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Probabilistic Seismic Hazard Model for Vanuatu

by Jenny Suckale* and Gottfried Grünthal

Abstract This study develops a preliminary probabilistic seismic hazard model for Vanuatu. The area of investigation, formerly referred to as the New Hebrides, lies in the center of a chain of partly volcanologically active islands that mark the present-day boundary between the Australia-India plate and the microplate of the North Fiji basin. The seismicity of the Vanuatu arc is dominated by an east-dipping subduction zone, which shows striking structural anomalies in the central part between 14° and 18° S. Our historical catalog contains 7519 events within the Vanuatu region for the period from 1964 to 2003, drawn from the global teleseismic catalogs by the United States Geological Survey/National Earthquake Information Center (USGS/NEIC, see Data and Resources section) and *Engdahl et al.* (1998). As a measure of seismic hazard, we use horizontal peak ground acceleration (PGA) and horizontal spectral ground acceleration (SGA) at a period of 1 sec. The hazard estimates are based on a logic-tree approach to account for the epistemic uncertainties associated with our analysis. Our results suggest that the entire island arc experiences a high and uniform seismic hazard. Typical values for PGAs range from 0.65*g* to 0.77*g* with a 10% probability of exceedence in 50 yr. For Port Vila, the capital and largest city in Vanuatu, we additionally present a PGA hazard curve and a uniform hazard spectrum over the period range 0.1–2 sec.

Introduction

This study constitutes the first attempt at constructing a probabilistic seismic hazard model for Vanuatu. Two prior seismic hazard estimates exist for that region. First, *Prevot and Chatelain* (1984) applied a deterministic intensity-based technique to quantify seismic hazard in Vanuatu. However, given the very limited macroseismic database, the few reliable intensity estimates, and the limitations of the deterministic method itself, we consider the probabilistic approach to be more appropriate. Second, the global seismic hazard assessment program (GSHAP) assembled a world map with mean peak ground acceleration (PGA) estimates for a 475 yr return period (*Giardini et al.*, 1999; *Shedlock et al.*, 2000). The estimates from this global project for Vanuatu, which are part of the study area provided by *McCue* (1999), are not directly comparable to our more detailed area study. The goal of GSHAP was to produce a global map based on a more or less homogeneous methodology and never intended to be as precise as the localized hazard assessment we develop in this study.

We follow the general definition of seismic hazard as the frequency or probability that the ground-motion amplitude exceeds a certain threshold at a specific site.

We use horizontal PGA and horizontal spectral ground acceleration (SGA) measured in *g* as the hazard-relevant quantities. Our methodology follows the generally accepted approach of *Cornell* (1968) and *McGuire* (1976) augmented with a logic tree. This article is organized as follows: the first part sketches the geological and tectonic setting of the Vanuatu island arc, the second section summarizes the data used in the analysis, and in the third section we discuss our probabilistic seismic hazard analysis (PSHA) and present our results. Finally, we compare our results with prior findings for the southwest Pacific region.

Tectonic Setting

The Vanuatu islands extend about 1200 km along a north-northwest–south-southeast trend between latitudes 10° and 22° S from the Solomon arc in the north to the Matthew-Hunter Ridge in the south (Fig. 1). Though apparently simple on a large scale, the archipelago is a complex tectonic unit resulting from an interplay between the active subduction, the collision with several major submarine ridges and basins, the spreading of the North Fiji basin, and possibly a paleosubduction that became inactive in Late Miocene time (e.g., *Coleman*, 1970; *Hanuš and Vaněk*, 1983, 1991).

Pelletier et al. (1998) updated a tectonic map for the area around the North Fiji basin. According to

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Figure 1. Bathymetric map of the Vanuatu arc. Major islands and important geological features are named. Port Vila, the capital of Vanuatu, is underlined. The most active volcanoes are indicated by triangles. The Global Positioning System-based estimates of convergence rates along the Vanuatu arc with respect to the Australian plate are indicated in mm/yy (Calmant *et al.*, 2003). Two tectonically important segments, the main collision segment and the Ebate segment, are delineated by dashed lines.

their results, the region is characterized by a large variation in both consumption rate along the arcs and opening rate along the spreading centers in the back-arc basins. Based on these spatial variations in convergence rates, Calmant *et al.* (2003) subdivided the Vanuatu subduction zone into four segments. A similar partition has also been proposed by Greene *et al.* (1994) and Meffre and Crawford (2001) and is corro-

borated by seismic evidence (Chatelain *et al.*, 1986; Christova *et al.*, 2004). These studies suggest that the segmentation of the subduction zone is an important determinant of seismic hazard in Vanuatu.

Geodetic measurements (Calmant *et al.*, 1995; Taylor *et al.*, 1995; Calmant *et al.*, 1997, 2003) have yielded large lateral variations in the convergence rates along the Vanuatu arc with respect to the

Figure 2. Epicenters of earthquakes with $M_w \geq 5$ that occurred in the respective depth bins: 1–34 km (upper left), 34–60 km (upper right), 60–120 km (lower left), and >120 km (lower right). The most striking irregularity occurs at depths >60 km, where a lowered seismicity rate is observed for the central region. Generally subduction activity is less dispersed at deeper depth (>60 km). Backarc activity in the overriding plate extends down to a depth of ~60 km.

Australian plate (Fig. 1). Starting at approximately 120 mm/yr in the north, the convergence rates decay rapidly to about 35 mm/yr in the arc segment facing the d'Entrecasteux Ridge. The minimal convergence rate is found on Malekula (28 mm/yr). The area south

of Malekula is characterized by intense shear deformation (*Calmant et al.*, 2003). Continuing southward, the convergence rate increases off the shore of Efate to about 90 mm/yr and peaks at 124 mm/yr on Tanna (Fig. 1). In the reference frame of the North Fiji basin,

Figure 3. Seismicity profiles of the subducting slab along the Vanuatu island arc. The six profiles are numbered from north to south. For the diagrams, all events with $M_w \geq 5$ were projected onto a common plane perpendicular to the trench. The x-coordinate denotes the focal depth of the events and the y-coordinate denotes their distance from the western edge of the respective segment. The horizontal lines at -60, -120, and -200 km depth indicate the three depth bins used in the three seismic source zone models.

the northern and southern blocks rotate in opposite directions, causing the segment between them to translate eastward and collide at approximately 55 mm/yr with the North Fiji basin.

Numerous authors (*Pascal, 1974; Choudhury et al., 1975; Chung and Kanamori, 1978; Maillet et al., 1983; Collot et al., 1985; Geist et al., 1993; Greene et al., 1994; Taylor et al., 1995; Meffre and Crawford, 2001*) attributed the fragmentation of the Vanuatu arc to the collision of the overriding plate

with the d'Entrecasteaux Ridge and, to a lesser degree, with the West Torres Massif and the Loyalty Island Chain (Fig. 1). *Wallace et al. (2005)* demonstrated that active rifting in the North Fiji basin is probably related to these collisions as well. Another important factor influencing the deformation of the plate contact zone is the presence of rigid, old (Miocene) crustal blocks in the forearc (*Daniel and Katz, 1981; Collot et al., 1985*).

Because of their heightened importance for seismic

hazard, we discuss two segments in detail: the block facing the d'Entrecasteaux Ridge (labeled main collision segment in Fig. 1) and the area around the island of Efate (labeled Efate segment in Fig. 1).

Apart from its low convergence velocity, the main collision segment is characterized by three other unusual features: (1) The trench vanishes off the shore of Espiritu Santo and northern Malekula (*Chatelain et al.*, 1986; *Greene et al.*, 1994). (2) The forearc is characterized by unusually large islands. These islands are located 30 km from the zone of subduction, a position that would normally correlate with the middle of the trench arc slope in most intraoceanic island arcs. (3) A zone of crustal shortening extending from 13°30' S to 16°30' S is concentrated along its eastern margin. *Pelletier et al.* (1998) posited a present-day crustal shortening rate of 55 mm/yr for this area (Fig. 1). Contrary to the rest of Vanuatu, seismic activity along the eastern margin is higher than along the western margin as a result of backarc shortening. Backarc events are often associated with both coseismic and long-term vertical displacement (*Lagabriele et al.*, 2003).

These observations substantiate the dominant role of the main collision segment for modeling the seismicity and dynamics of the Vanuatu arc. In anticipation of our results, we obtain slightly higher seismic hazard estimates in this segment, particularly for the area facing the d'Entrecasteaux Ridge, compared to the neighboring segments. We believe this to be consistent with the geologic and tectonic evidence summarized here.

For the purpose of developing a seismic hazard model for Vanuatu, it is important to devote special attention to the area 16°30'-18° S (Efate segment, Fig. 1) because the island of Efate, with the national capital Port Vila, is home to 30,000 out of the approximately 187,000 inhabitants of Vanuatu and thus has the highest population density in the country. The Efate segment is squeezed between the eastward translating main collision segment (Fig. 1) and the rotating southern block, suggesting that it is a right-lateral transition zone accommodating the shear between the two neighboring segments (*Calmant et al.*, 2003).

Earthquake locations from both worldwide and local networks show a sizable gap in the Wadati-Benioff zone in the Efate segment (*Prévot et al.*, 1991). The distribution of seismicity at different depths is illustrated in map view in Figure 2 and in the form of six seismicity profiles of the subduction zone in Figure 3, respectively. These six seismicity profiles (Fig. 3) highlight notable lateral variations in the Wadati-Benioff seismicity in Vanuatu. The low rate of seismic activity stands out particularly clearly for depths of 60-120 km in Figure 3, profile 4. Previous authors (*Choudhury et al.*, 1975; *Louat and Pelletier*, 1989;

Chatelain et al., 1992, 1993) have interpreted this feature as evidence for a detachment of the middle segment from the lower part of the downgoing slab. It has also been hypothesized that a shallow double seismic zone exists within the descending Australian plate beneath the central part of Vanuatu (*Prévot et al.*, 1994). As we discuss in detail in our seismic source zone models, capturing different valid interpretations of this seismic gap is crucial for adequately modeling seismic hazard in Vanuatu.

The complex tectonic interplay between the subduction zone and its three buoyant indenters has not only left its imprint on the slab but has also had important consequences for the forearc and backarc. In the forearc, it has led to large rates of uplift (*Taylor et al.*, 1990, 1995), which are probably associated with extensive faulting or folding on the surface of Espiritu Santo or Malekula (Fig. 1). The results from the Ocean Drilling Project (*Greene et al.*, 1994) indicate that a large number of straight strike-slip faults related to the recent collision cut across the entire arc. However, *Meffre and Crawford* (2001) could not confirm this result through analysis of aeromagnetic or surface information. They suggested that the forearc is divided into 50-100 km long blocks, which is consistent with *Taylor et al.* (1990) who found differences in the rates and pattern of uplift between different areas in the forearc. The ramifications of the collisions for the backarc are less obvious, but *Wallace et al.* (2005) demonstrated that a link exists between backarc rifting and the presence of buoyant blocks in subduction environments, not only for Vanuatu but also for other subduction zones. In fact, a number of large events reaching moment magnitudes (M_w) of up to 7.5 (*Regnier et al.*, 2003) have occurred along the central backarc trench, which delineates the eastern boundary of the arc segment colliding with the d'Entrecasteaux Ridge.

Data

We merge two different global data sources to obtain a suitable seismicity data base for Vanuatu: the United States Geological Survey/National Earthquake Information Center (USGS/NEIC) catalog (see Data and Resources section) and the Engdahl catalog (*Engdahl et al.*, 1998). In order to calculate earthquake recurrence, the following information must be available: date, origin time, location, focal depth, and a magnitude of specified type. We discard events with unknown magnitude type. This restriction leaves 6735 events in the USGS/NEIC catalog for the Vanuatu area (specified as 11° S - 22° S and 164° E - 172° E) through December 2003. We complement this data set with 784 events from the Engdahl catalog that are not contained in the USGS/NEIC catalog.

Overall, our database contains a total of 7519 events for the time period 1964-2003. For each of these events, one of the following three magnitude types is listed: M_w , bodywave magnitude (m_b), or surface-wave magnitude (M_S). In order to convert m_b and M_S to M_w we fitted regressions to the data based on the maximum likelihood approach for each magnitude type and both catalogs (see Fig. 4).

- $M_w = 1.2690M_S - 1.0436$ for the USGS/NEIC catalog.
- $M_w = 1.2765M_S - 1.0825$ for the Engdahl catalog.
- $M_w = 0.7813m_b + 1.5175$ for the USGS/NEIC catalog.
- $M_w = 0.7601m_b + 1.6562$ for the Engdahl catalog.

It is common practice not to explicitly consider the earthquake depth in these magnitude regressions (Utsu, 2002). In the case of Vanuatu, two additional difficulties arise when trying to account for depth. First, the uncertainty associated with the depth localization is considerable for the great majority of events, and second, not all depth intervals contain enough events to develop a reliable regression model.

We checked the magnitude-dependent completeness of the catalog by plotting the cumulative number of earthquakes per magnitude bin over time (Fig. 5). A magnitude bin is considered complete for the years in which a roughly constant slope can be fitted to the cumulative number of earthquakes. The catalog

proves to be complete since 1964 for $M_w \geq 5.2$. We discard incomplete time and magnitude intervals.

Method and Analysis

We follow the well-known approach of PSHA developed by Cornell (1968). Additionally, we use a logic-tree approach to capture the epistemic uncertainties inherent in our analysis. The calculations are carried out with the software FRISK88M© by Risk Engineering, Ltd. (1997). The PSHA methodology entails two crucial steps: (1) the analysis of geologic, tectonic, and seismic data to identify the locations of earthquake sources in the subsurface along with their likely magnitudes and recurrence frequencies and (2) the estimation of the ground motions that these sources will produce throughout the study area. In the following section we detail the modeling approach for these two core components of our PSHA. We also summarize the essentials of the logic-tree approach before moving on to the Results section.

Seismic Source Models

The tectonic setting of Vanuatu poses two key challenges for constructing the seismic source model:

Figure 4. Magnitude conversion for the global catalogs from USGS/NEIC (see Data and Resources section) and Engdahl *et al.* (1998). The dots indicate earthquakes for which M_w and either M_S (upper two figures) or m_b (lower two figures) are listed. The best linear fit is shown as a straight line. The formulas for the two regressions are given in the text.

Figure 5. Cumulative number of earthquakes in eight magnitude bins for our global catalog. Each line represents one magnitude bin as detailed in the legend, which also gives the total number of events in each bin. A magnitude bin is considered complete if the graph is approximately linear. For the smallest two magnitude bins ($4.8 \leq M_w \leq 5.2$ and $4.2 \leq M_w \leq 4.7$), we highlight the earliest year for which the respective bin can be considered complete by a dot. All other bins are complete from 1964 on.

(1) different tectonic interpretations of the seismic gap in the central part of the Vanuatu arc have to be taken into account, and (2) the various seismic sources contributing to seismic hazard (from a catastrophic megathrust event to low-magnitude volcanic swarms) have to be modeled adequately.

Modeling the Seismic Gap. The accumulated evidence provided by geodetic measurements (e.g., Calmant *et al.*, 1995; Taylor *et al.*, 1995; Pelletier *et al.*, 1998; Calmant *et al.*, 2003), focal mechanisms (e.g., Calmant *et al.*, 2003; Christova *et al.*, 2004), and bathymetry data (e.g., Greene *et al.*, 1994) all point to a shear zone cutting through the subduction zone north of Efate. These observations in conjunction with the lack of seismic activity in the central slab segment for depths >60 km (Fig. 3, profile 4) indicate that the seismic gap might be genuine. Investigations of intraplate coupling point in a similar direction: Taylor *et al.* (1995) examined the coupling of the eastward translating block facing the d'Entrecasteaux Ridge. They found that this segment has a convergence deficit compared to the global plate-motion model NUVEL-1A that could not be explained by strain accumulation due to strong coupling. Similarly, Calmant *et al.* (1997) reported strong lateral variations in intraplate coupling and hypothesized that these might have caused the Malekula earthquake with M_S 7.3 on 13 July 1994. Taken together, the available evidence favors the interpretation that the seismic gap is indeed genuine. If this is the case, the absence of recent large thrust events in this region should not be taken as an indication for a locally strong coupling of the plates

leading to accumulation of strain energy and increasing the probability of a catastrophic earthquake.

On the other hand, it is certainly possible that strain accumulation is taking place in the area around Efate (Chatelain and Grasso, 1992). Efate is located in the center of an active subduction zone where the maximum compressive stress is thought to be nearly horizontal and slab-normal all along the arc (Christova *et al.*, 2004). Combined with the important implications of this scenario for seismic hazard, it is imperative to include it into the PSHA. This is achieved through the logic-tree approach, which allows for the incorporation of conflicting interpretations of the geotectonic evidence in combination with the usage of three different source zone models A, B, and C (Fig. 6). Model A is based on the interpretation that the Vanuatu arc is fractured into six segments of approximately 200 km length at shallow depths (0–60 km), and that the seismic gap at 60–120 km is genuine (Fig. 6, top row). Model B assumes that despite variations in seismicity on smaller scales, the Vanuatu subduction zone is split into only two segments. Similar to model A, the gap zone is modeled as an area of a naturally lower seismicity rate, in between two actively subducting slabs (Fig. 6, middle row). Finally, model C represents the scenario of a single intact slab with strain accumulating in the central segment (Fig. 6, bottom row). This entails a significantly elevated seismic hazard around Efate compared to the other two models.

Crustal and Volcanic Sources. The fragmentation of the Vanuatu subduction zone into blocks implies that

Figure 6. The three seismic source zone models A, B, and C in comparison. Note that the depth division into shallow (0–60 km), intermediate (61–120 km), and deep (121–200 km) seismicity is identical for all three models. The source zones for model A are shown in the top row, for model B in the middle row, and for model C (coarse) in the bottom row. The gray scales highlight the division of the area into zones of diffuse seismicity (light gray), backarc activity (intermediate gray), and forearc and subduction seismicity (dark gray).

crustal sources contribute prominently to the seismicity, as discussed in the tectonic setting and illustrated in Figure 3. These seismicity profiles also indicate that crustal and volcanic sources, particularly in the backarc and the central segment of Figure 3, profile 4), extend down to 60 km depth. The fact that

crustal and volcanic activity extends to these unusually large depths is probably related to the collision of the overriding plate with the three buoyant ridges in the forearc (Fig. 1).

The first zonation map in Figure 6 (top left) illustrates our crustal seismotectonic source zones. Areas

of intense seismic activity in the forearc and backarc are flanked by zones that we refer to as diffuse seismicity (shaded in light gray). We chose this designation to highlight the fact that we consider a significant share of events in these areas to represent erroneous locations. Because seismicity in both the forearc and backarc is strongly affected by the collision with submarine ridges, the zonation closely follows these collision zones. We single out the central backarc trench (zone CBAT) because earthquakes with $M_w \geq 7.5$ are known to have occurred on that fault (Regnier *et al.*, 2003) and the Aoba region, which is sandwiched in between the subduction/collision to the west and the central backarc trench to the east (Figs. 2 and 3). Seismic swarms associated with volcanic activity characterize this zone (e.g., Rouland *et al.*, 2001).

Seismic Sources Associated with the Subducting Slab.

The subduction seismicity in Vanuatu extends down to almost 700 km in certain areas. Because the contribution to the hazard decreases drastically with increasing distance and depth, we discard events below 200 km focal depth. This cutoff point is motivated by the data used to derive the attenuation relation models discussed in the following section in more detail and as said, by the negligible contribution of these very deep events to the expected PGA. We subdivide the reduced depth range of 0–200 km into three depth bins: shallow (0–60 km), intermediate (60–120 km), and deep (120–200 km). These bins are primarily motivated by the sizable gap in the Wadati-Benioff zone at intermediary depths (60–120 km) in the central segment and lowered seismicity rates in the neighboring zones (Figs. 2 and 3). Previous studies of seismicity patterns in Vanuatu have relied on similar depth divisions (Christova *et al.*, 2004).

We model the dip of the subducting slab as mutually offset source zones shown in Figure 6. Models A and B are based on the assumption that the slab in Vanuatu is fractured into a northern and southern segment for depths >60 km (Fig. 6, top and middle rows). This split of the subduction zone into two halves has been confirmed by many studies (e.g., Chatelain *et al.*, 1986; Greene *et al.*, 1994; Taylor *et al.*, 1995; Calmant *et al.*, 2003). The two models vary, however, in their approach to the existence of a megathrust in Vanuatu. Model A represents the scenario of an intensely fractured upper plate, the segments of which are only locally coupled to the descending slab (Fig. 6, top row). Rupture is confined to each of the six segments in the forearc and backarc, and there is no megathrust. In model B, the split of the descending slab into two segments is thought to extend to shallow depths (0–60 km) entailing the formation of two megathrusts, one in each segment (Fig. 6, middle row). Model C represents the scenario of a single me-

gathrust capable of rupturing the entire island arc. This is reflected in the fact that the subduction is modeled as one homogeneous zone (Fig. 6, bottom row).

We note that the possible absence of a currently active megathrust at shallow depths (0–60 km) as captured in model A is consistent with prior studies of the largest earthquakes in Vanuatu, which have been related to either strong lateral variations in intraplate coupling (Calmant *et al.*, 1997), asperities (Chatelain *et al.*, 1983) or the central backarc thrust (Regnier *et al.*, 2003). Another unusual yet important characteristic of the seismicity in Vanuatu is that normal and strike-slip faulting events occur all along the arc (Christova *et al.*, 2004).

Declustering. The seismicity in each source zone is modeled by a Poisson distribution, specifically adapted to the activity rate in the respective zone by the Gutenberg-Richter parameters a and b and the maximum expected magnitude distribution. Assuming a Poisson distribution requires that foreshocks and aftershocks are both separated out from the seismicity catalog because these cannot be regarded as independent from the mainshocks. Interestingly, clustering in Vanuatu seems to be limited to shallow depths (0–60 km). One possible explanation for this phenomenon might be that most clusters are associated with volcanic activity (Rouland *et al.*, 2001). To quantify this observation we test the null hypothesis that earthquakes with focal depths of 60–200 km are temporally Poisson-distributed. Performing an χ^2 goodness-of-fit test we could not reject this null hypothesis at conventional significance levels. This result suggests that deep events are indeed Poisson-distributed. This observation is in accordance with the analysis of clustering behavior in other subduction zones by Wyss and Toya (2000).

Therefore, we only decluster the seismic catalog for shallow depths (0–60 km) to reduce it to independent mainshocks. The algorithm used is based on Musson (1999), and the parameters of the magnitude-dependent time and distance windows follow a slightly modified procedure developed by Grünthal *et al.* (1985), also described in Burkhard and Grünthal (2009). Through a series of tests we adapt the size of the magnitude-dependent time and space windows to the high seismic activity in Vanuatu. For each magnitude bin, the adequate size is determined by the minimal size in time and space that still yields a catalog of Poisson-distributed events. In the case of Vanuatu, the windows turned out to be about half the size of those identified for continental Europe by Grünthal and Wahlström (2006).

Seismicity Parameter. The seismicity in each source zone is characterized by the frequency-magnitude

parameters a and b of the declustered data and the maximum expected magnitude. Because some of the source zones of models A and B do not contain sufficient data to perform regressions, we aggregate zones for the estimation of b -values. The criteria for the aggregation are (1) the source zones lie in the same depth range, and (2) they have comparable levels of seismic activity. We follow *Weichert* (1980) in estimating the frequency-magnitude parameters with the maximum likelihood method. Two typical examples of frequency-magnitude plots are shown in Figure 7. Table 1 lists the computed b -values for all source zones of model A, and Figure 8 shows the plots of the source zones. The b -values vary between 0.65 and 0.75 (see Table 1). Although we computed b -values for all source zones, we emphasize that those obtained for the zones of diffuse seismicity are less reliable. As discussed in the context of the source zone models, we

Figure 7. Magnitude-frequency relations for two exemplary source zones: the southern block at shallow depths (0-60 km) from model A (top) and the deep subduction zone (120-200 km) from model C (bottom). The source zones for the respective depth bin and seismicity model are displayed in the lower left-hand corner of the diagram with the investigated zone shaded in gray. The cumulative annual frequency of events (in steps of 0.5 magnitude units) is indicated as a dot. The best fit for events with $M_w > 5$ is displayed as a solid line. For the southern block (top) 175 events were used for the fit yielding the b -value $b = 0.710(\pm 0.023)$; in the deep subduction zone (bottom) 588 events were utilized to determine the b -value of $b = 0.751(\pm 0.032)$. The minimum magnitude was set to M_w 5 and is marked by a vertical solid line.

Table 1

Seismicity Parameters for Model A*

Number	Region	b -value	$\nu(4.5)$	M_{max2}
Seismicity Parameter for Depth Range 0-60 km				
1	Diffuse-West	1.58	3.26	6.8
2	Northern segment	0.71	7.49	8.3
3	Torres Massif collision	0.71	6.21	8.0
4	D'Entrecasteaux collision	0.71	4.77	7.7
5	Central segment	0.71	10.77	7.9
6	Southern segment	0.71	10.05	7.6
7	Loyalty collision	0.71	3.10	7.3
8	Backarc-North	0.71	2.08	6.6
9	Aoba	0.71	3.59	8.0
10	Central backarc trench	0.71	3.73	7.5
11	Backarc-Efate	0.71	1.93	6.9
12	Backarc-South	0.71	2.76	7.5
13	Backarc-Loyalty	0.71	0.96	6.4
14	Diffuse-East	1.58	3.03	6.5
Seismicity Parameter for Depth Range 60-120 km				
1	Diffuse-Northwest	1.58	1.18	5.9
2	Diffuse-South	1.58	1.57	5.9
3	Northern segment	0.65	8.97	7.9
4	D'Entrecasteaux collision	0.65	6.08	7.7
5	Gap zone	0.65	1.03	7.3
6	Southern segment	0.65	5.75	7.9
7	Diffuse-Northeast	1.58	1.00	7.2
Seismicity Parameter for Depth Range 120-200 km				
1	Diffuse-West	1.58	1.18	5.9
2	Northernmost segment	0.75	4.36	7.3
3	Northern segment	0.75	23.14	8.2
4	Gap zone	0.75	0.63	6.3
5	Tanna	0.75	4.33	8.2
6	Southern segment	0.75	2.61	7.8
7	Diffuse-East	1.58	0.17	5.7

*See Figure 8 for the numbering of source zones in the depth ranges 0-60 km, 60-120 km, and 120-200 km.

suspect that the seismic activity in these zones is partly spurious.

In prior studies *Acharya* (1971) found comparable b -values of 0.81 for shallow depths (0-70 km) and 0.71 for intermediary depths (70-300 km). For events exceeding 300 km of focal depth, *Acharya* (1971) obtained b -values as low as 0.48; no comparable deep-focus event is considered in this study. We hypothesize that the limited coverage of seismic networks in the

Figure 8. Plots of source zones for model A. (a) Zones for depth range 0-60 km. (b) Zones for depth range 60-120 km. (c) Zones for depth range 120-200 km. See Table 1 for seismicity parameters for model A.

1970s might explain these very low b -values at great depths. Hofstetter *et al.* (2000) reported higher b -values than Acharya (1971), ranging from 1.05 to 1.64 for various zones and depth ranges. These higher b -values as compared to our estimates are largely accounted for by the fact that Hofstetter *et al.* (2000) used non-declustered data. Evidently, declustering dramatically decreases the number of low-magnitude events included in the regressions, yielding lower b -values. Acharya (1971) did not elaborate in detail on clustering, but the limited number of events included in his study suggests that most of them are mainshocks.

In our study we describe the frequency of earthquakes within each source zone by the annual rate of earthquakes $\nu(M) = 10^{a-bM}$ exceeding the minimum magnitude $M_{min} = 4.5$. The $\nu(4.5)$ values vary significantly for the different source zones, partly because they depend on the volume of the source zone. Still, it is interesting to note that the maximum of $\nu(4.5) = 10.77$ is reached in the central segment around Efate (see Fig. 6, Table 1, Fig. 8a), which is not accounted for by its size. An overview of the seismicity parameter [b -value, $\nu(4.5)$] and maximum magnitude $M_{max\ 2}$ computed for model A is given in Table 1, and the source-zone plots are shown in Figure 8.

The range of probable upper bound magnitudes is based on the largest historic event that has occurred in the respective zone. But because of the limited observation period, the maximum observed magnitude M_{obs} is only a lower bound for the range of maximum expected magnitudes. For the logic tree we will therefore consider the uncertainty in this parameter and use three different increments for the maximum expected magnitude: $M_{max\ 1} = M_{obs} + 0.25$, $M_{max\ 2} = M_{obs} + 0.5$, and $M_{max\ 3} = M_{obs} + 0.75$ (for the values of $M_{max\ 2}$ used in model A, see Table 1 and Fig. 8).

Ground Motion

We select four attenuation relations (Crouse, 1991; Youngs *et al.*, 1997; Takahashi *et al.*, 2000; Lussou *et al.*, 2001) for our seismic hazard calculations. The criteria for the selection are (1) the usage of subduction zone data, (2) the quality of the data used for the derivation, (3) the explicit inclusion of focal depth as a variable, and (4) the incorporation of high enough magnitudes. Finally, we argue that the four attenuation relationships chosen reflect the epistemic diversity of available expertise concerning empirical attenuation.

The approaches by Crouse (1991) and Youngs *et al.* (1997) both use the same functional form, with the difference that Youngs *et al.* (1997) additionally differentiates between interface and intraslab earthquakes. The uncertainties associated with the location of most earthquakes in our catalog complicate their

classification as interface or intraslab events. Thus, we follow Youngs *et al.* (1997) in using the focal depth as a criterion for this classification: We assume that events in the shallow depth range (0-60 km) are generally interface earthquakes, and that the majority (80%) of those at greater depths (>60 km) are intraslab events (Youngs *et al.*, 1997). There is no doubt that this assumption is an oversimplification of the actual seismicity, but given the quality of data available at the present time, it is not feasible to aim for inclusion of greater detail.

None of the described attenuation models is applicable over the whole range of seismicity data in Vanuatu; Takahashi *et al.* (2000) and Lussou *et al.* (2001) both restricted their analyses to shallow events. Accordingly, we use their attenuation relations only in our hazard calculations for the shallow depth range (0-60 km). Crouse (1991) originally derived his attenuation model in order to estimate the expected ground motion of earthquakes in the Cascadia subduction zone. In contrast to Youngs *et al.* (1997), he does not comment on the applicability of his model to other subduction zones. Youngs *et al.* (1997) suggest that their relation appropriately describes the attenuation for subduction zone interface and intraslab earthquakes of $M_w \geq 5$ for distances of 10-500 km. However, their data set contains no records of very deep earthquakes. Their deepest event occurred at a focal depth of 229 km, and only 7 earthquakes in the depth range 150-200 km are taken into account for the regression analysis.

Thus, we note that the attenuation relations used here might not accurately model the ground motion generated by deep (>150 km focal depth) events. However, the ramifications of this limitation for our study are minor. Events originating deeper than 200 km are discarded due to their negligible contribution to seismic hazard. We also investigate to which degree the depth range 120-200 km is modeled realistically by the applicable attenuation relations by Crouse (1991) and Youngs *et al.* (1997) and find that both possibly overestimate the ground motion generated by deep events. We observe that the ground motion for an event of given magnitude located at a given epicentral distance increases with increasing depth of the event. Whether this tendency represents an artifact or a real feature is unclear (R. R. Youngs, personal commun., 2009). However, the hazard contributions of events in the deep depth range (120-200 km) remain small as expected (see Results section).

An additional issue arises from the fact that Youngs *et al.* (1997) use the closest distance to the rupture surface as a measure of distance for their regressions. In accordance with the three other models, we use hypocentral distance instead. For small events this is an appropriate substitute. For large events, the differ-

ence between these two source-to-site distance metrics can be considerable and introduces a potentially large bias. In order to quantify this bias, we adapt the technique suggested by *Scherbaum et al.* (2004) to convert the given hypocentral distances to rupture distances for crustal earthquakes. A comparison of the ground motions based on these two different distance measures shows that this conversion has only a small effect on the final result. Also, the additional precision gained through the conversion is outbalanced by the well-known problem of quantifying the uncertainties associated with different distance metrics occupying neighboring branches of a logic tree (*Scherbaum et al.*, 2004; *Bommer et al.*, 2005). Therefore, we continue to use the hypocentral distance to model source-to-site distances in the attenuation relation by *Youngs et al.* (1997) but are aware of the bias that is inherent in analyses of this type.

Before moving on to the discussion of the logic-tree approach, we believe that a brief justification for using only empirical attenuation relationships in this preliminary PSHA for Vanuatu is in order. Empirical attenuation relationships such as the four used in this study are obviously limited by the availability of ground-motion data. This caveat applies not only to deep events (see previous discussion) and those at short (<50 km) distances (*Youngs et al.*, 1997) but most importantly to megathrust events. Megathrust events dominate seismic hazard in subduction environments and are at the same time associated with recurrence intervals in the range of a few hundred years. Thus, they are inevitably underrepresented in most earthquake catalogs upon which empirical attenuation relationships rely. Significant progress in capturing the hazard contributions of megathrust events

has come from stochastic finite-fault ground-motion models (*Silva et al.*, 1990; *Wong et al.*, 2000). These more sophisticated models have greatly improved our understanding of seismic hazard in the Cascadia subduction zone (*Gregor et al.*, 2002). Unfortunately, the adoption of an analogous approach for Vanuatu is hampered by our limited understanding of the control that segmentation along a convergent margin exerts on earthquake magnitude, location, and rupture dynamics. Conflicting evidence exists regarding this crucial question. While the great Sumatra-Andaman earthquakes in 2004 and 2005 terminated abruptly along a common boundary (e.g., *Franke et al.*, 2008), the great Solomons earthquake on 1 April 2007 cut through the subducting Simbo Ridge transform seemingly unhindered and in doing so was the first megathrust rupture to involve two subducting plates (*Taylor et al.*, 2008). Further challenges for a more comprehensive approach to seismic hazard than the preliminary one proposed in this study include evidence for strong lateral variations in intraplate coupling (*Calmant et al.*, 1997), the partitioning of interseismic and coseismic displacements (*Lagabrielle et al.*, 2003), the role of asperities (*Chatelain et al.*, 1983), and the importance of the central backarc trench (*Regnier et al.*, 2003).

Logic-Tree Approach

We use the logic-tree approach to account for the epistemic uncertainties associated with a probabilistic hazard assessment. The main contributors to uncertainty are (1) the attenuation models, (2) the definition of seismic zones, and (3) the derivation of seismicity

Figure 9. Logic tree for the shallow depth range (0–60 km) including the source zone models, the ground-motion models, the frequency-magnitude parameters, and the maximum magnitudes. The corresponding branches for the other two depth ranges follow the same setup but use different attenuation relations: *Youngs et al.* (1997), intraslab mechanism (40%), *Youngs et al.* (1997), interface mechanism (10%), and *Crouse* (1991) (50%).

parameters. They can be represented in a logic tree as shown in Figure 9. Therein, each level of the tree represents one source of epistemic uncertainty and each terminal node represents one state of nature. Corresponding to each terminal node there is a hazard curve with an assigned weighting that is the product of the weighting of all intermediate branches in the path from the root to the terminal node.

Apart from the Gutenberg–Richter parameters a and b , it is common to use the parameters α and β to calculate the annual rate of earthquakes $\nu(M)$ defined in the previous section. The relation between the parameters is given by $\nu(M) = e^{\alpha-\beta M} = 10^{a-bM}$. The weighting of the magnitude-frequency parameters β and ν is based on a statistical rationale applied by Grünthal and Wahlström (2006); in a normal distribution 68% of the probability mass is contained within one standard deviation above and below the mean. Accordingly, the intervals $(-\infty, \mu - \sigma)$ and $(\mu + \sigma, \infty)$ each carry about 16%. The point estimates of the Gutenberg–Richter parameters are accordingly weighted with 0.68. The upper and lower bound branches (+1.40, and -1.40,) are weighted with 0.16, accordingly. Note that the factor ± 1.4 is chosen such that the areas below the intervals $(-\infty, \mu - \sigma)$ and $(\mu + \sigma, \infty)$ are again split into two equal halves.

For reasons of simplicity, the displayed diagram (Fig. 9) only refers to the shallow depth range (0–60 km). The only difference between the shallow branch and those for the deeper depth ranges is the choice of attenuation relations. Because the ground-motion models by Takahashi *et al.* (2000) and Lussou *et al.* (2001) are not applicable at large depths, we replace the weighting of the attenuation relations by Youngs *et al.* (1997), intraslab mechanism (40%), Youngs *et al.* (1997), interface mechanism (10%), and Crouse (1991) (50%) for the intermediate and deep depth range. The weighting of the three source zone models A, B, and C implies that the seismic gap around the island of Efate is primarily (with 80% probability) considered to be an area of generally low seismicity. As already discussed both in the context of tectonic setting and for the seismic source zone models, the majority of available evidence supports this interpretation (e.g., Chatelain *et al.*, 1986; Taylor *et al.*, 1990; Chatelain *et al.*, 1992; Chatelain *et al.*, 1993; Prévot *et al.*, 1994; Greene *et al.*, 1994; Calmant *et al.*, 1995; Taylor *et al.*, 1995; Calmant *et al.*, 2003).

Results

The aim of this study is to evaluate seismic hazard on a Cartesian grid of sites spaced by 0.1° throughout Vanuatu. For each site we first compute the appropriate seismicity parameters based on the source model

and then estimate the PGA level that is expected to be exceeded in 50 yr with a 10% probability. The latter requires the specification of ground conditions for each site, which should be chosen based on the local geology. Two site conditions, rock and stiff soil (see Table 2), capture most of the complexity of ground conditions on the Vanuatu Islands. Sites located in the immediate vicinity of igneous outcrops or on exposed terraces of sedimentary rock are best represented by rock conditions, and all other sites by stiff soil conditions (Table 2).

The key results of our computations are shown in Figures 10, 11, and 12. All of these maps refer to a 475 yr return period or, equivalently, a 10% probability of exceedence in 50 yr. The colored areas highlight the exact domain over which the hazard calculation was performed. It is important to note that the computational domain extends well beyond the islands themselves because a spurious decrease in hazard might arise in the immediate vicinity of a boundary. For example, the top right and bottom left hazard map in Figure 10 (rock 0–200 km and soil 0–120 km) and the top right hazard map in Figure 12 (rock 50%) show a narrow rim of strongly decreasing acceleration values along the southeastern boundary of the computational domain. This is due to the areal limitation of our source zone model and has no practical meaning.

Figure 10 highlights the limited importance of the deep depth range (120–200 km). It shows the expected median PGA in Vanuatu for varying site conditions and treatment of deep events. Figure 11 shows the expected median SGA for periods of 1 sec and both site classes that are relevant for Vanuatu. Both maps are based on events from the entire depth range considered, namely 0–200 km. Finally, Figure 12 compares different quantiles of our hazard estimate (PGA) for rock sites and depths from 0 to 200 km.

Three aspects of Figure 10 merit further discussion: (1) Holding the site condition constant, we find that the inclusion of the depth range 120–200 km increases the expected median PGA along the Vanuatu arc by roughly $0.1g$. In the case of stiff soil, the highest level of seismic hazard ($0.77g$) is reached in the

Table 2

Definition of Site Conditions Used in the Attenuation Relationships

Attenuation Relation	Site Categories and Classification Criterion
Youngs <i>et al.</i> (1997)	Rock and soil
Takahashi <i>et al.</i> (2000)	Medium and stiff soil (EC8 classification)
Lussou <i>et al.</i> (2001)	Sites C and D (EC8 classification)
Crouse (1991)	No site specification

Figure 10. The maps show the expected median PGA in units of g with a 10% probability of exceedence within 50 yr (475 yr return period). The upper left-hand figure is calculated for rock sites considering only events at shallow (0-60 km) and intermediary (60-120 km) depths; the upper right-hand figure also refers to rock sites, but includes the entire depth range 0-200 km. Accordingly, the bottom left-hand figure is calculated for stiff soil and depths <120 km, and the bottom right-hand figure is calculated for stiff soil and the full depth range 0-200 km. As expected, the contribution of deep events (>120 km) is small.

east of Espiritu Santo if events with focal depth 0-200 km are considered. If those in the range of 120-200 km are neglected, the maximum level of seismic hazard decreases to roughly $0.67g$ for the same area.

The situation is analogous for rock conditions. Thus, the hazard contributions of deep events (120-200 km) are limited, and it is justified to discard even deeper events (>200 km). However, despite the limited con-

Figure 11. Probabilistic seismic hazard maps showing the median SGA for a period of 1 sec in units of g with a 10% probability of exceedence within 50 yr (475 yr return period). Both maps include the full depth range (0-200 km). The difference is that the left hazard map is based on rock conditions and the right map is based on stiff soil.

tribution of deep events (120-200 km) to seismic hazard, they should not be excluded a priori from the hazard assessment because seismic activity in the Wadati-Benioff zone intensifies at depth >120 km compared to the intermediate depth range (60-120 km). (2) Our results confirm that stiff soil leads to significantly higher seismic hazard than rock. For rock conditions the expected median PGA with a 10% probability of exceedence in 50 yr varies in the interval 0.51-0.66 g , and for stiff soil conditions the corresponding median PGA lies within the larger interval 0.56-0.82 g . Overall, we consider most sites in Vanuatu to be best represented by stiff soil conditions, particularly the densely inhabited areas along the shore of Efate. (3) We find that the spatial distribution of seismic hazard is rather uniform. Given the considerable uncertainty of this analysis, the differences in expected median PGAs such as the one obtained for Malekula (0.77 g) and the one obtained for Efate (0.65 g) might indicate a trend but are not significant. Nonetheless, it is interesting to note that *Nunn et al.* (2006) also arrived at the conclusion that seismic hazard at Malekula might be elevated based on an analysis of oral traditions recalling the disappearance of islands.

Although the seismicity is dominated by the sub-

duction, there is no indication that proximity to the subduction zone is directly correlated with the level of seismic hazard. This has two reasons. First, most of the islands are located at a fairly similar distance to the trench and are not very wide. Second, crustal and volcanic sources contribute notably to seismic activity, predominantly in the backarc, where one of the largest events in our data has occurred (*Regnier et al.*, 2003). The seismic sources in the backarc offset the slightly lower hazard from subduction events. This is particularly relevant for the backarc area at 13°30' S to 16°30' S that is characterized by crustal shortening and high seismic activity along its eastern margins.

The logic-tree approach allows us to examine the sources of uncertainty associated with our analysis (Fig. 12). All four hazard maps are based on the site condition rock and the depth range of 0-200 km. The four hazard maps are based on the 16%, 50%, and 84% quantiles and the mean value of the distribution of estimated PGAs obtained from the logic-tree approach for a 475 yr return period (Fig. 12). The differences between the four maps are due to epistemic uncertainty. The aleatory variability controls the absolute level of hazard. Note that the prior mean hazard estimates by *McCue* (1999) in the context of GSHAP lie between our 16% and 50% quantile.

Figure 12. Four quantiles of the expected PGA with a 10% probability of exceedence in 50 yr (475 yr return period). All maps are based on rock conditions and include focal depths of 0–200 km. The 16% quantile (upper left), median (upper right), mean (bottom left), and 84% quantile (bottom right) quantify the variance inherent in this probabilistic assessment.

In addition to our nationwide analysis of the level of seismic hazard, we also evaluate hazard specifically for Port Vila, the capital and largest city of Vanuatu. The ground conditions at Port Vila are well-constrained through a prior study (Regnier *et al.*, 2000) and correspond to the stiff soil classification used here. Figure 13 shows the probabilistic seismic hazard curves for Port Vila corresponding to the mean as well as the 16%, 50%, and 84% quantiles of the

distribution. Figure 14 shows the uniform hazard spectrum, that is, the expected SGA for periods between 0.1–2 sec in the form of the 16%, 50%, and 85% quantiles and the mean value. The ground-motion models used here only allow the calculations at 5 periods, where all models provide the appropriate common parameters. We hope that these estimates might be useful in the design of more resilient building structure in Port Vila.

Figure 14. Probabilistic hazard curve for Port Vila. We plot the probability of exceedence over the expected PGA in g. Computations are based on stiff soil conditions and include focal depths of 0–200 km. The uncertainty associated with the computation is indicated by the 16% quantile, median, mean, and 84% quantile in analogy to the hazard maps plotted in Figure 12.

Discussion

The two main challenges for constructing a seismic hazard model for Vanuatu are (1) to allow for conflicting geodynamical interpretations of the arc, particularly with respect to the sizable gap in the Wadati-Benioff zone at depths >60 km below the island of Efate (Figs. 2 and 3), and (2) to accurately model the ground motions caused by the various seismic sources, most importantly by the megathrust. We approach these challenges by constructing three different source zone models (Fig. 6), each representing a distinct interpretation of the observational evidence. While each model by itself is an incomplete representation of the complex interplay between subduction, collision with submarine ridges, and backarc rifting, a combination of all three models accurately reflects our present knowledge of seismicity patterns in Vanuatu. An important caveat in our estimation of seismic hazard in Vanuatu is the lack of ground-motion models developed specifically for Vanuatu and our limited understanding of the rupture dynamics of megathrust events in segmented arcs. Because megathrust events dominate seismic hazard, advancing our ability to model them would constitute the most significant step toward refining our

Figure 13. Expected SGA with a 10% probability of exceedence in 50 yr (475 yr return period) for different periods in seconds at Port Vila. We plot the probability of exceedence over the expected SGA in g. Computations are based on stiff soil conditions and include focal depths of 0–200 km. The uncertainty associated with the computation is indicated by the 16% quantile, median, mean, and 84% quantile in analogy to the hazard maps plotted in Figure 12. The dashed line segment indicates that the spectra of the median and median-u values were adapted slightly according to the two upper curves.

assessment of seismic hazard beyond the preliminary model presented in this study.

According to our estimates, the PGA values in Vanuatu are considerably higher than the results of *McCue* (1999) with less spatial variations along the island arc. The deviations are particularly strong for the islands north of Epi and east of the Aoba basin. The comparatively higher hazard estimates of our study compared to *McCue* (1999) might reflect the problem that backarc activity was not fully taken into account in prior analyses. Despite the previously mentioned caveat, we are confident that the spatial homogeneity of seismic hazard is a robust result.

A comparison with the hazard maps for New Zealand (*Stirling et al.*, 2002) also suggests that the general level of seismic hazard we obtained for Vanuatu is realistic. *Stirling et al.* (2002) report PGAs in the range of $0.1g$ – $1.0g$ for a 475 yr return period. The spatial variation of seismic hazard is much higher in New Zealand, but that is to be expected given the different tectonic setting. Apart from studies of New Zealand (*Stirling et al.*, 2002), Fiji (*Jones*, 1997), and Australia (e.g., *Gaull et al.*, 1990) few systematic hazard assessments are available for countries in the southwest Pacific despite its richness in seismicity. Our work provides an important first step toward filling this gap. Data limitations and our incomplete understanding of rupture dynamics in segmented arcs prevent us from building a more complex hazard model at the present time. We hope that future research will further refine our analysis.

Data and Resources

The USGS/NEIC catalog was searched using http://neic.usgs.gov/neis/epic/epic_rect.html (last accessed May 2005). We incorporate both the USGS/NEIC Preliminary Determinations of Epicenters (PDE) 1973 present database and the National Geophysical Data Center (NGDC) Significant Earthquakes Database.

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References

- Acharya, H. (1971). Magnitude-frequency relations and deep-focus earthquakes, *Bull. Seismol. Soc. Am.* **61**, no. 5, 1345–1350.
- Bommer, J. J., F. Scherbaum, H. Bungum, F. Cotton, F. Sabetta, and N. A. Abrahamson (2005). On the use of logic trees for ground-motion prediction equations in seismic-hazard analysis, *Bull. Seismol. Soc. Am.* **95**, no. 2, 377–389.
- Burkhard, M., and G. Grünthal (2009). Seismic source zone characterization for the seismic hazard assessment project PEGASOS by the Expert Group 2 (EG 1b), *Swiss J. Geosci.* **102**, no. 1, 149–188.
- Calmant, S., P. Lebellegard, F. Taylor, M. Bevis, D. Maillard, J. Recy, and J. Bonneau (1995). Geodetic measurements of convergence across the New Hebrides subduction zone, *Geophys. Res. Lett.* **22**, no. 19, 2573–2576.
- Calmant, S., B. Pelletier, P. Lebellegard, M. Bevis, F. W. Taylor, and D. A. Phillips (2003). New insights on the tectonics along the New Hebrides subduction zone based on GPS results, *J. Geophys. Res.* **108**, no. B6, 2319.
- Calmant, S., B. Pelletier, R. Pillet, M. Rgnier, P. Lebellegard, D. Maillard, F. Taylor, M. Bevis, and J. Recy (1997). Interseismic and coseismic motions in GPS series related to the MS 7.3 July 13, 1994 Malekula earthquake, central New Hebrides subduction zone, *Geophys. Res. Lett.* **24**, no. 23, 3077–3080.
- Chatelain, J. L., and J. R. Grasso (1992). Spatial and temporal seismic energy release in the Efaté region (central New Hebrides island arc): Evidence for buckling? *Geophys. Res. Lett.* **19**, no. 11, 11571160.
- Chatelain, J. L., R. K. Cardwell, and B. L. Isacks (1983). Expansion of the aftershock zone following the Vanuatu (New Hebrides) earthquake on 15 July 1981, *Geophys. Res. Lett.* **10**, no. 5, 385–388.
- Chatelain, J. L., B. Guillier, and J. P. Gratier (1993). Unfolding the subducting plate in the central New Hebrides Island Arc: Geometrical argument for detachment of part of the downgoing slab, *Geophys. Res. Lett.* **20**, no. 8, 655–658.
- Chatelain, J. L., B. L. Isacks, R. K. Cardwell, R. Prevot, and M. Bevis (1986). Patterns of seismicity associated with asperities in the central New Hebrides Island arc, *J. Geophys. Res.* **91**, no. B12, 2497–2519.
- Chatelain, J., P. Molnar, R. Prevot, and B. Isacks (1992). Detachment of part of the downgoing slab and uplift of the New Hebrides (Vanuatu) islands, *Geophys. Res. Lett.* **19**, no. 14, 1507–1510.
- Choudhury, M. A., G. Poupinet, and G. Perrier (1975). Shear velocity from differential travel times of short-period ScS-P in New Hebrides, Fiji-Tonga and Banda Sea regions, *Bull. Seismol. Soc. Am.* **65**, no. 6, 1787–1796.
- Christova, C., C. H. Scholz, and H. Kao (2004). Stress field in the Vanuatu (New Hebrides) Wadati-Benioff zone inferred by inversion of earthquake focal mechanisms: Evidence for systematic lateral and vertical variations of principal stresses, *J. Geodyn.* **37**, no. 2, 125–137.
- Chung, W. Y., and H. Kanamori (1978). Mechanical model for plate deformation associated with aseismic ridge subduction in the New Hebrides arc, *Tectonophysics* **50**, no. 1, 29–40.
- Coleman, P. J. (1970). Geology of the Solomon and New Hebrides Islands, as part of the Melanesian re-entrant, southwest Pacific, *Pacific Sci.* **24**, 289–314.
- Collot, J. Y., J. Daniel, and R. V. Burne (1985). Recent tectonics associated with the subduction collision of the d'Entrecasteaux zone in the central New Hebrides, *Tectonophysics* **112**, no. 1–4, 325–356.
- Cornell, C. (1968). Engineering seismic risk analysis, *Bull. Seismol. Soc. Am.* **58**, no. 5, 1583–1606.
- Crouse, C. (1991). Ground-Motion attenuation equations for earthquakes on the Cascadia subduction zone, *Earthq. Spectra* **7**, no. 2, 201–236.
- Daniel, J., and H. Katz (1981). D'Entrecasteaux Zone, trench and western chain of the central New Hebrides island arc: Their significance and tectonic relationship, *Geo-Mar. Lett.* **1**, no. 3–4, 213–219.
- Engdahl, E. R., R. van der Hilst, and R. Buland (1998). Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. Seismol. Soc. Am.* **88**, no. 3, 722–743.
- Franke, D., M. Schnabel, S. Ladage, D. R. Tappin, S. Neben, Y. S. Djajadihardja, C. Müller, H. Kopp, and C. Gädicke (2008). The great Sumatra-Andaman earthquakes-Imaging the boundary between the ruptures of the great 2004 and 2005 earthquakes, *Earth Planet. Sci. Lett.* **269**, no. 1–2, 118–130.
- Gaull, B., M. Michael-Leiba, and J. Rynn (1990). Probabilistic earthquake risk maps of Australia, *Aust. J. Earth Sci.* **37**, 169–187.
- Geist, E. L., M. A. Fisher, and D. W. Scholl (1993). Large scale deformation associated with ridge subduction, *Geophys. J. Int.* **115**, no. 2, 344–366.
- Giardini, D. (1999). The GSHAP Global Seismic Hazard Map, *Ann. Geofis.* **42**, no. 6, 1225–1228.
- Greene, H., J. Collot, M. Fisher, and A. Crawford (1994). Neogene tectonic evolution of the New Hebrides island arc: A review incorporating ODP drilling results, in *Proc. of the Ocean Drilling Program, Scientific Results*, C. O. Fox (Editor), Vol. 134, Ocean Drilling Program, College Station, Texas, 1946.
- Gregor, N. J., W. J. Silva, I. G. Wong, and R. R. Youngs (2002). Ground-motion attenuation relationships for Cascadia subduction zone megathrust earthquakes based on a stochastic finite-fault model, *Bull. Seismol. Soc. Am.* **92**, no. 5, 1923–1932.
- Grünthal, G. (1985). The updated earthquake catalogue for the German Democratic Republic and adjacent areas-statistical data characteristics and conclusions for hazard assessment, *3rd International Symposium on the Analysis of Seismicity and Seismic Risk*, Liblice/Czechoslovakia, 17–22 June 1985, Proceedings I, 19–25.
- Grünthal, G., and R. Wahlström (2006). New generation of probabilistic seismic hazard assessment for the area Cologne/Aachen considering the uncertainties of the input data, *Nat. Haz.* **38**, no. 1–2, 159–176.
- Hanuš, V., and J. Vaněk (1983). Deep structure of the Vanuatu (New Hebrides) island arc: Intermediate depth collision of subducted lithospheric plates, *New Zealand J. Geol. Geophys.* **26**, 133–154.
- Hanuš, V., and J. Vaněk (1991). Paleoplates buried in the upper mantle and the cyclic character of subduction, *J. Geodyn.* **13**, no. 1, 29–45.
- Hofstetter, A., A. Shapira, K. Bulehite, T. Jones, K. Ma, A. Malitzky, A. Papabatu, G. Prasad, M. Regnier, G. Shorten, A. Singh, M. Stephen, and L. Vuetibau (2000). Frequency-Magnitude Relationships for seismic areas around the capital cities of Solomon, Vanuatu, Tonga and Fiji Islands, *J. Seism.* **4**, 285–296.
- Jones, T. (1997). Probabilistic earthquake hazard assessment for Fiji, in *Technical Report 46*, GSO Record, Canberra, Australia.
- Lagabrielle, Y., B. Pelletier, G. Cabioch, M. Regnier, and S. Calmant (2003). Coseismic and long-term vertical displacement due to backarc shortening, central Vanuatu: Offshore and onshore data following the M_w 7.5, 26 November 1999 Ambrym earthquake, *J. Geophys. Res.* **108**, no. B11, 2519.
- Louat, R., and B. Pelletier (1989). Seismotectonics and present-day relative plate motions in the New Hebrides-North Fiji basin region, *Tectonophysics* **167**, 4155.
- Lussou, P., P. Bard, F. Cotton, and Y. Fukushima (2001). Seismic design regulation codes: Contribution of K-NET data to site effect evaluation, *J. Earthq. Eng.* **5**, no. 1, 13–33.
- Maillet, P., M. Monzier, M. Selo, and D. Storz (1983). The d'Entrecasteaux Zone (South-West Pacific)-a petrological and geochronological reappraisal, *Mar. Geol.* **53**, no. 3, 179–197.
- McCue, K. (1999). Seismic hazard mapping in Australia, the southwest

- pacific and Southeast Asia, *Ann. Geofis.* **42**, no. 6, 1191-1198.
- McGuire, R. (1976). FORTRAN computer program for seismic risk analysis, Technical Report 76-77, *U.S. Geological Survey Open File Report*.
- Meffre, S., and A. J. Crawford (2001). Collision tectonics in the New Hebrides arc (Vanuatu), *Isl. Arc* **10**, no. 1, 33-50.
- Musson, R. (1999). Probabilistic seismic hazard maps for the North Balkan region, *Ann. Geofis.* **42**, no. 6, 1109-1124.
- Nunn, P. D., M. Baniala, M. Harrison, and P. Geraghty (2006). Vanished islands in Vanuatu: New research and a preliminary geohazard assessment, *J. Roy. Soc. New Zealand* **36**, no. 1, 37-50.
- Pascal, G. (1974). Contribution à l'étude de la sismicité des Nouvelles-Hébrides, *PhD Thesis*, Faculté des Sciences de l'Université de Paris VI.
- Pelletier, B., S. Calmant, and R. Pillet (1998). Current tectonics of the Tonga-New Hebrides region, *Earth Planet. Sci. Lett.* **164**, no. 1, 263-276.
- Prévo, R., and J. Chatelain (1984). Sismicité et risque sismique à Vanuatu, *Technical Report*, ORSTOM, 5-38.
- Prévo, R., J. Chatelain, S. Roecker, and J. Grasso (1994). A shallow double seismic zone beneath the central New Hebrides (Vanuatu): Evidence for fragmentation and accretion of the descending plate, *Geophys. Res. Lett.* **21**, no. 19, 2159-2162.
- Prévo, R., S. Roecker, B. Isacks, and J. Chatelain (1991). Mapping of low P wave velocity structures in the subducting plate of the Central New Hebrides, southwest Pacific, *J. Geophys. Res.* **96**, no. B12, 19825-19842.
- Regnier, M., S. Calmant, B. Pelletier, Y. Lagabrielle, and G. Cabioch (2003). The Mw 7.5 1999 Ambrym earthquake, Vanuatu: A back arc intraplate thrust event, *Tectonics* **22**, no. 4, 1034.
- Regnier, M., S. Morris, A. Shapira, and A. Malitzky (2000). Microzonation of the expected seismic site effects across Port Vila, Vanuatu, *J. Earthq. Eng.* **4**, no. 2, 215-231.
- Risk Engineering Ltd. (1997). FRISK88Mc Users Manual, updated version 1.70.
- Rouland, D., A. Cisternas, R. Denkmann, H. Dufumier, M. Regnier, and M. Lardy (2001). The December 1994 seismic swarm near Aoba (AMBAE) volcano, Vanuatu, and its relationship with the volcanic processes, *Tectonophysics* **338**, no. 1, 23-44.
- Scherbaum, F., J. Schmedes, and F. Cotton (2004). On the conversion of source-to-site distance measures for extended earthquake source models, *Bull. Seismol. Soc. Am.* **94**, no. 3, 1053-1069.
- Shedlock, K., D. Giardini, G. Grünthal, and P. Zhang (2000). The GSHAP Global Seismic Hazard Map, *Seismol. Res. Lett.* **71**, no. 6, 679-689.
- Silva, W., R. Darragh, C. Stark, I. Wong, J. Stepp, J. Schneider, and S. Chiou (1990). A methodology to estimate design response spectra in the nearsource region of large earthquakes using the band-limited-white-noise ground motion model, in *Proc. of the Fourth U.S. National Conf. on Earthquake Engineering*, Vol. 1, 487-494.
- Stirling, M. W., G. H. McVerry, and K. R. Berryman (2002). A new seismic hazard model for New Zealand, *Bull. Seismol. Soc. Am.* **92**, no. 5, 1878-1903.
- Takahashi, T., S. Kobayashi, Y. Fukushima, J. Zhao, H. Nakamura, and P. Somerville (2000). A spectral attenuation model for Japan using strong-motion data base, in *Proc. of the 6th International Conf. on Seismic Zonation*.
- Taylor, F. W., M. G. Bevis, B. E. Schutz, D. Kuang, J. Recy, S. Calmant, D. Charley, M. Regnier, B. Perin, M. Jackson, and C. Reichenfeld (1995). Geodetic measurements of convergence at the New Hebrides island arc indicate arc fragmentation caused by an impinging aseismic ridge, *Geology* **23**, no. 11, 1011-1014.
- Taylor, F. W., R. W. Briggs, C. Frohlich, A. Brown, M. Hornbach, A. K. Papabatu, A. J. Meltzner, and D. Billy (2008). Rupture across arc segment and plate boundaries in the 1 April 2007 Solomons earthquake, *Nat. Geosci.* **1**, no. 4, 253-257.
- Taylor, F. W., R. L. Edwards, and G. Wasserburg (1990). Seismic recurrence intervals and timing of aseismic subduction inferred from emerged corals and reefs of the Central Vanuatu (New Hebrides) frontal arc, *J. Geophys. Res.* **95**, no. B1, 393-408.
- Utsu, T. (2002). Relationships between Magnitude Scales, in *International Handbook of Earthquake & Engineering Seismology*, W. H.-K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), 1, 733-746.
- Wallace, L. M., R. McCaffrey, J. Beavan, and S. Ellis (2005). Rapid microplate rotations and backarc rifting at the transition between collision and subduction, *Geology* **33**, no. 11, 857-860.
- Weichert, D. H. (1980). Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes, *Bull. Seismol. Soc. Am.* **70**, no. 4, 1337-1346.
- Wong, I. G., and W. J. Silva (2000). Predicting great earthquake ground shaking in the Pacific northwest from the Cascadia subduction zone, in *Penrose Conf. 2000: Great Cascadia Earthquake Tricentennial, Program Summary and Abstracts*, Oregon Department of Geology and Mineral Industries, Special Paper 33, 141-143.
- Wyss, M., and Y. Taya (2000). Is background seismicity produced at a stationary Poissonian rate? *Bull. Seismol. Soc. Am.* **90**, no. 5, 1174-1187.
- Youngs, R. R., S. J. Chiou, W. J. Silva, and J. R. Humphrey (1997). Strong ground motion attenuation relationships for subduction zone earthquakes, *Seism. Res. Lett.* **68**, no. 1, 58-73.

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