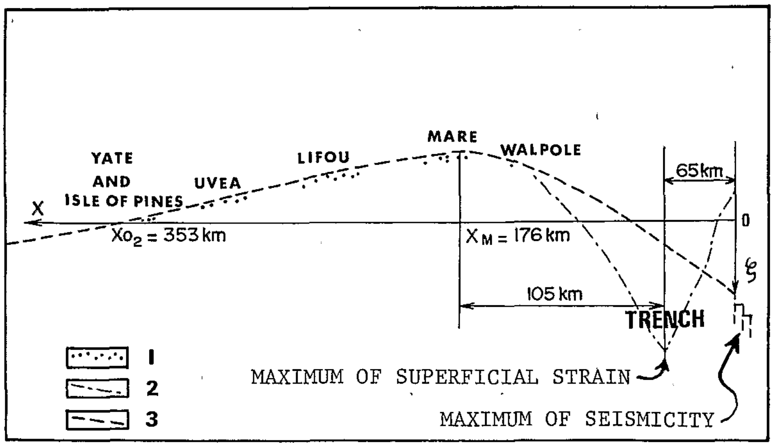

FIG. 2. Topographic profiles perpendicular to the trench axis and theoretical deflection curve. Coral reefs (1), bathymetric profile of the trench (2), and theoretical deflection curve (3).

approximately 76 ± 5 km (computed from the distance between the maximum and the zero).

A difficulty arises, however, in fitting the outer wall of the trench with the topographic shape of the underthrusting lithosphere. It seems that the trench, which is the locus of the maximum relative strain, is a zone of fracturing of the upper part of the lithosphere (Le Pichon *et al.* 1974). In the theoretical model the free edge of the lithosphere would be located at a distance of 65 km east of the trench axis under the frontal arc (Fig. 2). This model is strongly supported by the energy release computed by Louat (1975). Indeed the maximum energy release is located along an axis parallel to the trench at a distance of 50–60 km east of the trench (Fig. 3).

Another interpretation is given by Turcotte (Turcotte, personal communication, 1975) who suggests that the rheological properties of the lithosphere change along its profile, and that although it is quite elastic in the part from zero to the summit of the bulge, it becomes plastic when the stresses reach high values in the part of the downgoing plate with the smallest radius of curvature. A recent paper by Caldwell *et al.* (1975) shows from Aleutian, Kuril, Bonin, and Mariana profiles that horizontal forces may be neglected, and that the bending lithosphere behaves elastically.

Dynamic Aspect and Subduction Rate

Dubois *et al.* (1975) have shown that if the

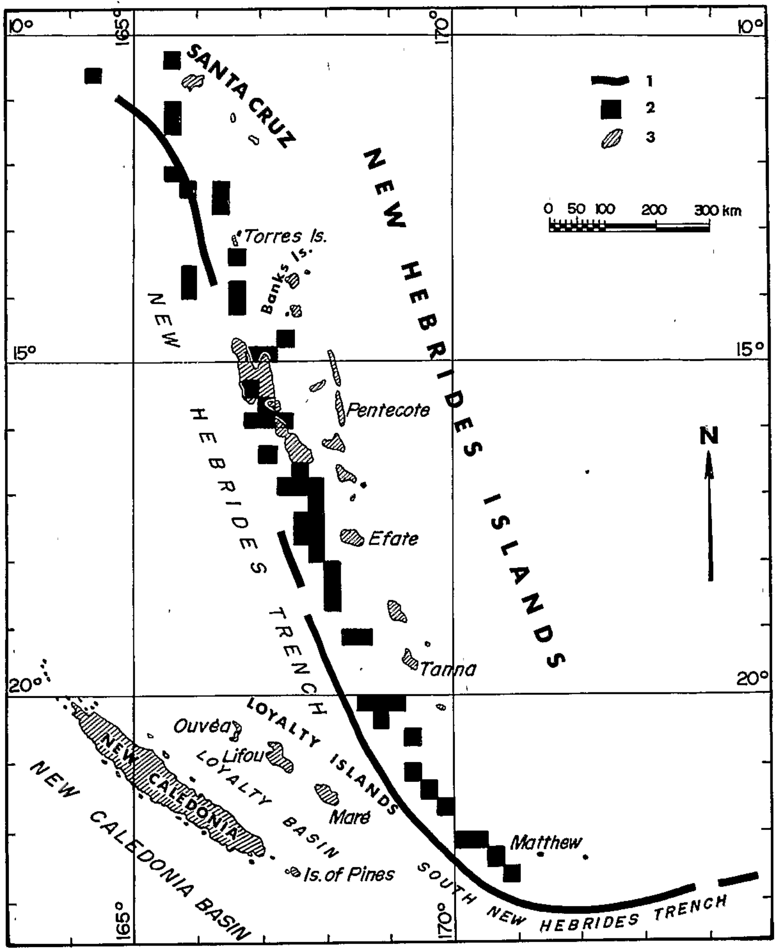

FIG. 3. Superficial seismicity (hypocenters from 0 to 50 km). Trench axis (1), maximum of seismic energy release (2), and islands (3). After Louat (1975).

ages of uplifted rocks are known accurately then the horizontal velocity of the underthrusting plate can be calculated from the uplift rate. This method was applied using known ages from Niue Island, and a subduction rate of 9 cm/year was obtained.

The first derivative of the theoretical deflection equation ([1]) is

$$[6]\quad \frac{d\xi}{dx} = \frac{2P_b\lambda^2(\alpha^2 + \beta^2)}{\beta(\rho_m - \rho_w)g(3\alpha^2 - \beta^2)} \times e^{-\alpha x}(\alpha \sin \beta x + \beta \cos \beta x)$$

In [4] and [5] the values of N_b and P_b are unknown, but the relationship between N_b and P_b can be determined by using [1] at the top of the bulge (*i.e.* the value of ξ_M at Maré is 140 m). Also if Hank's (1971) estimate of $N_b/P_b = 10$ is used for the New Hebrides example then $N_b = 1.35 \times 10^{16}$ dyne/cm and $P_b = 1.35 \times 10^{15}$ dyne/cm. With $\Gamma = 2.0 \times 10^{30}$ dyne/cm the value of $N_b/4\Gamma$ in [4] and [5] is $\frac{1}{10}$ of the value of λ^2 and so

$$\alpha \approx \lambda + \lambda/20; \quad \beta \approx \lambda - \lambda/20$$

Using the estimate of $N_b/P_b = 5$,

$$\alpha \approx \lambda + \lambda/35; \quad \beta \approx \lambda - \lambda/35$$

For simplification in determining the derivative and the values in Table 1, if we assume that $\alpha = \beta = \lambda$ then [1] and [6] are reduced to

TABLE 1.

Distance to the edge of the plate (km)	Uplift rate (cm/1000 years) for different values of subduction rate			
	5 cm/year	7 cm/year	10 cm/year	13 cm/year
190	2.098	2.937	4.196	5.455
200[a]	3.650	5.110	7.300	9.490
210	4.735	6.628	9.469	12.310
220[b]	5.427	7.598	10.854	14.110
240	5.907	8.270	11.814	15.358
250	5.819	8.147	11.639	15.130
260	5.568	7.795	11.136	14.477
280[c]	4.780	6.692	9.560	12.428
300	3.809	5.332	7.618	9.903
320	2.831	3.964	5.663	7.361

[a] Maré.
[b] Lifou.
[c] Isle of Pines.

$$[7]\quad \xi = \frac{-2P_b\lambda}{(\rho_m - \rho_w)g}\, e^{-\lambda x} \cos \lambda x$$

$$[8]\quad \frac{d\xi}{dx} = \frac{2P_b\lambda^2}{(\rho_m - \rho_w)g}\, e^{-\lambda x}(\cos \lambda x + \sin \lambda x)$$

From the uplift rate and the subduction rate we obtain the following relation:

uplift = slope × subduction rate

If fitting the topography to the theoretical curve is correct then the subduction rate can be calculated from the uplift rate by using [8]. Results are shown in Table 1.

Results and Interpretation

Coral samples from uplifted terraces on Lifou, Maré, and the Isle of Pines have been collected at various elevations above present sea level. All the corals come from their original growth position upon the flat reef terrace, and, by analogy to the present living reefs around these islands, they are considered to be representative of ancient sea levels.

The corals were dated by the ^{230}Th/^{234}U method, and the results are presented in Table 2. Three samples (Lifou 11, 12, and Maré 123) are considered to have reliable ages as there has been no recrystallization of aragonite to calcite. The other samples from Maré (160, 161, 163) show some recrystallization. Their ages, however, are in good agreement with Maré 123. Fontes (J. Ch. Fontes, personal communication) has noted that the stable isotope ratios of these samples are evidence for the preservation of initial composition. The age of the coral from the Isle of Pines is unreliable because it has been recrystallized by as much as 30%, and it was the only sample dated from this site.

The two corals from the +3.5 m terrace on Lifou give ages of about 180 000 years B.P. This corresponds to the age of reef complex VIII from the Huon Peninsula, New Guinea (Chappell 1974), for which a sea level of the order of −20 m was calculated. Assuming that this sea level estimate is correct then the corresponding mean uplift rate of Lifou since this time is of the order of 13 ± 0.5 cm/1000 years.

On Maré island the set of samples at an elevation of 2 to 5 m corresponds closely to the 107 000 years sea level (reef complex VI of Bloom *et al.* 1974) the elevation of which was −15 m; the uplift rate since this time is 15.9 cm/1000 years to 18.7 cm/1000 years. But if we use the elevation of −6 m (reef complex of Bloom *et al.* 1973) we get an uplift rate of 7.4 cm/1000 years to 10.3 cm/1000 years. Because of the uncertainties of the altitudes of Maré samples and of the sea level at 107 000 years, we shall ignore the values of Maré.

The only sample from the Isle of Pines appears to correspond to the well established +5 m sea level that occurred during the last interglacial (reef complex VII of Bloom *et al.* 1973). This indicates a mean uplift rate of 12.7 ± 2.5 cm/1000 years.

By using the uplift values in Table 1 together with [8], one can determine the subduction rate. Uplift is tabulated according to the distance to the zero (edge of the plate) and for different subduction rates. The subduction rates as determined from the uplift values are: Lifou 12.0 ± 0.5 cm/year, and Isle of Pines 12.8 ± 2.5 cm/year. Assuming a constant rate during the last 200 000 years, one obtains an average subduction rate of 12.4 ± 1.5 cm/year.

The value of 12 cm/year seems high. In this area the plate tectonics are controlled by the relative motion of the Pacific and Indian plates, of which the pole of rotation is to the south (50°S, 179°W for McKenzie and Sclater (1971), 59.8°S, 178°E for Minster *et al.* (1974)). On a circle centered on the pole of rotation crossing both Tonga and the New Hebrides at the latitude of 20°S the relative motion of the two plates is about 10 cm/year (9.87 cm/year using McKenzie and Sclater's pole and rotation rate and 9.77

TABLE 2. Stable isotope, radiochemical data, and ages of coral samples from the Loyalty Islands and New Caledonia

Sample No.	Altitude (m)	Aragonite (%)	$\delta^{18}O$/PDB	$\delta^{13}C$/PDB	U (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	Age (× 10^3 years)
Lifou 11	3.5±0.5	100	−3.66	+0.56	2.32±0.03	1.09±0.01	0.84±0.03	189±17
Lifou 12	3.5±0.5	100	−3.64	−0.90	2.30±0.04	1.12±0.01	0.82±0.03	174±16
Maré 123	3.2±0.3	100	−3.82	−0.08	2.48±0.03	1.10	0.61	98±15
Maré 160	2.0±0.3				2.45±0.03	1.08	0.60	95± 3.5
Maré 161	5.0±1.0	86	−3.48	−0.36	2.20±0.03	1.09	0.57	90± 4
Maré 163	5.0±1.0				2.68±0.04	1.09	0.61	98± 3.5
Isle of Pines 13:	20 ±3	70			2.68±0.04	1.10	0.71	118±8

NOTES: Stable isotopes measured by J.Ch. Fontes (Laboratoire de Géologie Dynamique, Paris). The ages of Maré 123, 160, 161, 163 and Isle of Pines 13 are from Bernat *et al.* (1976). % Aragonite: X-ray measurement by F. Melières (Laboratoire de Géologie Dynamique, Paris).

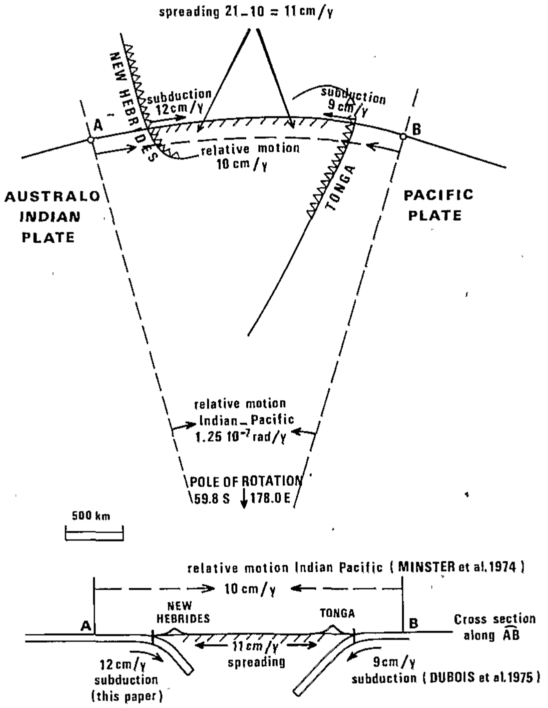

FIG. 4. Relative motion between the Indian and Pacific plates. Along the arc AB the subduction rate towards the east (New Hebrides) is 12 cm/year, the subduction rate towards the west (Tonga) is 9 cm/year, so the total rate of subduction of lithosphere is 21 cm/year. The relative movement between A and B is 10 cm/year. This implies secondary spreading at the rate of 11 cm/year between the two subduction zones.

cm/year using Minster *et al.*'s pole and rotation rate). Adding the subduction rate at the New Hebrides trench of 12 cm/year to the opposite subduction rate of 9 cm/year at the Tonga trench, one obtains a total subduction rate of 21 cm/year.

If the values calculated for the subduction rates are correct, the presence of secondary spreading between the two opposite subduction zones is indicated (Fig. 4). Since the relative motion of the two plates is 10 cm/year this implies a secondary spreading rate of 21 − 10 = 11 cm/year between the two opposite subduction zones.

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