Structural and Other Aspects of the New Caledonia-Norfolk Area

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ABSTRACT

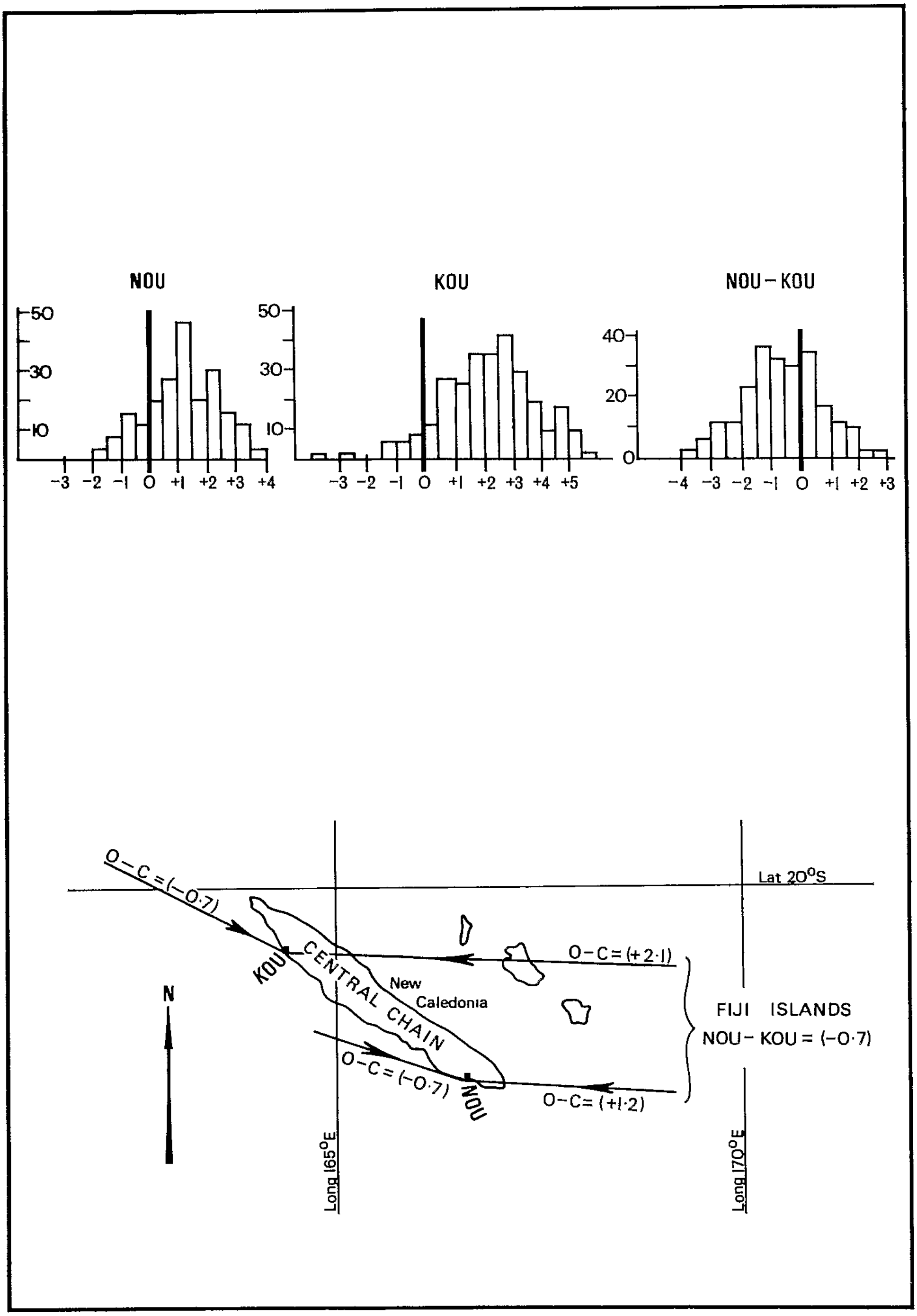
Seismic data suggests that crustal thickness under the west coast area of New Caledonia is about 20 ± 2 km but is about 35 ± 4 km under its Central Chain. The propagation of Rayleigh waves along the Norfolk Ridge, between New Zealand and Noumea, indicates a crust averaging 20-25 km.

The New Caledonian ultramafic massifs, emplaced probably during the Upper Eocene, are relics of a thick peridotite slab which was originally much more extensive. The massifs rest upon sediments and basaltic rocks of Eocene age.

The sea-level changes of the Pleistocene and Holocene are marked by uplifted terraces and other topographic features. These markers have been dated radiometrically and indicate the existence of relatively high sea-levels resulting from both eustatic and tectonic movements. The hypothesis is put forward that these movements resulted from a positive flexure of the Australo-Tasmantis plate before its descent beneath the oceanic lithosphere.

INTRODUCTION

The Norfolk Ridge runs continuously from the D'Entrecasteaux fracture zone (17° S) to the north of New Zealand (34° S). Its main NW-SE trend in the northern part (essentially made up of New Caledonia and its prolongations) becomes north-south in the central part and then resumes a NW-SE direction toward its southern end. The eastern side of its northern part is bounded by a submarine pluto-volcanic range revealed by the uplifted atolls in the Loyalty Islands. Between New Caledonia and the Loyalties there is a basin with steep walls and with a flat bottom, made up of fine mud and calcareous-siliceous fill. The New Caledonian Arc and that of the New Hebrides converge at a point located around 22° 30′ S, where the Hebrides Trench is contiguous to the southern prolongation of the Loyalty range. South of this point the trends of these two arcs diverge.


NOU
KOU
NOU – KOU
Lat 20°S
O–C = (–0·7)
O–C = (+2·1)
KOU
CENTRAL CHAIN
New Caledonia
N
FIJI ISLANDS
NOU – KOU = (–0·7)
O–C = (–0·7)
NOU
O–C = (+1·2)
Long 165°E
Long 170°E

DATA ON THE DEEP STRUCTURE OF THE NEW CALEDONIA ARC AND NORFOLK AREA

The study of *P* wave propagation gives information on the deep structure of New Caledonia. From eastern directions, the residuals of *P* wave arrivals (observed *minus* computed arrival times) from deep-focus earthquakes in the Fiji area are positive both in Noumea and Koumac seismological stations; inside the area there are local differences. The arrivals are later in Koumac than in Noumea (Fig. 1).

From the north, the Longshot nuclear test provided interesting data. For the same epicentral distance we find a relative delay of 3·5 s between Melanesia and Europe and 1 s between Australia and Melanesia. These delays may be explained in three ways: as delays at the source, or under the station, or along the ray-path.

Davies and MacKenzie (1969) have shown that a part of this delay is at the source, as an effect of the plate under the Aleutian Arc. The second part, 1 s, between Melanesia and Australia, surely has its source under the stations, because we cannot agree with the third explanation: a delay in the deep mantle between two close ray-paths would imply very marked lateral variations.

We consider that the delay in *P* arrivals from the north, the east and south-east probably arise from a low-velocity upper mantle. Local differences (0·7 s) exist inside this area (i.e. between Koumac and Noumea), which can be explained in terms of topographic effects and the presence of a crustal root under the Central Chain of New Caledonia.

From the west and north-west, however, early arrivals (0·8 s) are observed for New Britain and New Guinea earthquakes.

In a further study, the equation of propagation of *P* waves,

$$T=\frac{\Delta}{v}+a,$$

from New Hebrides normal focus shocks was found to be linear and the values of the constant term of the equation give indications of the thickness of the crust for the rays crossing the Central Chain (for details see Dubois 1969, 1971).

The sum of these data (Fig. 1) provide evidence, first, of a root under the Central Chain of New Caledonia of approximately 15 km; second, of a total crust thickness of about 35-39 km under the central chain but about 22 km under the western coastal area; and, third, of an upper mantle with low *P* wave velocities toward east and north and high *P* wave velocity towards the north-west (the *fossil slab* effect).

The propagation of Rayleigh waves was studied between Noumea and Koumac. It was possible to compute the phase velocity for a seismic path from a Tonga earthquake. In Fig. 2 the correspondence of peaks and troughs on records at Noumea and Koumac was examined. The matrix inversions method of Haskell (1953) was used

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Fig. 1 Time residuals of *P* waves from Fiji deep-focus earthquakes at New Caledonia stations: Noumea (NOU) and Koumac (KOU). Interval of class is 0·5 s. A histogram for stations pair NOU-KOU is shown. Arrivals are later in Koumac than in Noumea. In part after Dubois, 1971.

to compute theoretical models for different thicknesses of the crust. The best (Fig. 2) corresponded to a thickness of 22 km with a *P* wave velocity of 6·2 km/s and *S* wave velocity of 3·6 km/s. There is good agreement in interpretation of body wave and Rayleigh wave propagation data.

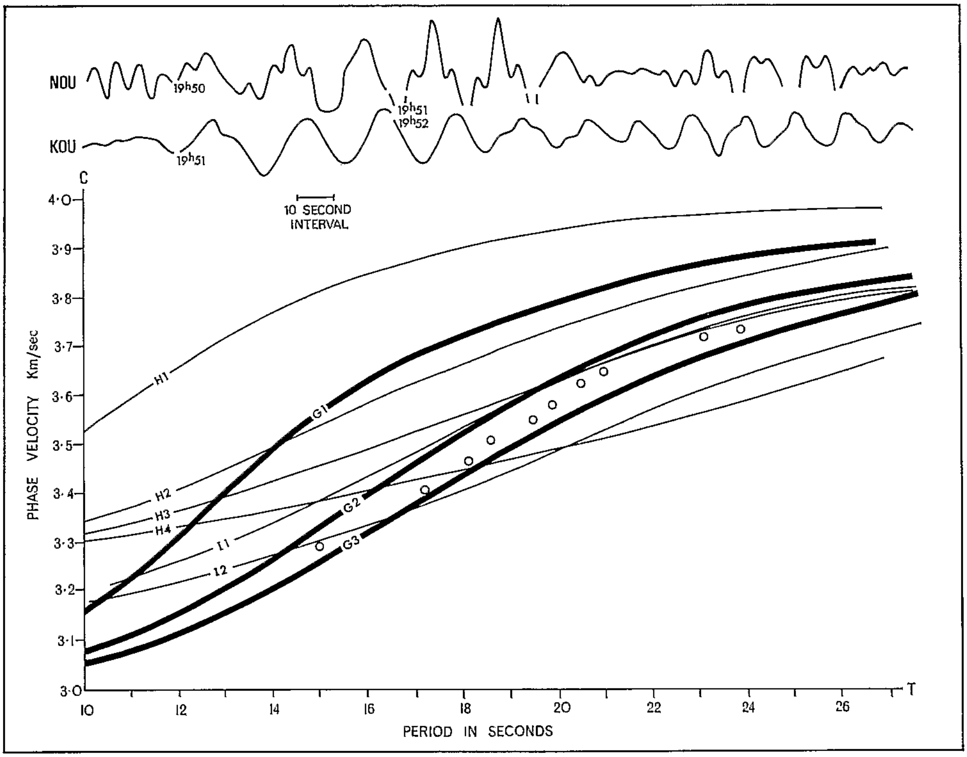

Fig. 2 Correspondence of peaks and troughs (phases of Rayleigh waves) on seismogram records at Noumea and Koumac, following a Tongan earthquake with epicentre on the Noumea-Koumac line. The observed and computed dispersion curves (using Haskell's method) for models I, H and G are shown. After Dubois, 1971.

From the south, an earthquake in New Zealand gave good records in Noumea of *P* wave propagation along a path following the Norfolk Ridge. From the study of the group velocity of Rayleigh waves on seismogram records in Noumea, it can be seen that the dispersion curve (Fig. 3) is quite intermediary between continental and oceanic dispersion (number 5 in the classification of Saito and Takeuchi 1966), and corresponds to a mean crustal thickness of 25 km along the path. This observation is a proof of the continuity of the New Caledonia and Norfolk Ridge.

Coming back to the deep structure of this arc, it appears that the topography and roots under the Central Chain of New Caledonia can only explain half of the 2 s delay observed between east and west *P* wave arrivals in Noumea and Koumac, respectively. The presence of fossil lithosphere dipping eastward under New Caledonia may explain this difference. A statistical study of residuals and a calculation according to the Davies and MacKenzie (1969) method is to be undertaken later to examine precisely this point.

MAIN GEOLOGICAL EVENTS

New Caledonia is made of sedimentary and metamorphic formations ranging in age from Permian to Miocene. The most prominent are tholeiitic basalts and also huge ultramafic massifs which were emplaced probably in the Upper Eocene (Routhier 1953, Guillon & Routhier 1971).

The emplacement of ultramafic material took place at a later stage of the Alpine orogeny, following the emplacement of the basalt which appears especially on the west coast of New Caledonia. The ultramafic massifs, with an area of 7,000 sq. km, are distributed throughout the length of the island. A great massif covers the southern part of the island; then there is a series of isolated massifs spread along the axis of a syncline parallel to the west coast (Guillon 1971).

The ultramafic massifs generally rest on the basalts, but can also be found lying unconformably on sedimentary formations—mostly those of Cretaceous to Eocene age—tightly folded, imbricated and overturned towards the south-south-west. The floor of the massifs, which show a thick serpentinitic fringe, is either horizontal or dips NNE at an angle of 10°, increasing progressively from south-west to north-east and reaching 50° on the east coast, where strong gravimetric anomalies (170 mgal) are found, corresponding to a thickness of ultramafic material of 8 km (Crenn 1953).

The order of superposition, peridotites-on-basalts, is contrary to that generally found in alpine-arc situations. Because of mineralogical similarities (especially of clinopyroxene) in the basalts and peridotites, it is likely, however, that these rocks are co-magmatic. It is possible they come from the differentiation of a highly-picritic magma of non-alkaline character (Challis & Guillon 1971) and that their respective emplacement has taken place later during the Alpine orogeny.

The ultramafic massifs are mostly harzburgites, dunites and orthopyroxenites, and some chromitic seams. These rocks are disposed in the massifs with regular rhythmic banding, which shows that the ultramafic massifs have the form of broken folds with a large curvature and generally overtilted towards the south-south-west. This layering is strongly discordant on the floor of the massifs which represents, as in New Guinea (Davies 1968), a major structural discontinuity. It is likely that the ultramafic massifs represent a nappe structure, the root of which may be found on the east coast of New Caledonia, and that their emplacement could be the consequence of thrusting of the oceanic plate onto the continental margin.

The emplacement of the ultramafic massifs is followed by the intrusion of granodiorites, adamellites and hornblende-quartz diorites, which appear either in the ultramafic rocks (cutting them discordantly), or in the sedimentary formations. But the granodiorites and diorites are never found far from the contact between the

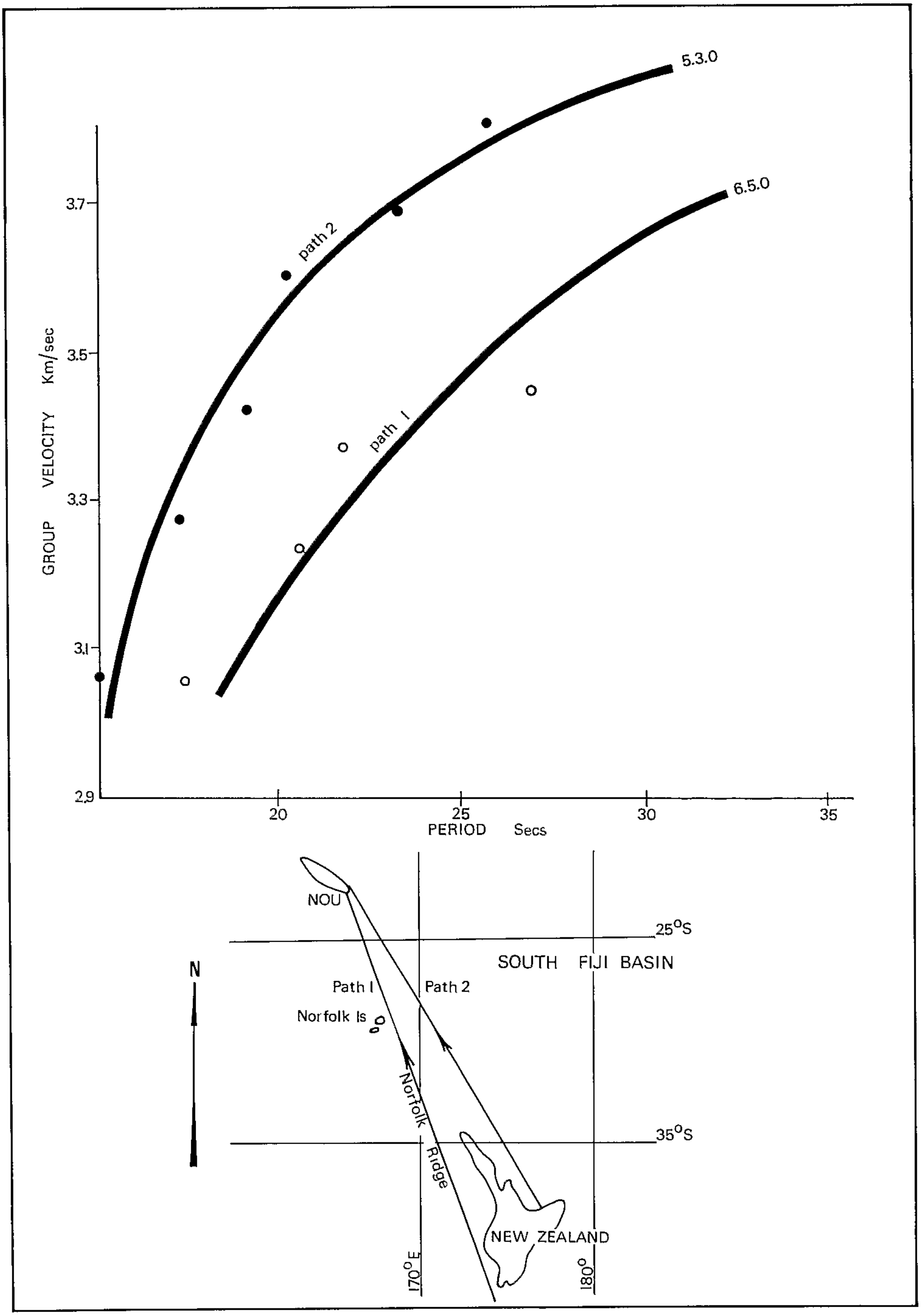

Fig. 3 Dispersion curve of group velocity of Rayleigh waves from a New Zealand

ultramafic massifs and their substratum. The emplacement of these rocks represents the last magmatic occurrence in the geological history.

DYNAMIC ASPECT OF POST-UPPER EOCENE MOVEMENTS OF THE NEW CALEDONIAN AND LOYALTY ARCS

New Caledonian Arc

(*a*) *Upheaval accompanying peneplanations.* The isostatic upheaval of New Caledonia can be traced by making a geomorphological survey of the ultrabasic rock massifs. These peridotites are easily weathered and have been subjected at least since the Miocene to the effects of a tropical to insular subtropical climate. Weathering of the lateritic type has left a residue mainly made up of iron hydroxides which have accumulated in place and by mechanical reworking effects in the depressions. Intensive chemical erosion (at present 28 mm per 1,000 years according to Baltzer and Trescases 1971) and the reworking of residual laterites have caused the lowering and flattening of the topography. Several successive levels, forming tiers or terraces, can be observed along the topographic profiles (Trescases 1969). The ironstones and laterites characterizing these surfaces have enabled them to be at least partially preserved in the landscape. With each resumption in isostatic movement, the state of equilibrium toward which the topography is tending is broken, the surface being formed is uplifted, and erosion begins to destroy it. In this way the highest surface ('peneplain' according to Davis 1925), which is also the oldest, is found at an altitude of more than 1,000 m in the middle of the island and at 300 m toward the edges. The second surface (intermediate level according to Wirthmann 1965) is 150-300 m below the 'peneplain'. The third surface (former piedmonts—Trescases 1969) is 500-600 m below the intermediary level.

The peridotites (with a density of 3·0-3·3, depending on the degree of serpentinization) make up a sheet which once covered a much larger area than that now observed (Routhier 1953, Guillon & Routhier 1971). In particular, large areas in the central zone must have been covered, and now all that remains are relict ultrabasic blocks. The ablation of all or part of such a dense covering layer may have caused the uplift of the island by isostatic compensation. In this case the highest areas would correspond to the most intensive erosion.

The major morphological feature suggests an uplifting in which isostasy probably played the leading role. The slowness of the phenomenon, spread out over several million years, and the fact that the crust is thin on the western and eastern edges of New Caledonia have certainly caused crustal flexures with very short curve radii (*relaxation curve* according to Nadai 1963). The upthrusting phenomenon caused an upswell of crust which is laterally absorbed within a short distance and thus must have been limited to New Caledonia and its edges.

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earthquake. The dispersion curve corresponds to a mean crustal thickness of 25 km along the path.

(*b*) *Subsidence*. The subsidence phase which follows was first observed by Davis (1925) and later confirmed by Routhier (1953). The longitudinal warping previously observed continued.

(*c*) *Quaternary upheaval*. In New Caledonia the presence of uplifted undercuts, beaches and reefs at different levels has already been described (Avias 1949, 1959; Routhier 1953, Launay & Recy 1970), and various radiometric measurements have recently been published by Baltzer (1970) and Launay and Recy (1971).

The Isle of Pines, south-east of New Caledonia, appears as a massif of lateritized peridotites. It is almost entirely peneplaned with a rim of terraces which represent successively uplifted coral fringing reefs running down to the sea. A coral sample taken from the top part of the oldest reef at 20 ± 3 m altitude was dated by the ionium/thorium method and showed an age of $118{,}000 \pm 8{,}000$ years B.P. On the eastern part of the island, a NNE-SSW trending hill, consisting of cross-bedded coral sand, is 79 m high. The age of this formation is different to that of the coral shelves but is unknown.

On the eastern and western shores of New Caledonia, outliers of coral terraces or shelves at 3 and 6 m altitude show an age between 25,000 and 35,000 years B.P. The formation of these coral outliers may be attributed to the high sea-level period of about 30,000 B.P. (estimated to be somewhat less than 10 m above the present sea-level by Faure and Elouard 1967). The presence of sea-level traces at a higher altitude than the dated levels, in particular near Hienghène, appears to indicate the existence of prior movements in some areas.

An examination of more recent markers has revealed the existence in New Caledonia, since the middle Holocene up to the present, of positive tectonic movements with a mean rate, as calculated on the basis of Shepard's eustatic variation curve, of 1-2 mm per year and often less. The results of these eustatic and tectonic movements indicate a higher relative sea-level between 7,000 and 2,000 B.P. The mechanism resulted in uplifted fossil beaches which are often prolongations of the present beach.

The mean rate of upheaval estimated for the top of the uplifted shelf at the Isle of Pines (118,000 B.P., altitude +20 m), appears to be very slow (i.e. 0·1-0·2 mm per year) as compared with the mean upheaval rates calculated during the middle and upper Holocene in the Isle of Pines, at Dumbea on the south-east coast and Mara on the west coast, if the Shepard and Curray curve is taken as a reference for the eustatic variation. If this observation were to be confirmed by additional radiometric dating, this would lead to the determining of a slow upheaval movement combined with spasmodic positive and perhaps negative oscillations.[1]

Loyalty Arc

The petrographic data we now have on the Loyalty submarine ridge come solely from samples gathered on Ile Maré. The presence of basalts with olivine (oceanic-type volcanism) and of gabbros with olivine, both quite comparable to those we know in New Caledonia, has been established. These rocks are probably the result of the thorough differentiation of strongly picritic parent material. An analysis of a basalt sample from the top of Rawa butte by the potassium-argon method produced an

[1] We succeeded in finding only positive readjustments during the Holocene.

age of 29 $\pm$ 4 m.y., i.e. Upper Oligocene or Lower Miocene (Chevalier 1968). At a few localities on top of these basalts there are volcanic tuffs containing reworked organic limestone pebbles with a microfauna of probable Aquitanian age (R. Anglada, C. Froget & J. P. Massé, pers. comm.).

(*a*) *Subsidence phase.* The coral atoll of Ile Maré lies on top of a volcanic substratum. The subsidence of the arc leading to the formation of Ile Maré and other Loyalty atolls is therefore post-Aquitanian. Chevalier attributes a Neogene age, based on examination of the corals, to the oldest parts of the reef complex.

The observation of a Neogene subsidence phase in New Caledonia and the Loyalty Islands does not, at present state of understanding, enable any conclusion to be reached on a possible common origin or perhaps a synchronization of this phenomenon in the two regions.

(*b*) *Recent upheaval phase.* An upheaval movement with decreasing amplitude (following the trend of the arc from SE to NW) brought about the emergence of various atolls. Ile Maré (altitude of 130 m) was uplifted more than Lifou located farther north. Only the south-eastern part of Ouvea atoll emerges, and still farther north Beautemp-Beaupré atoll remains submerged.

The madreporian fauna gathered at the top of the reef ring, and examined by Chevalier revealed a lower Pleistocene age; he suggests, however, that it may be younger.

Radiometric age measurements on three coral samples taken from the lowest terraces on Ile Maré between 2·7 and 3·2 m altitude revealed ages corresponding to a high sea-level period about 30,000 years B.P. (Launay & Recy 1971). Therefore, the upheaval of the southern part of the Loyalty Arc appears to have begun in the Pleistocene and to have continued up to the present.

An upheaval movement appears to have begun in the lower Pleistocene, influencing the south-eastern part of the Loyalty group, while the north-western part remained unaffected; the amplitude diminished from south-east to north-west. Later, a similar movement affected New Caledonia, the amplitude being greatest to the south, but the uplift is clearly less in the southern part of the New Caledonian Arc than in the southern part of the Loyalty group.

The following general aspects may now be stressed. The New Caledonia-Norfolk and Loyalty Arcs are parallel; the New Hebrides Trench is arcuate. Their opposing convexities are tangential at a point located slightly south of Ile Maré. The migration and burial of the Australo-Tasmantis plate underneath the oceanic slab at the level of the New Hebrides Trench may have caused a positive flexure in the plate prior to its downward movement. The stresses were probably greater (because of the warping of the dipping lithosphere) and the flexure correspondingly more marked (Dubois, Launay & Recy, in press) around the tangential area between the opposing convexities of the trench and the New Caledonia-Norfolk system.

On the basis of a recent calculation of the thickness and rigidity of the lithosphere in this area—60+5 km and $0{\cdot}7{\cdot}10^{12}$ dynes/sq. cm according to Dubois (1968, and unpublished data 1971), the flexural parameter was found to be equal to 150 km (Walcott 1970). Taking Lliboutry's diagram (1969) and using Nadai's relaxation curves (1963), the flexure in the western part of the New Hebrides (cf. Fig. 4) can

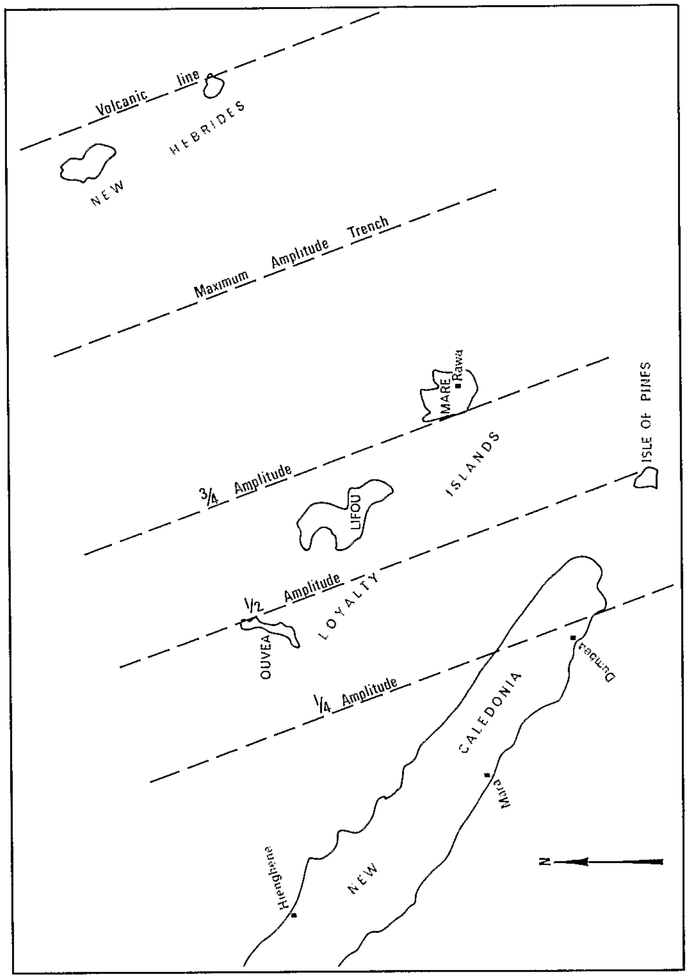

Fig. 4 Pattern of a positive flexure in the Australo-Tasmantis plate, New Hebrides-Loyalty Islands area.

be plotted before it dips underneath the insular arc (expansion from south-west to north-east). This expansion of 5 cm per year (Dubois 1969) shows that the amplitude increases from $\frac{1}{2}$-$\frac{3}{4}$ in the space of 72 km in 1·4 m.y. Between Uvea and Maré there is an altitude drop (over a period of 2·3 m.y.) of about 100 m corresponding to a distance of about 120 km in the direction of expansion. The result of this is an uplifting of the Loyalty Islands by 4·3 cm per 1,000 years (Fig. 4). Geological observations appear to agree with this pattern (Launay & Recy 1971). The pattern is certainly more complex south of the arc as the result of the curvature of the structure. However, this is only a first approximation.

Beginning in the lower Pleistocene (with reference to the age of the corals on the

Maré reef ring) the migration of the plate brought the southern part of the Loyalty Arc into the zone of influence of the flexure. Then in the middle or upper Pleistocene the southern part of the New Caledonian Arc began to be similarly effected. Assuming a flexure-lithosphere interaction, these spatial effects would decrease, beginning at the maximum amplitude line (Fig. 4). Likewise, there would be a difference in time, with the zones furthest away being more recently affected. Observations on Quaternary tectonics appear to conform to both these requirements. Such a flexural upswell of the lithosphere does not exclude the possibility of crustal or local readjustments, as is suggested by the upfolding of the Yaté uplifted shelf and by the Hienghène undercuts.

CONCLUSION

We have attempted to link seismological, petrographic and geodynamic data together in order to propose various structural hypotheses. The seismological data reveal the existence of a continuous ridge with a relatively thin crust along the New Caledonia-Norfolk alignment.

The accumulation of ultrabasic rocks may be explained as a consequence of the movement of the Australo-Tasmantis block dipping underneath the oceanic plate in the area of New Caledonia in the Upper Eocene. This accumulation was accompanied by erosion and shear faulting which generally influenced the structure of the New Caledonian Arc. The mechanical and chemical erosion of a large proportion of the peridotitic cover led directly to peneplanations and then to upheaval movements by isostatic compensation. This phenomenon, which was spread out in time, was probably limited to New Caledonia. As well, there were superimposed eustatic variations which complicated the isostatic readjustments.

The hypothesis of a flexure of the lithosphere (the Australo-Tasmantis plate) before it dips underneath the oceanic plate at the site of the New Hebrides Trench provides an explanation for the Quaternary tectonic observations made in New Caledonia and the Loyalty Islands. The upheaval effects decrease south-westwards.

We cannot yet specify the exact amplitude of these movements, but the pattern proposed, which includes the flexuring of the lithosphere and accompanying isostatic compensations, approximates well to the seismological and geological data so far obtained for the region.

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