GEOPHYSICAL RESEARCH LETTER, VOL. 20, NO. 8, PAGES 655-658, APRIL 23, 1993

# UNFOLDING THE SUBDUCTING PLATE IN THE CENTRAL NEW HEBRIDES ISLAND ARC: GEOMETRICAL ARGUMENT FOR DETACHMENT OF PART OF THE DOWNGOING SLAB

Jean-Luc Chatelain [1,2], Bertrand Guillier [2,3], and Jean - Pierre Gratier [2]

Abstract. In the central part of the New Hebrides island arc a sizable gap exists in the seismic activity. Seismic observations in the zone of the gap have been previously interpreted as either related to a detachment of part of the downgoing slab or associated with a continuous slab. We give a geometrical argument which, added the seismic observations from these previous studies, adds one step in favor of the detachment hypothesis. After unfolding the downgoing plate and restoring it to its initial state, using a 3D balance technique, we show that the gap can be filled with three pieces. Two of these pieces are seismic zones located beneath the seismic gap and the third one is a deep (550 - 650 km) seismic zone located about 200 km north-east of the arc. These three pieces could be detached parts of the subducting plate.

## Introduction

On a regional scale the overall configuration of the subduction zone of the New Hebrides island arc, where the Australian plate plunges beneath the Pacific plate, is relatively uniform down to a depth of about 300 km [Dubois, 1971; Isacks and Molnar, 1971; Pascal et al. 1978].

In the central part of the arc, however, there is a well pronounced interruption of seismic activity, as identified by both global networks [e.g. Pascal et al., 1978] and local networks [e. g. Marthelot et al., 1985; Prévot et al., 1991]. In map view, the gap in activity extends between approximately 18.5° S (between the islands of Erromango and Efate), and 15.5°S (the southern part of Santo island) (Figure 1). In depth the gap has an asymmetric shape: beneath the islands of Malekula and Efate it starts at a depth of about 85 km and extends at least 150 km in the downdip direction, thinning to a width of only about 30-40 km below a depth of only 30-40 km beneath Santo island [see Chatelain et al., 1992].

We have explored the geometrical possibility of filling the seismic gap with pieces of slab that are detached from the main subducting slab. Our approach is to apply a geological method similar to the balanced cross section technic, extended to three dimensions (balanced surfaces; see Gratier et al. [1991]), to the central New Hebrides island arc. We find that, after restoration of the subducting plate into its initial sate, the seismic gap observed in this part of the arc can be filled by (1) two seismicaly active zones located underneath the gap and (2) a nearly horizontal seismic zone located beneath the Fiji basin. This geometrical argument, added to several seismic observations from previous studies, favors the hypothesis that in the zone of the seismic gap the downgoing slab is not continuous and that the three seismic zones used to fill the gap could be detached parts of the downgoing plate.

[1] ORSTOM, Nouméa, Nouvelle Calédonie.

[2] Laboratoire de Géophysique Interne et de Tectonophysique, CNRS, Université Joseph Fourier, Grenoble, France.

[3] Institut Français d'Etudes Andines, Santa Cruz, Bolivia.



Paper number93GL00681
0094-8534/93/93GL-00681$03.00

## Seismic observations in the zone of the seismic gap and their interpretations

Several seismic observations have been made in the zone of the seismic gap. Body 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 [Goula and Pascal, 1979; Grasso et al., 1983; Prévot et al., 1991]. Choudhury et al. [1975] have shown that ScS waves coming through the seismic gap are attenuated. The zone of the seismic gap is also related to a 750 °C positive thermal anomaly [Prévot et al., 1991]. These observations lead to two opposite interpretations of the geometry of the subducting slab:

1.- Studies based on the seismicity distribution [Pascal, 1974; Pascal et al. 1978], or on attenuation of ScS waves [Choudhury et al., 1975] favor the detachment of the part of the slab located beneath the seismicity gap. Louat et al. [1982] suggested the possibility of a detachment of part of the slab among several other possibilities. Chatelain et al. [1992], relate the uplift of the central part of the island arc to the sinking of a piece of lithosphere located beneath the seismic gap.

2.- On the other hand, Isacks et al. [1981] and Marthelot et al. [1985] argue for a continuous dipping slab. The seismic gap is interpreted as the trace at depth of the subduction of the D'Entrecasteaux ridge (located on the surface between Santo and Malekula islands; see figure 1). The seismic observations mentioned above are associated to scattering.

Finally, Louat et al. [1988] compiling all previous studies have come to the conclusion that it is impossible to decide whether the slab is continuous or that the bottom portion of the slab is detached.

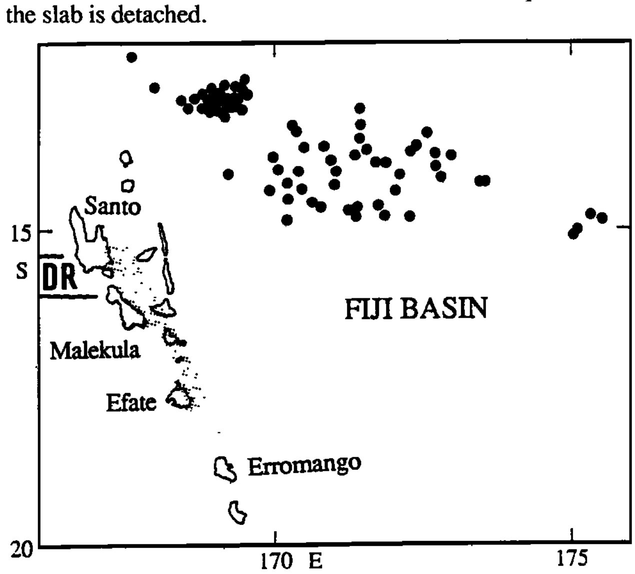


Fig.1. Map showing the location of the islands of the central part of the New Hebrides island arc and the Fiji basin. Closed circles represent deep earthquakes located beneath the north Fiji Basin. The locations of earthquakes were taken from Pascal et al. [1978] and Hamburger and Isacks [1987]. The location of the gap in seismic activity is shown by the light shaded area. Also shown is the location of the D'Entrecasteaux ridge (DR).

Deep earthquakes beneath the Fiji basin

Another important seismic feature observed in the region of figure 1 is the presence beneath the north Fiji basin of a broad nest of seismic activity between about 550 to 650 km in depth, even though along the New Hebrides arc earthquakes do not occur below a depth of 300 km [Dubois, 1971; Pascal et al., 1973]. This nest is located to the north-east of the arc between latitudes 12°S and 15°S (Figure 1). The results from Isacks and Molnar [1971] suggest that this surface is a nearly horizontal slab of lithosphere. From seismic wave attenuation studies, Barazangi et al. [1973] and Pascal et al. [1973] found that it is a piece of detached slab from the Australian plate. Hamburger and Isacks [1987], however, argue that it is a piece of the formerly subducting Pacific plate, although they do not rule out the possibility that it is a portion of the presently subducting Australian plate. Moreover, during the rotation of the New Hebrides arc from its position 8 My ago towards its present position, the respective positions of the seismic nest and of the seismic gap coincided, at about 6 My ago (see figure 7 of Hamburger and Isacks, [1987]).

Description of the Balanced Surface Method

To verify that several pieces of a deformed (folded and faulted) surface can be put back together into their initial horizontal state, these pieces of surface must be unfolded and restored, just as a folded and torn sheet of paper may be smoothed with an iron and the unfolded pieces fitted together without voids nor overlaps. The major assumption is that the surface was folded and faulted without stretching parallel to its surface. The compatibility constraints on the surface geometry can then be tested using a balanced surface method.

The three-dimensional balance method used in this study has been described by Gratier et al. [1991]. It is performed in three successive steps :

(1) Any scattered data (structure-contour maps, cross sections...) defining the folded surface are interpolated by partitioning the entire folded and faulted surface into several folded pieces delimited by the faults. The interpolated gridded xyz values defining the folded pieces are then used to describe each one by a network of triangular elements considered as being rigid.

(2) Each of the folded pieces is restored to an horizontal surface representing its initial state by laying flat the triangle elements. Then the best fit of each triangle in the hole defined by its neighbors is obtained by minimizing voids and overlaps using a least-square method. This is performed using the program UNFOLD [Gratier et al., 1991]. The reliability of the geometry of each unfolded surface is tested by the degree of fitting between all triangular elements [see Guillier and Gratier, 1991].

(3) After restoration of each folded surface, the unfolded pieces have to be fitted together with reduced voids and overlaps along their edges. This step is simply done by a trial and error method using an interactive graphic program which allows one to translate and rotate the unfolded zones.

The program UNFOLD has already been tested and used in several studies, and works by unfolding compressional features [Gratier et al., 1991] as well as extensional features [Guillier and Gratier, 1991; Gratier and Guillier, 1993]. Attempts were made by Guillier and Gratier [1991] to unfold non-developable surfaces (surfaces that have been stretched, even partially): bad values of the degree of fitting were obtained. Such non-developable surfaces may be clearly distinguished from true developable surfaces with good fitting values [Gratier and Guillier, 1993]. Therefore, a good degree of fitting is an *a contrario* prove that the feature that can be unfolded was folded and faulted without stretching parallel to its surface.

Unfolding and Restoration of the New Hebrides Slab

The present state of the subduction has been described with four folded pieces (Figure 2). The pieces were chosen as follows: (1) the subducting plate above the seismic gap, (2) the horizontal nest of seismic activity located beneath the Fiji Basin, and (3) and (4) the two seismic zones located beneath the seismic gap. The location of earthquakes on successive

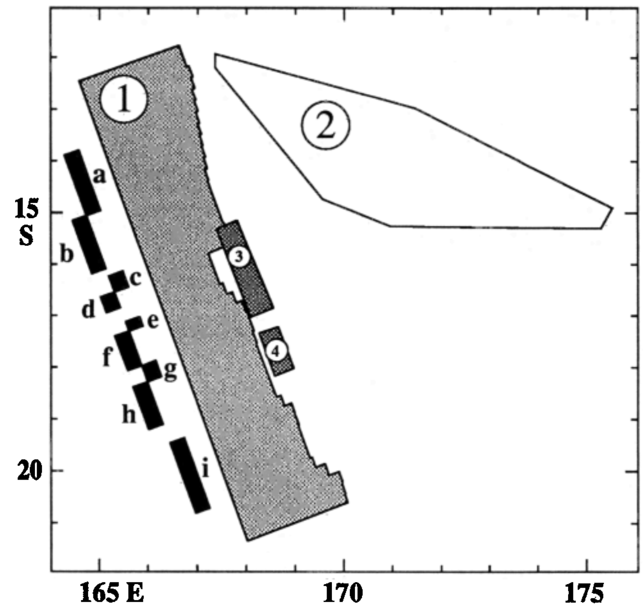


Fig. 2. Map view showing the present state of the Wadati-Benioff zone in the central New Hebrides island arc (shaded areas 1, 3 and 4) and contour of the deep earthquakes located beneath the north Fiji Basin (white area 2). The areas defining the Wadati-Benioff zone are projections of the Wadati-Benioff zone onto the surface. Black bars with letters indicate the location of some of the cross sections used to contour the Wadati-Benioff zone, which are presented in figure 3.

vertical cross sections were used to draw the top of the subducting plate (Figure 3). The lines representing the top of the subducted plate were then interpolated in order to define the folded surface of the four pieces. We used earthquake locations from Pascal et al. [1978], Coudert et al. [1981], Isacks et al. [1981], plus selected data from the ISC catalog and unpublished data from the local ORSTOM - Cornell seismic network. It should be pointed out that delimiting the top of the subducted plate using earthquake locations is a subjective task, especially in the zone of contact with the upper plate. But the uncertainties are small compared to the plate dimensions and do not influence significantly the final results.

The initial state of the slab was considered to be horizontal and flat, i.e. as the plate would have been before subduction. As piece 2 is presently horizontal, it has not been unfolded and has been used in its present state. The three other pieces were unfolded as described in the previous section. For each of the pieces, the degree of fitting is excellent. It is comparable to the one obtained in the reference cases (experimental and theoretical) of Guillier and Gratier [1991]. This fact shows that the restoration of the three pieces can be done without stretching or contraction parallel to the surface of each piece.

Unfolding of piece 1 does not by itself fill the seismicity gap . Piece 2 alone is not sufficient to fill the hole, but with addition of pieces 3 and 4 it is possible to fill the entire gap with reduced voids and overlaps, with the four pieces restored to their initial horizontal state (Figure 4).

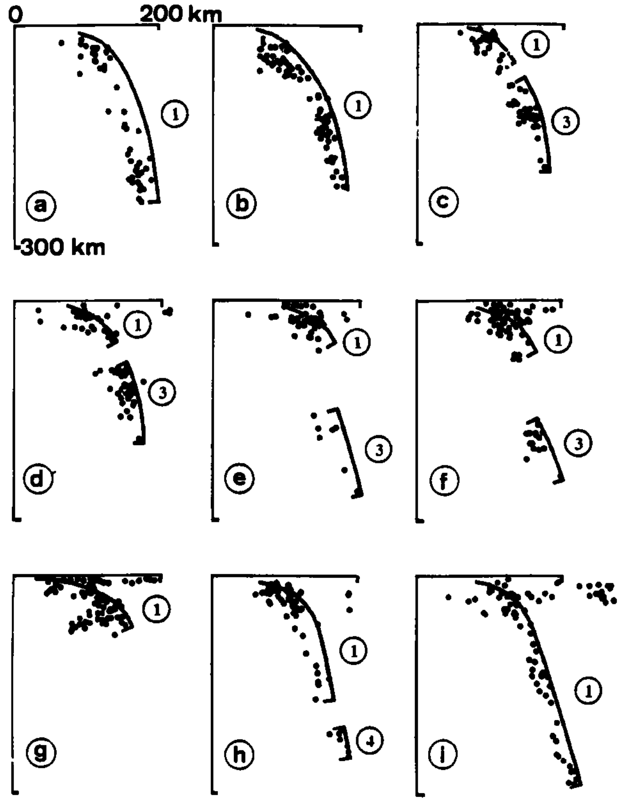


Fig. 3. Examples of vertical cross sections taken along the central New Hebrides island arc used to draw the top of the subducting plate (black lines). The lines representing the top of the subducted plate are interpolated by the UNFOLD program, thus defining the surfaces and shapes of seismic zones 1, 3 and 4. The locations of these sections are shown in figure 2. The direction of the plane of projection for each section was taken perpendicular to the black bars of figure 2. The contour of the Wadati-Benioff zone has been obtained using 31 cross sections from various sources as indicated in the text.

## Discussion and Conclusion

The reconstructed subducting plate that we have obtained shows that the hypothesis of detachment of part of the slab is geometrically possible. This argument, together with the observations of attenuation of seismic waves, low seismic velocities and positive thermal anomaly described in the first section, favors the hypothesis that the gap of seismicity observed in the central part of the New Hebrides island arc is due to detachment of the bottom of the slab.

In this case, given the relative position of the pieces of detached slab with respect to the subducting plate, the detachment could have occured in two stages. The flat seismic zone beneath the Fiji basin (piece 2) could have detached from the subducting plate about 6 My ago, during the rotation of the New Hebrides island arc (see figure 7 of Hamburger and Isacks [1987]). The two seismic zones located beneath the seismic gap (pieces 3 and 4), given their positions from the top of the gap could have detached about 1My ago [Chatelain et al., 1992].

There is no definitive explanation on how this double detachment could have occured. Choudhury et al. [1975] proposed that it could have been produced by the subduction of an ancient mid-oceanic ridge. This model is plausible as, for example, the D'Entrecasteaux ridge has a mid-oceanic ridge-like structure [Collot et al.,1985; Burne et al., 1988].

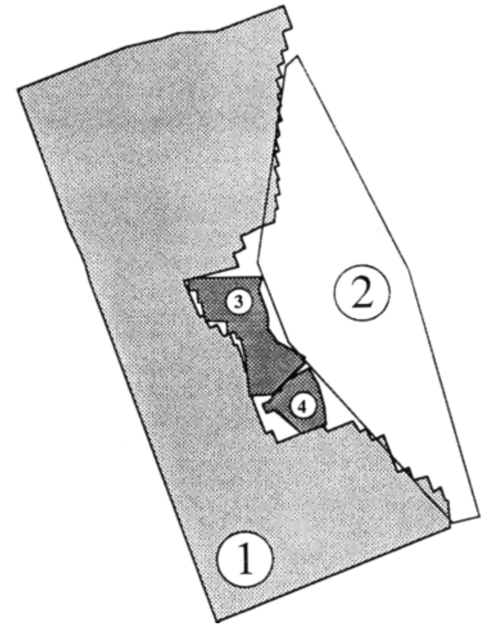


Fig. 4. Restoration of the subducting plate into its initial undeformed state after unfolding of pieces 1, 3 and 4 and their assemblage. Piece numbers are the same as in figure 2. The good fit obtained for the assemblage of the four pieces shows that it is possible to reconstruct an initial continuous slab.

In any case, the floor of the subducting plate in this part of the arc shows at present an intricate pattern of major normal and transform faults close to the trench [e.g., Goula and Pascal, 1979; Collot et al.,1985; Daniel et al., 1986], that makes plausible a scenario where the subduction of one or several similar features would have caused the detachments in the subducted slab.

The data used in this paper obviously do not allow us to detail such a scenario. However, our geometrical argument, combined with seismic observations, supports the hypothesis that the subducting slab in the central part of the New Hebrides island arc would not be continuous and that the gap in seismic activity could be due to detachments of the bottom of the slab.

*Acknowledgments.* This work was supported by the Institut de Recherche pour le Développement en Coopération (ORSTOM), and the Laboratoire de Géophysique Interne et Tectonophysique of Université J. Fourier (Grenoble, France).

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J.-L. Chatelain and J.-P. Gratier, IRIGM-LGIT, Domaine Universitaire, BP 53X, 38041 Grenoble CEDEX, France.
B. Guillier, IFEA, Santa Cruz, Bolivia.

(Received October 28, 1992;
revised January 21, 1993 ;
accepted February 25, 1993.)