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Communication

Subduction of Submarine Arc Volcanoes Beneath the Solomon Islands Arc

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Abstract: In the Solomon Islands, arc magmas are erupting on the subducting Australia Plate. These island (Simbo) and submarine arc volcanoes (Kana Keoki, Coleman and Pavuvu) are about to be recycled by rapid subduction. We identify eight of their former equivalents beneath the forearc by the morphologies and deformation structures that are characteristic of seamount subduction. Tsunamigenic earthquakes recently nucleated just ahead of two of the subducting seamounts. A third (Pavuvu), that has indented the subduction front and uplifted the lower forearc, is associated with a historic earthquake gap. It is positioned such that a rupture there has the potential for tsunami waves to impact the capital, Honiara.

Keywords: submarine arc volcanoes; subducted seamounts; tsunami earthquakes; Solomon Islands

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1. Introduction

Volcanic island arcs are produced by the subduction of one oceanic plate beneath another that liberates fluids into the wedge of mantle between them (e.g., [1]). But what happens if the subduction polarity reverses and the newly subducted lithosphere includes a seafloor spreading center? Such is the case in the Solomon Islands of the southwest Pacific (Figure 1; [2–5]). This currently unique circumstance creates several unusual features. First, as seen in Figure 1, there is no bathymetric trench where the 0–6 Ma Woodlark Basin is subducted [6]. Second, there is an along-strike gap in the subducting lithosphere (a "slab window") that allows a portion of the opposite polarity Pacific slab to remain attached, as seen in the earthquake seismicity, and to provide the slab pull to accrete the upper portion of the Ontong Java Plateau in the Malaita accretionary prism between the North Solomon Trench and the Kia–Korigole–Kaipito Fault [3,5,7,8]. Third, there are arc-composition volcanoes on both sides of the subduction front [4,9–15]. The eruption of arc volcanoes on a plate being subducted beneath their own volcanic island arc results in a circular material path reminiscent of ouroboros, which is the ancient symbol that depicts a snake swallowing its tail (as an emblem of wholeness or infinity).

Many aspects of the volcanism in the Solomon Islands are unusual. The main chain of volcanic islands adjacent to the young Woodlark Basin (the New Georgia Group) is abnormally close (50–60 km) to the subduction front and does not sit above a Wadati–Benioff zone. There are arc-composition volcanoes in the forearc (Rendova and Kavachi) as well as large arc-composition edifices on the subducting plate (including Simbo Island, Kana Keoki and Coleman seamounts; [9–12,16]). Swath bathymetry and acoustic imagery now allow us to add to this inventory the Pavuvu submarine volcano, which sits on 5.2 Ma (magnetic Chron 3.4) crust and uplifts the toe of the forearc slope at 9.5° S (Figures 1 and 2), and to identify a further eight seamounts that have been recently subducted beneath the steep forearc lower slope (Figure 2). We present bathymetric, acoustic and magnetic images of these features and describe their characteristics. We show that although the subducting seamounts and forearc substrate are quite different from other regions where they have been identified and modeled, their morphological expression and associated deformation structures appear to be similar. We comment on the implications of this for the occurrence of earthquakes and tsunamis in the region.

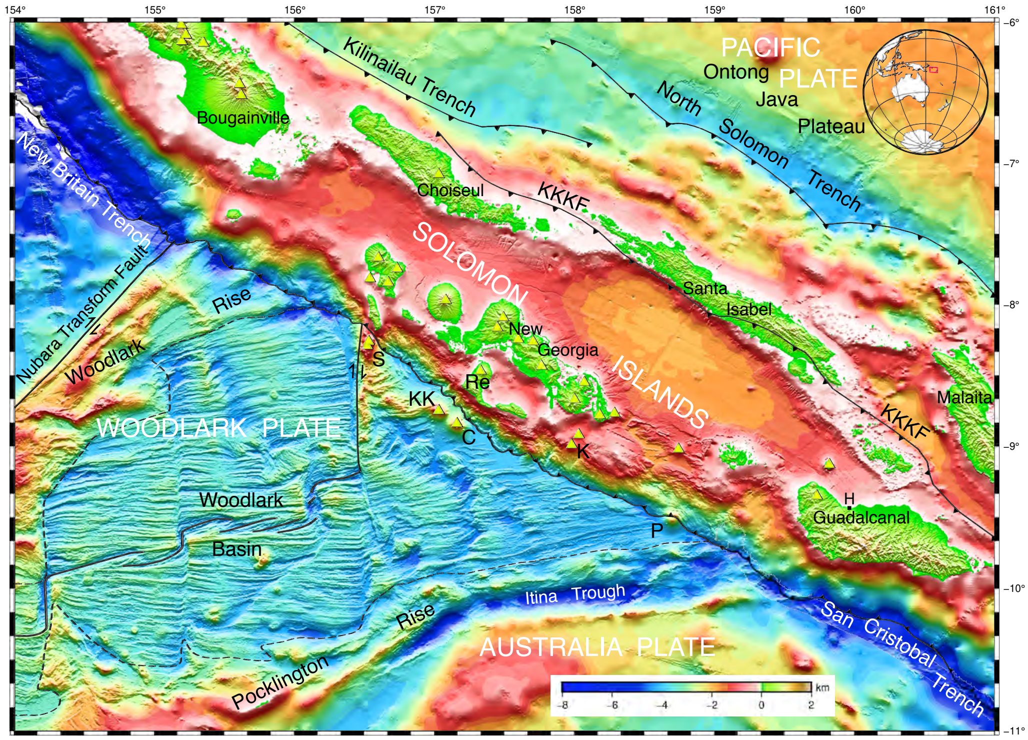

Figure 1. Plate boundaries and named features of the eastern Woodlark Basin–Solomon Islands region, on a base map of bathymetry and topography, sunlit from the north. The boundary between the oceanic crust and rifted margins of the Woodlark Basin is drawn as a dashed line. Active volcanoes from the Smithsonian catalog [15] are located with yellow triangles. Volcano abbreviations include C, Coleman; K, Kavachi, KK, Kana Keoki; P, Pavuvu; Re, Rendova; S, Simbo. KKKF is the Kia–Korigole–Kaipito Fault. H locates the capital, Honiara.

Convergence between the NW-moving Pacific plate and the NE-moving Australia plate is rapid (102.5 km/Myr toward 259° across Guadalcanal [17]. GPS measurements, earthquake seismicity and multichannel seismic profiles show that that convergence is not all accounted for by subduction along the New Britain and San Cristobal Trenches, but that some still occurs at the Kilinailau and North Solomon Trenches and also on faults within the islands [5,18–21]. The Woodlark Basin is opening close to orthogonal to that overall convergence having, within the Brunhes Chron, synchronously reoriented its spreading axes and ceased spreading on the segment east of the Simbo Fracture Zone and Ranongga Transform Fault (Figures 1 and 2 [16,22–24]).

The eastward-deepening and -thinning rifted margins (Woodlark Rise in the north; Pocklington Rise and Itina Trough in the south) have been subducted eastwards beneath the Solomon Islands arc, but the deep New Britain and San Cristobal Trenches each terminate against them [6,25]. In between, there is no bathymetric trench nor outer rise where the young (0–6 Ma) lithosphere of the Woodlark Basin is being subducted, it being too weak to sustain plate flexure (Figures 1 and 2). The rifted margins of the basin localize tears in the subducting slabs and isolate its little-sedimented, hydrothermally cooled, and embrittled young lithosphere that deforms with local rather than flexural isostasy [25].

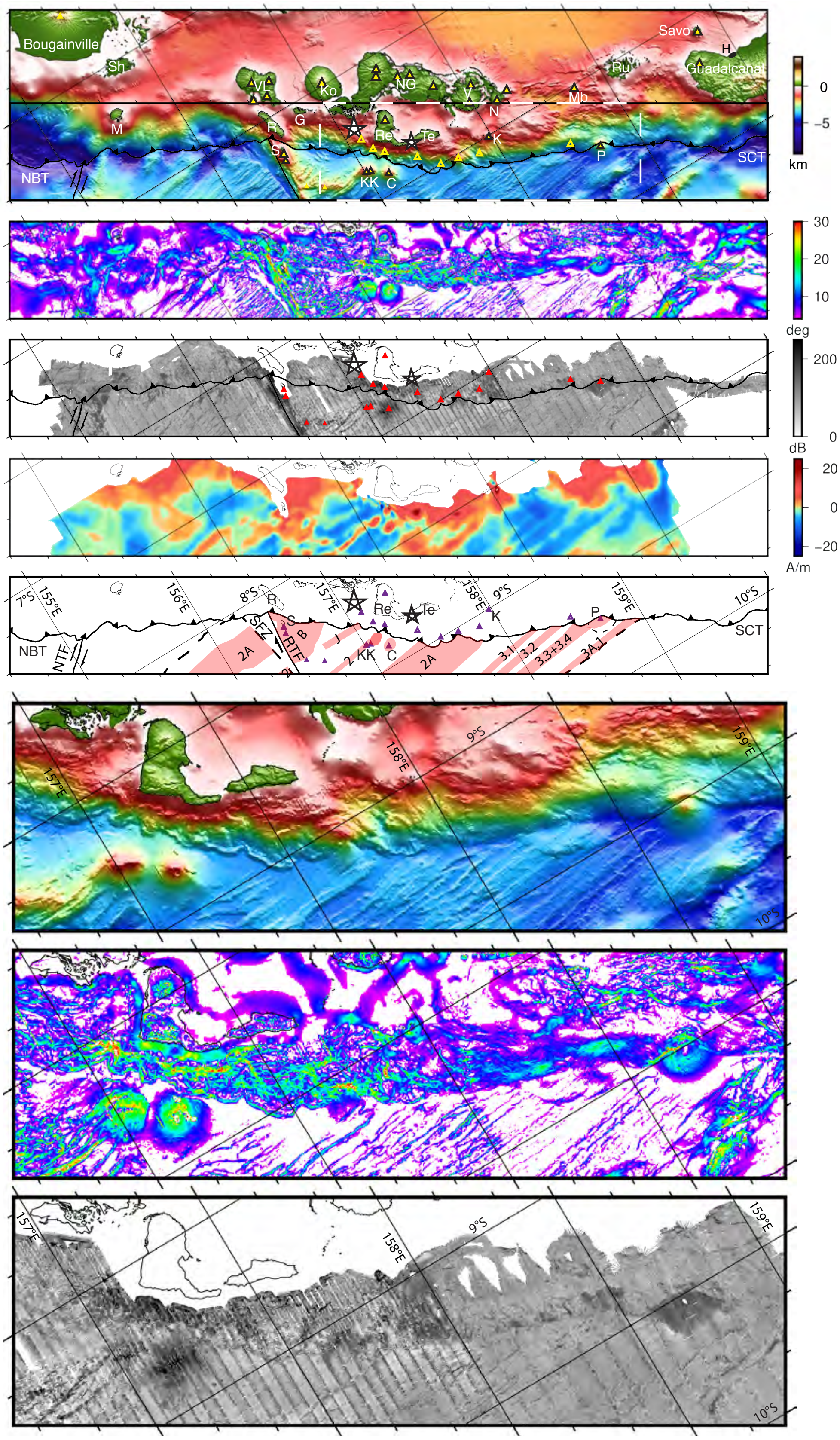

Figure 2. (**Upper half**) shows a five-panel collage of data along and astride the southern subduction front of the Solomon Islands, between the conjugate rifted margins of the Woodlark Basin (dashed

line). The top bathymetry and topography panel is twice as wide as the lower four panels in order to show the main volcanic chain and to provide geographic context. The second panel shows topographic slope (in degrees), the third (**middle**) panel shows seafloor acoustic imagery, the fourth panel shows magnetization, and the fifth (**bottom**) panel shows seafloor spreading magnetic lineations, which are identified and labeled following [22,26]. Data in the top, middle and bottom panels are overlain with the subduction front and transform fault plates boundaries, epicenters of the 2007 and 2010 tsunamigenic earthquakes (stars), active arc volcanoes at the surface (filled triangles) as per the Smithsonian catalog [16] plus Pavuvu, as well as our inferred subsurface locations of 8 volcanoes subducted under the forearc (unfilled triangles). Abbreviations include faults (NTF, Nubara Transform; RTF, Ranongga Transform; SFZ, Simbo Fracture Zone), islands (G, Ghizo; Ko, Kolombangara; M, Mono; Mb, Mborokua; N, Nggatokae, R, Ranongga; Re, Rendova; Ru, Russel, S, Shortland; Te, Tetepare; V, Vangunu; VL, Vella Lavella), submarine volcanoes (C, Coleman; K, Kavachi; KK, Kana Keoki; P, Pavuvu) and H = Honiara. Lower half shows an enlargement of the data in the top three panels within the focus area outlined by a white dashed box in the top panel.

Notwithstanding the weakness of the young oceanic lithosphere, there is paleo-sea-level evidence from coral reef heads and solution notches of episodic Holocene–Quaternary uplift/subsidence of the New Georgia Group consistent with strong subduction coupling, with strain being released in large, infrequent megathrust ruptures [27–30]. This was confirmed by the largest earthquake recorded in the Solomon Islands, namely the tsunamigenic 1 April 2007 Mw 8.1 thrust that ruptured about 300 km along-strike from Rendova to the southwest of south Bougainville, mainly propagating to the northwest and crossing two plates boundaries: the Ranongga Transform Fault and Nubara Transform Fault (Figure 2; [29–34]). The adjoining segment adjacent to Rendova and Tetepare ruptured 50+ km along-strike to the southeast in a shallow depth (5.2 km) and dip (22°) Mw 7.1 tsunami earthquake on 3 January 2010 [35].

2. Methods

Two marine geophysical surveys provide total-coverage bathymetry, acoustic imagery and interpolated magnetic field data of the eastern Woodlark Basin and Solomon Islands forearc. The first, in 1993 on R/V Hakurei Maru #2, employed a Hydrosweep swath-mapping system and a track-line spacing of 2.5 nautical miles. The second, in 2004 on R/V Kilo Moana, employed an EM120 swath-mapping system and a track-line spacing of 5 nautical miles. Island topography was added from the results of NASA's Shuttle Radar Topography Mission. We calculated surface slopes from the bathymetry and topography. We calculated a seafloor magnetization solution from a 3D inversion of the compiled bathymetry and magnetic anomaly data [36]. These data and their volcano-tectonic interpretation including seafloor spreading history are presented in Figure 2.

3. Results

Figure 2 (upper half) presents a 5-panel collage of data along and astride the southern subduction front of the Solomon Islands between the conjugate rifted margins of the Woodlark Basin, with the top panel being twice as wide to capture the main volcanic chain and provide geographic context. Data in the top, middle and bottom panels are overlain with the subduction front and transform fault plates boundaries as well as the epicenters of the 2007 and 2010 tsunamigenic earthquakes. Seafloor spreading magnetic lineations shown on the bottom panel, inferred from the magnetization data (4th panel) following [22,26], confirm the young age of the basin (0–6 Ma).

The graben and horsts of the rifted margins produce salients and re-entrants, respectively, in the scalloped subduction front (Figure 2 top panel). The northern ridge of the Woodlark Rise projects under Mono Island and Simbo Ridge projects under Ronongga Island, both of which are uplifting. The highest Holocene uplift rates occur in the two outer forearc areas of Tetepare/Rendova and Ranongga (5–8 mm/year; [27,34]; Tetepare has the highest Quaternary uplift rate [34]). Mann et al. [27] attribute the uplift of Tetepare and southern Rendova to the contact and coupling between recently subducted high seamounts, like the yet-to-be-subducted Coleman and Kana Keoki volcanoes.

Volcanoes on the subducting Australia Plate whose rocks have been sampled and analyzed include Simbo Island, Kana Keoki and Coleman seamounts [9–14,16]. The rocks constitute an arc-tholeiitic and calc-alkaline suite of basalts, basaltic andesites, high-Mg andesites and dacites similar to those of the New Georgia island arc, except that high-Mg picrites have not been reported. Though yet to be sampled, the unsubducted part of the Pavuvu volcano has a conical morphology and acoustic imagery indicative of a volcaniclastic apron, similar to Coleman seamount (Figure 2, top 3 panels), and it is likely of similar arc composition. The arc-composition subducting volcanoes occur only on the young Woodlark Basin oceanic crust; they do not occur on the rifted margins nor on older lithosphere subducting to either side.

In Figure 2 (upper half) top, middle and bottom panels, active arc volcanoes at the surface (whether subaerial or submarine) are indicated by filled triangles, as per the Smithsonian catalog [15] plus Pavuvu. In addition, we identify with unfilled triangles our inferred subsurface locations of eight volcanoes subducted under the forearc, half of which are south of Rendova/Tetipare. Note that two are located downslope from the epicenters of the 2007 and 2010 large-magnitude earthquakes. Each of the subducted volcanoes is associated with a trailing, often cuspate, indentation in the subduction front. The summit of one, at 157.7°E, has only just gone under the forearc, such that its trailing flank is still visible in the bathymetry and acoustic imagery (Figure 2). It has a magnetization high as does another, south of the 2010 earthquake, whereas a subducted seamount south of Rendova is associated with a dipole magnetization anomaly (Figure 2).

To better visualize the morphologies and structures associated with subducting the seamounts, we show 3D views from an elevation of 30° of the bathymetry at a vertical exaggeration of 3 to 1. As Figure 3 shows, the summit of Pavuvu seamount is yet to be subducted. Its leading flank has uplifted and folded/faulted the lower forearc slope, like a cone pushed under a rug. This figure shows the oldest (5–6 Ma) extant abyssal hills of the Woodlark Basin, which is bordered to the south by rifted remnants of the Pocklington Rise and the Itina Trough graben. We interpret that another subducted seamount exists beneath the forearc northwest of Pavuvu. Its summit is located beneath a small lower-slope ridge with a circular collapse structure above its trailing flank and an indentation in the subduction front (Figure 3).

Figure 4 shows that the twin-peaked Kana Keoki seamount and the conical Coleman seamount have yet to reach the subduction front, which is scalloped by seven cuspate indentations from adjacent to Kavachi to just west of Rendova, each of which is associated with a subducted seamount. This cluster of seven subducted seamounts sits on crust that is 1–3.5 Ma (magnetic anomalies J-2A) and occurs where the outer forearc slope is steepest (Figure 2). As mentioned above, the summit of the second one from the east has only just gone under and uplifted the lower forearc slope such that its unsubducted trailing flank is still visible. The subducted seamount south of the 2010 earthquake left a sizable indentation in the subduction front, but the largest of those is associated with the subducted seamount south of the 2007 earthquake (Figures 2 and 4).

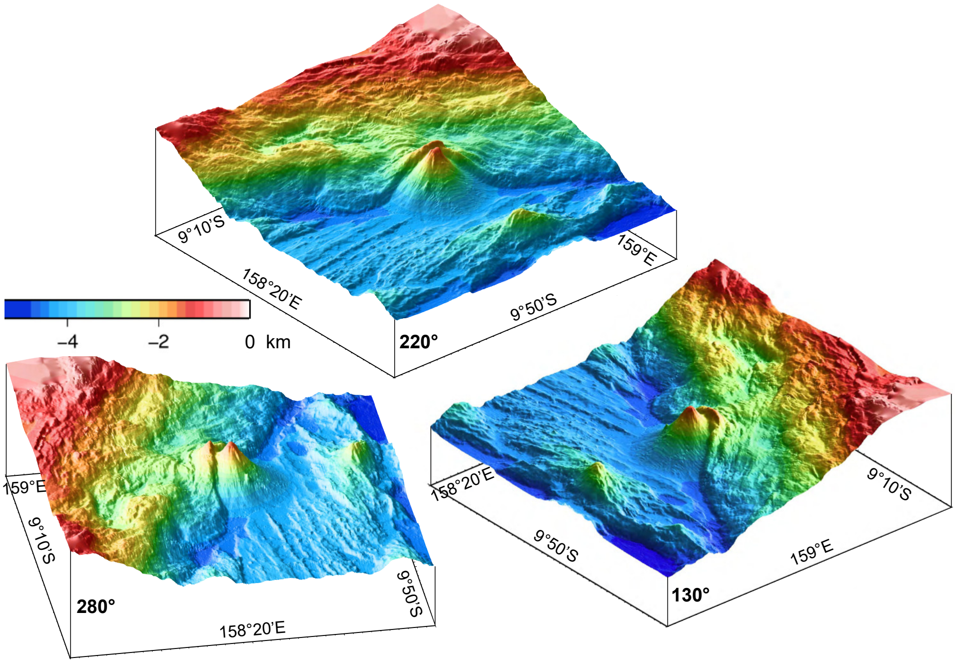

Figure 3. Three 3D bathymetry views (from 130°, 220° and 280°) of the Pavuvu submarine volcano being subducted under the forearc. The view elevation is 30° and the vertical exaggeration is 3:1.

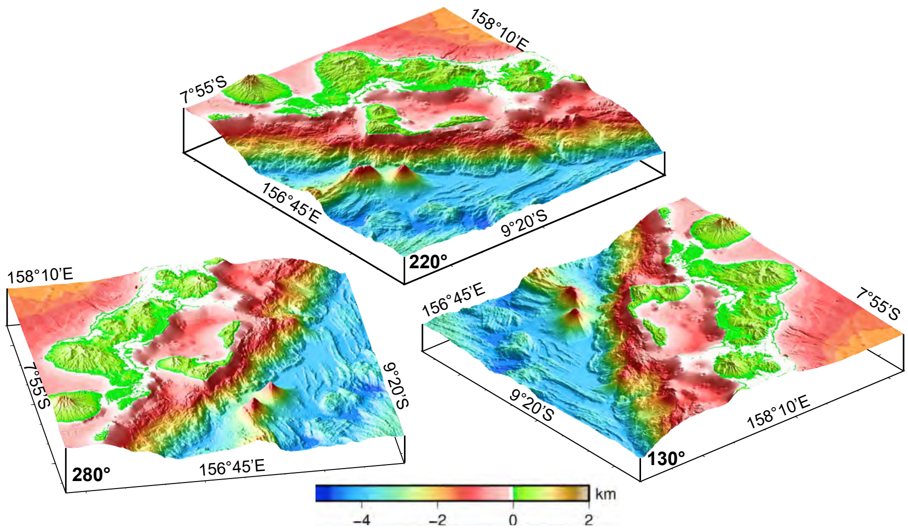

Figure 4. Three 3D topography views (from 130°, 220° and 280°) of the Kana Keoki and Coleman submarine volcanos that are about to enter the scalloped subduction front of the New Georgia forearc that has been deformed by 7 subducted seamounts (located in Figure 2). The view elevation is 30° and the vertical exaggeration is 3:1.

4. Discussion

The morphological and structural characteristics of subducting seamounts under the Solomon Islands forearc appear similar to those off Costa Rica [37], with their overriding topographic bulges, headwall slump scars, trailing circular collapse structures and trench indentations. This is remarkable for several reasons. The composition of the seamounts being subducted is quite different, being arc-like instead of mid-ocean-ridge-like. The forearc substrates are also quite different; where sampled south of Rendova and Kavachi, the Solomons forearc is igneous and volcaniclastic arc rocks [9], whereas the Costa Rica forearc is a sedimentary accretionary prism [37]. Analogue and numerical models that reproduce the morphological expression and associated deformation structures of subducting seamounts off Costa Rica and elsewhere use rigid indenters to deform accreting unconsolidated sediments, with a backstop of more consolidated (cohesive) sediments [38–40]. That these models also well describe the Solomons case perhaps indicates that the arc seamounts are similarly rigid and upstanding on the unflexed subducting lithosphere and that the igneous and volcaniclastic forearc is more of an unconsolidated pile than coherent igneous crust. The same is not the case for the Izu–Bonin–Mariana forearc, which does not show similar structures despite subducting very large seamounts on the old Pacific Plate [41].

Whether subducting seamounts act as asperities with increased friction where earthquakes initiate, or instead act as barriers to earthquake propagation as a result of friction being too high or too low, has been debated (e.g., [40,42,43]). The mechanical modeling of subducting seamounts predicts that stresses are increased, and earthquakes are promoted, ahead of rather than behind them [40,44]. As Watts [42] discuss, a seamount formed on a weak plate compared to a strong plate is more likely to be strongly coupled to the overriding plate, being more locally compensated and retaining more of its buoyancy. Both of these factors appear to apply for the 2007 Mw 8.1 and the 2010 Mw 7.1 tsunamigenic ruptures that nucleated just ahead of subducting seamounts on a very weak plate (formed 1 and 2 Ma, respectively; Figure 2).

There is a >120-year gap in large earthquakes where the Pavuvu volcano on 5–6 Ma lithosphere has begun to subduct under the forearc adjacent to the Russel Islands (Figures 1 and 2; [34,45]). The eastern edge of that gap is defined by a M 7.3 earthquake on September 16, 1926 that produced a tsunami that flooded the western Guadalcanal coast [35]. A tsunamigenic rupture slightly further west, in the seismic gap between the Pavuvu submarine volcano and the Russel Islands, has the potential for its easterly-traveling tsunami waves, refracted by the shoaling bathymetry, to wrap around NW Guadalcanal and impact the capital, Honiara (Figures 1 and 2).

5. Conclusions

High-standing (~3 km relief) island-arc-composition volcanoes occur on the unflexed, young (0–6 Ma) lithosphere of the Woodlark Basin. They and former equivalents are being rapidly subducted under the southern forearc of the Solomon Islands with morphologies characteristic of other areas of seamount subduction, including overriding topographic bulges, headwall slump scars, trailing circular collapse structures and trench indentations. Twenty-first century tsunamigenic earthquakes occurred just ahead of two of the subducting seamounts that formed on very weak lithosphere 1 and 2 Ma. A >120-year gap in large earthquakes occurs where the Pavuvu submarine volcano has begun to subduct under the forearc adjacent to the Russel Islands.

Author Contributions: B.T. was invited to contribute this paper to the Special Issue on Submarine Volcanism, wrote the first draft and designed/labeled the figures. B.T. and A.M.G. oversaw the collection of the swath bathymetry, acoustic imagery and magnetics data. E.K.B. produced the computer-generated graphics using Generic Mapping Tools (GMT) software. A.M.G. compiled the marine geophysical data and was the first to produce the 3D graphics of the Solomon Islands bathymetry such as those used in Figures 3 and 4. All three authors reviewed the manuscript and revised the text and figures. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The swath bathymetry, acoustic imagery and magnetics data used in this study are available for download from the Rolling Deck to Repository (R2R; https://www.rvdata.us/, accessed on 1 April 2023) and NOAA's National Centers for Environmental Information (NCEI; https://www.ncei.noaa.gov/maps/bathymetry/, accessed on 1 April 2023).

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Conflicts of Interest: The authors declare no conflict of interest.

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