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## Coseismic and long-term vertical displacement due to back arc shortening, central Vanuatu: Offshore and onshore data following the $M_w$ 7.5, 26 November 1999 Ambrym earthquake

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[1] This paper presents a combined analysis of data collected both onshore and offshore in the epicentral region of the  $M_w$  7.5, 26 November 1999, Ambrym earthquake. This offshore event occurred at the southern end of the back-arc thrust belt of the Vanuatu subduction zone, east of the island of Ambrym and resulted in permanent uplift of the eastern tip of the island. The data presented include (1) interpretation of older seismic lines across the tectonic front, (2) compilation of aftershock sequences, (3) postseismic bathymetry from multibeam surveys, (4) measurements of permanent coseismic ground motion using desiccated red algae, uplifted beaches, and uplifted coral colonies, and (5) dating of raised corals exposed along the coastal cliff. The active scarp of the main fault appears 13 km east of the eastern tip of Ambrym (40 km long, 2 km depth, 950 m maximum step). Uplift rates of 3.5–4 mm/yr for the past 8000 years are calculated by dating raised corals. This leads to a longer seismic recurrence interval of 375 years for events similar to that of 1999, assuming no interseismic subsidence. Postseismic ground motion was monitored using stainless steel marks set at three sites along the uplifted coast in January 2000. No significant motion could be recorded during the 2 years following the event, but slight subsidence cannot be ruled out. Finally, our results confirm that the back-arc belt of central Vanuatu is an active tectonic crustal wedge propagating eastward that accommodates more shortening than the Vanuatu subduction zone to the

west. **INDEX TERMS:** 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 7209

Seismology: Earthquake dynamics and mechanics; 7220 Seismology: Oceanic crust; 8102 Tectonophysics:

Continental contractional orogenic belts; 9355 Information Related to Geographic Region: Pacific Ocean;

**KEYWORDS:** coseismic, long term, uplift, back arc, Vanuatu

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### 1. Introduction

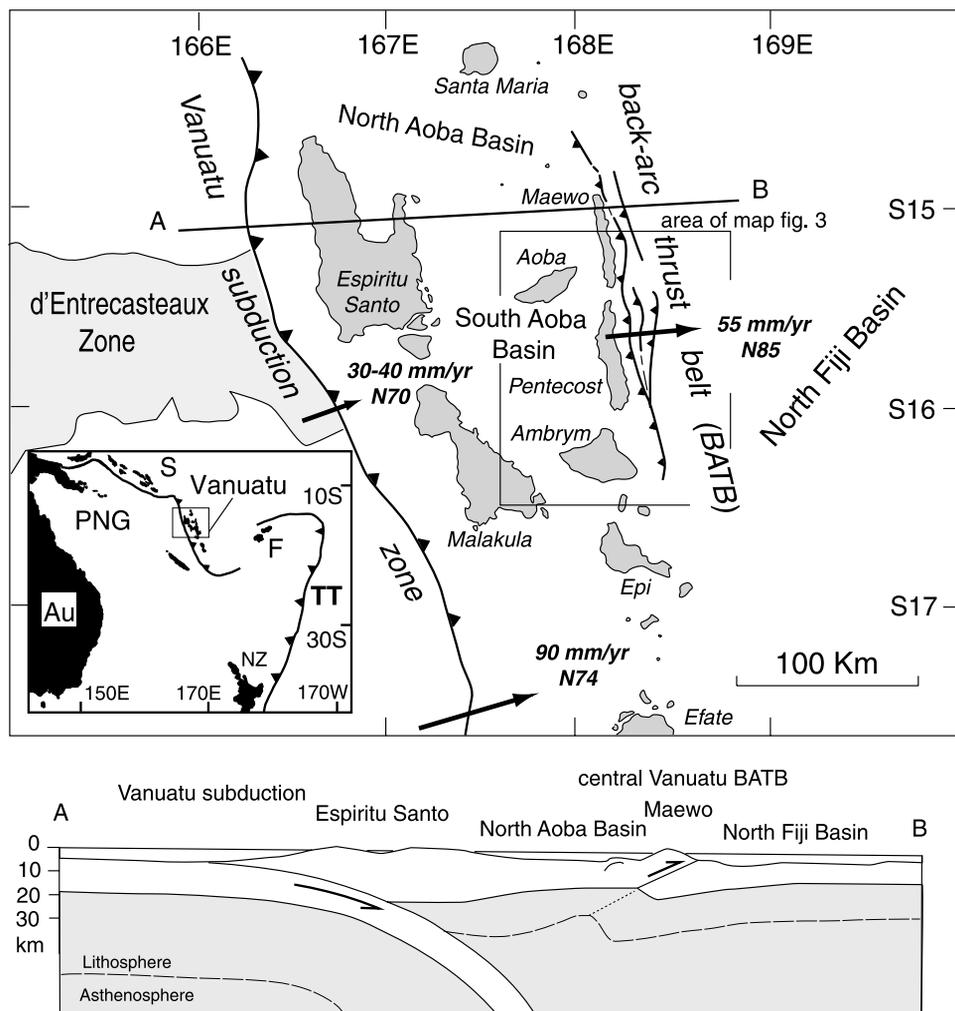
[2] Coupled offshore-onshore studies of coseismic and long-term effects of plate convergence in ocean islands environment are relatively uncommon. In contrast to terrestrial environments, accurate geological markers of permanent vertical ground displacement are not easily observed in

the marine environment. In this paper we present the results of a case study in the region of the island of Ambrym, Vanuatu, where effects of a major compressive seismic event have been studied both onshore and offshore by the means of various geophysical and geological approaches.

[3] Plate convergence processes along the central Vanuatu subduction zone are strongly dependent on the effects of the subduction-collision of the d'Entrecasteaux Ridge and associated chain of seamounts, forming the d'Entrecasteaux Zone. Convergence is accommodated along two opposite verging boundaries: the subduction zone itself to the west, and the eastern limit of the back-arc region to the east, that extends along 350 km from 13.20°S to 16.40°S, referred to hereafter as the back-arc thrust

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**Figure 1.** Location map of the studied area and simplified crustal section (AB) across the Vanuatu subduction and the back-arc thrust belt (BATB) of central Vanuatu. Section AB is modified after an original section by *Collot and Fisher [1988]*, including results of both seismic refraction and gravity data analysis. Convergence vectors are from *Calmant et al. [2003]*. Location map labels are Au, Australia; F, Fiji; NZ, New Zealand; PNG, Papua New Guinea; S, Solomon Islands; TT, Tonga Trench.

belt (BATB) following the terminology of *Calmant et al. [2003]* (Figure 1). The  $M_w$  7.5, 26 November 1999, Ambrym earthquake was the largest known thrust earthquake that occurred in the BATB [*Pelletier et al., 2000*]. The epicenter of this event is located offshore, about 10 km northeast of the Ambrym Island. This event corresponds to the activation of the southern part of the compressive boundary between the back-arc region and the oceanic crust of the North Fiji basin and resulted in permanent uplift of the easternmost portion of the coast of Ambrym [*Pelletier et al., 2000*]. Preliminary location of the complete seismic sequence was possible using local data from the Institut de Recherche pour le Développement (IRD) network [*Régner et al., 2001*]. Accurate locations as well as complete aftershock distribution are given by *Régner et al. [2003]*.

[4] Because of its location in a relatively well known region, and within a seismic network, the 1999 Ambrym event is a favorable case for detailed studies of active thrusting in an oceanic environment. The general tectonic setting of this region has been investigated during the last

two decades using mostly geophysical studies and deep-sea drilling (ODP Leg 134), as reported in the first section of this paper. Recent GPS-derived motion vectors obtained along the entire Vanuatu arc [*Calmant et al., 2003*] (Figure 1) constrain the amount of expected convergence in the study area.

[5] In this paper, we present the results of a combined analysis of data collected after the main shock both onshore along the uplifted coast of Ambrym and offshore, over the epicentral region, by the means of a full coverage, multi-beam bathymetric survey of the R/V *L'Atalante*. Interpretation of seismic lines already collected along the eastern border of the back-arc region is also used to better constrain the present-day tectonic context of this major event. These data collectively allow us to investigate the coseismic and long-term ground displacements associated with the evolution of the thrust fault involved in the November 1999 earthquake sequence. They finally lead us to propose a model of crustal shortening explaining the progressive uplift of the eastern border of the back-arc domain of Vanuatu,

including the islands of Maewo and Pentecost, in relation with the collision of the d'Entrecasteaux Zone.

## 2. Geological and Tectonic Setting

### 2.1. Regional Geology

[6] The New Hebrides (Vanuatu) island arc extends over 1700 km and delineates a major convergent boundary along which the Australian plate is subducting eastward beneath the North Fiji back-arc basin, which is part of the Pacific plate. Between 14°30s and 17°00s, the structure of the central Vanuatu arc is strongly perturbed by the subduction-collision of the d'Entrecasteaux Zone [Collot *et al.*, 1985; Collot and Fisher, 1991], a remnant of a former Eocene related arc [Maillet *et al.*, 1983; Collot *et al.*, 1992; Greene *et al.*, 1994]. South of the d'Entrecasteaux Zone, the Vanuatu arc consists of a single chain of both active and extinct volcanoes (Efate, Erromango, Tanna) parallel to a well-defined physiographic trench. By contrast, in front of the d'Entrecasteaux Zone, the subduction zone lacks a deep trench [Collot *et al.*, 1985], and the arc is characterized by the presence of large islands, arranged into three parallel chains: the western, central, and eastern chains [Mitchell and Warden, 1971; Carney and MacFarlane, 1982]. The western and eastern chains bound a wide, intra-arc sedimentary basin, the Aoba basin, with maximum seafloor depth and sedimentary infill of 3.5 km and 6 km, respectively. The eastern chain marks the limit between the back-arc domain and the oceanic crust of the actively opening North Fiji back-arc basin [Auzende *et al.*, 1995; Pelletier *et al.*, 1998].

[7] The western chain comprises two large islands, Malakula and Espiritu Santo, mostly composed of deformed and uplifted deep-sea pelagic and volcanoclastic sediments of late Oligocene to late Pliocene age [Carney and MacFarlane, 1982; MacFarlane *et al.*, 1988]. The shores of these islands are also characterized by extensive series of raised Quaternary reef terraces [Taylor *et al.*, 1980, 1987], indicating Holocene uplift rates ranging from 2 mm/yr at Malakula to 6 mm/yr to the southwest of Espiritu Santo [Jouannic *et al.*, 1980; Taylor *et al.*, 1980, 1987; Cabioch and Ayliffe, 2001].

[8] The central chain corresponds to three active volcanoes, from north to south, the Santa Maria, Aoba, and Ambrym Islands. Ambrym consists of a basal shield edifice topped by a very large tuff cone surrounding a 12-km-wide caldera [Robin *et al.*, 1993]. Caldera formation could be as young as 2000 years B.P. The northern part of the island exposes older volcanic rocks belonging to a previous edifice of possible late Pleistocene age [New Hebrides Geological Survey, sheet 6, 1976].

[9] The eastern chain is composed of two linear, N-S oriented islands, the Maewo and Pentecost Islands delineating the eastern limit of the Aoba basin (Figure 2). Both islands have much in common; they expose deeply dissected Mio-Pliocene volcanoclastic sediments and volcanic rocks emplaced in a marine environment, underlying uplifted Quaternary reef terraces (Figure 3). These islands represent parts of the eastern edge of the deep Aoba basin that have been uplifted and tectonized in response to compression along the BATB [Pelletier *et al.*, 1994]. The oldest rocks from the eastern chain belong to the Basement Complex, an

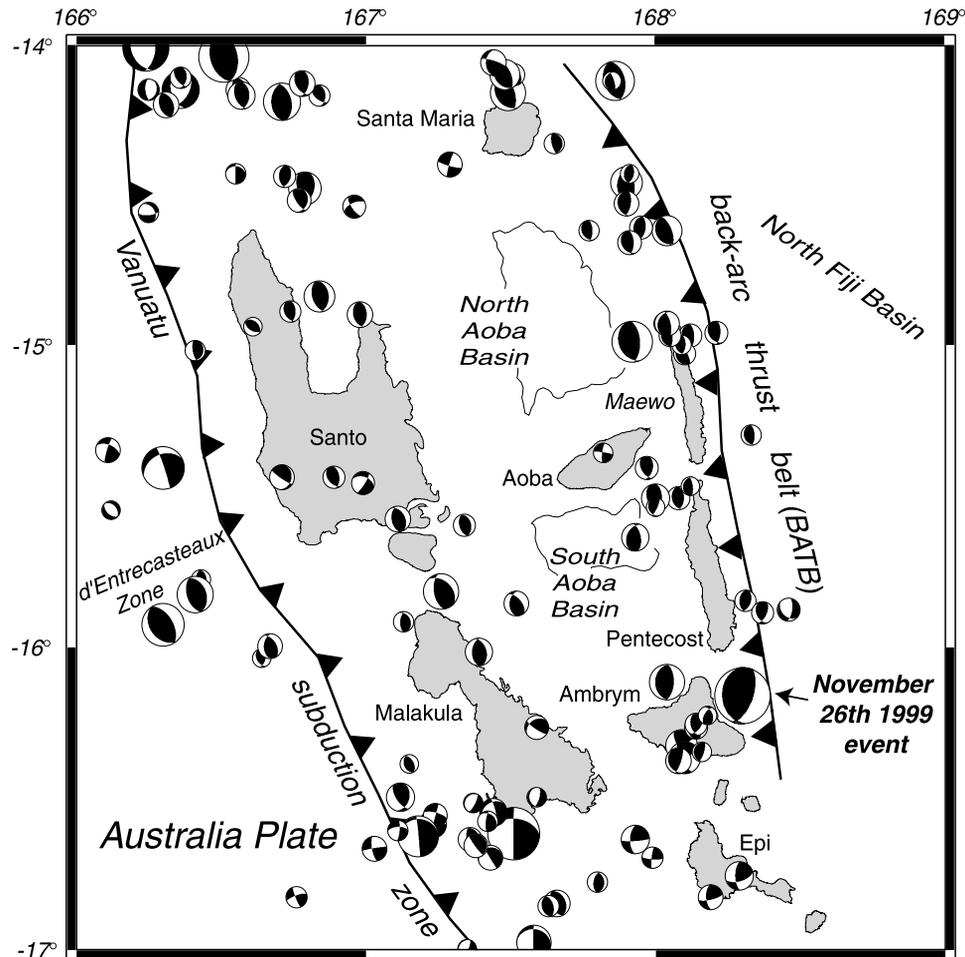
ophiolite suite with oceanic affinities exposed in the southern part of Pentecost (Figure 3). This suite could represent the tectonized border of the oceanic crust and mantle of the Aoba basin, but has also been considered as enclosing the magmatic products of the waning Vitiaz magmatic arc [MacFarlane *et al.*, 1988, and references herein]. The latest tectonic event that affected this complex is thought to have occurred during the middle to late Pliocene (circa 3.5 Ma) [MacFarlane *et al.*, 1988]. Because of the fact that only very few field investigations of this complex have been conducted until now and that reliable geochronological ages are unavailable, it is not possible to assess the proposed hypotheses for its origin. Pentecost also exposes marine sedimentary strata of volcanoclastic origin interbedded with lava flows and pyroclastic deposits of Miocene to Pliocene age. It is capped by Pliocene to Pleistocene coral reef limestones, culminating at 946 m at Mount Utanenmeretak. Maewo is characterized by a basement composed of sedimentary sequences including marine epiclastites, pyroclastic breccias, tuffaceous and pelagic foraminiferal mudstones of early to middle Miocene age, underlying upper Miocene basaltic lava formations. It is capped by Quaternary coral reef limestones exposed at a maximum altitude of 811 m.

[10] In cross section, both Maewo and Pentecost exhibit the structure of a regional anticline, with local faulting (Figure 4a). They probably began their most recent phase of emergence during the late Quaternary, at roughly the same time as the islands of the western chain. On the basis of previous work, MacFarlane *et al.* [1988] concluded that the Maewo and Pentecost Islands have risen nearly 1000 m during the past 500 kyr. Late Quaternary uplift rates of 2.73 mm/yr and Holocene uplift rates of 3.2 mm/yr at Pentecost were first proposed by previous authors on the basis of age estimation and correlation of reef terraces with Papua New Guinea terraces [Mallick and Neef, 1974]. This rate is not considered as reliable by Taylor [1992], as no isotopic ages or reasonable basis for such correlations exist. However, when assuming a lower age of 1.8 Ma for the coral formations now exposed at an altitude of 950 m at the summit of Pentecost, an average Quaternary uplift rate of 0.5 mm/yr must be considered as a minimum. Nevertheless, a progressive increase in the shortening rate at the BATB boundary is likely, in response to a decrease of the subduction rate to the west due to collision of the d'Entrecasteaux Zone.

### 2.2. The Back Arc Thrust Belt of Central Vanuatu: A Review of Previous Investigations

#### 2.2.1. Refraction and Gravimetry Data

[11] The deep Aoba basin is divided into two parts by Aoba Island. The North Aoba basin is deeper (3000 m depth) and larger than the South Aoba basin (2000 m depth). Refraction profiles and gravity data indicate that the crust beneath the North Aoba basin is 11–13 km thick, including 4–5 km of sediments in the central part of the basin and has basal velocities with clear oceanic affinities [Holmes, 1988; Collot and Fisher, 1988; Pontoise *et al.*, 1994] (Figure 1). Refraction profiles shot over the western border of the North Fiji basin at the latitude of Maewo Island confirm that the crust of this basin is of oceanic origin with a thickness of 8 km [Pontoise *et al.*, 1994]. An



**Figure 2.** Shallow seismicity of the central Vanuatu region (NEIC location). Only the events large enough to have a CMT solution (CMTS) are reported for the period 1977–1999. The position of the 26 November 1999 Ambrym event is from the local ORSTOM-IRD network, solution being from CMTS. Note that the back-arc thrust belt (BATB) of central Vanuatu is characterized by almost pure compressive events.

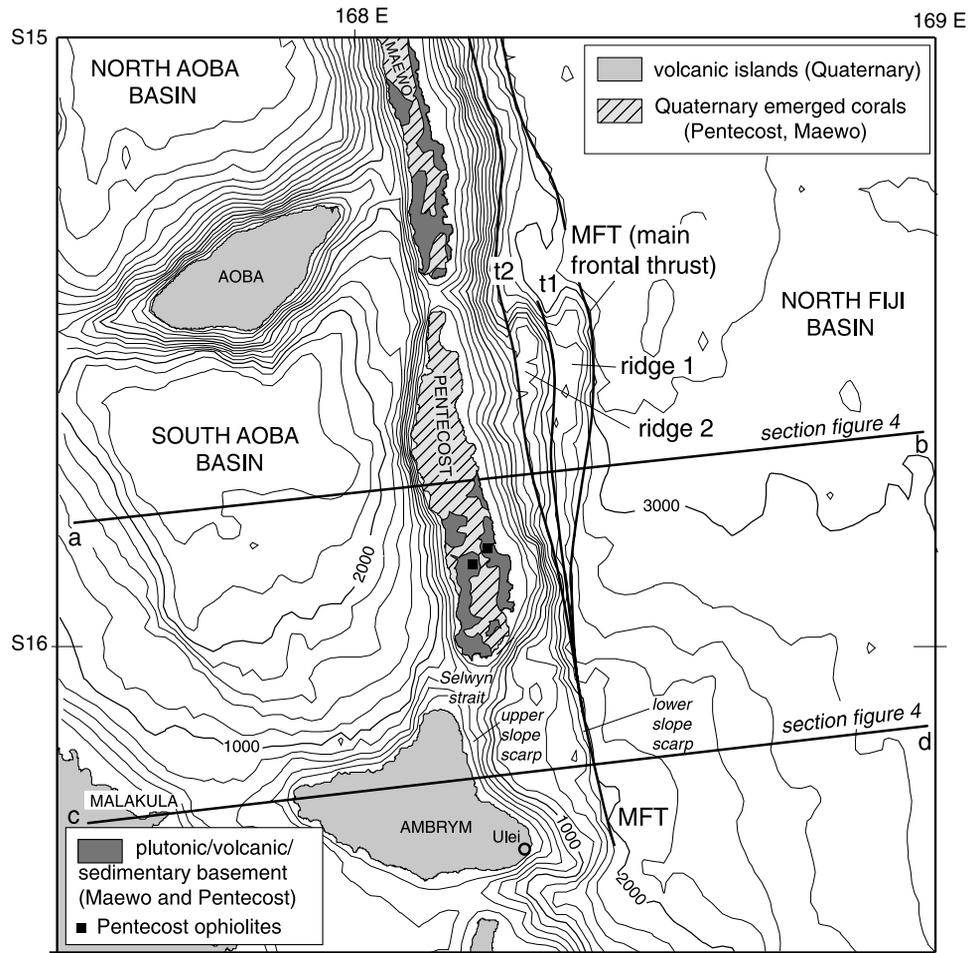
asymmetrical crustal root up to 19 km depth, corresponding to a positive gravity anomaly over Maewo Island has been inferred [Collot and Fisher, 1988] (Figure 1). The anomaly is interpreted as resulting from the presence of an abnormal volume of rocks with a rather high density ( $2.70 \text{ g/cm}^3$ ) matching the density of Miocene volcanoclastites. These series may also include serpentinized peridotites or strongly altered oceanic crust. As earlier proposed by Collot and Fisher [1988], such an anomaly can be related to the tectonic doubling of the crust below Maewo, indicating that the eastern chain is being thrust over the oceanic crust of the North Fiji basin.

### 2.2.2. Drilling and Seismic Reflection Data

[12] Drilling in the North Aoba basin during ODP Leg 134 provided detailed stratigraphic and tectonic information allowing us to infer the succession of stratigraphic and tectonic events that affected this region [Greene et al., 1994; Pelletier et al., 1994]. Deep marine volcanoclastic sedimentation and volcanism occurred from the middle Miocene to the Pliocene. Compression was initiated in the latest Pliocene, as the result of the d'Entrecasteaux Zone entering the subduction zone. During the Quaternary,

the entire arc has been subjected to compressional stress and acted as a rigid block. Therefore the Aoba basin has the general shape of a wide syncline with two compressive borders: the Vanuatu trench-d'Entrecasteaux Zone boundary to the west and the BATB, to the east [Pelletier et al., 1994].

[13] Evidence of compressional deformation within the North Aoba basin itself is provided by (1) SeaBeam bathymetry and MCS lines data collected during site surveys of ODP Leg 134 in the eastern North Aoba basin [Daniel et al., 1989] and (2) in situ observations at ODP site 833 in the eastern North Aoba basin [Greene et al., 1994]. Folding and thrusting of sediments of the eastern North Aoba basin are well expressed immediately north of Maewo Island. The axes of faults and folds are oriented  $N170^\circ$ . They are associated with  $N110^\circ$  trending strike slip faults which agrees with a main horizontal compressional stress oriented  $N80^\circ$  [Daniel et al., 1989]. A similar direction of horizontal compressional stress has been deduced from analysis of reverse faults observed on cores of hole 833 [Pelletier et al., 1994], from borehole elongation and from orientation of vertical drilling-induced fractures [Chabernaud, 1994]. In addition, a thrust fault



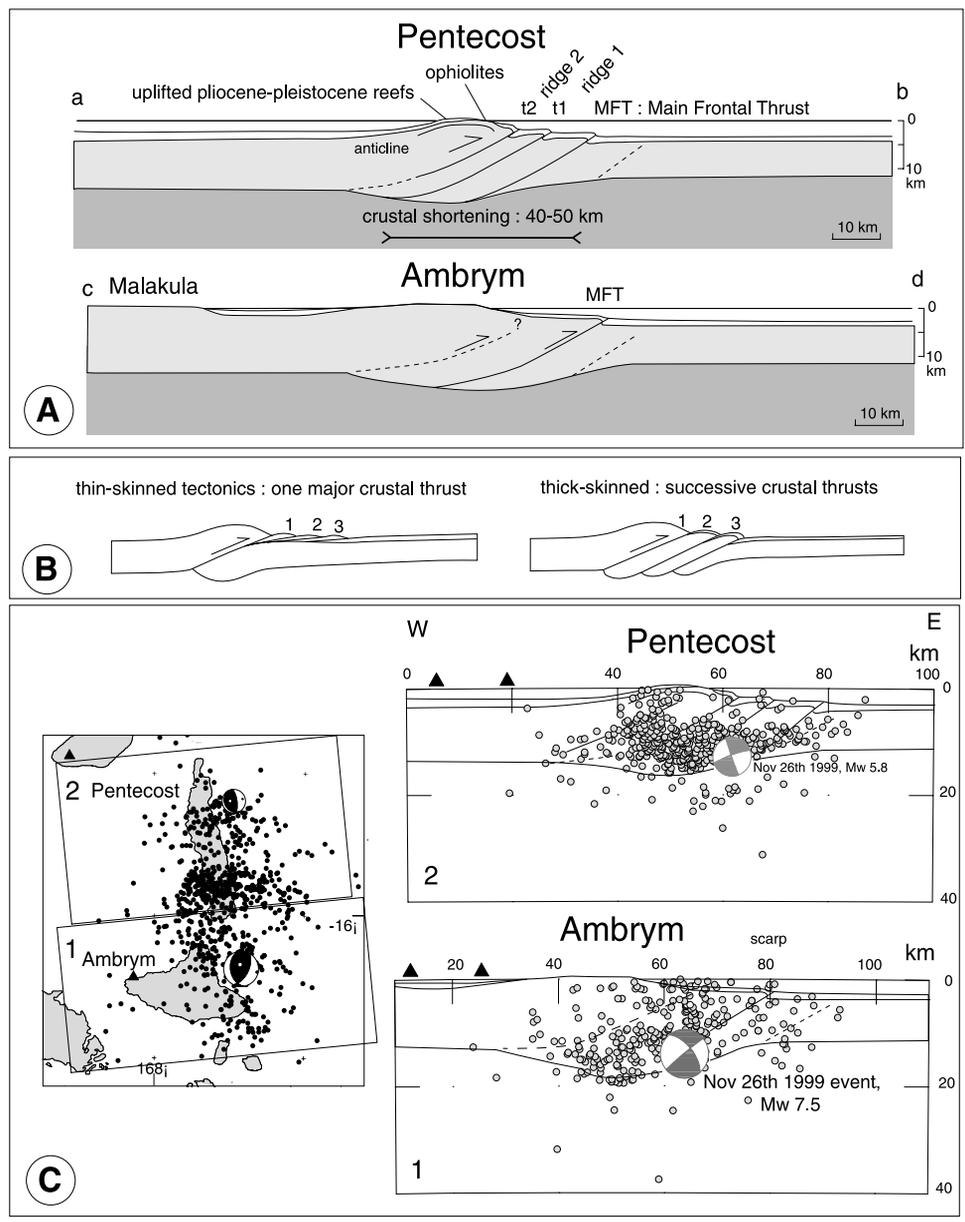
**Figure 3.** Bathymetric map of the back-arc thrust belt (BATB) of central Vanuatu based on a compilation of data from various sources after *Pelletier et al.* [1998]. Contour interval is 200 m. The location of the thrusts east of the Maewo-Pentecost-Ambrym axis is based on information from Figure 5. Exposures of Quaternary corals on Pentecost and Maewo are reported after *Mallick and Neef* [1974]. Sections ab and cd are shown on Figure 4.

with northwest apparent vergence is observed along a seismic line oriented NW-SE, north of Aoba [*Pontoise et al.*, 1994].

### 2.2.3. Seismological Data and Kinematic and Geodetic Constraints on Amount of Shortening

[14] As compiled in Figure 2, seismological data reveal that the eastern border of the Aoba basin is mostly characterized by shallow earthquakes (0–30 km depth) showing thrust fault focal solution mechanisms with *P* axes having generally an E-W orientation, indicating that this region is undergoing active horizontal compression and related shortening [*Collot et al.*, 1985; *Louat and Pelletier*, 1989]. The crustal shortening rate at the BATB was at first estimated to be 3.6–8.3 cm/yr [*Taylor et al.*, 1995]. Refined estimates based on slip vector, geodetic measurements and magnetic anomalies data in the North Fiji basin provide a convergence rate of 4–6 cm/yr between the eastern Aoba basin boundary and the North Fiji basin oceanic crust [*Pelletier et al.*, 1998]. Recent GPS measurements involving the entire Vanuatu arc [*Calmant et al.*, 2003] indicate displacement values of 55 mm/yr in a N85° direction along the BATB at

the latitude of Pentecost (Figure 1). Displacement rates of 30–40 mm/yr were calculated along the subduction-collision zone involving the d’Entrecasteaux Zone in front of Santo and Malakula, along a N70° direction [*Calmant et al.*, 2003]. Therefore a total of 85–95 mm/yr is accommodated as a whole between the Australian plate and the North Fiji basin crust along a transect at the latitude of the d’Entrecasteaux Zone, in accordance with the Pacific-Australia plate motion given by global models. Considering that the collision of the d’Entrecasteaux Zone started at the Pliocene-Pleistocene boundary (1.8 Ma) [*Pelletier et al.*, 1994], a maximum total crustal shortening of 100 km in the back-arc region at the latitude of Pentecost can be estimated assuming a constant rate of shortening at the present-day value. However, shortening of only 50 km is obtained when considering that the shortening rate increased progressively from zero to the present-day rate. This latter shortening amount is in good agreement with estimations of the total volume of actively deformed rocks indicated by the distribution of aftershock seismicity [*Régnier et al.*, 2003] and with the fact that the crustal root below Maewo extends to



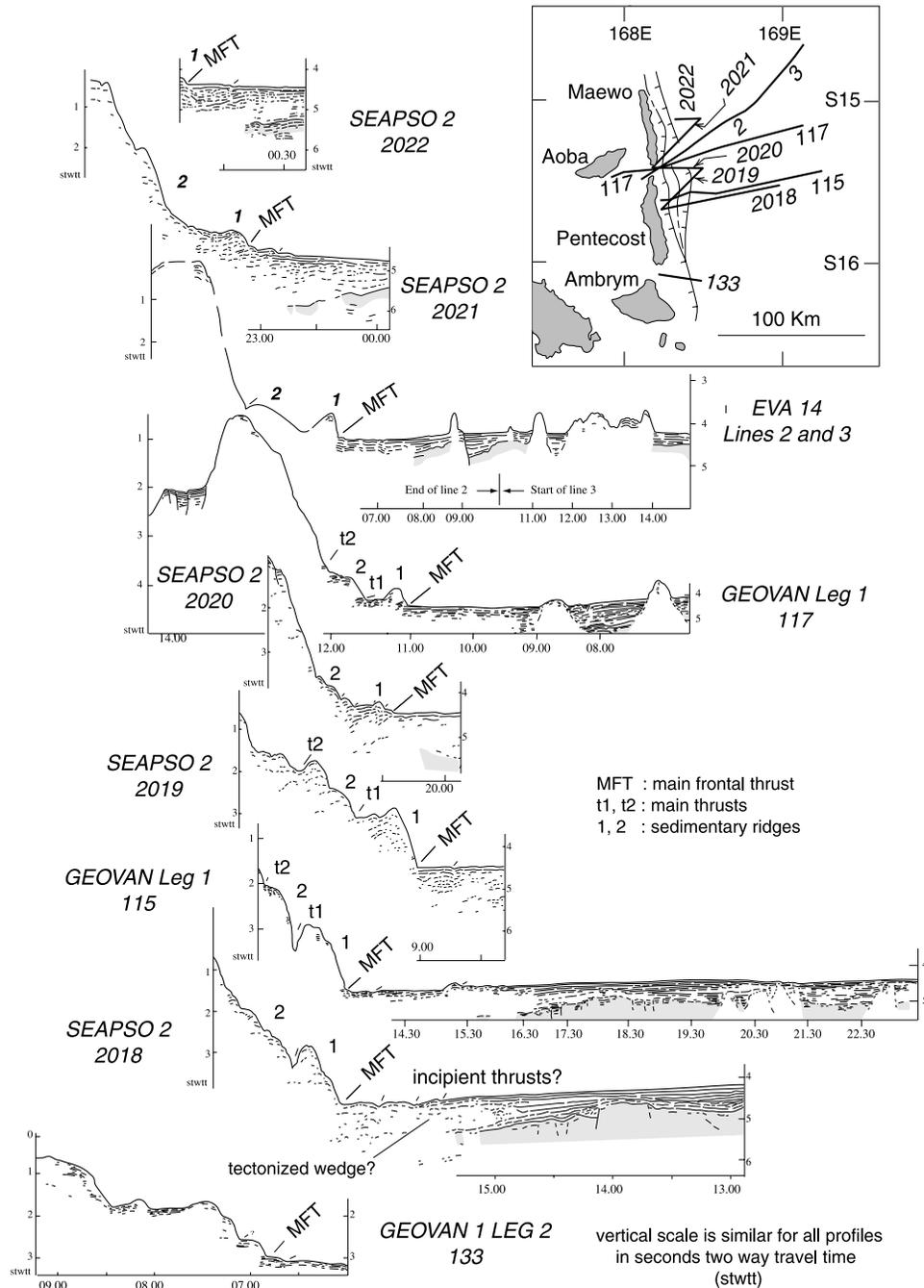
**Figure 4.** (a) Hypothetical crustal sections ab and cd through Ambrym and Pentecost based on interpretations of various geophysical and bathymetry data. Sections are located on Figure 3. Crustal structure is after *Collot and Fisher [1988]* for a transect north of Maewo (Quaternary sediment thickness: 1 km; Moho depth is 8 km in the North Fiji basin and 12 km in the Aoba basin; crustal root beneath Pentecost and Ambrym is 18–20 km depth as calculated beneath Maewo Island). (b) Cartoons showing thin-skinned versus thick-skinned tectonic models beneath Pentecost. Seismicity distribution favors a thick-skinned model. (c) A superposition of the foreshock and aftershock distributions from *Régnier et al. [2003]* on hypothetical crustal sections proposed in this study.

depths of 18 km, suggesting a doubling of the crust in response to compression.

**2.3. Thrusting of the Back Arc Region Over the Oceanic Crust of the North Fiji Basin: Interpretation of Seismic Lines Collected East of Maewo and Pentecost**

[15] As shown in Figure 3, the eastern side of Pentecost and Maewo Islands presents a steep slope toward the North Fiji basin, extending to depths of 3000 m with a roughly constant N170° strike. At the southern tip of Pentecost, the

continuous scarp marking the upper slope branches into two scarps. The upper scarp (down to 1200 m) exhibits a regular semicircular outline and follows the shores of the southernmost part of Pentecost and the eastern part of Ambrym. The lower slope scarp east of Ambrym is remarkably linear along a N170° direction, and follows the 2000 m isobath. It parallels the orientation of Pentecost and Maewo. North of the southern tip of Pentecost, the base of the island slope progressively evolves northward into a succession of two well-defined ridges (ridges 1 and 2), 10 km wide, 30–40 km



**Figure 5.** Compilation of line drawings from old seismic lines obtained along the BATB during GEOVAN Leg 1 and 2 (1980), SEAPSO2 (1985), and EVA14 (1987) cruises. Vertical scale is similar for all sections.

long, and roughly 1000 m high, which ends abruptly at the latitude of the strait separating Pentecost from Maewo. East of Maewo, similar ridges are also present, although less developed. The deepest ridge (ridge 1), to the east of Pentecost, is N-S oriented and lies at depth between 3000 and 2200 m. The western ridge (ridge 2) is oriented N175° and lies at depth of 2000–1400 m. Therefore the eastern side of Pentecost and Maewo displays the overall morphology of an accretionary wedge composed of ridges that could correspond to tectonic units including accreted sedimentary material.

[16] In order to confirm the tectonic origin of ridges 1 and 2, we have interpreted a series of unpublished seismic lines perpendicular to the N170° trending steep slopes of Maewo and Pentecost (Figure 5). The profiles have been collected earlier during various cruises: GEOVAN Legs 1 and 2 (1980), SEAPSO2 (1985), and EVA14 (1987). They are stored in archives at the IRD Centre of Nouméa in New Caledonia. The longest lines traverse the western North Fiji basin along distances of more than 100 km eastward of Pentecost and Maewo shorelines (lines 115, 117, and 2–3, Figure 5), over undisturbed, flat areas lying at 3000–3200 m

depth. These western areas are characterized by relatively thick, well-defined sedimentary sequences, with local evidence of postdepositional volcanism. The oceanic basement is generally found between 4 and 5 s two way travel time (ttwt). It shows evidence of normal faulting. One of these faults has probably been reactivated during an earthquake displaying an unusual normal faulting focal mechanism offshore southern Pentecost (Figure 3). The thickness of the sedimentary cover far from Pentecost and Maewo is generally of 0.5 s ttwt that is roughly 500 m thick. The sedimentary sequences thicken toward the islands, reaching up to 1–2 km as shown by profiles 2021 and 2022. As shown by profiles 2018, 115, 2021, and 2022, the basement progressively deepens toward the west, below Maewo and Pentecost, in good agreement with underthrusting of the North Fiji basin crust beneath the Aoba basin crust. The western parts of all profiles collectively show that the sedimentary sequence of the North Fiji basin is strongly tectonized when approaching Maewo and Pentecost Islands. Profiles 115 and 2018 show that the continuity of the seismic reflectors progressively decreases toward the west, which is indicative of an increase in tectonic disruption or of fluid activity. Therefore, from the seismic lines, the ridges observed on the bathymetry map appear to be the results of sediment deformation and stacking.

[17] Ridges 1 and 2, as defined from the bathymetry, are well observed on the seismic lines, and are separated by linear lows, which are interpreted to be the surface expression of thrust faults. The foot of the deepest ridge (ridge 1) is considered to correspond to the location of the main active fault accommodating present-day shortening of the sedimentary sequence. It is referred to as the main frontal thrust (MFT) in Figure 5. Faults located farther west (labeled thrusts t1 and t2) may be older. To the south, the main frontal thrust and thrusts t1 and t2 merge together into one single thrust at the base of the scarp extending east of Ambrym. This indicates either that the total amount of shortening is lower east of Ambrym compared to east of Pentecost, or that reduced sedimentary supply close to Ambrym causes less-developed sedimentary ridges. This is indeed in agreement with the fact that Pentecost represents the uplifted border of the Aoba basin, with high relief, whereas Ambrym results partly from recent volcanic constructions. The scarp east of Ambrym is imaged by profile 133 (Figure 5). It is locally 900 m high and shows a composite slope including two steps. It has been mapped in detail during the survey with R/V *l'Atalante* as reported in section 4.

#### 2.4. Models of Crustal Structure Below Pentecost and Ambrym

[18] The data presented above suggest that thickening of the crust beneath Maewo [Collot and Fisher, 1988] can be regarded as the result of stacking of oceanic crust slices at the compressive back-arc boundary of the Aoba basin. Because of geological similarities between Maewo and Pentecost and to the morphological N-S continuity of the Aoba basin border, a similar model can be proposed for the crustal structure beneath Pentecost, and most probably southward, east of Ambrym.

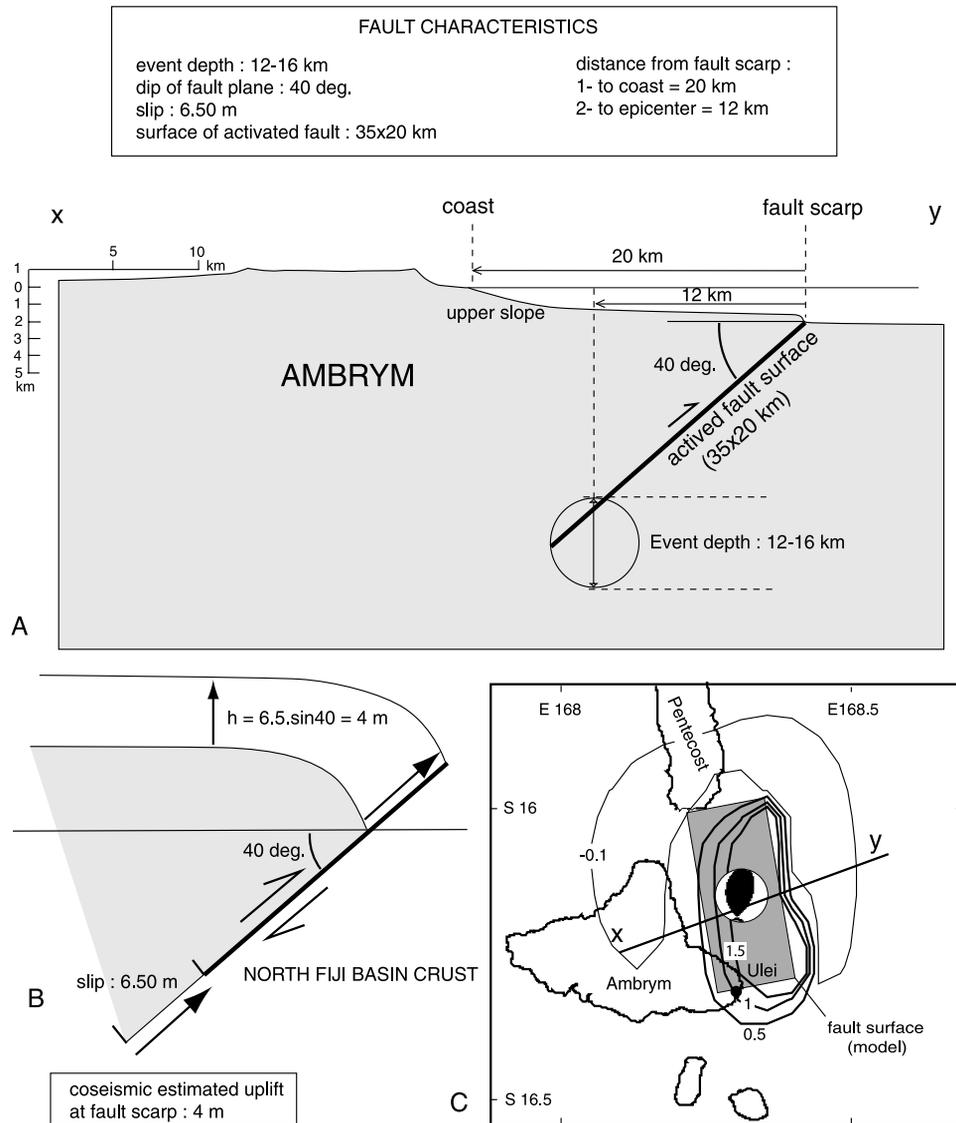
[19] The interpreted simplified structure of the BATB along geological tectonic cross sections through Pentecost

and Ambrym is shown in Figure 4a. The proposed geometries are constrained by data reported above. These are (1) the thickness of the oceanic crust of the North Fiji basin of 8 km, [Pontoise *et al.*, 1994], (2) the thickness of the oceanic crust of the Aoba basin of 11–13 km [Pontoise *et al.*, 1994], (3) the 1–2 km thickness of the sedimentary cover of the North Fiji basin (this study), (4) the 4 km maximum thickness of the sedimentary cover of the North Aoba basin [Pontoise *et al.*, 1994], (5) the presence of an asymmetrical crustal root of 18 km below Maewo [Collot and Fisher, 1988], (6) the downbending of the North Fiji basin crust when approaching Pentecost and Maewo (Figure 5), and (7) the occurrence of sedimentary ridges indicating an accretionary-prism-like structure east of Pentecost, including three thrust faults that merge into one fault to the south, eastward of Ambrym (Figures 3 and 5).

[20] In Figure 4c the interpreted cross sections through Pentecost and Ambrym are plotted together with the distribution of foreshocks and aftershocks of the November 1999 earthquake from two regions given by Régnier *et al.* [2003]. The seismicity under Pentecost is distributed throughout a very large crustal volume. Events are located down to a depth of 20 km and are scattered over a distance of 40 km west and east of Pentecost. This fits well with the interpretation that the studied area corresponds to a major crustal thrust boundary that has accommodated a large amount of shortening since 1.8 Ma. Event distributions show rather well-defined alignments with dips of 30–40° that match a structure involving faults cutting through the entire crust. This suggests that the deformation is not localized along one major fault below Pentecost but is rather distributed along few thrusts that could correspond to the thrusts t1, t2, and MFT defined above. Indeed, an important question is to know whether the accretionary-prism-like structure east of Pentecost and Maewo corresponds to thick-skinned or to thin-skinned-type tectonics. As shown in Figure 4b, thin-skinned tectonics would imply that the observed thrust faults east of Pentecost (t1, t2, and MFT) merge into a major decollement located at the limit between the basement and the sedimentary cover. In this case, only one major thrust fault cutting through the entire crust should be present. By contrast, thick-skinned tectonics would imply that each of the thrusts t1, t2 and MFT corresponds to different faults extending through the entire crust. The aftershock distribution near Pentecost (Figure 4c) is more consistent with the presence of several crustal faults and hence a thick-skinned tectonic model.

### 3. Characteristics of the $M_w$ 7.5, 26 November 1999 Ambrym Event

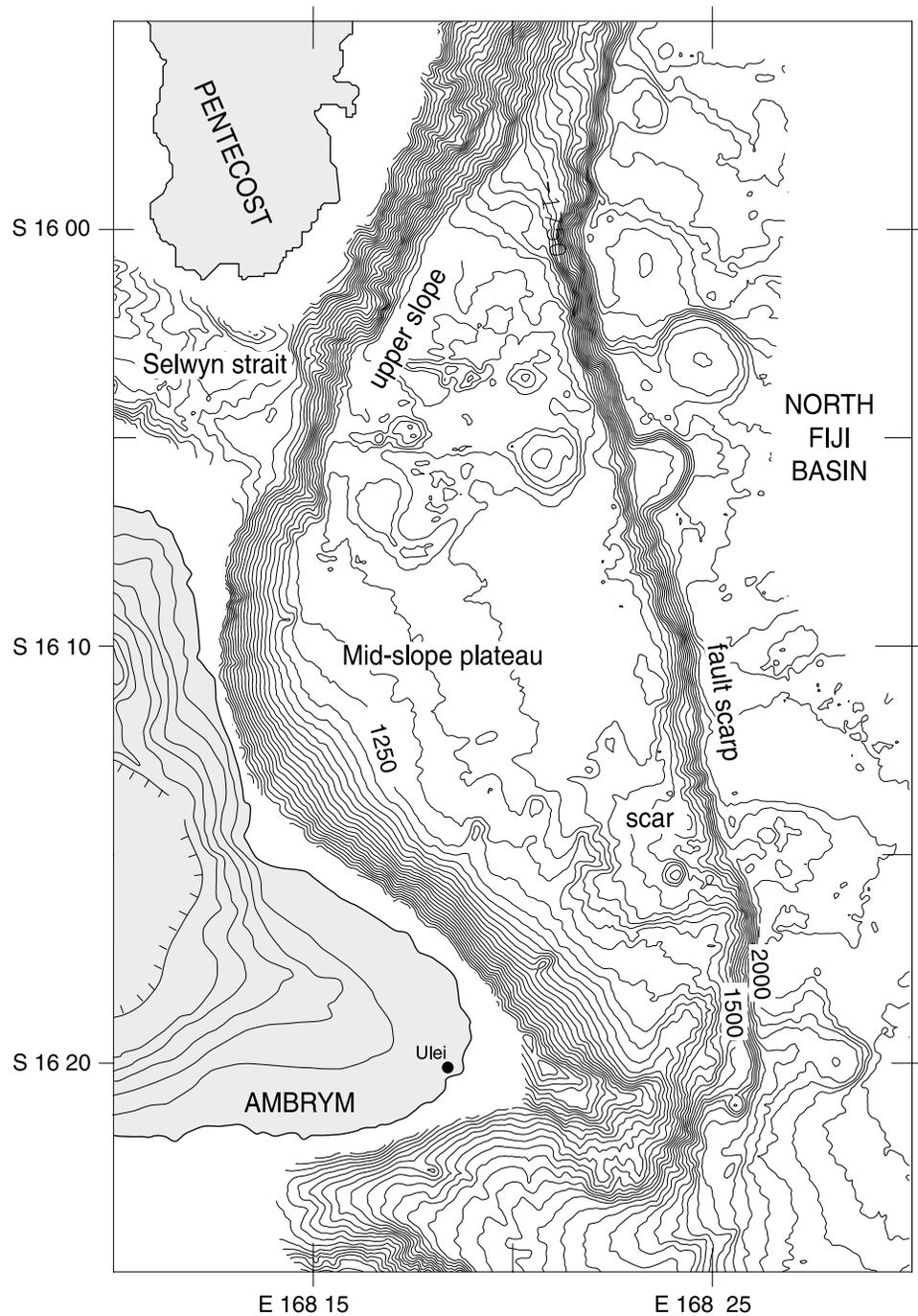
[21] The  $M_w$  7.5 shock was at first located between Ambrym and Epi Islands by USGS (16.43°S, 168.23°E, 33 km) and to the northeast of Ambrym by Harvard (CMTS location at 16.02°S, 168.33°E, 20 km). On the basis of local travel times, the main shock has been located northeast of Ambrym Island at 16.188°S, 168.288°E, at a depth between 12 and 16 km, by the IRD network in Vanuatu [Régnier *et al.*, 2003] (Figures 2 and 6). The regions most severely damaged by the seismic event are the eastern and north-eastern parts of Ambrym and the whole southern part of Pentecost where felt intensity reached 7–8 on the Mercalli



**Figure 6.** (a) Interpreted cross section  $xy$  through Ambrym showing the fault that ruptured during the 26 November 1999 event. See location of section  $xy$  in Figures 6c and 9. Fault geometry is constrained by the position of the fault scarp and by the dip of the fault as given by the focal mechanism solution [Régnier *et al.*, 2003]. Hypocenter deduced from local IRD network, as well as the attitude of the fault plane deduced from coseismic GPS-measured displacements and from field-observed uplifts both agree well with this reconstructed geometry. (b) Estimated uplift ( $h$ ) at fault scarp according to the coseismic slip along the fault and the dip of the fault. Local collapse of the upper part of the scarp is expected in response to growing of the topography. (c) Dislocation model [Okada, 1985] showing simulated vertical motions (in m). Thick lines delineate upward displacements (+0.5, +1, +1.5 m). The rectangle shows the surface projection of the fault plane.

scale. A destructive tsunami was associated with the earthquake [Pelletier *et al.*, 2000]. The final focal mechanism solution (centroid moment tensor solution, CMTS) published by Harvard in 2000 indicates a  $N174^{\circ}30'$  trending, and  $30^{\circ}$  westerly dipping nodal plane with a rake of  $67^{\circ}$ , revealing strike-slip component. Hanging wall moved in the  $N110^{\circ}$  direction. Data from the local IRD network suggests that the strike and dip of the fault plane are  $N167^{\circ}$  and  $40^{\circ}$ , respectively [Régnier *et al.*, 2003]. Using the regional data, the source duration has been estimated to be 50 s. The Ambrym earthquake produced regional crustal displacements

that have been recorded over the whole central Vanuatu by the GPS network [Pelletier *et al.*, 2000; Régnier *et al.*, 2003]. The GPS-recorded horizontal component of these coseismic displacements trends mostly eastward and reaches  $\sim 35$  cm at the western tip of Ambrym Island, the GPS mark closest to the epicenter. A dislocation model [Okada, 1985] has been fit to the data set made of the 30 GPS horizontal displacements and the direct measurements of vertical motion at East Ambrym, South Pentecost, Paama, and Lopevi. The rupture model obtained (Figure 6c) is a simple rectangular fault with constant slip and a rake of



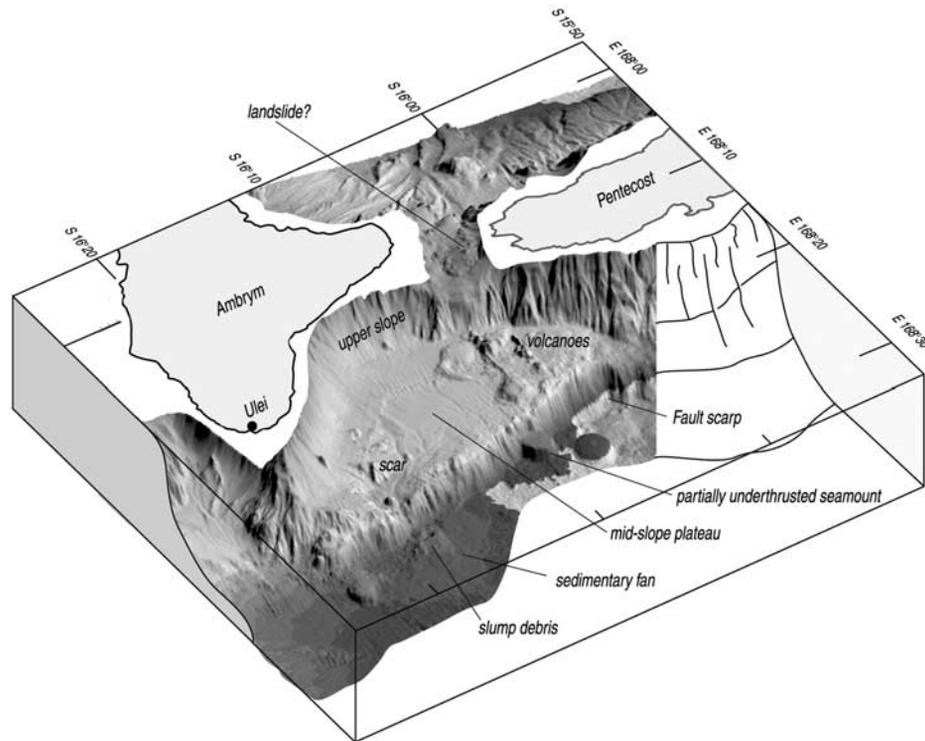
**Figure 7.** Multibeam echo sounder-derived bathymetric map obtained from the ALAUF1 cruise of R/V *L'Atalante* in March 2000. Contour interval is 50 m.

67°. The best fitting fault and slip [Régnier *et al.*, 2003] are in good agreement with seismological results, namely a  $35 \times 20$  km fault centered at 16.15°S, 168.31°E at a depth of 7.5 km, and a slip of 6.5 m (for an elastic modulus  $\mu = 0.35$ ) initiated on a plane dipping 40° and trending N170°. Régnier *et al.* [2003] note however that misfits between the seismological, the GPS-derived and the in situ observations may be explained by along-fault variations of the amplitude and orientation of the coseismic slip. Curvature of the fault plane with a stronger dip toward the surface could also contribute to slight discrepancies between the

fault model and field data which suggest high deformation closer to the surface.

#### 4. Bathymetric Survey and Offshore Study of the Main Fault Trace

[22] In order to characterize the morphological expression of the major fault involved in the 26 November 1999 Ambrym event we have conducted a 24-hour bathymetric and acoustic imagery survey of the epicentral region, east of the islands of Ambrym and Pentecost using the R/V



**Figure 8.** Three-dimensional view of the region east of Ambrym from bathymetric data shown in Figure 7.

*L'Atalante*, in March 2000, during the early days of the *Alaufi* cruise [Pelletier *et al.*, 2001]. Four ship tracks were made parallel to the coasts of Ambrym and Pentecost with one passage within the Selwyn Strait (Figure 7). Seafloor ranging in depth from 300 m to 3000 m was mapped with full coverage using the SIMRAD EM 12 dual multibeam echo sounder between 16°27'S and 15°50'S. The most striking feature of the mapped area is a remarkably linear scarp, 40 km long, with a N165° orientation. The foot of the scarp coincides with the 2000 m isobath. The scarp ranges in height from 400 to 950 m and exhibits a slightly incised, steep slope (26%), suggesting a recent age for the scarp fault. However, in one place, northeast of the eastern point of Ambrym, the scarp is partially incised by a short valley. Upslope, the valley connects to a circular depression resembling a landslide scar with slumped blocks inside. Downslope, the valley connects to a 15-km-wide sedimentary fan, probably resulting from material removed from the scar above (Figures 7 and 8). This is the only large landslide that has been found along the scarp. For this reason, if the tsunami related to the Ambrym event is not of purely seismic origin, this slump may be a possible candidate for the genesis of a tsunamogenic landslide. Another candidate for a possible major landslide has been detected in the western side of the Selwyn Strait, right in front of Bay Martelli, using imagery data and bathymetry (Figure 7). However, because of possible occurrence in this region of very recent lava flows, it has not been possible to confirm this observation from our data on board. Dredging or coring will be necessary to pursue this investigation.

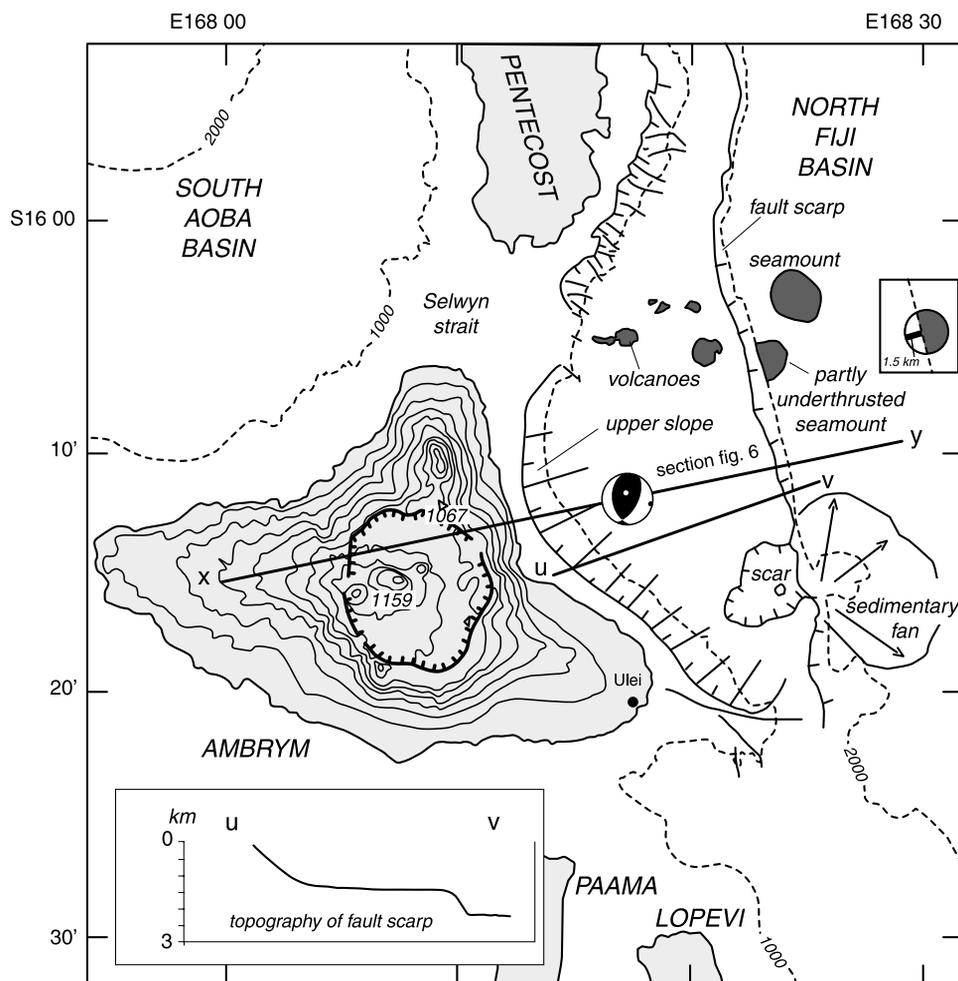
[23] Above the rectilinear fault scarp, the seafloor lying between 1500 and 1250 m depth forms a triangular-shaped,

flat plateau of 16 km maximum width, the middle slope plateau (Figures 7 and 8). It is bounded to the west by the curvilinear upper slope of the eastern Ambrym margin. This slope is remarkably smooth, thus contrasting with the upper slope of Pentecost which shows numerous gullies, probably in relation to a different geology. Bathymetry and acoustic imagery record (not shown here) indicate that recent volcanic edifices (mounds and flows) are present on the midslope plateau, at the southern tip of the midslope plateau at the junction of the fault scarp and the upper slope, and possibly within the Selwyn Strait (Figure 8).

[24] East of the fault scarp, in areas deeper than 2000 m, the seafloor of the North Fiji basin is relatively flat and characterized by the presence of flat-topped circular seamounts. The largest seamount is 4.5 km in diameter with an elevation of 400 m. It is located to the north of a smaller seamount (around 3.5 km) with a half-disk outline, located against the fault scarp. This peculiar geometry strongly suggests that this seamount originally exhibited a circular outline and that one third of the seamount has been underthrust beneath the mid slope plateau, along a reverse fault.

[25] Finally, this survey mapped the linear scarp representing in all likelihood the surface expression of the fault that broke during the Ambrym 1999 event. Its orientation in map view (N165°) is indeed very close to that of the west dipping plane of the fault mechanism solutions. In addition, as shown in Figure 6a, there is a very good fit between the location of the scarp revealed by bathymetry and the calculated position of the surface fault trace inferred from seismology and GPS-derived rupture geometry.

[26] Scarp growth results from successive thrusting events. Taking as a reference the 26 November 1999, event



**Figure 9.** Structural sketch of the area east of Ambrym based on the data of the survey of R/V *l'Atalante* shown in Figure 7. The estimated amount of seamount surface that has been underthrust below the fault scarp is shown in the upper right.

which involved a slip of 6.5 m along the fault surface, an uplift of about 4 m and an eastward horizontal displacements of about 5 m (510 cm) of the hanging wall can be expected at the fault scarp, for a rake of  $90^\circ$  (Figure 6b). Considering that no aseismic slip occurred along the fault, 150 coseismic events similar to the one of 26 November 1999, Ambrym are thus necessary to produce a 600-m-high scarp ( $600 \text{ m}/4 \text{ m} = 150$ ). Recurrence intervals for such an event remain unknown due to data lacking relative to previous event with similar magnitude. However, a minimum return time of 93 years may be inferred using the present-day GPS-derived convergence motion of 5.5 cm/yr at the BATB ( $510 \text{ cm}/5.5 \text{ cm/yr} = 93 \text{ years}$ ), which in turn yields a minimum age of 13,950 years ( $93 \text{ years} \times 150 \text{ events}$ ) for the scarp. A minimum age of the scarp can be deduced also from the analysis of the multibeam bathymetry. Assuming that the seamount partly underthrust along the scarp has a circular shape, its buried portion is estimated at 1.5 km (Figure 9), which allows us to infer a minimum age of 27,272 years for the scarp ( $150,000 \text{ cm}/5.5 \text{ cm/yr}$ ). This, in turn implies a minimum seismic recurrence interval of 181 years ( $27,272 \text{ years}/150 \text{ events}$ ). Thus several lines of evidence suggest that the main thrust fault scarp east of

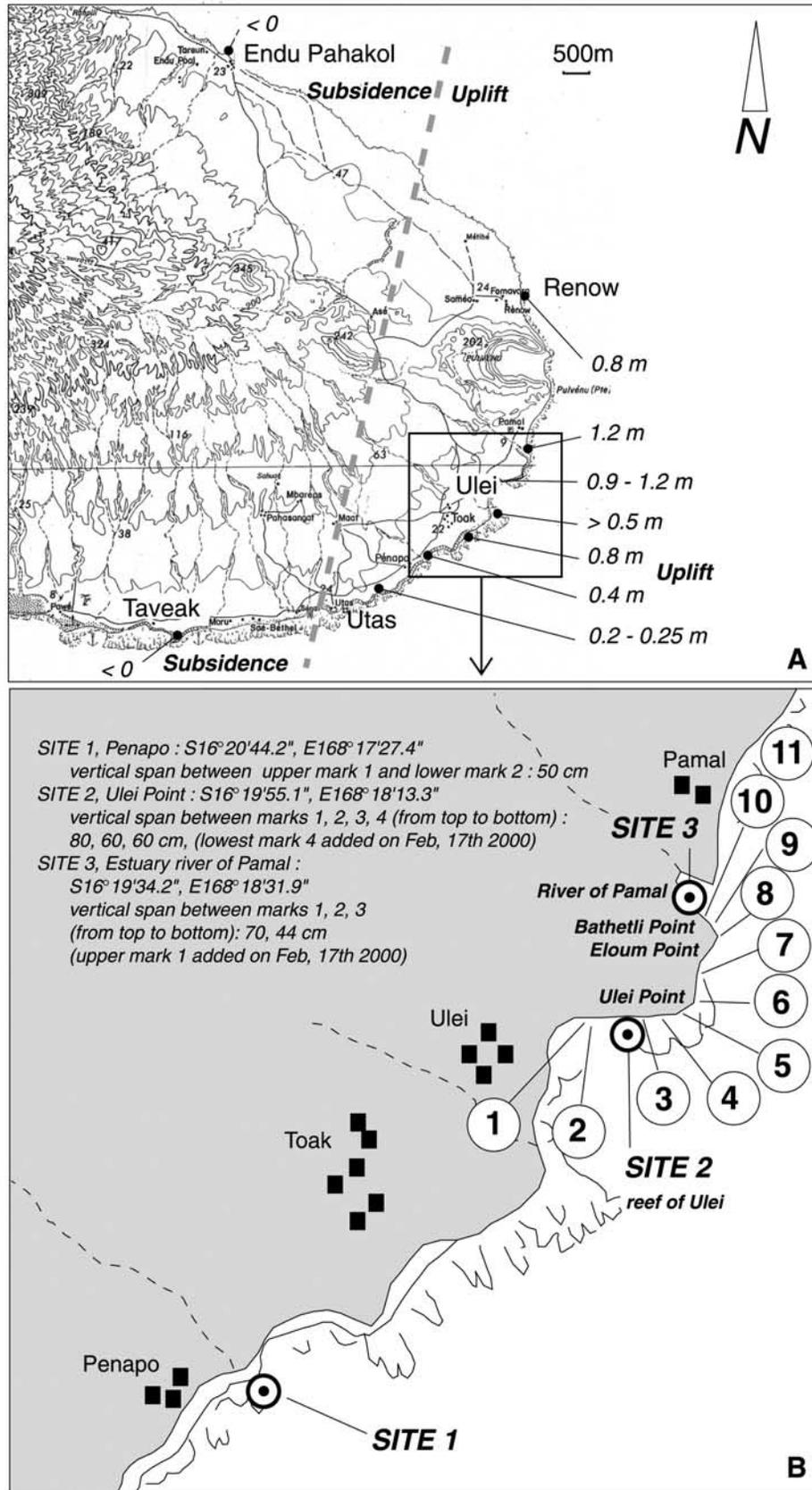
Ambrym is recent and has a minimum age of 15,000–27,000 years. For comparison, when taking as a reference the return times of 236 and 107 years estimated in the western chain from coral emergence associated with  $M_s$  7.5 events in North Malakula and North Espiritu Santo, respectively [Taylor *et al.*, 1990], this scarp should be at least 16,050–35,400 years old (16,000–35,000 years).

## 5. Estimates of Coseismic and Postseismic Vertical Displacements From Coastal Exposures

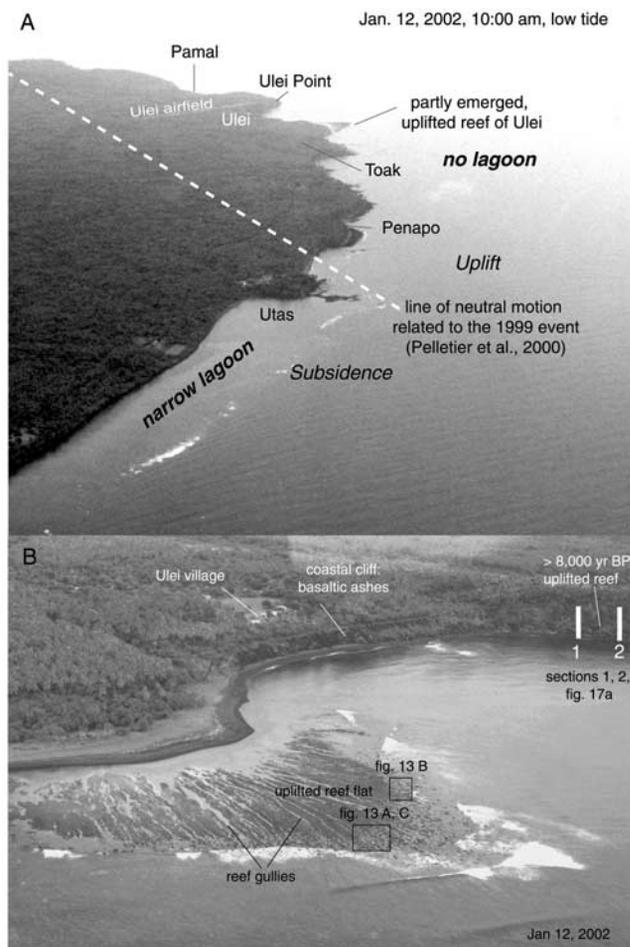
[27] The region of Ambrym that underwent coseismic uplift, close to the villages of Ulei and Pamal has been surveyed five times by members of our team: in December 1999, in January 2000, in February 2000, in October 2000 and finally in January 2002. These field surveys allowed successive observations of characteristic features linked to uplift which are well exposed along the coast. Section 5.1 presents a detailed review of these observations.

### 5.1. Estimates of Coseismic Vertical Displacements

[28] Direct observations and measurements of ground uplift along the coast have been made from 11 to 14



**Figure 10.** (a) Coseismic uplift measured 2 weeks after the 26 November 1999 event [Pelletier et al., 2000]. (b) Detailed location map of the region of Ulei showing the three sites along the coast (sites 1, 2, and 3) where stainless steel shim marks have been set in order to monitor long-term postseismic vertical ground motions. Sites labeled 1 to 11 refer to detailed geological cross sections shown in Figures 17a and 17b.



**Figure 11.** (a) Aerial view of the study area on January 2002. Note that the line of neutral motion defined by ground observations along the coast immediately after the earthquake [Pelletier *et al.*, 2000] coincides with the limit between the eastern coast without lagoon, undergoing uplift, and the coast with a narrow lagoon undergoing subsidence. This suggests that long-term topographic evolution is consistent with coseismic ground motion. (b) Aerial view of the coast near Ulei village taken in January 2002 showing the uplifted reef.

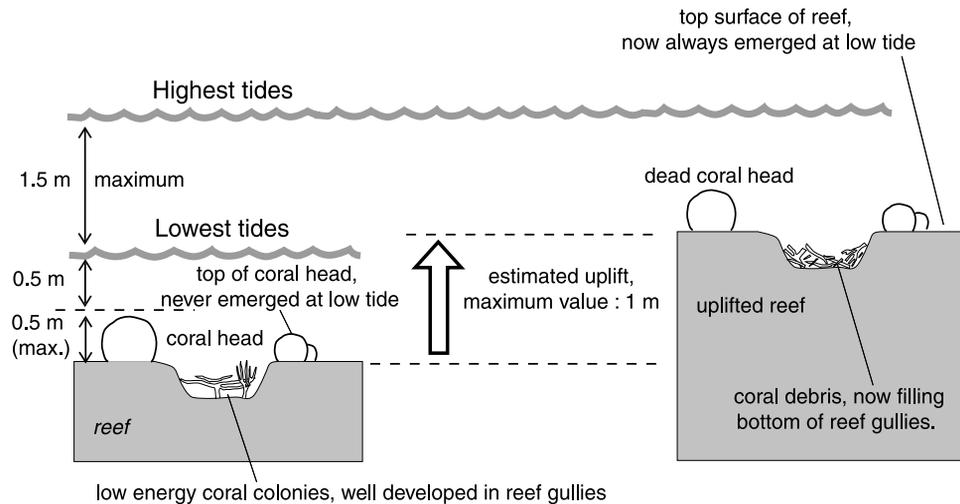
December 1999, 2 weeks after the earthquake at the southeast point of Ambrym Island, the closest emerged region to the epicenter [Pelletier *et al.*, 2000]. Observations are based mostly on the reaction of biological markers such as red algae and various corals to the permanent uplift and therefore to exposure at sunlight. Evidence of uplift with values up to 1.20 m was collected between villages of Utas and Métihé (Figure 10). These coseismic vertical displacements provide strong constraints on the location and size of the surface rupture associated with this thrust-type faulting earthquake. In particular, these data allow us to trace the nodal line of zero vertical motion across southeast Ambrym (Figures 10 and 11).

[29] The first evidence of important coseismic uplift was provided by the occurrence of numerous domal forms of dead corals (compare *Goniastrea*), 30–50 cm in diameter, lying on the uplifted fringing reef flat located immediately

southeast of Ulei village [Pelletier *et al.*, 2000] (Figures 11, 12, 13a, 13b, and 13c). These coral heads, as well as the reef basement on which they live, are now exposed well above their highest level of survival (HLS as defined by Taylor *et al.* [1987]). Since the earthquake, they are always emerged at low tide and cannot survive (Figure 12).

[30] Tides in Vanuatu have amplitudes ranging from 50 to 150 cm, with an average of less than 1 m. The tidal cycle includes succession of low-low water (LLW), high-low water (HLW), low-high water (LHW) and high-high water (HHW) occurring over more than 24 hours. In normal conditions, the domal forms of coral live in coastal waters at depths so that they are never emerged, even at low tide since they do not make microatolls and have a spherical shape. They generally have at least a few tens of centimeters of water above them. As shown in Figure 12, about 1 m of uplift is necessary to account for the present-day situation observed on the uplifted flat reef of Ulei. At the edge of the uplifted reef, dead coral colonies, including tabular and branching forms, occupy the bottom of the parallel gullies typical of these fringing reefs (Figures 11 and 12) and are now also emerged at low tide. Such coral forms only grow within very calm environments, in no less than one meter of water. This confirms that the total amount of uplift was at least one meter here. A strong smell of dead animals and vegetals was still present when we returned to this site in October 2000, but the smell almost disappeared in January 2002. No form of life had colonized the uplifted reef in January 2002, except some crust of red algae. The temporarily emerged fragile forms of branching *Acropora* and *Porites* were still in growth position in October 2000 (Figure 13a), but in January 2002, we could notice that in any place, all the corals were broken into numerous pieces. Some decimeter-sized coral domal heads were upside down, and abundant coral debris were infilling the former gullies contributing to flatten the dead reef (Figure 13c).

[31] Along the rocky coasts near Penapo, near Toak, near Ulei Point, at Eloum Point, at Bathetli Point, near the estuary of the river of Pamal and near Renow (Figure 10), the best recorder of uplift was a white fringe resulting from the desiccation of calcareous red algal encrustings [Pelletier *et al.*, 2000]. Such calcified algae can be used as indicators of sea level [Adey, 1986]. Such a phenomenon has been described previously along the rocky coast of Chile after the Antofagasta earthquake [Ortlieb *et al.*, 1996]. In these environments, submerged blocks and basal part of coastal cliffs of massive lavas are encrusted with continuous veneers of red algae that always live below the HLW and can be emerged few hours at LLW. In areas of higher energy, algal patches often occur above the LLW because of more frequent watering resulting from waves breaking. These calcareous algae originally of pink color rapidly turn into white when exposed to the sunlight. The maximum vertical extension of the white fringe is observed in the portion of coast between Ulei and Pamal. It locally reaches more than 1.5 meter, including 50 cm of patches in the upper part of the fringe (Figures 14a, 14b, and 15). This led workers to propose a total uplift of 1.2 m [Pelletier *et al.*, 2000]. According to new observations made in this region in October 2000 and in January 2002, this value appears to be underestimated, and we propose a revisited maximum uplift of 1.5 m.



**Figure 12.** Cartoon depicting the behavior of the flat reef of Ulei in relation with coseismic uplift.

[32] First evidence for beach uplift have been obtained for 7 December 1999, that is, 12 days after the earthquake by one of us (B. Pelletier) near Ulei. The preseismic highest water line (HWL) was well delineated at that time by coral and algae debris outlining the base of the former beach slope. The location of the postseismic HWL was observed at high tide. The 1 m offset between former and new HWL corresponds to the coseismic uplift (Figures 16a and 16b). This value is therefore equivalent to the one deduced from the coral heads exposed on the reef flat east of the beach, and from the white fringe of desiccated red algae exposed along the rocky coast north of the beach. In February 2000, 3 months after the event, plants typical of these tropical coastal environments (*canavalia obtusifolia*, Leguminosae (P. Cabalion, personal communication, 2000)) that never grow lower than the upper limit of the beach slope, started to grow down, along the former slope toward a new level of upper beach (Figure 16c). In October 2000, the former beach slope was entirely invaded by these plants (Figure 16d).

[33] The uplift decreases rapidly northward and southward of Ulei-Pamal region and reaches zero near Métihié to the north, and Utas to the south [Pelletier *et al.*, 2000] (Figure 10). No sign of uplift has been found from Utas to Taveak along the southern coast of East Ambrym, and at Endu Pahakol on the north coast of East Ambrym (Figure 10). Locally, at Utas, the upper limit of living red algae is submerged at low tide, indicating subsidence. This constrains the location of the neutral line of vertical motion (Figures 10 and 11). An aerial survey of the Paama and Lopevi Islands and of the eastern coast of south Pentecost including Martelli bay was operated on 16 February 2000. We observed no white fringes along these rocky coasts, which led us to conclude that areas located farther north and farther south of Ambrym show no sign of uplift. As shown by elastic dislocation models (Figure 6c), the high gradient of very localized vertical motion indicates that the rupture zone is relatively shallow beneath the eastern part of the island.

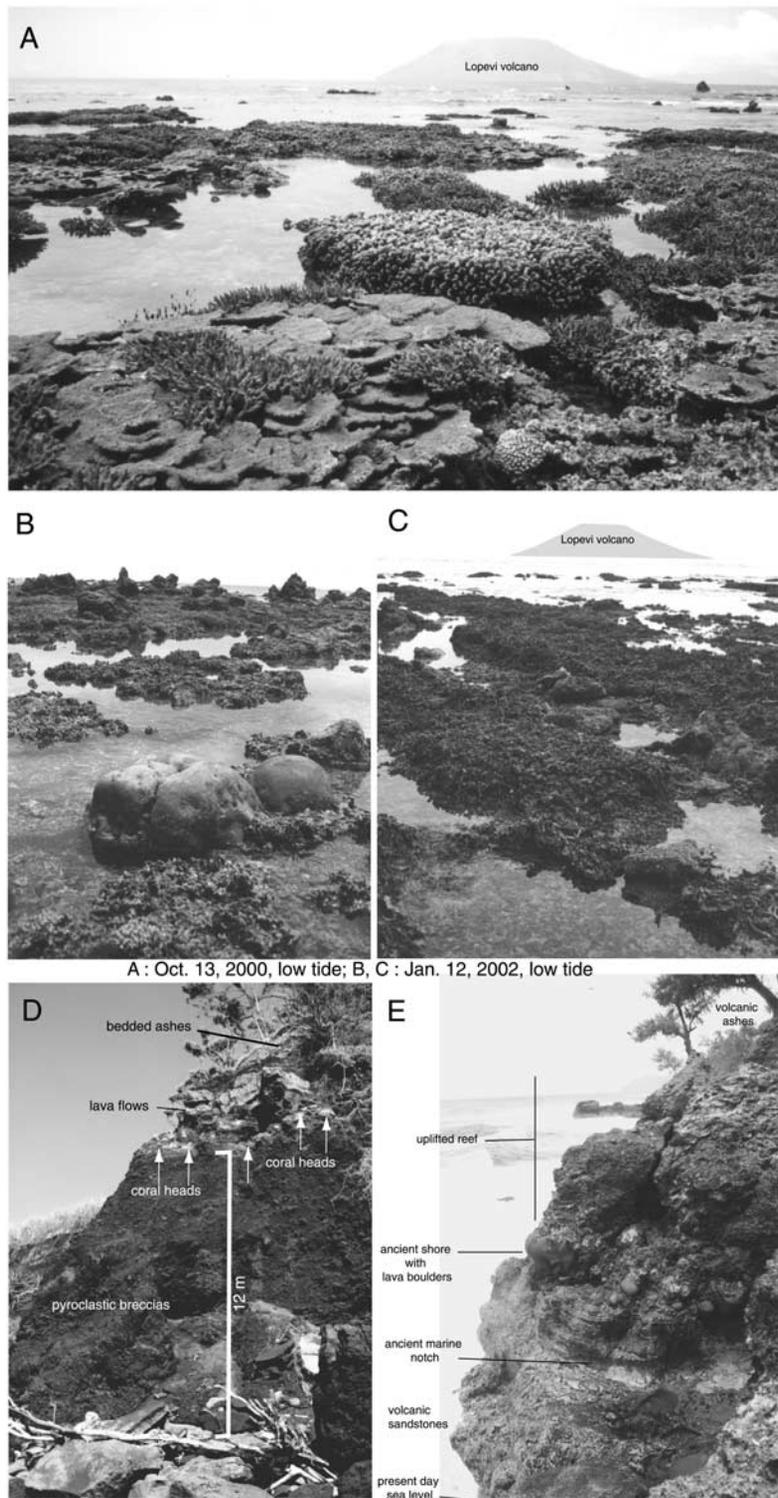
## 5.2. Investigating Possible Postseismic Vertical Motions at the Southeastern Point of Ambrym

[34] In the general context of the BATB of central Vanuatu, topography is created in response to compres-

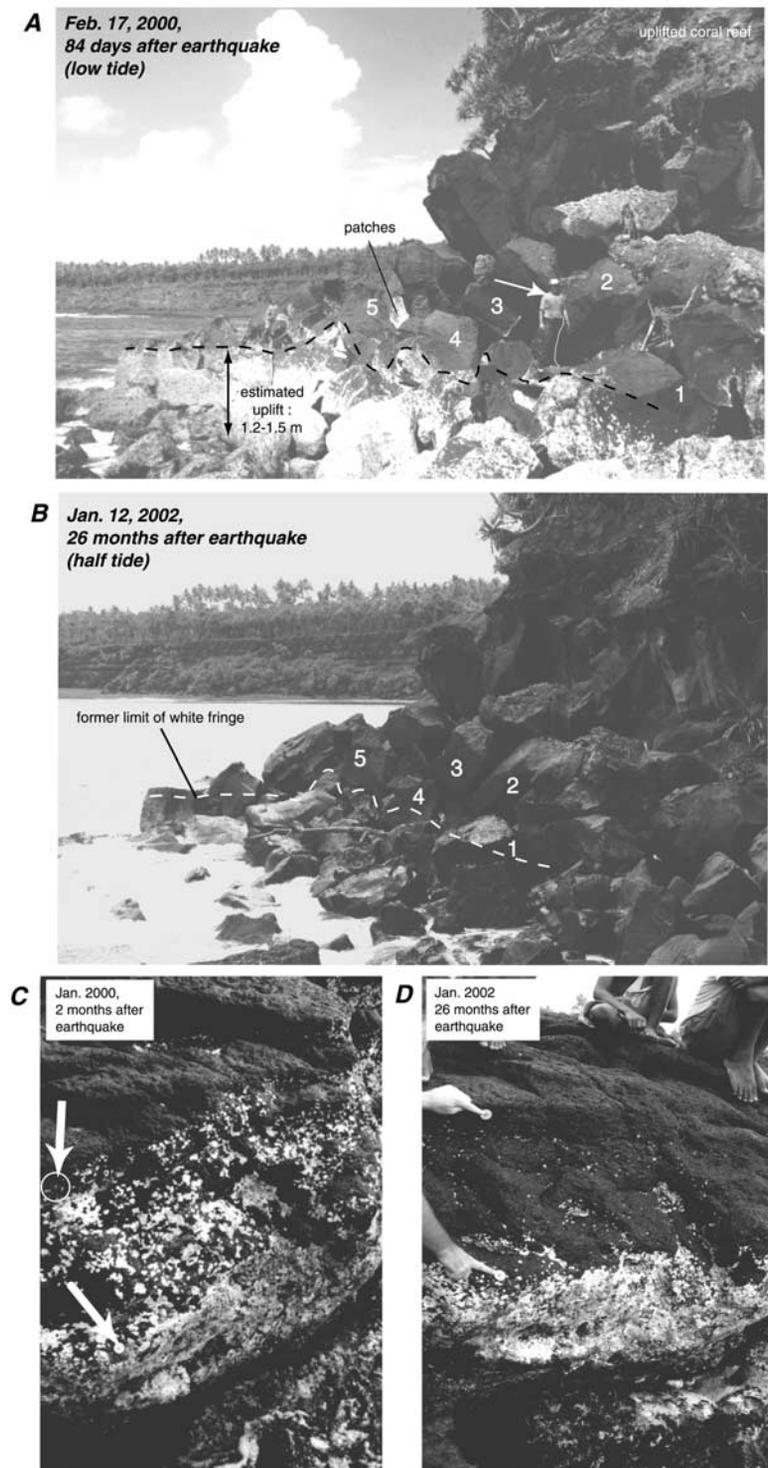
sion and stacking of ocean crustal sheets, as shown by the cases of Maewo and Pentecost Islands. Taylor *et al.* [1990] have shown that coseismic motion cannot account for the total amount of uplift of the western chain of central Vanuatu and that other mechanisms not directly related to the seismic cycle are necessary in order to explain increase of topography. In the case of the BATB, data are very scarce and the ratio of aseismic versus coseismic slip as increments of permanent uplift has never been estimated. Furthermore, no data are currently available from this region to help quantifying the amount of any possible postseismic, long-term subsidence triggering decrease in topography. The quantification of amount of postseismic uplift or relaxation is therefore an important goal for the future. However, our study can only provide records of motion in the 2 years following the event, and further studies are needed to continue this work.

[35] The white fringe of desiccated red algae progressively disappeared in response to physical and biological subaerial alteration and erosion, as observed at Ulei Point (Figures 14a and 14b). This suggests that the relative sea level did not change significantly after the event and therefore that no significant subsidence or uplift occurred during the immediate postseismic phase. In order to better follow possible postseismic variations of relative sea level we set a series of stainless steel marks at three selected sites along the uplifted coast. From south to north, these are: site 1 close to Penapo village, site 2 along the coast between Ulei beach and Ulei Point, and site 3 at the estuary of the river of Pamal. The GPS locations of these sites are given in Figure 10. The sites have been visited three times during the two years following the earthquake in order to monitor possible immediate postseismic vertical motion. We note that monitoring over a longer period of time will be necessary in order to describe a more significant long-term postseismic evolution.

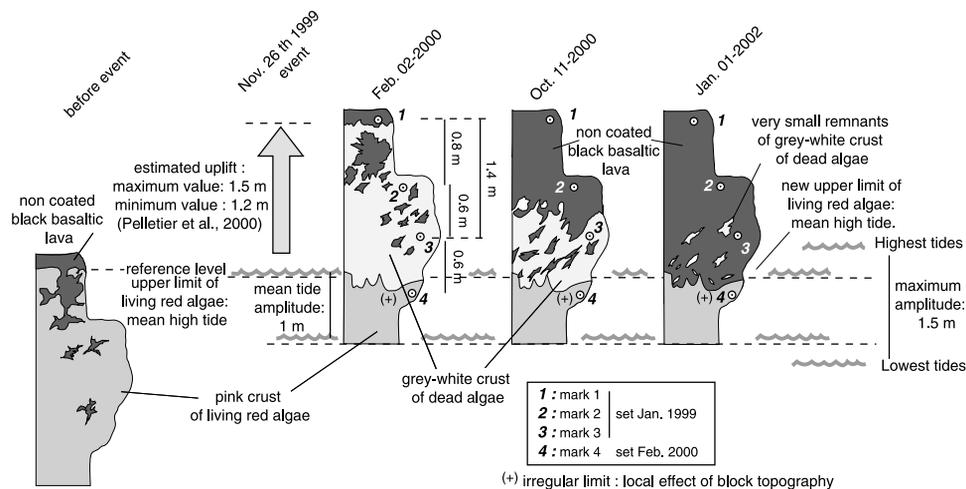
[36] The marks are shims of stainless steel, 3.16 cm in diameter with a central hole of 0.9 cm which have been fixed into the rocks using stainless steel screws and plastic pegs into 5 mm diameter drilled holes. The sites are located on exposures of massive lavas (Penapo and Pamal) and on one lava block, several m<sup>3</sup> of volume, located within other



**Figure 13.** Photographs of the uplifted reef terrace of Ulei taken in (a) October 2000 and (b, c) January 2002. Note that the dead fragile branching forms of emerged corals are still intact in October 2000 but broken into pieces in January 2002 because of wave action. The Lopevi volcano is in the background of Figures 13a and 13c. Figure 13b shows emerged coral heads as discussed in Figure 12. (d) Uplifted coral heads on top of pyroclastic breccias along the coast near the beach of Ulei (section 1, Figure 17a). (e) Photograph of site of section 8 (Figure 17b) at Eloum Point showing evidence of former sea level stands including marine platform and notch, coastline boulders and pebbles, and uplifted coral reef.



**Figure 14.** (a, b) Two successive photographs of a same area of the coast close to Ulei Point, taken in February 2000 and in January 2002 showing the disappearance of the white algal fringe due to the 26 November 1999 uplift. Numbers refer to same blocks of lava on each view. Geologist shown for scale in upper photograph (arrow). Uplifted coral colonies more than 8000 years cal B.P. old are observed in upper part of photograph. (c, d) Evolution of the white fringe of dead encrusting calcareous red algae between January 2000 and January 2002 at site 1 close to Penapo (see GPS location in Figure 10), where two steel marks have been set. At this site, a significant part of the former white fringe is still preserved below the lower mark in 2002.



**Figure 15.** Cartoon depicting the schematic behavior of the stain of red calcareous algae in relation with uplift due to the 26 November 1999 event and following exposure to atmospheric conditions. This evolution is defined by observations at site 2, where four marks have been set (location in Figure 10) in January 1999 and February 2000 (details given within Figure 10 caption). No clear recolonization of the shim marks by red algae has been visible during 2 years. This suggests that the region did not undergo significant subsidence following coseismic uplift within the period of survey.

very large blocks close to Ulei Point. This block cannot move under the forces of wave action. At each site, we set the marks in order to fix some major limits at the time of the setting. These limits include the boundary between the living red algae and the white fringe, the boundary between the white fringe and the patches, and the upper limit of patches, which is the upper limit where red algae developed. These marks were set during the second week of January 2000, and were revisited one month later (16 February 2000), 10 months later (10 October 2000) and 24 months later (12 January 2002).

[37] At site 1, two marks separated by 50 cm have been set at the boundary between the black lavas and the upper patches, and at the upper limit of the continuous white fringe (Figures 14c and 14d). Pink living encrusting algae are observed 50 cm below the white fringe. In January 2002, the white stains between the two marks had completely disappeared. The evolution of the biological markers between January 2000 and October 2000 can be summarized in Figure 15 from observations at site 2 of Ulei Point where four marks were set. The three upper marks (marks 1, 2, and 3) were set in January 2000. They are separated by distances of 80 and 60 cm. The upper mark outlines the upper limit of the white fringe and the lower one was set close to the transition between the white fringe and the pink crust. An additional, lower mark (mark 4) was set in February 2000 as a LLW tide rendered the upper limit of the pink crust accessible. At that time, the white stain is still well visible, but white patches are in regression due to wave and subaerial erosion. The regression is well observed in October 2000 and was almost complete in January, 2002. In addition, at that time the red algae had not grown significantly over the lowest mark. The results relative to the evolution of the white fringe at site 3 are similar to that of sites 1 and 2.

[38] Finally, the analysis of biological markers indicates that no significant and measurable subsidence occurred after

the 1999 event here. However, it is possible that vertical motion of the order of some mm/year cannot be detected through this method during this short time period.

## 6. Long-Term Uplift

[39] Analysis of general morphology of the eastern part of Ambrym reveals that regions of the coast that underwent uplift are characterized by the absence of a lagoon whereas regions that underwent subsidence coincide with the presence of a narrow lagoon along the southern coast, west of Utas (Figure 11). These observations, indicating that coseismic and long-term vertical motions occur in phase at the same place, suggest that repeated events similar in location and magnitude to the one of 26 November 1999 are likely responsible for the shape of the coast.

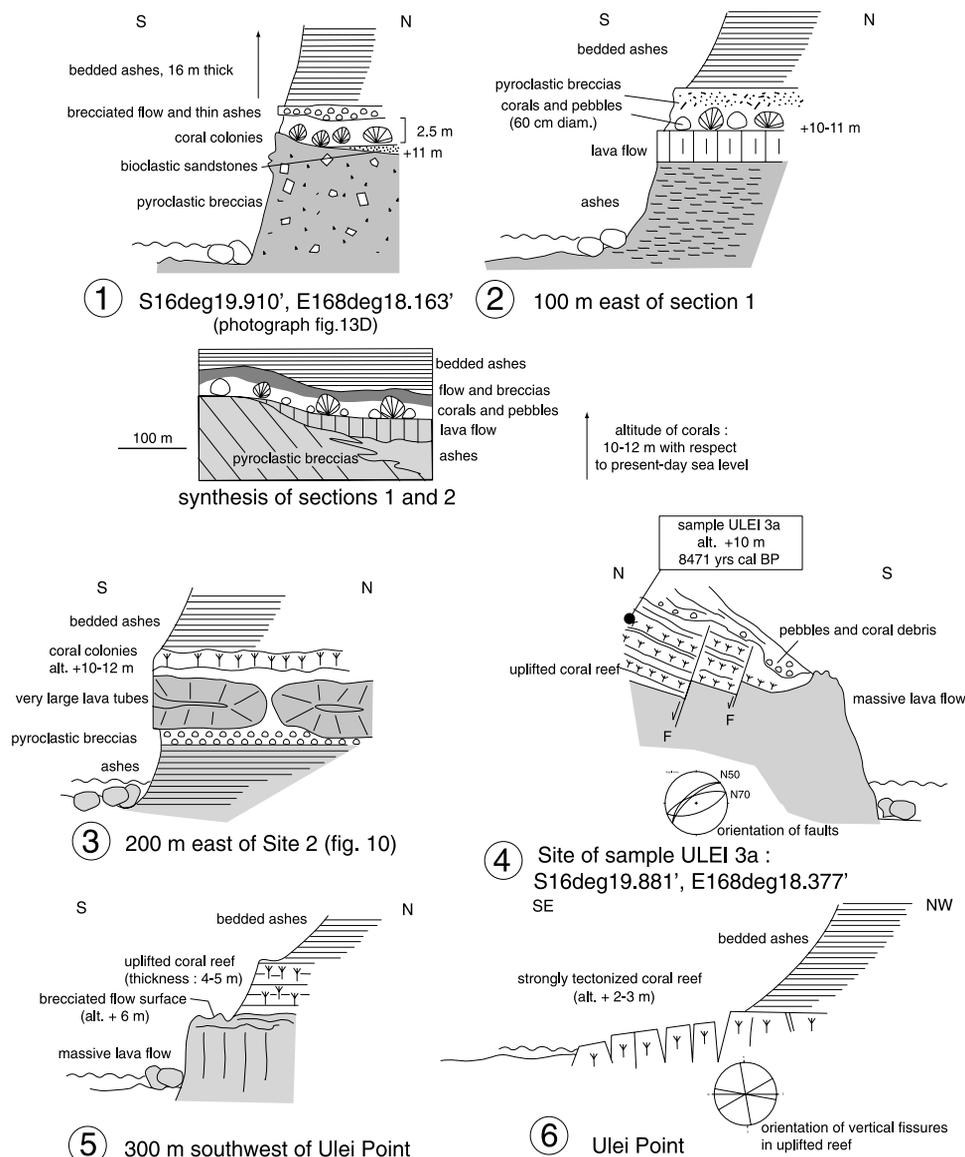
[40] Moreover, the portion of the coast of Ambrym that was subjected to the maximum coseismic uplift is also characterized by the occurrence of sedimentary layers composed of both raised corals (scattered colonies) and raised reef (bioconstructions). These layers have been reported on the map of the New Hebrides Geological Survey sheet 6 (1976). They are exposed in the coastal cliffs between villages of Ulei and Pamal. No other point of the coast of Ambrym expose similar raised corals. Thus in order to estimate the long-term uplift rate and the related uplift seismic recurrence interval, the raised coral and reef levels have been studied and mapped in detail and several corals have been dated.

### 6.1. Description of Raised Coral Occurrences

[41] Detailed stratigraphical studies have been conducted at 11 localities reported on Figure 10. The corresponding geological cross sections are shown on Figures 17a and 17b. Photographs of typical exposures are shown on Figures 13b and 13e (section 1 in Figure 17a and section 8 in Figure 17b). Coral colonies and associated reefal formations are found at



**Figure 16.** Evolution of the uplifted beach of Ulei during 1 year following earthquake (see text for explanation).



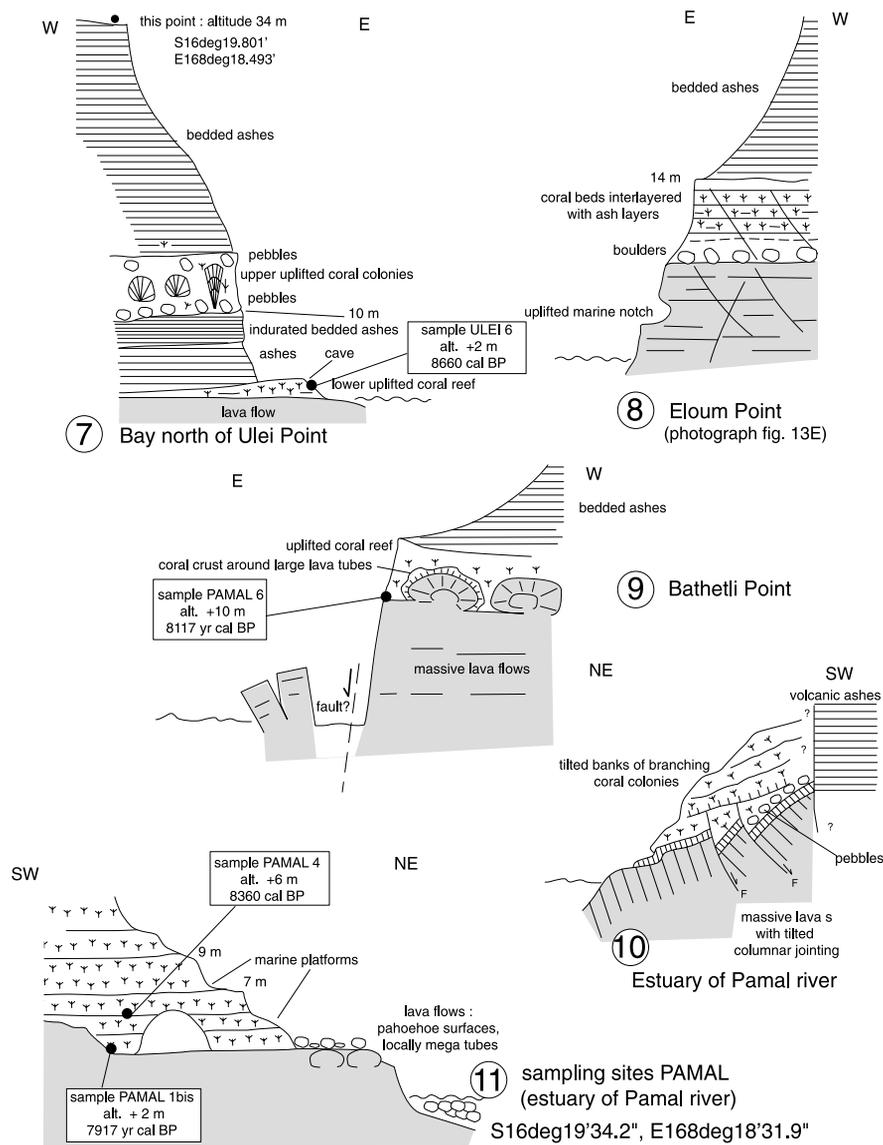
**Figure 17a.** Detailed geological sections along the uplifted coast southeast of Ambrym Island between Ulei and Pamal showing typical sequences including the interlayered reef and coral beds. Sections 1 to 6 are located in Figure 10. Photograph of site of section 1 is shown in Figure 13d. Location of samples of dated corals is indicated.

an altitude ranging from 2 m to 14 m (Figures 17a and 17b). They generally overlie (1) pyroclastic breccias (locality 1), (2) massive basaltic lava flows (localities 4, 5, 10, 11), some of them showing cordate surfaces typical of pahoehoe lavas, (3) very large lava tubes (localities 3, 9, and 11), and (4) volcanic sandstones (locality 8, Figure 17b). They rarely overlie thinly bedded ashes (localities 2 and 3), probably because coral colonies develop preferentially over hard, massive substrates. In addition, volcanic activity and related ash deposits may have locally prevented the establishment of coral colonies.

[42] Gravels and large pebbles of volcanic rocks encrusted by coralline algae locally underlie the raised corals. At all localities, bedded volcanic ashes form the upper part of the sections. This suggests that rapid burying under fine-grained products due to a volcanic eruption can be responsible for

the brutal death of the coral colonies. This event could be linked to the creation of the Ambrym caldera 2,000 years ago [Robin *et al.*, 1993]. In one place, north of Ulei Point, two levels of uplifted reef or coral beds are observed (section 7, Figure 17b). This suggests that at least two major volcanic eruptions occurred during the time interval corresponding to the formation of the uplifted reef colonies. In few, rare localities, at Eloum Point for example, corals are interlayered with numerous ash beds (section 8, Figure 17b) indicating that effects of repeated volcanic eruptions were recorded locally.

[43] In some sections, only small scattered coral colonies formed by few coral heads are found upon bedded ashes. They are often interlayered between two levels of beach gravels and pebbles which are indicators of coastline environments with high energy (section 7, Figure 17b).



**Figure 17b.** Detailed geological sections along the uplifted coast southeast of Ambrym Island between Ulei and Pamal showing typical sequences including the interlayered reef and coral beds. Sections 7 to 12 are located in Figure 10. Photograph of site of section 8 is shown in Figure 13e. Location of samples of dated corals is indicated.

Such mixed levels including both coral heads and pebbles do not constitute coral reefs in the strictest sense. They demonstrate that the settlement and development of successive coral reef episodes occurred in very shallow waters, close to the sea surface, probably within rapidly changing environments.

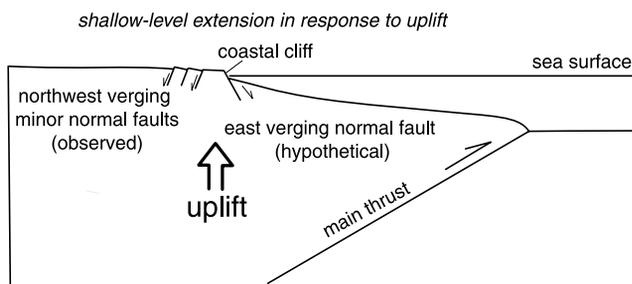
[44] At locality 4 (Figures 10 and 17a), the uplifted coral formation consists of a 3-m-thick layer composed of successive beds of tabular and branching corals. This layer is tilted  $35^\circ$  toward the south and is crosscut by normal faults dipping toward the northwest. Normal faults dipping toward the southwest have been also observed within a 5-m-thick layer of bedded corals at the estuary of Pamal river (section 10, Figure 17b). Local unconformities within the upper coral beds suggest that faulting started during coral growth. In this context of regional shortening

and compression, normal faulting is interpreted as the local tectonic response to regional uplift, mostly due to gravity forces (Figure 18) [Ota *et al.*, 1997]. However, storm damages within massive coral formations cannot be ruled out locally [Bourrouilh-le-Jan and Talandier, 1985; Hughes, 1993].

## 6.2. Dating of Raised Corals: Long-Term Mean Uplift Rate and Seismic Recurrence Interval

[45] The corals were sampled in growth position and their altitude and position were determined using a barometer “altiplus” and a hand-held GPS (Garmin 12CX). Vertical accuracy of survey approach is about 0.5 m. In the laboratory, the samples were screened using standard X-ray diffraction techniques for detecting the presence of low-magnesian calcite. Those containing usually more than 98%

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**Figure 18.** A model that may explain observed and suspected extensional tectonic features in response to the uplift of the hanging wall of the main thrust fault east of Ambrym.

of aragonite were selected for dating by the TIMS U/Th or AMS <sup>14</sup>C methods. If the sample is found to be low-magnesian calcite, indicating diagenetic processes under subaerial conditions, then it was rejected for dating. Ages have been obtained from five coral samples exposed in sections 4, 7, 9 and 11, at altitudes of 2 m, 6 m, and 10 m. (Figures 17a and 17b). Ages obtained (Table 1) fall within a range of about 750 years, between 7917 years cal B.P. and 8660 years cal B.P.

[46] We calculated the uplift rates using as a reference the last postglacial sea level curve based on coral dating from Tahiti [Bard et al., 1996]. Knowing the age of dated corals, we calculate the difference between its present-day altitude and its theoretical depth on this curve. The resulting difference thus provides a value of the total uplift for the calculation of the uplift rate (Table 1). However, the deduced rate is a minimum rate because the living depth ranges of individual corals have not been taken into account, and the coral are thus considered to live at a depth of 0 m. On the basis of the stratigraphical analysis presented above, this assumption is the most probable because the raised reef and coral levels are generally interbedded between beds of gravels and pebbles typical of beach environments. Therefore the mean uplift rate estimates range from 2.14 to 4.07 mm/yr at Pamal and Ulei (Figures 17a and 17b and Table 1). The lower value may be underestimated.

[47] In conclusion, given a 4 mm/yr mean Holocene uplift rate and a 1.5-m coseismic uplift (as in the case of the  $M_w$  7.5, 26 November 1999 event), and assuming that all the uplift is coseismic and that no postseismic subsidence

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occurs, a recurrence interval of 375 years is calculated. This, in turn, yields a maximum of 56,250 years for the thrust fault scarp east of Ambrym.

### 7. Discussion and Conclusion: The $M_w$ 7.5, 26 November 1999 Ambrym Earthquake and the Back-Arc Thrust Belt of Central Vanuatu

[48] This integrated study of the  $M_w$  7.5, 26 November 1999, Ambrym earthquake provides a number of results relative to the tectonic behavior of the BATB of central Vanuatu. More generally, it demonstrates the need to link onshore and offshore data to study short- and long-term evolution of compressive boundaries in oceanic environments. The east Ambrym site is exceptional in that it exposes recently uplifted corals located 13 km west of a major compressive fault scarp. There are no multiple raised terraces around the east coast of Ambrym because of the peculiar outline of the island, with an east-west promontory; only the tip of the promontory is subjected to uplift. In addition, corals developed solely in places where the basement of lava flow is solid enough to allow colony settlement. Localities with a substrate of soft volcanic ash do not allow coral growth. Thus coral colonies tend to form discontinuous patches along a stratigraphic level instead of a continuous reef terrace.

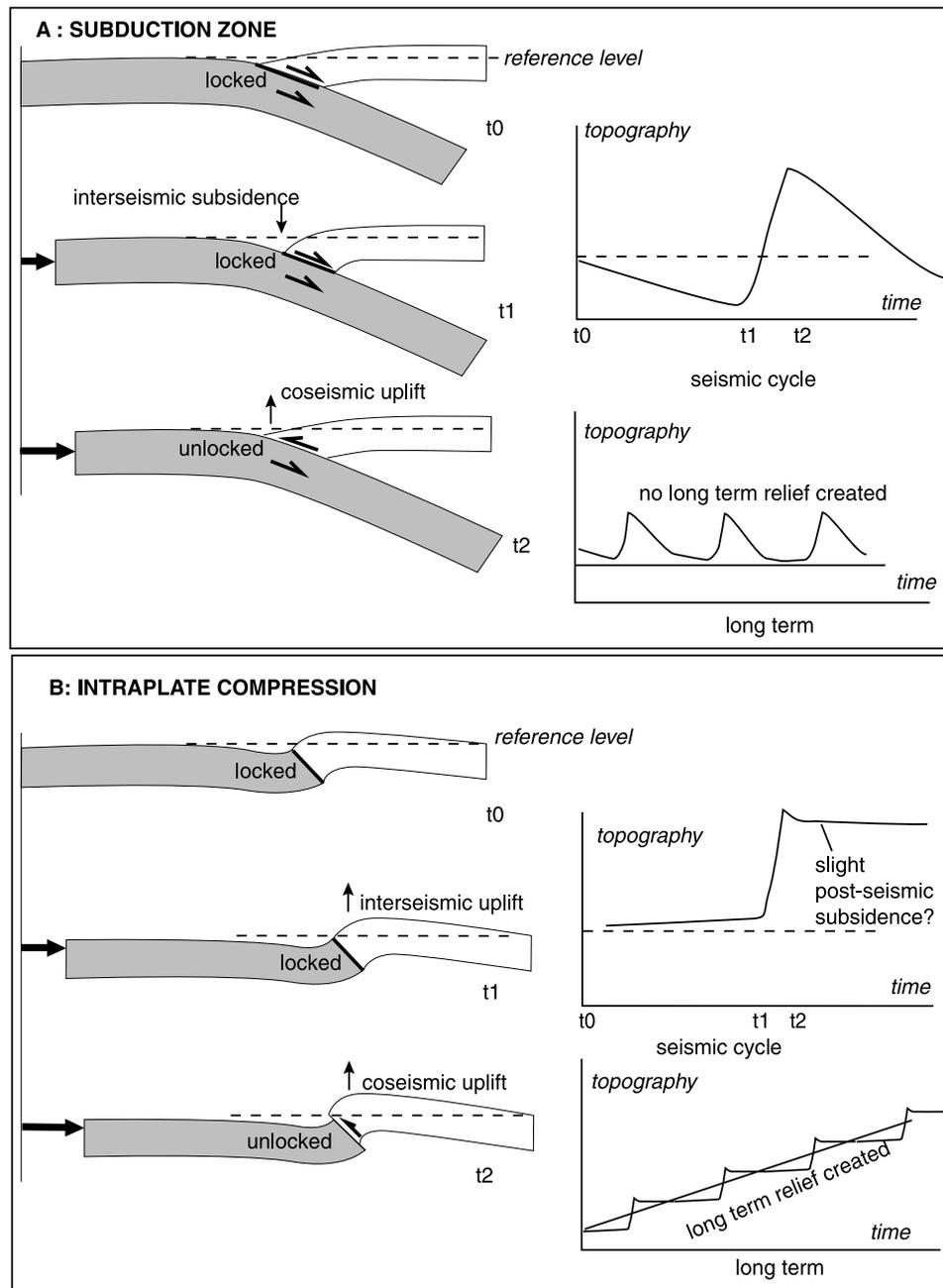
[49] Our compilation of data from various sources, including regional seismology, GPS-derived plate motions, interpretation of seismic lines and ODP drilling results, demonstrates that the eastern limit of the back-arc region of the central Vanuatu subduction zone east of Maewo, Pentecost and Ambrym displays various features typical of major compressive orogenic boundaries. This limit corresponds to a main thrust front where upper oceanic lithosphere of the eastern part of the Aoba basin is thrust over the oceanic crust of the North Fiji basin. Moreover, at present, active thrusting develops east of the Maewo-Ambrym axis which indicates that the crust of the North Fiji basin is also involved in the compressive system. Therefore the BATB of central Vanuatu appears to be an active tectonic crustal wedge, propagating eastward, progressively incorporating units of oceanic lithosphere belonging to the western North Fiji basin. This represents a relatively uncommon example of an orogenic front occurring within a purely oceanic environment.

[50] Detailed bathymetry obtained with the EM12-dual multibeam echo sounder east of Ambrym reveals the presence of a major thrust fault scarp lying 20 km east of the epicenter of the  $M_w$  7.5, 26 November 1999, Ambrym earthquake. The location and azimuth of this

**Table 1.** Ages of Uplifted Corals Sampled Along the Southeastern Coast of Ambrym<sup>a</sup>

Sample	Present-Day Altitude, m	Percent Aragonite	Age		Depth Related to SL Curve, m	Uplift, m	Uplift Rate, mm/yr
			TIMS U/Th, years B.P.	<sup>14</sup> C, years cal B.P.			
PAMAL1bis	+2	100		7917	17	19	2.14
Pamal-4	+6	100	8360 ± 29		23	29	3.46
PAMAL 6	+10	99.5		8117	19	29	3.57
ulei-3a	+10	100	8471 ± 24		24.5	34.5	4.07
ulei-6	+2	100		8660	25	27	3.12

<sup>a</sup>See location in Figures 10, 17a, and 17b. Calibration after Stuiver et al. [1998].



**Figure 19.** Simple earthquake recurrence models for theoretical situations of pure subduction and pure intraplate compression. (a) In case of subduction, a quantity of material is constantly removed out of the system from below. Therefore, even in context of plate convergence, permanent topography is not created. In this ideal case, the subduction boundary is the locus of interseismic subsidence followed by coseismic uplift. (b) In the case of intraplate convergence, as exemplified by the BATB of central Vanuatu including islands of Maewo, Pentecost, and Ambrym, it is impossible to remove material from below, and there is a constant stacking of crustal material at the boundary. Therefore topography can be constantly created during the interseismic as well as coseismic periods. In the specific case of Ambrym the amount of interseismic ground motion has not been evaluated. Long-term uplift is confirmed by the occurrence of uplifted reefs.

400-m to 900-m-high, N165° trending, 40-km-long, linear scarp agrees closely with the seismologically derived location of the hypocenter of the 26 November 1999 earthquake and with the dip and strike of the reconstructed fault plane. Thus we conclude that the scarp corresponds

to the surface expression of a major fault plane that has been reactivated during the November 1999 event.

[51] Our study reveals a spatial correlation existing between the November 1999 coseismic vertical displacements and the long-term vertical motion. First, the point

along the southeast coast of Ambrym, where the narrow lagoon disappears coincides with the neutral line of instantaneous motion deduced from the first postseismic investigations [Pelletier *et al.*, 2000]. This indicates that the line along which long-term subsidence (leading to lagoon development) ceases, is roughly at the same location as the neutral line of elastic, instantaneous deformation. Second, the presence of raised coral reefs exposed at an altitude of 12 m in the same portion of the coast that underwent maximum coseismic uplift, suggests that the same thrust fault plane is regularly activated to shape the East Ambrym coast and to form the offshore scarp east of Ambrym. Although no detailed studies of previous earthquakes were possible, this coincidence could be a rough indication that the segment of the BATB fault system responsible for the Ambrym earthquake always ruptures with the same behavior in the same portion of the fault. This type of behavior would tend to support either the characteristic earthquake model or the uniform slip model, rather than a variable slip model [Schwartz and Coppersmith, 1984; Scholz, 1990] for the Ambrym fault segment.

[52] A mean uplift rate of 3.5–4 mm/yr for the past 8000 years has been derived from the altitudes and dating of raised corals at the eastern tip of Ambrym. This uplift rate is much higher than previously thought for the eastern chain of central Vanuatu and is at the upper end of range for the western chain. The age of the thrust fault scarp east of Ambrym which results from the cumulative effects of successive events, and the average seismic uplift recurrence interval for a  $M_w$  7.5 event in this part of back-arc area have been estimated in four different ways: (1) the GPS-derived present-day convergence motion, (2) the inferred slip for the November 1999 earthquake, (3) the morphology of the fault scarp and (4) from the ages of raised Holocene corals. These different data suggest an age of the scarp ranging from 15,000–27,000 to 56,250 years, and a minimum and maximum recurrence interval of 93–173 years and 375 years, respectively.

[53] We have found abundant evidence that the BATB does not behave as a typical subduction zone, but rather as an intraplate thrusting boundary. Long-term uplift in the region leads to the creation of high relief such as the islands of Maewo and Pentecost where Quaternary coral formations are found at altitudes close to 1000 m. Theoretical subduction earthquake cycles are characterized by opposite patterns of coseismic and interseismic motions [Scholz, 1990]. As shown on Figure 19a, in typical subduction boundaries, the subduction fault is locked during the interseismic phase leading to subsidence of the forearc region which rebounds elastically during earthquakes. During repeated similar cycles, no significant relief is created at the converging boundary. Underthrust material is never added to the converging system which is therefore unable to grow in volume. In the case of the November 1999 Ambrym event, we have shown that coseismic uplift occurred in a region also showing long-term uplift. No evidence for significant postseismic subsidence has been observed over a period of two years after the 26 November 1999 event, although slight subsidence cannot be ruled out. We feel confident that the steel markers which have been set will be useful for monitoring any future vertical motions.

[54] Finally, we may conclude that the seismic cycle along the BATB exhibits characteristics more similar to that of intracontinental thrusts where uplift is accumulated creating relief. As shown in Figure 19b, we may assume that both coseismic and interseismic patterns of vertical motions are positive along the BATB, even if interseismic subsidence cannot be ruled out locally. Underthrust tectonic slices are added to the orogenic system during convergence, leading to crustal thickening and to permanent creation of relief. The deformed volume has been increasing since the initiation of compression at the BATB boundary and thrust faults propagating from west to east have reduced the surface of the North Fiji basin. Finally, in front of the subduction of the d'Entrecasteaux Zone, the subduction processes accommodate less shortening than the BATB of central Vanuatu to the east.

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