GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 14, PAGES 1507-1510, July 24, 1992

DETACHMENT OF PART OF THE DOWNGOING SLAB AND UPLIFT OF THE NEW HEBRIDES (VANUATU) ISLANDS

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Abstract. Several seismological observations suggest that there is a gap within the downgoing slab of Australian lithosphere plunging beneath the New Hebrides, and ages of elevated coral terraces on the New Hebrides Islands suggest that the islands are rising rapidly. We suggest that the creation of the gap in the slab, within the last 1 M.y., occurred by part of the slab detaching from the rest and sinking rapidly into the underlying asthenosphere. This lowered the downward force on the slab at shallower depths and therefore on the overriding plate, and the continued decrease of this force, as the deeper slab sinks freely, has allowed the islands above it to rise. Although this suggestion cannot account for all aspects of the uplift of the islands, it provides a simple mechanism for explaining the fairly young uplift and its distribution along the New Hebrides arc.

Introduction

The horizontal movements of plates of lithosphere are the most dramatic, and probably the most important, manifestations of the convection within the mantle. Accordingly, their study has rendered vertical movements, which occur at rates lower by one to two orders of magnitude, a second order phenomenon. Yet, even if vertical movements are slow and of small magnitude, their mere existence in different tectonic settings provides important constraints on geodynamic processes occurring within the mantle. For instance, rapid uplift might be due to the detachment of portions of mantle lithosphere from the overlying material and the sinking of it into the asthenosphere. Bird [1979] and England and Houseman [1989] suggested that such a phenomenon and the replacement of the detached lithosphere by hotter material from below occurred in Late Cenozoic time beneath the Colorado Plateau in the western United States and beneath the Tibetan Plateau, respectively. We pursue this possibility for the New Hebrides arc.

Seismic evidence for a gap in the downgoing slab

Several seismological observations indicate that the slab of lithosphere plunging beneath the New Hebrides island arc has a major gap or hole within it.

First, there is a gap in the intermediate depth seismic zone (Figure 1). Beneath the islands of Malekula and Efate earthquakes with depths greater than about 85 km are sparse, both as located with global networks [Pascal et al., 1978] and local networks [Marthelot et al., 1985; Prevot et al., 1991]. The gap in activity extends at least 150 km in the downdip direction, and could be much wider. To the north-northwest, beneath Espiritu Santo, it thins to a width of only about 30-40 km below a depth of only 30-40 km. North of Espiritu Santo, the gap is yet less well defined, but south of Efate it seems to be wider, attaining a width of about 100 km. South of Erromango, it again is not well defined.

Second, seismic waves passing through the widest part of this seismic gap, beneath Malekula and Efate, are severely attenuated [Marthelot et al, 1985] and travel with relatively low average velocities [Grasso et al., 1983; Prevot et al., 1991], phenomena that do not characterize continuous lithosphere. Short period seismographs simply do not record S-waves traversing the widest part of the aseismic region. P-wave velocities within this region are clearly lower than within most of the area where intermediate depth seismicity is common.

Since intermediate depth seismic zones are commonly associated with zones of low attenuation and relative high seismic wave velocities, and therefore with downgoing slabs of lithosphere [e.g., Mitronovas and Isacks, 1971; Oliver and Isacks, 1967], it logically follows that each of the absence of earthquakes, the high attenuation, and the low P-wave velocities suggests the absence of lithosphere. In fact, from the sharpness of the discontinuity in the seismicity, Pascal et al. [1978] suggested that such a gap might exist.

The lack of continuity of the downgoing slab suggests, but by no means requires, that the gap formed within the downgoing slab after it was subducted. We suspect that had there been a gap within the lithosphere before it was subducted, there would be a record of such a hot region in the overriding lithosphere. Accordingly, we may use the dimensions of the gap and the rate of underthrusting to place a limit on when detachment of the slab occurred. The downdip width of the gap in seismicity increases from 100 km in the south-southeast to at least 150 km beneath Malekula. The dimensions of the high-attenuation and high-velocity regions are less well constrained, so let us use the dimensions of the aseismic region to define the width of the gap in the slab. The downdip distance from the top of the gap to the trench is about 100 km [Prevot et al., 1991]. Underthrusting occurs at a rate of about 85 km/Ma [DeMets et al., 1990]. Thus, if the gap formed within subducted lithosphere, it is likely to have formed since roughly 1 Ma, and probably more recently. Let us assume 0.5 to 1 Ma.

If the gap formed by the deeper part of the slab detaching from the upper part, the rate that the gap opened should be given approximately by the width of the gap divided by 0.5 to 1 M.y. Thus, rates of opening of 100 to 300 km/Ma, or more, seem likely. With a convergence rate of 85 mm/a, the sinking rate of the deeper part should be 200-400 km/Ma.

Uplift of the New Hebrides Islands

Most of the New Hebrides islands are capped by Quaternary coral limestone [Mitchell and Warden, 1971]. Moreover, most of this limestone has been assigned ages of Middle or Late Quaternary. Thus, it seems to have emerged from below sea level since 1 Ma, and in most cases as recently as 200-500 ka. Note that this relatively short period of geologic time lies within the period when the gap in the downgoing slab seems to have formed.

Accurate dating of corals on different islands suggests average rates of uplift since roughly 150 ka of slightly less than 1 mm/a on the Torres Islands in the north [Taylor et al.,

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Paper number 92GL01389
0094-8534/92/92GL-01389$03.00

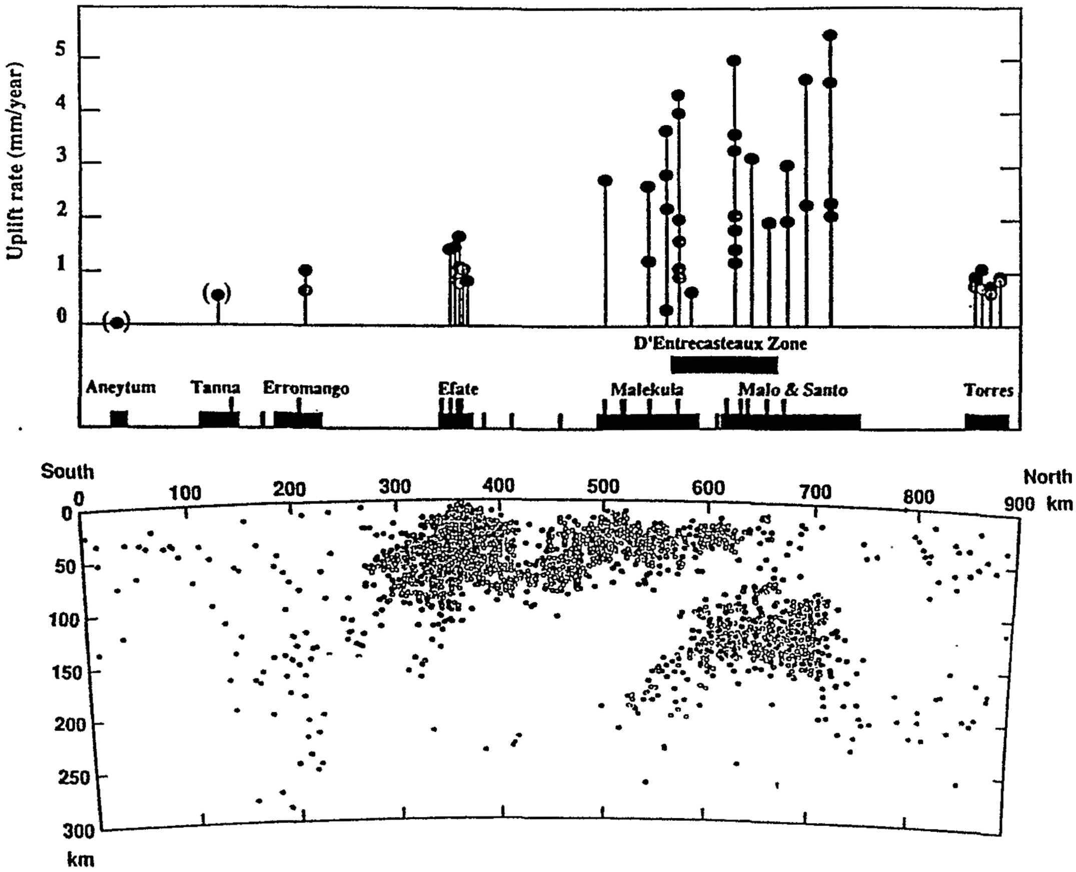

Fig. 1. Seismicity and uplift rates along the New Hebrides island arc, from Aneytum Island to the Torres islands. The seismicity (bottom) is shown on a vertical cross section starting at the point located at 20.5° S 170° E (km 0), along an azimuth of 340°, in a direction perpendicular to plate convergence. Open circles represent selected earthquakes located by the local ORSTOM/Cornell network from 1978 to 1990; filled circles represent PDE locations from May 1968 to 1990 for earthquakes located using 100 or more stations (earthquakes with assigned depth of 33 km were removed). Uplift rates for Holocene (filled circles), and Late Quaternary (open circles) periods are shown at the top of the figure. Uplift rate sources are referenced in the text. Circles between parenthesis denote uplift rates based on nonquantitative observations on Aneytum Island [Jouannic et al., 1982] and Tanna Island [Taylor, personnal communication, 1992]. Islands are shown by horizontal black bars, the D'Entrecasteaux zone by a grey bar, and stations of the local ORSTOM/Cornell network are represented by black vertical bars.

1985], 3-5 mm/a on Espiritu Santo [Jouannic et al., 1982], 2-3 mm/a on Malekula [Jouannic et al., 1982], roughly 1 mm/a on Efate [Neef and Veeh, 1977], 0.6-1mm/a on Erromango [Neef and Hendy, 1988], and lower rates farther south (Figure 1). Jouannic et al. [1982] stated that clear emergent coral reefs and terraces are present on Tanna, but they seem to be absent on Aneytum farther south (Figure 1). This pattern of uplift is somewhat complicated by average rates for the last few thousand years (Holocene) on Espiritu Santo and Malekula, but not on the Torres Islands, being roughly two times higher than those of periods averaged over the last 28-150 ka [Jouannic et al., 1982; Taylor et al., 1985, 1987]. As discussed below, it is also complicated by large variations in uplift rates not only along east-west profiles, but also along north-south profiles on individual islands. In any case, the most rapid uplift has occurred near, if not directly above, the areas where the gap in the downgoing slab has developed.

Possible relationships of detached lithosphere to uplift

The correlations in both time and space clearly point toward a cause-and-effect relationship between the gap in the slab and the uplift. Defining a quantitative physical relationship between them, however, is not obviously amenable to a simple analysis, especially when the dynamic processes of normal, steady state subduction remain poorly understood. Rather than constructing a complex model for a process that is only tentatively suggested, let us use the sinking of a rigid sphere through a viscous medium as a simple model for the detachment and sinking of the deeper part of the slab.

First, consider Stokes's Problem of an infinite viscous fluid of viscosity, η, through which a sphere of radius, a, and density difference $d\rho$ sinks under the influence of gravity, g. The velocity is: $U = 2\, \delta\rho\, a^2\, g / 9\, \eta$. For $\delta\rho = 100$ kg/m^3, g = 10 m/s^2, and $\eta = 2 \times 10^{20}$ Pa-s [e.g., Nakata and Lambeck, 1989], a sphere of radius 50 km will sink at 80 km/Ma. Increasing the radius of the equivalent sphere to 100 km, making the sphere more streamlined, or embedding it in a fluid with a downward component of velocity, can yield a rate of 300 km/Ma. Thus, the sinking of the slab at a rate somewhat faster than attached slabs presently sink is certainly plausible. The physical situation differs from Stokes's Problem in that the Earth's surface should alter the flow, but

Morgan [1965, p. 6179] showed that the rate of sinking is reduced approximately by a factor of $(1 - 3\,a/4\,D)$, where D is the depth of the center of the sphere below the surface. Given the uncertainties in the relevant parameters, there is no problem finding a set consistent with rates of sinking of 200-400 mm/a.

The sustained uplift of the islands for hundreds of thousands of years requires that, whatever process causes it, that process was not simply the instantaneous removal of a force pulling the surface down. Studies of Pleistocene rebound demonstrate that isostatic rebound occurs rapidly, in periods of only a few tens of thousands of years or less [e.g. Peltier, 1982; Walcott, 1973]. Thus, the continued uplift for 100 ky or more at rates of 1 mm/a or more requires that a normal stress, changing with time, be applied to the base of the overriding plate of plate.

A sinking body will cause flow of the surrounding viscous fluid, and this flow will, in turn, pull the overlying surface downward. Two competing effects determine the magnitude of the deflection. First, all fluid flow and hence all viscous stresses depend upon the speed at which the body sinks through a fluid otherwise undisturbed; this speed should increase as the body sinks deeper and farther from the surface, where the flow of material around the body is restricted. Second, fluid flow is more rapid, and viscous stresses are greater near the body than far from it; thus, for a given speed of the body, a shallow body deflects the surface more than a deep one.

The simplest analogous, and relevant boundary conditions are for a sphere within a fluid with a flat rigid boundary at the top. Then, an estimate of the normal stress on that surface can be converted into a deflection of surface analogous to that of the Earth by $\sigma = -\Delta\rho\, h\, g$ [e. g. Morgan, 1965], where σ is the normal stress (positive for tension), $\Delta\rho$ is the difference in density between the crust and the fluid through which the material rises (water for the islands), and h is displacement of the surface.

Morgan [1965] obtained an approximate solution for the velocity field and stress field surrounding a sphere sinking into a viscous medium below a rigid surface, which is accurate for small ratios of the radius of the sphere to its depth. Using his equation (11) for the vertical component of velocity of the fluid, his (12) for pressure, and the relationship of them to the normal stress, his (13), the normal stress at the surface is

$$\sigma = (2\,a^3\,\delta\rho\;g/3)\,[(3D^3/R^5) + (a^2\,D/R^5) - (5D^3\,a^2/R^7)] \quad (1)$$

where $R = (D^2 + r^2)^{1/2}$, r is the horizontal distance from the center of the sphere, and terms of order $(a/D)^3$ have been neglected.

The corresponding deflection is

$$h = -(2\,a^3\,\delta\rho\,/3\,\Delta\rho\,)[(3D^3/R^5)+(a^2\,D/R^5) - (5D^3\,a^2/R^7)] \quad (2)$$

The absence of viscosity in this expression results from the speed of the fluid depending inversely on it, and the stress in the fluid being proportional to the product of that speed and the viscosity.

Let us simplify this by considering the point directly over the sphere, at r = 0:

$$h = -\,(2\,a^3\,\delta\rho\,/3\,\Delta\rho\,)\,[(3/D^2) - (4\,a^2/D^4)] \quad (3)$$

Notice first that for a = 50 km, and for D = 100 km, 200 km, and 300 km, the magnitudes of the deflection are about 830 m, 290 m, and 130 m. Hence surface uplifts would be several hundred meters above an equivalent sphere dropping from a depth of 100 km to 200 or 300 km.

The speed that the surface moves up can be obtained by differentiating (3):

$$dh/dt = (2\,a^3\,\delta\rho\,/3\,\Delta\rho\,)\,[(6/D^3) - (16\,a^2/D^5)](dD/dt) \quad (4)$$

where dD/dt is simply the rate that the sphere sinks and is positive for all time. Again using a = 50 km, and assuming a sinking rate of 400 km/Ma, the calculated rates of surface uplift directly over the sphere at depths of 100, 200, and 300 km are 3.3 mm/a, 1.0 mm/a, and 0.3 mm/a, respectively. These speeds are only useful for a crude comparison, in part because they are based on an approximation, but more importantly because the model of a sphere is obviously a poor geometric representation of the detached slab. Our point here is simply that rates of uplift of the order of millimeters per year are quite reasonable for the surface above a detached slab sinking freely into the asthenosphere.

Inconsistencies with this interpretation

The discussion above is meant to demonstrate that the detachment of a piece of the downgoing slab and its effect on the fluid motion beneath the New Hebrides arc could account for the relatively rapid uplift of the islands. In presenting this argument, however, we have glossed over some details of the uplift that cannot be explained by a freely sinking slab and associated fluid flow, but that instead suggest other mechanical processes.

First, the highest rates of uplift, on Espiritu Santo, do not overlie the widest or most pronounced gap, beneath Malekula and Efate. Moreover, the average uplift rates on Espiritu Santo and Malekula, but not on the Torres Islands, seem to be roughly two times faster during the last few thousand years than during the last 100 kyr. Although one could concoct mechanisms to account for these peculiarities, such as the plausible suggestion of different dates of detachment for the underlying slab, they obviously are not easily explained by one simple detachment.

In addition, the uplift rates (Figure 1) are quite scattered, with different parts of different islands rising at quite different rates, suggesting that the islands are fractured into separate blocks [e.g., Isacks et al., 1981; Taylor et al., 1980, 1987]. The uplift also varies markedly from east to west across the islands with maximum values relatively close to the trench on Espiritu Santo and Malekula, the islands closest to the trench, and decreasing rapidly eastward [e.g. Taylor et al., 1987]. These variations manifest themselves as tilts of the islands, or of parts of them [e.g. Taylor et al., 1980], some of which have detected geodetically [Bevis and Isacks, 1981; Mellors et al., 1991]. Moreover, substantial changes in uplift have been clearly associated with earthquakes [e.g., Edwards et al., 1988; Taylor et al., 1980, 1987, 1990]. None of these aspects can be explained by the smooth processes associated with viscous flow outlined above.

The common explanation for the rapid uplift of the New Hebrides Islands is that subduction of the relatively light D'Entrecasteaux Ridge buoys up the inner wall of the trench [e.g., Collot et al., 1985; Jouannic et al., 1982; Taylor et al., 1980, 1987, 1990]. Similarly, the gap in the downgoing slab of lithosphere has been ascribed to some flaw in it because of the D'Entrecasteaux Ridge [e.g. Marthelot et al., 1985]. We do not want to deny these possibilities, particularly in light of the spatial and temporal details of the uplift mentioned in the preceding paragraph, but we do note that the D'Entrecasteaux Ridge is a small feature (width ≈ 100 km, see Collot et al. [1985]) compared with the distribution of uplift (Figure 1). It intersects the arc between central Espiritu Santo and northern Malekula, about 200 km north of Efate and about 200 km south of the Torres Islands, where rates of late Quaternary uplift are approximately 1 mm/a. Thus, whereas the subduction of the D'Entrecasteaux Ridge may contribute to the complexities of the deformation of the New Hebrides Islands, it does not provide an obvious explanation for the widespread, relatively rapid uplift of the islands along the arc. This aspect may require a more deep-seated process, and we suggest that the fluid dynamics associated with a freely sinking slab is a possible process that can account for it.

Acknowledgments. We thank C. Baldassari, F. Bondoux, R. Campillo, M. Chauvin (deceased), C. Douglas, R. Foy, L. Mollard, D. Nakedau, J.C. Willy, E. Yakeoula, and all others involved in the data collection and analysis operations. This work was supported by the Institut de Recherche pour le Développement en Coopération (ORSTOM), NASA under grant NAG5-795, and the Laboratoire de Géophysique Interne et Tectonophysique of Université J. Fourier (Grenoble, France).

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(Received May 4, 1992;
accepted June 15, 1992.)