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SOME NEW EVIDENCE ON LITHOSPHERIC BULGES CLOSE TO ISLAND ARCS

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ABSTRACT

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The wavelength and position of the crest of the bulge in a lithospheric plate being subducted at a trench is difficult to determine from bathymetric profiles because of topographic irregularities. It is therefore proposed that Bouguer anomaly profiles and the position of the outer gravity maxima be used to determine these parameters as there is a close correspondence between the flexed lithosphere and the gravity profiles.

A gravity profile across the New Hebrides Trench has been used in conjunction with observations on the level of raised atolls of the Loyalty Islands to determine the crest—trench distance and the wavelength of the lithosphere in this region. These give values which agree well with theoretical predictions. However, it has not yet been possible to determine the rate of elevation of the Loyalty atolls.

On Niue Island of the Cook Archipelago, the rate of elevation is known from radiometric soil methods and in the absence of a gravity profile, a bathymetric profile has been used to determine the parameters of this bulge at the Tonga Trench. This yields a rate of convergence of 9 cm/year. However, the results do not have sufficient accuracy to resolve whether ancillary basinal growth is presently taking place in the Lau-Havre Trough, which could otherwise be ascertained by comparing the rate of convergence at the trench with the rate of spreading at associated mid-ocean ridges.

INTRODUCTION

Recently we proposed an interpretation of the uplift of the Loyalty Islands group as the result of an upward bulge of the lithosphere before its underthrusting beneath the New Hebrides island arc (Dubois et al., 1973 and 1974). The observed uplift can be explained by a bulge in the lithosphere modelled by a thin elastic plate. The problem of lithospheric flexure has been studied by a number of workers: Gunn (1943), Lliboutry (1969), Walcott (1970), Hanks (1971), Watts and Talwani (1974). In the computations the lithosphere is considered as a very large thin sheet of uniform thickness and homogeneous rheological properties floating on a fluid of negligible viscosity compared to the viscosity of the sheet.

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The well-known equation giving the deflection ξ as a function of the distance x to the axis where applied external forces is:

$$EI d^4\xi/dx^4 - (\rho_m - \rho_w)\xi g = 0$$

where E is the modulus of elasticity of the sheet, I is the cross-sectional moment of inertia of the sheet at a point on the x-axis, ρ_m is the density of material underlying the sheet, ρ_w is the density of the material above the sheet and g is the average gravity.

The four constants of integration are determined from the boundary conditions of the problem: for the condition that $\xi = 0$ for great distances and the sheet is semi infinite with a free edge at the origin, we get:

$$\xi = \frac{2Pb\lambda}{(\rho_m - \rho_w)g} e^{-\lambda x} \cos \lambda x$$

where $\lambda = \left[\frac{(\rho_m - \rho_w)g}{4D}\right]^{1/4}$

and $D = EH^3/12\ (1 - \sigma^2)$

where H is the thickness of the lithosphere and σ the Poisson's ratio, $1/\lambda$ is the flexural parameter of Walcott (1970) and Pb is the vertical force/unit width applied at the origin.

The equation given by Hanks (1971) is more general and takes into account the horizontal force Nb applied at the origin, the predicted shape of the lithosphere is, however, similar, particularly with regard to the wavelength involved.

In the application of lithospheric flexure near a subduction zone, the distance x is measured from a point beneath the island arc where the downward bending of the lithosphere ceases to be elastic (D.L. Turcotte, personal communication, 1974). This point is not known exactly and must be assumed.

Hanks (1971) interpreted the outer ridge of the Kurile Trench in terms of flexure of the lithosphere. Then Watts and Talwani (1974) made a global investigation of the outer gravity high, seaward of deep-sea trenches, which is associated with this outer bulge. However, the observations on the uplifted Loyalty atolls provide for the first time, accurate topographic investigations of the relative differences in level of the reef crowns which can be easily measured.

TOPOGRAPHIC EVIDENCE

Loyalty Islands

In previous papers (Dubois et al., 1973, 1974), we gave the shape of the bulge near the New Hebrides subduction zone (Fig. 1). We considered the

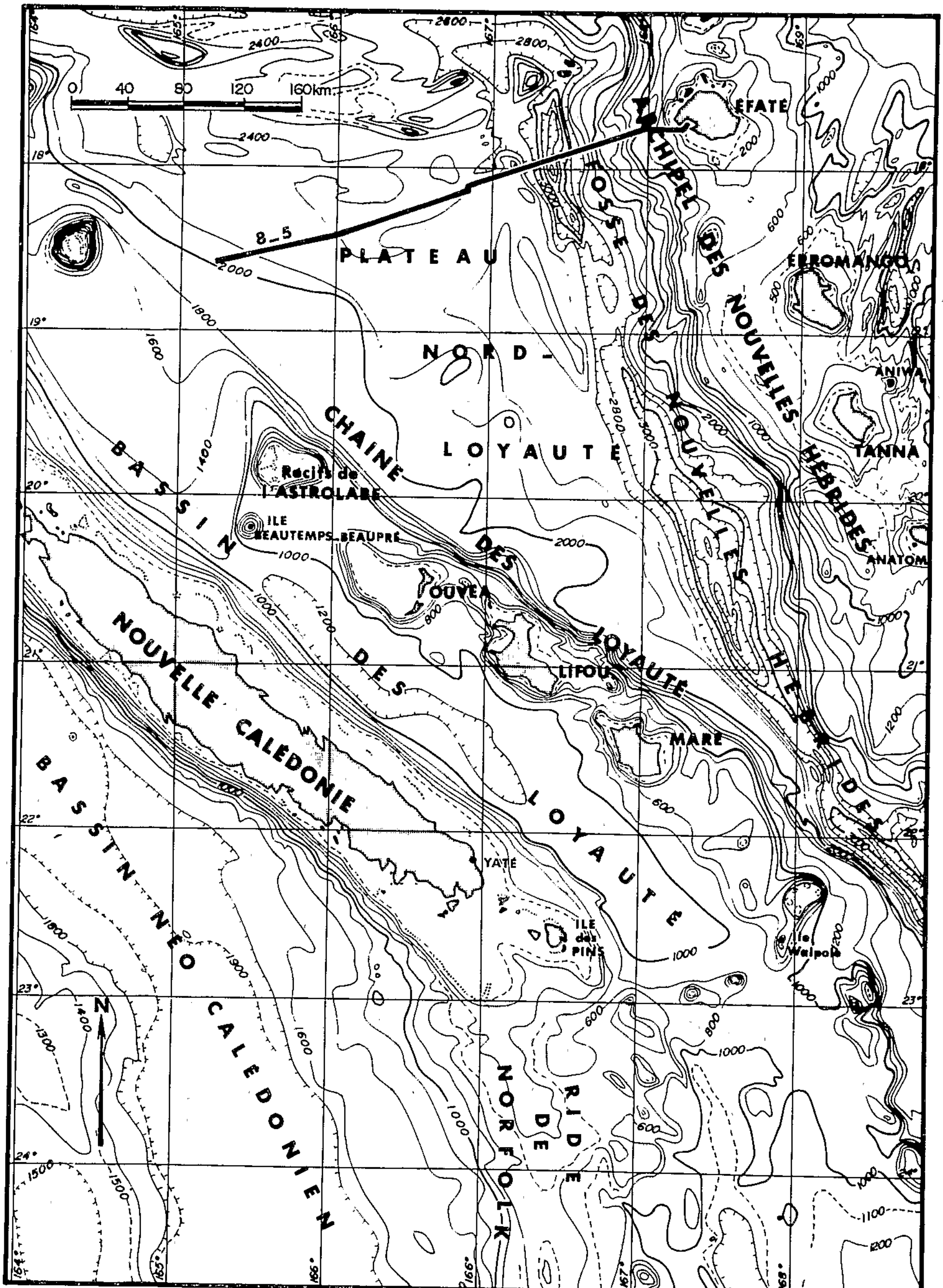

Fig. 1. Bathymetric map (from Scripps, 1972) of the bulge area relative to the new Hebrides subduction. *8—5* = gravity profile from Luyendyck et al., in press.

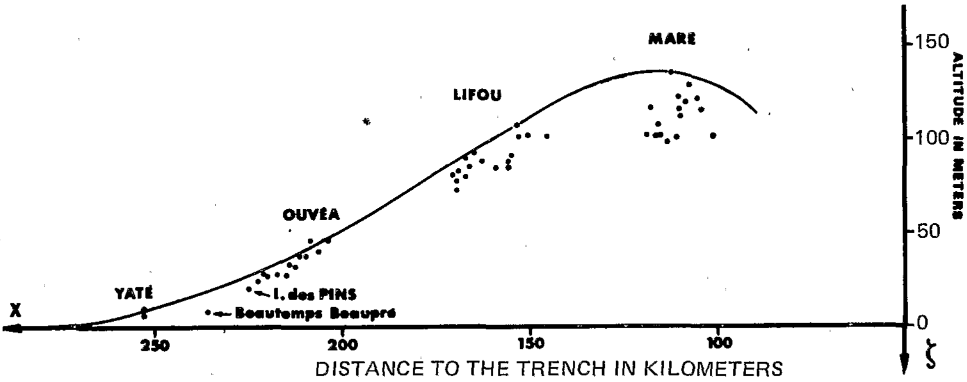

Fig. 2. Superimposition of the theoretical curve of deflection:

$$\xi = \frac{2Pb\lambda}{(\rho_m - \rho_w)g} e^{-\lambda x} \text{ (for } 1/\lambda = 80 \text{ km)}$$

with topographic measured points relative to their distance perpendicular to the trench axis.

highest points of the reefs on every island and their distances to the trench and we fitted the theoretical curve of flexure according to different values of the flexural parameter. In this way, taking the top of the bulge on the trench axis (Lliboutry, 1969) we obtained a value of $1/\lambda = 130$ km. We can now precisely fix this point if we consider a detailed topographic profile. On Fig. 2, we have plotted the highest points on the edges of the reefs as a function of their distance to the New Hebrides trench axis. This was done for Mare, Lifou, Ouvea, Beautemps—Beaupre Islands, the Isle of Pines, and the southeastern part of New Caledonia (Yate reefs). On this topographic profile, the shape of the flexural curve appears. The top of the flexure appears to be near Mare and the zero value somewhere to the west of Yate. The difference in distance between this maximum and zero is about 180 km in a direction perpendicular to the trench axis. It represents the distance $3\pi/2\lambda$ (maximum) $-3\pi/4\lambda$ (zero), which is equal to $3\pi/4\lambda$ from the equation of the deflection. This yields a value of approximately 80 km for $1/\lambda$.

The position of the maximum deflection will be also fixed by the gravity high on a gravimetric profile (see below).

Niue island

We have found in the Cook Islands area, an instance similar to the Loyalty Island uplift. Niue Island is an isolated coral island at 19° 00S, 169° 50′W on the east side of the Tonga island arc and at a distance of about 270 km from the trench, measured along the direction perpendicular to the trench axis. It has a raised circular reef 65—71 m above sea level, indicating that the island was once an atoll. A lagoonal basin that no longer holds water, is now 30 m above sea level at its centre and occupies by far the greatest part of the island's area (Schofield, 1967; Summerhayes, 1966). A magnetic survey shows that the limestone is underlain by a caldera-shaped volcanic substructure.

As with the Loyalty Islands, there are emerged marine platforms formed by wave erosion during eustatic stillstands in sea level. These occur at elevation of 35—40 m, 20—25 m, 12—14 m and submerged terraces corresponding to recent lower sea levels.

Shofield (1967) indicates that Niue is the sole emergent representative of a large group of volcanoes, the evolution of which is not clearly understood (Schoffield, 1967). In our opinion, it is possible to interpret this uplift as the result of a lithospheric bulge seaward of the Tonga arc.

Fieldes et al. (1970) suggest from the study of radiometric activity of the soils, that the date of emergence of the raised lagoonal basin is probably less than 200,000 years ago and that of the edge of the lagoon is 700,000 years ago. This difference in age of emergence between the lagoon and its edge is in agreement with the predicted uplift due to convergence at the trench, the edge emerging before the center of the lagoon.

We have obtained a bathymetric profile to the south of Niue Island which shows very well the shape of the bulge close to the Tonga Trench. On this profile, the wavelength is about 350 km and its amplitude 240 m. These measurements have been made on a smoothed bathymetric profile and permit only a rough approximation for these values. However, we can deduce from the geometry that Niue Island would shift horizontally toward the trench by 64 km for an observed uplift of 70 m. If one assumes that the age given is exact, this movement has occurred during a period of 700,000 years, with a spreading rate of 9 cm/year. The same value is found with the uplift of the lagoon during 200,000 years. This spreading rate is an absolute value for the underthrusting of the Pacific Plate under Indo-Australian Plate. This compares well with the value given by Le Pichon (1968). From this spreading rate it is not possible to judge whether significant inter-arc spreading in the Lau-Havre Basin has occurred, as has been proposed by Karig (1970). Because of the inaccuracy in determining ages and the exact geometry of the bulge, only an approximate value of the total spreading has been obtained. However, with better estimates of the above from good gravity profiles, it should be possible to obtain sufficiently accurate values of the spreading which would enable estimates to be made of sea-floor accretion by other mechanisms than normal sea-floor spreading (at the mid-ocean ridge).

GRAVIMETRY

A bulge occurring in a lithosphere in which the low-density crust has a constant thickness would produce a regional positive gravity anomaly whose wavelength would correspond to that of the bulge. We searched for such an anomaly in the gravimetric profiles crossing island arcs given by Talwani et al. (1961) for the Puerto Rico Trench and Tonga Trench, Vening Meinesz (1964) for Indonesia, Peter et al. (1965) for the Aleutian Trench and Solomon and Biehler (1969) and Luyendyck et al. (in press) for the New Hebrides Trench.

A gravity high is apparent on every profile but it is disturbed on profiles of free-air anomaly by the effects of short-wavelength bathymetric irregularities. Bouguer anomalies largely remove this noise and better reveal the effect of the bulge. A good example of this is the profile given by Luyendyck across the New Hebrides arc at the latitude of Vate Island (Fig. 1).

In a very recent study Watts and Talwani (1974) have shown that large positive gravity anomalies associated with some island arcs from satellite data must originate from sources other than a downgoing slab. They conclude that the computed gravity effect of simple models of flexure of the oceanic plate approaching an island arc generally explain both the amplitude and wavelength of the outer gravity high.

The length of the Luyendyck profile across the New Hebrides arc is not sufficient to measure the wavelength, but we can observe the position of the crest of the bulge relative to the trench axis. This distance is about 70—80 km.

On the isostatic profile published by Vening Meinesz (1964) for Indonesia (Fig. 3) and on the profile published by Kogan (in press) across the Tonga Trench, the distance between the trench and the crest of the gravity high is about 100—110 km.

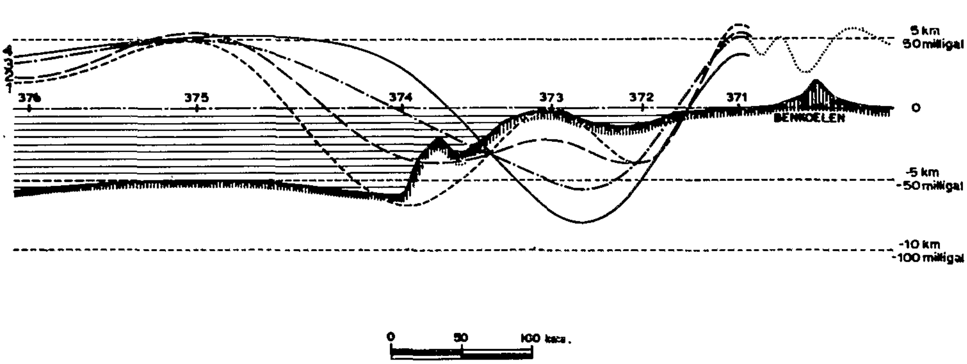

Fig. 3. Gravity profile of the Indian Ocean near Sumatra (over Benkoelen).
1. Local isostatic anomalies T = 20 km.
2. Local isostatic anomalies T = 30 km.
3. Regional isostatic anomalies T = 30 km, R = 116.2 km.
4. Regional isostatic anomalies T = 30 km, R = 232 km.
T is compensation depth, R is computed regional effect.
(After F.A. Vening Meinesz, 1964.)

CONCLUSION

In this study of the Loyalty and Niue Islands, we notice that the method of using uplifted atolls to determine the shape of the deflection curve is very accurate but a problem remains in the determination of the exact position of the crest of the bulge and, hence, the distance to the trench axis. Observations of gravity highs on marine profiles give this distance as about 80 km for the Loyalty area and about 100—110 km for Tonga and Indonesia (Vening Meinesz, 1964; Watts and Talwani, 1974; Kogan, in press).

The problem in using uplifted atolls is how to obtain accurate ages of the emergence of the edge of the fossil atoll and consequently to deduce from the rate of uplift the horizontal spreading rate of the underthrusting plate.

For Niue Island, this was obtained from radioactivity measurements of the soils and yielded an approximate convergence rate of 9 cm/year. The accuracy of this estimate is not sufficiently high for the calculation of secondary spreading activity by comparison with the spreading rate obtained from marine magnetic anomalies associated with accretion at the mid-ocean ridge.

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