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UPLIFT MOVEMENTS IN NEW CALEDONIA—LOYALTY ISLANDS AREA AND THEIR PLATE TECTONICS INTERPRETATION

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ABSTRACT

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The uplift movements of the New Caledonia and the Loyalty Islands, which are located on the Indian lithospheric plate that descends beneath the New Hebrides arc, have been studied in the geological context. This paper concentrates on the older (since Oligocene) uplift of the ultramafic peneplain in New Caledonia and the younger (since about 2 m.y.) regional uplift of the Loyalty Islands and southern New Caledonia. We computed the amount of uplift and deformation caused by three possible processes: erosional unloading, eustatism, and flexure of the lithosphere as it underthrusts beneath the New Hebrides island arc. The calculations indicate that the older uplift cannot be completely explained by erosional unloading of New Caledonia and may be partially caused by dynamic factors not yet understood. Eustatic uplift of New Caledonia in compensation for the rise in sea-level is also of insufficient amplitude to explain the uplift observed since about the last 2 m.y. Studies of the flexure of the lithosphere caused by subduction beneath the New Hebrides arc provide an explanation for the observed récent uplift of the emergent atolls of the Loyalty Islands.

INTRODUCTION

New Caledonia is an island * whose long axis strikes approximately at 310° and it is the emergent part of a submarine structure called the Norfolk ridge. To the east of it lie the Loyalty Islands which are the uplifted parts of a submarine volcanic ridge which is parallel to the strike of New Caledonia (see Fig. 1). Further east the New Hebrides trench is oriented along 340°. These three structures bend and converge towards a point, located south of Maré Island where the New Hebrides trench becomes tangential to the southern prolongation of the Loyalty Islands; beyond this point the Norfolk ridge and Loyalty chain are directed more north—south, whereas the trench curves to-

* New Caledonia is 400 km long, about 45 km wide, surface area 18,000 km^2. It is surrounded by a barrier reef which extends 200 km beyond the northern limit of the island.

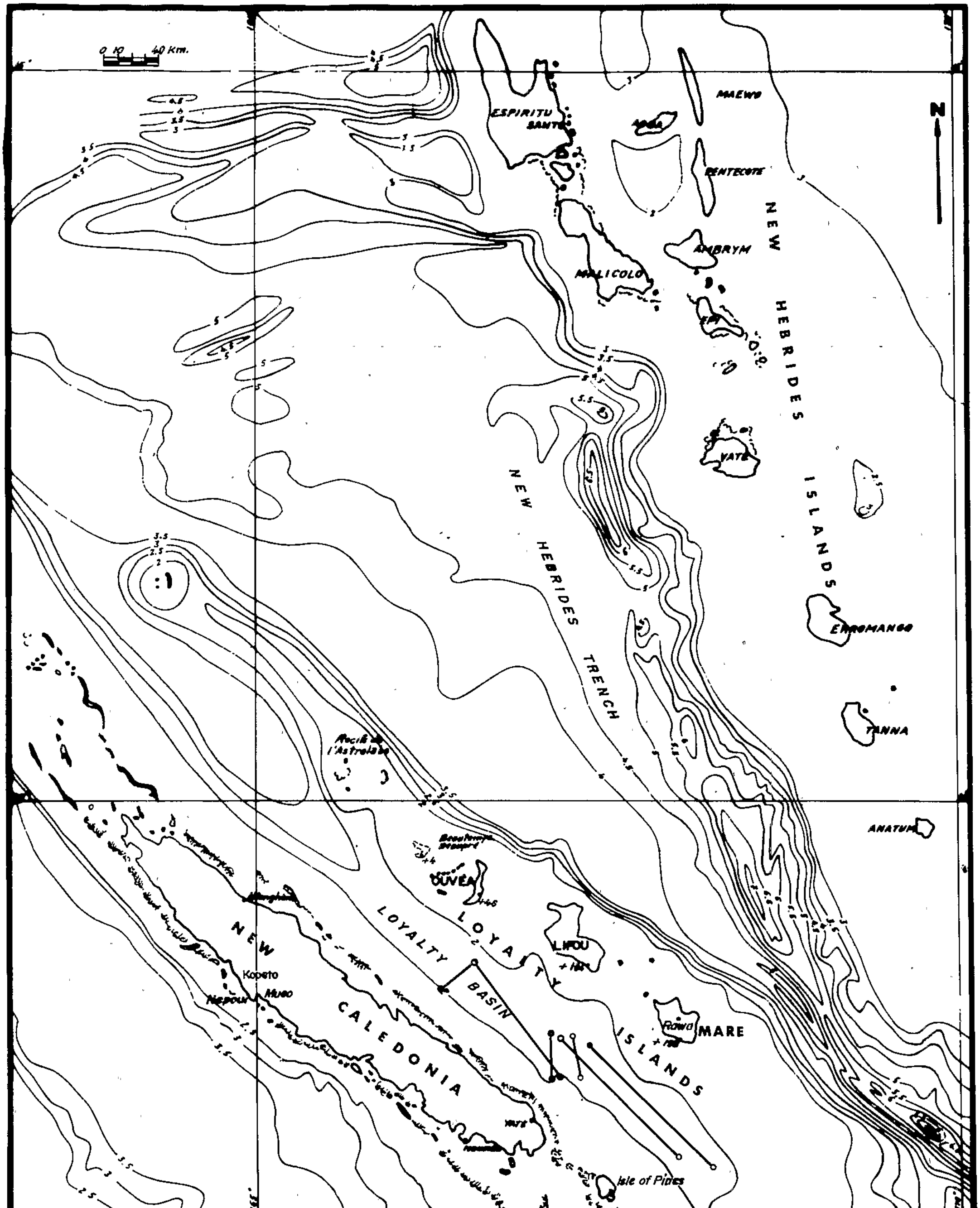

Fig. 1. New Caledonia—Loyalty Islands. Bathymetric and seismic tracks (o———o) in the Loyalty basin.

wards the east. Between New Caledonia and the Loyalty Islands lies the flat and regular Loyalty basin.

The particular structural arrangement of the New Caledonia—New Hebrides area is distinguished by the dip of the "continental plate" underneath the oceanic one and by the existence of partly emerged ridges in situ on the dipping lithosphere, near the subduction zone; this provides data for comparison between the theoretical scheme of the bulge and the observed facts.

Such a deformation of the lithosphere before its dip has already been introduced as a likely hypothesis by Lliboutry (1969) and Hanks (1971), but had never been observed over landmarks as accurate as the uplifted atolls.

GEOLOGICAL HISTORY OF NEW CALEDONIA AND LOYALTY ISLANDS

Main orogenic phases

The geological history of New Caledonia begins with the Permian tuffs (Avias, 1953; Routhier, 1953; Guillon, 1969). From the Permian to the Upper Eocene the formations are volcano-sedimentary and sedimentary rocks (greywackes, shales, sandstones) accumulated in a trench called the Melanesian trench. Since the Permo-Trias different orogenic phases have influenced these strata. The last (i.e., the Alpine orogeny) begins after the emplacement of Eocene flysch deposits and reaches its highest point at the limit of the Eocene—Oligocene. At the end of the main orogenic phases, the emplacement of peridotites occurred, probably during an Oligocene obduction phase (Guillon and Routhier, 1971). This peridotite emplacement is the last major orogenic occurrence on the island. Activity on the volcanic Loyalty Islands ceased at about 10 m.y. ago (J.H. Guillon and J. Recy, private communication, 1974). After the last main orogenic phase, New Caledonia and the Loyalty Islands came under the influence of a different kind of tectonics. These consisted of uplift movements of large amplitude.

Uplift movements in New Caledonia

Four phases have been put forward by Davis (1925), then they were successively precised by Routhier (1953) and Trescases (1969, 1973).

Phase I: Peneplanation of peridotites

After their emplacement, the peridotites have been affected by an intense erosion which began in the Early Miocene (Routhier, 1953). Routhier showed the presence of nickeliferous clays in the Miocene of Nepoui. This weathering has resulted in a peneplanation, the remains of which are visible as tabular relief. The peridotites, which at present cover 30% of the New Caledonia surface, covered a much greater surface just after their emplacement; the present thickness is much less than the original (Routhier, 1953; Guillon and Routhier, 1971), and therefore a great mass of material of high density has been eroded since the Early Miocene at the latest.

Phase II

After peneplanation, New Caledonia was uplifted and the peneplaned peridotites eroded. The peneplain remnants can be observed at elevations greater than 1,000 m in the central part of the island. Their altitude is less on the eastern and western borders and on the extremities, especially in the south where they occur below an altitude of 300 m. This is seen on the Kopeto massif: the upper peneplain dips gently to the west coast. The Mueo Formations which are dated as Miocene seem to belong to the same surface of peneplanation (Gonord and Trescases, 1970). Therefore, the upheaval movement must be later than Miocene. The existence of two other surfaces of laterisation below the peneplain indicates interruptions during uplift. The general movement does not seem to be regular in time or in space. Moreover, post-Miocene tectonic activity which was active until fairly recently has cut off the peneplain in blocks of different altitude (Orlof and Gonord, 1968; Gonord and Trescases, 1970).

This uplifting phase has continued until recently as is seen in the youth of the river profiles. Its amplitude is small at the present coasts compared with the central parts where it is much greater (e.g., the marine Miocene outcrops only in the middle part of the west coast with a few tens of meters average height). The axis of the bulge is not a straight line because the uplift has been guided by the anterior structural fractures which have regionally modified the effects of the movement. The tilting of the island towards the west during this phase is still an hypothesis and it is at present impossible to determine if the barrier reef of the west coast had already begun to build itself in response to this tilt. We can only note that the northern and southern limits of New Caledonia, the western slope and the continental platform have well-developed reefs while the east coast has not. Thus, uplift movements during the second phase are asymmetrical across the island. The large quantity of eroded material, the continuity of the movement since the Miocene, the general irregular figure of the residual peneplain and the existence under the central chain of New Caledonia of a 35 km thick crust which thins quickly to 18—20 km (Dubois, 1971) under the present coasts indicate that the phenomena of isostatic equilibrium took an important part in the observed uplifting.

Phase III

The subsidence phase, responsible for the submergence of low valleys and for the indents of the coast appears to be very recent. It is during this period that the great western barrier reefs have been built. Using data on the widths of the present river mouths, Davis (1925) concluded that the amplitude of the vertical movement was about 200 m. A drill hole on the islet Tenia on the western barrier reef has penetrated 226 m of coral limestones before reaching a substratum of phtanite similar to the Eocene one observed on the island (Coudray, 1971). The growth of the barrier reef in the northwestern extremity, the presence of islands and islets extending north and south of New Caledonia and the distance of the shores from the great barrier reef towards the north and south, could indicate that the longitudinal warping of phase II went on during the subsidence phase.

Phase IV

There are indications of a recent rise in relative sea-level: undercuts, uplifted beaches and reefs (Davis, 1925; Avias, 1949, 1959; Routhier, 1953). This rise has been attributed to a eustatic sea-level change and to tectonic movements for elevated beaches. Some recent works (Baltzer, 1970; Launay and Recy, 1970, 1972) have reported radiocarbon and ionum—uranium dating of corals and peats of mangroves.

Most of uplifted terraces between 2 and 4 m, above the zero of French Hydrographical Service, which frequently extend along the present beaches, appear to have been deposited during a high Holocene relative sea-level. On the eastern and western coasts of New Caledonia, some coral reefs were found between 3 and 6 m high and show a relative sea-level older than that of the Holocene one.

The Isle of Pines southeast of New Caledonia is an almost completely peneplained lateritized peridotite massif, surrounded by uplifted flat reefs down to sea-level. A sample of coral, picked up in the oldest part of the reef and measured by the Io/U method was 118,000 ± 8,000 years B.P. old (radiometric age measured by M. Bernat, I.P.G. Laboratory Paris, in Launay and Recy, 1972). The average uplift computed for the top of the flat reef appears very slow at $1\text{—}2 \cdot 10^{-4}$ m/y if we accept (for the age of this reef) a sea-level close to the present one or somewhat higher (Veeh and Chappel, 1970).

In the Yaté region in the southeast of New Caledonia, an old flat reef reaches a height of 10 m; its age, which could be similar to that of the Isle of Pines, is still unknown.

Uplift movements of the Loyalty Islands

The Loyalty Archipelago is a series of uplifted atolls the altitude of which decreases from southeast to northwest. The terraces and undercuts of the external cliff indicate the influence of the high sea-levels during the uplift of these atolls. Olivine basalts and dolerite (oceanic volcanism) are present on Maré Island. Samples of these rocks have been dated between 9 and 11 m.y. old (J.H. Guillon and J. Recy, personal communication, 1974). Some volcanic tuffs seem to lie on the basalts and include organogenous limestones, the microfauna of which is not well dated. These tuffs are covered with coral reefs which constitute the emerged atolls: Maré, Lifou, Ouvéa. Therefore, the subsidence phase which has generated the coral islands overlying the volcanic rocks is Pliocene (Chevalier, 1968).

After the subsidence, an uplift phase has caused the emergence of some atolls. The amplitude of the movement decreases from south to north along the Loyalty ridge: today Maré is 138 m high, Lifou 104 m, only the eastern part of Ouvéa is uplifted and is 46 m high. The Beautemps Beaupré and Astrolabe atolls are not yet uplifted (Fig. 1).

Madreporian fauna collected at the top of the Maré reef by Chevalier (1968) was dated as Early Pleistocene and could represent the beginning of the uplift. Ionium—uranium datings (M. Bernat, in preparation) carried out on corals collected in an undercut of Lifou at 12 m height showed ages around 120,000 years B.P. At this time the sea-level was 5 m above the present one (A.L. Bloom, personal communication, 1973). Thus it looks as if a tectonic uplift of 6 m has occurred since 120,000 years. It seems that an uplift movement has occurred in the southeastern part of the Loyalty Islands since the Early Pleistocene and continued until the present, whereas the northern part has not been affected. The average upheaval rate of Maré since the last approximately 2 m.y. is about $7 \cdot 10^{-5}$ m/year.

THE TECTONIC UPLIFT (POST-OLIGOCENE—PRESENT) OF THE NEW CALEDONIA—LOYALTY ISLANDS AND THE GENESIS OF THESE MOVEMENTS

We consider only the uplift movements for which there are more data than for the subsidence phases.

Phase II: Uplift

Phase II, which affected New Caledonia and the Isle of Pines, raised the peneplain up to a maximum altitude of about 1300 m for certain parts of the Kouakoué region; the initial altitude is not known but can be estimated at about a few hundred meters. The large quantity of material, eroded since the peridotite emplacement, indicates that the phenomenon of isostatic equilibrium has had an influence on the upheaval. The irregular spatial distribution of the uplift has affected the center of the island more than the extremities (including of course the coasts). The process was not one of banking as suggested by Davis (1925) and Routhier (1953) but very likely a system of compartments and faults. The upheaval was irregular in time as we note the existence of lateritized levels under the peneplain which indicates a long break in the uplifting process. Then there is the transition between the peneplanation (Phase I) and the uplift (Phase II). Such observations are inconsistent with the hypothesis of a direct connection between the unload made by erosion and the subsequent uplift.

If this unloading has occurred contemporaneously with other phenomena, its connection with the uplift phenomenon is difficult to estimate. Moreover, the uplift has lasted about 20—30 m.y. and it is a slow enough phenomenon for some readjustments of the crustal thickness to occur; the evolution of such a phenomenon is still poorly understood.

We will present in the next section the simple calculation which has allowed us to quantify some parameters.

Quaternary movements

Evidence of a regional movement which can be assigned to a bulge of the lithosphere.

The comparison of amplitudes and speeds of the uplift movements between the different dated levels reveals two separate movements. On the one hand a slow regional uplift movement for Loyalty Islands, Isle of Pines and probably the south of New Caledonia and on the other hand a rapid positive movement during Middle and Late Holocene for New Caledonia, the amplitude of which varies according to the locations. The slow movement can be likened to a very gradual, long wavelength, the effects of which seem to have begun as long ago as the Early Pleistocene in the southeastern part of Loyalty Islands, while its northwestern extension does not seem to be affected. In the northern part of the Loyalty arc the amplitude of the movement is definitely lower than that of the southern part.

If we look at the arrangement of the main structural features of the area (Fig. 1), we can imagine that the migration and burial of the Indian plate underneath the oceanic one at the level of the New Hebrides trench may have caused a flexure or, a bulge of the lithosphere, prior its downward movement (Dubois et al., 1973). The orientation of the axis of the bulge parallel to the dipping plane of the lithosphere is different from that of the New Caledonia—Loyalty arcs. During the quaternary migration of the plate, the New Caledonia—Loyalty Islands area would have progressively reached the zone of deformation stress generated by the bulge; the zones nearest to the axis suffering the greater uplift.

Measures of slope of some representative profiles of the flexure of the lithosphere

Measure of the levels of the Loyalty atolls. In the hypothesis of a regional bulge of the lithosphere, the Loyalty Islands are markers of the uplift-component of the plate movement. We assume that before the uplift the coral rings were at nearly the same altitude (which is true if we consider the present functional atolls set on volcanic ridges). If the atoll morphology has been altered during successive uplifts, it has occurred in the same way as is seen in field observations.

Table I gives the slopes of different segments of a profile directed 300—310° and joining the places where the altitude is maximum in the different islands. These places are located in the southeastern part of each island and this, in itself, constitutes a morphological homogeneity. We notice that the slope of the profile joining the tops of emerged atolls (Fig. 1) is maximum between Beautemps Beaupré and Ouvea (0.8 m/km) and decreases progressively southwards (0.388 m/km) between Lifou and Maré.

Measures of levels of the floor of Loyalty basin

The regular flat basin situated between New Caledonia and Loyalty Islands (Fig. 1) is well known from recorded bathymetric data (Coriolis cruises: May

TABLE I

Distances and gradients according to the maxima altitude in the different islands of the Loyalty arc. Direction of the profiles about 300°

	Maximal	Distance (km)			Gradient of profile (m/km)		
Beautemps Beaupré	+ 4 m						
		52.5			0.800		
Ouvéa	+ 46 m		147.5			0.677	
		95		235	0.610		0.570
Lifou	+ 104 m		182.5			0.504	
		87.5			0.388		
Maré	+ 138 m						

1966, November 1966, April 1967, June 1970), seismic data (Kimbla, 1971; Coriolis, 1971) and refraction data (Scripps Nova cruise, August 1967).

We accept the following:

(1) The Loyalty basin is a relatively old structure with a thick sequence of sediments (Fig. 2) laid down prior to 2 m.y. ago; its bottom was already flat in the central part of the basin.

(2) For the last 2 m.y. the slopes made by the bulge of the lithosphere (about 1/1000) have not altered the modes of sedimentation which have remained homogeneous in the central part of the basin.

Sedimentation, therefore, has not masked the differences of level as they increased proportionally.

Table II shows the slope of the bottom in some profiles, then the direction of steepest slope and the value of the gradient computed by Brooks' method (1970).

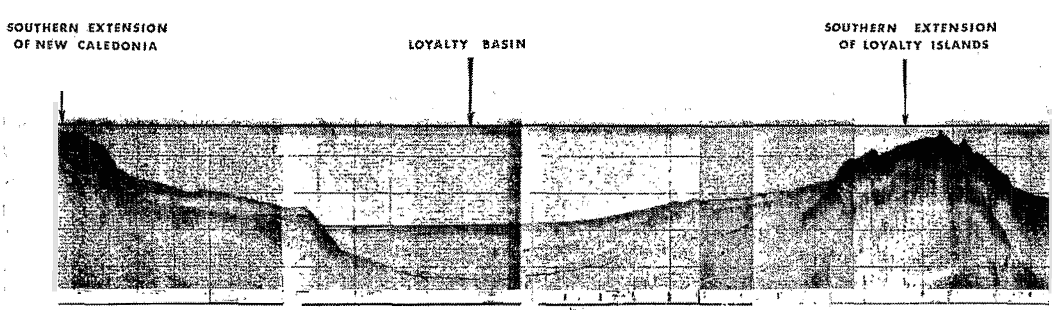

Fig. 2. Cross-section oriented perpendicular to the Loyalty Islands, south of Maré Island. Air gun profiling during 1971 Coriolis cruise C1 (ORSTOM and New South Wales University — Australia).

TABLE II

Measures of levels of the floor of Loyalty basin and slope of the different segments

Coordinates (S and E) of the extremities of the segments (degrees, minutes)	Depth (m)	Difference of level (m)	Length of the segment (km)	Azimuth of the segment (°)	Slope of the segment (m/km)	Cruise reference
21° 52.2 21° 35.0 167° 04.9 167° 04.4	2280—2310	30	34.1	359	0.88 *	Coriolis Bathymetry
22° 29.0 21° 39.0 168° 15.0 167° 20.0	2090—2200	110	130.8	314	0.84	Nova N_1, N_2 Refraction
22° 24.2 21° 36.6 168° 00.0 167° 07.0	2150—2253.5	103.5	133	320	0.78	Kimbla Air Gun
21° 52.2 21° 35.4 167° 16.8 167° 11.9	(2237—2250)	(13)	31	344	(0.42) *	Coriolis Bathymetry
21° 05.0 21° 16.2 166° 28.8 166° 16.1	2387—2415	28	29	225	0.96	Coriolis Bathymetry
21° 52.2 21° 05.0 167° 07.1 166° 28.8	2237—2387	150	123	316	1.22	Coriolis Bathymetry
Crossing point of the two preceding profiles 21° 05.0 166° 27.5	Brooks' Method			263	1.55	

* Consequence of looseness of the measure, the relative error of the short segments can be important.

We notice that the dip of the bottom according to the azimuth 314°—320°, (direction of the lineament of Loyalty Islands) is less steep in the southern part of the basin than in the northern part, which is in agreement with the observations made in the segments of profiles joining the tops of the Loyalty Islands. However, the values of this dip in different places in the basin are somewhat higher than those of the segment corresponding to the profile of Loyalty Islands. The azimuth of the line of steepest slope computed with Brooks' method is 263° in the central part of the basin and the value of the dip for this direction is 1.55 m/km. The azimuth 263° is nearly perpendicular to the supposed axis of the flexure of the lithosphere, i.e., parallel to the New Hebrides trench. These results confirm the hypothesis expressed before.

STUDY OF DIFFERENT MECHANISMS OF UPLIFT

Reminder of some definitions

By lithosphere we mean the upper mantle and crust constituting a rigid unit lying on "viscous" asthenosphere. We consider problems from the plate-tectonics point of view without considering movement of the plate and we computed all the physical obtainable parameters concerning the New Caledonia—Loyalty Islands area. Study of the propagation of body waves and surface waves (Dubois, 1969, 1971) in this region allows us to obtain an estimate of the physical parameters of the lithosphere (rigidity, Young's modulus, Poisson's ratio), and its thickness (60 ± 5 km). From these parameters it is possible to compute the flexural rigidity used in the equation of flexure problem (Lliboutry, 1969; Hanks, 1971). We considered an extreme range of values for the flexural parameter between $\alpha = 100$ km and $\alpha = 230$ km. The quantity of data in the study of flexure will allow us to prove the precision of this value as Walcott (1970) and Hanks (1971) do for similar observations.

First of all we will compute the consequences of excess loading and unloading on the vertical variations, then the flexure effect associated with the burial of the Indian plate underneath the New Hebrides arc.

Overloading and unloading

Part of the uplift movement observed on the coasts can be due either to the unloading of the emerged parts by erosion or to readjustment after eustatic changes. We have tried to quantify the amplitude of these movements. There are many possible solutions of loading or unloading of the lithosphere which can be solved by a differential equation of the form:

$$\Gamma\, d^4\zeta/dx^4 + A\zeta + C = 0$$

Γ is the flexural rigidity, ζ vertical displacement, x the distance to the point of application of loading, A and C depend on weight of the load and density of lithosphere. In polar coordinates, it is possible to compute the burial of the origin point and to integrate the load (or unloading) produced by successive rings at the origin as it moves over the area where loading has the maximum effect.

Uplifting caused by erosion

We refer to the measurements and hypothesis made by Baltzer and Trescases (1971) who observed a mechanical weathering of peridotites of 11 mm for 1000 years (density of material 1.8) and a chemical weathering of 27 mm for 1000 years * (density of material 3.3). We have extended these data to the whole of the island to simplify the computation. The upheaval induced by the unloading is given by the equation:

$$\Gamma \, d^4\zeta/dx^4 + \rho_m g\zeta = \rho_c hg$$

where ρ_m = density of asthenosphere, ρ_c = density of the material eroded away, h = its thickness. The resolution of this equation consists in writing ζ as a function of the distance to the load, it becomes a Bessel equation and may be solved using tables (Angot, 1965 (tables); Dubois et al., 1973). We found that an upheaval induced by the unloading would be 5.69 mm for 1000 years in the central part of the island i.e., 5.69 m for 1 m.y. for an erosion of a 38 m thickness (flexural parameter α = 140 km). The upheaval is less than 1/6 eroded thickness. If we ignore the effects of viscosity for the last 20 m.y. (the age of peneplanation of peridotites) the uplift in the center of the island induced by the unloading would not have been more than 114 m corresponding to 720 m material thickness eroded away. But during Phase II, the uplift was at least 1000 m in the central part of the island and that would involve an erosion of 9000 m of material and an erosion rate eight times greater than that given by Baltzer and Trescases (1971). To our present knowledge it appears unreasonable to attribute the uplift of the peneplain to erosional unloading alone.

Such a phenomenon surely has an influence, but it cannot be considered as a major one. This conclusion strengthens that made on the basis of geological observations.

Eustatism effect

Recently, from 15,000 to 20,000 years, the general sea-level increased about 100 m. This has resulted in a universal overload of the oceanic floors, therefore of the lithosphere except for the emerged lands: e.g., New Caledonia and Loyalty Islands (Fig. 3). It is equivalent to a force on the lithosphere, below still emerged land masses and directed upwards.

For New Caledonia, at the central point of the island, the computation shows an uplift of 4.7 m (α = 140 km) i.e., 1/20 the amplitude of the movement of sea-level. As for Maré, a similar computation shows 0.52 m. The Quaternary positive and negative eustatic changes can be compared to an oscillatory movement. They induce on New Caledonia an oscillation of approxi-

* 22 mm in Trescases (1973).

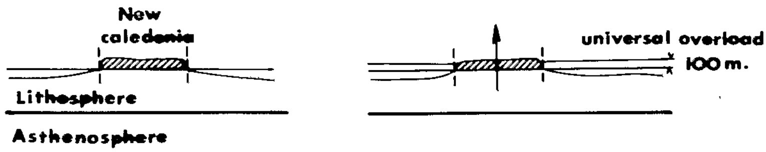

Fig. 3. Universal overload of the oceanic floors except for emerged lands. The arrow represents the direction of upwards force below still emerged land mass of New Caledonia.

matively the same period, with opposite direction and smaller amplitude. The eustatic changes cannot be explained with the quick uplift movement observed on some shores of New Caledonia during the Middle and Late Holocene.

Effect of the uplift of an island

When a volcano arises (Vening Meinesz, 1964; Walcott, 1970) or when an atoll emerges, an overload occurs and a sinking follows. We will see that the flexure effect explains the Loyalty Islands uplift. Because of this uplift, an overload occurs and involves a subsequent sinking given by:

$$F d^4\zeta/dx^4 + (\rho_m - \rho_c) g\, \zeta = (\rho_c - \rho_w)\, gh$$

where ρ_m ρ_c ρ_w are densities of asthenosphere emerged rocks and water. It could be possible to explain the decrease of the slope on the southern segment of the profile of Loyalty Islands by the increase in the load during the past. The computation of the sinking due to the mass of Maré shows small values in the center of the island: 1 m for $\alpha = 140$ km, 4.4 m for $\alpha = 60$ km. Such values cannot explain the decrease of the slope of the southern segments with respect to the northern ones on the profiles of the Loyalty Islands.

Thus the uplift movements observed in New Caledonia, and the Loyalty Islands area cannot be explained completely by the effects of loading and unloading, eustatism or emergence of a relief. However, these effects are not insignificant and can reach 1/6 of the total observed disturbing effect.

In these computations we have not considered the viscosity of the lithosphere. For the last 10,000 years it has been negligeable but beyond 1 m.y. it would be a significant factor. Nadai's (1963) relaxation curves give an approximation of the magnitude of the effect of these values which would have little or no effect on the values computed for the uplift of Maré.

Effect of flexure

The effects of flexure of the lithosphere before its dip underneath the New Hebrides are more compatible with field observations. Consider the classic schemes presented by Lliboutry (1969), (a small omission in eq. 35 of his paper affects only the amplitude of the bulge) and Hanks (1971). The elevation of the plate in terms of the distance to its edge where a vertical downward force and a horizontal plateward force are applied, is:

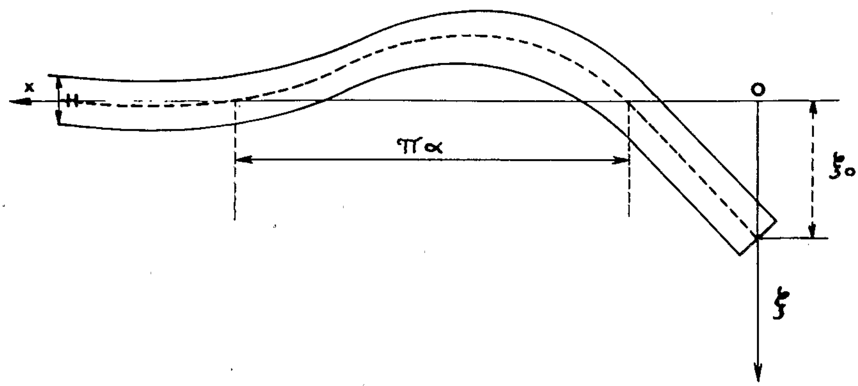

Fig. 4. Vertical cross-section of the rigid lithosphere perpendicular to the axis of the dip.

$$\zeta = \zeta_0 \left(\cos ax - \frac{B}{\zeta_0} \sin ax\right) e^{-ax}$$

where ζ_0 is the elevation at the edge, $a = 1/\alpha$, and B a constant depending on plate parameters (Young's modulus, rigidity, Poisson's ratio) and forces on the edge.

In fitting to the observations, the zero may be taken on the line of volcanoes (Lliboutry, 1969) or on the axis of the trench or better (P. Turcotte, personal communication, 1974) at the place, if known, where the elastic properties of the plates change in plastic properties. In every case, the first two values where the elevation is zero are given by the solution of $\cos ax - B/\zeta_0 \sin ax = 0$ or $\mathrm{tg}\, ax = \zeta_0/B$ and the horizontal distance between the first two solutions is π/a or $\pi\alpha$ depending only upon the flexural parameter. Thus, according to the equations of Lliboutry or Hanks we have the shape of the theoretical bulge with its "half wave length" $\pi\alpha$ proportional to the flexural parameter α.

From the data of parameters of the lithosphere in the studied area we know that the flexural parameter is probably in the range of 100—200 km. The shape of the plate was defined for different values of α.

If we then draw on a diagram (Fig. 5) the shape of the lithosphere in the plane perpendicular to the axis of the dip, at the same scale as the map, we see that New Caledonia, Ouvéa, Lifou and Maré are at different levels along the lithospherical slope. The shapes for α = 100, 130, 200 km are drawn.

It is possible to project on the same profile the different levels observed along the Loyalty Islands from Beautemps Beaupré (+4 m) to Maré (+ 138 m) and the theoretical graphs of flexure ζ/ζ_0, reducing the vertical scales proportionately so that correlation is possible. We observe (Fig. 6) that the slope of best fit to the observed profile is for α midway between 130 and 150 km, i.e., α = 140 km.

Thus, the model chosen for a lithosphere dipping underneath the New Hebrides arc with flexural parameter α = 140 km shows an excellent coinci-

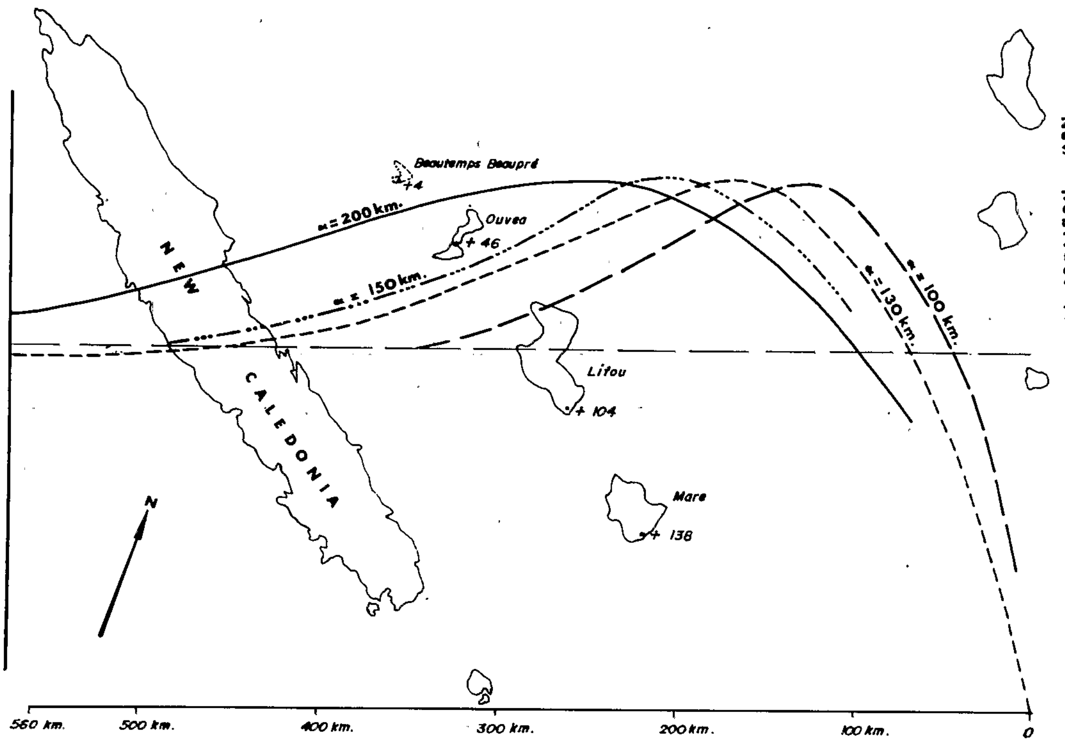

Fig. 5. Shape of the lithosphere for $\alpha = 100$, 130, 150, 200 km in the vertical plan perpendicular to the axis of the dip.

dence with the different values of uplift observed on the Loyalty Islands. On the floor of the Loyalty basin the azimuth of the exact dip is 263° (by Brooks' method) and shows a good correspondance with the azimuth of the axis perpendicular to the axis of the flexure of the lithosphere. However, the value of the gradient of the basin floor along this axis (1.55 m/km) is a little larger than that observed on the differences of levels of the islands (Fig. 6) and appears to approximate better the curves for $\alpha = 130$ to $\alpha = 100$ km. This computation has a lower degree of tolerance than that of the differences of levels on the islands because of inherent inaccuracies in the fixes for the extremities of the profiles.

Some kinematic factors are also applicable. The relative movement of the "Indian" plate with respect to that of the Fijian plateau has been studied and instantaneous relative motion is about a pole at 58°S and 179°E (Mackenzie and Sclater, 1971) with an angular speed $13.4 \cdot 10^7$ degrees/year. Le Pichon (1968) computed a speed of 7 cm/year for relative motion at the New Hebrides trench between 12°S and 17°S. In the studied area, this speed may be as small as 5 or 6 cm/year. Under these conditions (curve $\alpha = 140$ km, Fig. 5), Maré Island was 2 m.y. ago at the present altitude of Ouvéa for a relative speed of 5 cm/year or 1.4 m.y. ago for a relative speed of 7 cm/year.

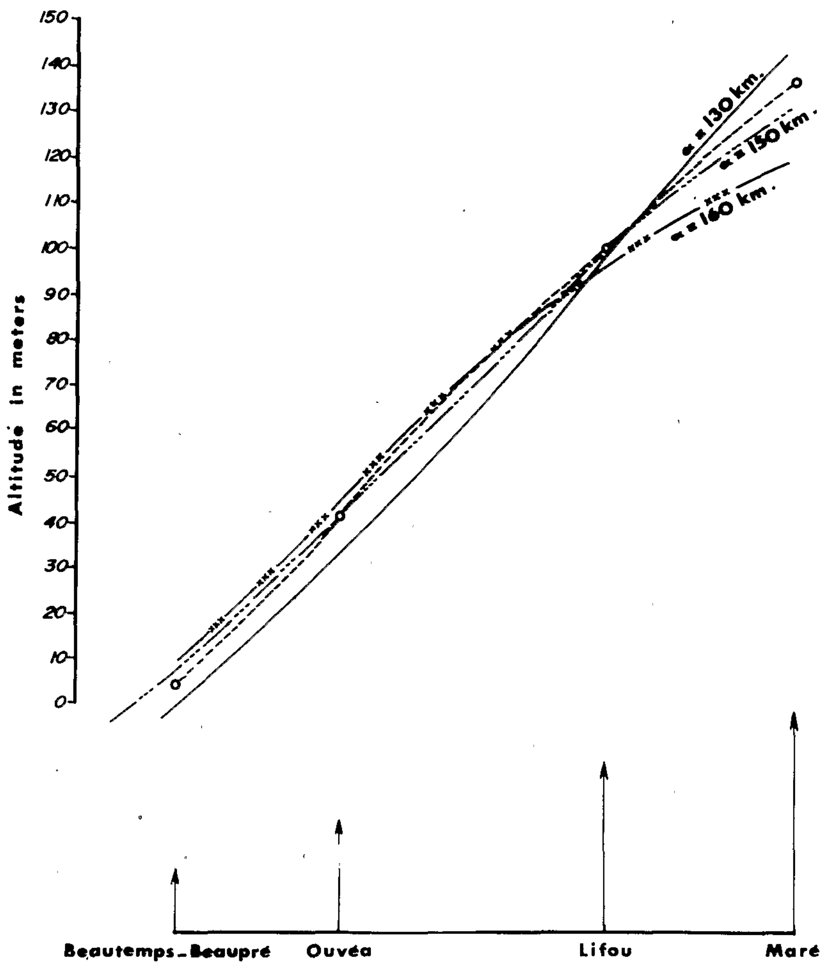

Fig. 6. Profiles of the islands, projected upon the direction 25° (o-------o). Adjustment of the flexure track for α = 130, 150, 160 km.

CONCLUSIONS

After the last uplift-phase referred to as the Alpine orogeny and determined by the existence of horizontal movements, we observe in New Caledonia only vertical movements (at least since the Oligocene). The formation of the Loyalty atolls in the Miocene and then their uplift, are two consequences of the horizontal movements of the Indian lithospheric plate. We carried out theoretical computations on the hypothesis of the lithospheric bulge in an attempt to explain the movements, particularly the vertical motion for which the data are better known.

In the Miocene, mechanical and chemical erosion in New Caledonia caused a smoothing of the relief and formation of the ultramafic peneplain. This phase was followed by an irregular uplift accompanied by faulting tectonics (Phase II) during which some blocks in the central part of the island were elevated about 1000 m at an average rate of $7 \cdot 10^{-5}$ m/year. If the unloading effect from erosion was the main cause of vertical movement, the lag between peneplanation and the beginning of the uplift and the irregularity of this uplift are hard to explain. According to a hypothesis of a very large, thin, rigid, elastic lithosphere, the computation within this study shows that the hypothesis of uplifting by unloading would have required the erosion of 9,000 m of material (with the same density as peridotite), i.e., an average erosion rate eight times faster than that observed on a catchment area by Baltzer and Trescases (1971). It appears, therefore, the unloading resulting from erosion was not the major cause of the uplift of the New Caledonia peneplain.

The study of the Quaternary vertical movements from the emerged marine formations, uplifted atolls and flat reefs, demonstrates the existence of an epiorogenic wave starting in the Quaternary (see epiorogenic waves described in Africa by Faure, 1971). This first affected the southeastern part of the Loyalty Islands (Maré), then the central part (Lifou, Ouvéa) and now the southern extremity of New Caledonia. The amount of uplift varies with the age of the movement. The north part of the Loyalty ridge (Beautemps Beaupré, Astrolabe reef) and the main part of New Caledonia are not affected by this wave. Its origin seems due to the existence of a bulge of the lithosphere by the Indian plate before its subduction at the New Hebrides trench. The azimuth of the axis of this bulge is parallel to that of the trench and is different from that of New Caledonia and the Loyalty Islands trend. During the movement of the plate, the southern part of the Loyalty Islands and New Caledonia have progressively reached the zone affected by the flexure and the bulge of the lithosphere.

The models of the lithosphere in the New Caledonia—Loyalty Islands area computed from seismological studies are in good agreement with the observations obtained from a static and from a dynamic point of view based on geological data. For a rate of horizontal movement of the plate of 7cm/year (Le Pichon, 1968) and a flexural parameter $\alpha = 140$ km, the average rate of computed uplift is about $7 \cdot 10^{-5}$ m/year since 1.4 m.y. ago which is in agreement with the estimated rate at Maré from the geological observations: i.e., commencement of emergence in the early Quaternary (1.4 m.y. ago Maré was at the same altitude as Ouvéa is now).

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