Rupture across arc segment and plate boundaries in the 1 April 2007 Solomons earthquake

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The largest earthquakes are generated in subduction zones, and the earthquake rupture typically extends for hundreds of kilometres along a single subducting plate. These ruptures often begin or end at structural boundaries on the overriding plate that are associated with the subduction of prominent bathymetric features of the downgoing plate[1,2]. Here, we determine uplift and subsidence along shorelines for the 1 April 2007 moment magnitude M_W 8.1 earthquake in the western Solomon Islands, using coral microatolls which provide precise measurements of vertical motions in locations where instrumental data are unavailable. We demonstrate that the 2007 earthquake ruptured across the subducting Simbo ridge transform and thus broke through a triple junction where the Australian and Woodlark plates subduct beneath the overriding Pacific plate. Previously, no known major megathrust rupture has involved two subducting plates. We conclude that this event illustrates the uncertainties of predicting the segmentation of subduction zone rupture on the basis of structural discontinuities.

The islands closest to the subducting Simbo ridge transform are Simbo, situated at the crest of the ridge on the subducting plate, and Ranongga, which is on the overriding plate only 8 km away (Fig. 1). Nowhere else on Earth are a pair of islands situated so close to one another across an active trench. This extraordinary setting has enabled us to measure coastal co-seismic uplift of up to 2.46 ± 0.14 m on overriding Ranongga and subsidence of 0.73 ± 0.14 m on subducting Simbo Island (Fig. 1 and Supplementary Information, Table S1). The uplift measurements enable us to place important constraints on the location, geometry and amount of fault slip as the rupture propagated from its epicentre and crossed the ridge-transform boundary.

Other locations where subduction consumes an oceanic spreading ridge-transform boundary are the southern Chile ridge in Chile and the Juan de Fuca/Gorda/Explorer ridges in northwestern North America (Cascadia). Here, young warm oceanic lithosphere elevates the spreading ridge and promotes strong coupling with the overlying plate[3,4]. One explanation for the very large 1700 Cascadia and 1960 Chile earthquakes is that the strong coupling inhibits aseismic plate motion and instead residual strain accumulates along the 'locked' plate boundary until it is released seismically. Previous historical earthquakes near the 1 April rupture area in the Solomon Islands had magnitudes M of 7.2 and less[5]. This was puzzling because Chile and Cascadia, where extremely young oceanic crust also subducts, have produced exceptionally large earthquakes ($M_W \geq 9.0$) (refs 6,7). The 1 April earthquake confirms that in the western Solomons, as in Chile and Cascadia, subducted young ridge-transform material is strongly coupled with the overlying plate.

In the western Solomons before 2007, the evidence for strong coupling was mixed. The absence of earthquakes larger than M7.2 occurring in 1900–2006 between 156° and 158° E seemed consistent with aseismic subduction and weak coupling[8]. There is also no known oral history suggesting that large tsunamis have struck New Georgia Group islands within the past few centuries. Yet the presence of three rapidly uplifting islands (Ranongga, Rendova and Tetepare) within only 5–35 km of the San Cristobal Trench axis suggests strong coupling[9,10]. In addition, in the western Solomons region there was evidence that slow interseismic strain accumulation preceded the sudden release of strain in 2007: we observed widespread coastal erosion at Ranongga Island during extensive fieldwork from 1991 onward and before 1 April, and local inhabitants' oral histories of slow island submergence[11] are consistent with interseismic strain accumulation.

Coastlines of the western Solomons preserve ample geologic evidence that the slowly accumulated strain is released abruptly. On the coasts of Ranongga, Rendova and Tetepare, we have observed multiple distinct palaeosea-level solution notches in limestone at 1–10 m above mean high tide level (Fig. 2) associated with nearby young emerged fossil corals[9,10]. Solution notches form primarily owing to bioerosion concentrated in a relatively narrow intertidal zone. Distinct notch levels indicate intervals of stationary relative palaeosea-level stand, and their widespread occurrence in the western Solomons suggests that discrete seismic or aseismic uplifts have occurred at times before the historical period. The 1 April 2007 earthquake confirms that the subduction zone beneath the western Solomons is strongly coupled and that strain is released in large, infrequent megathrust ruptures.

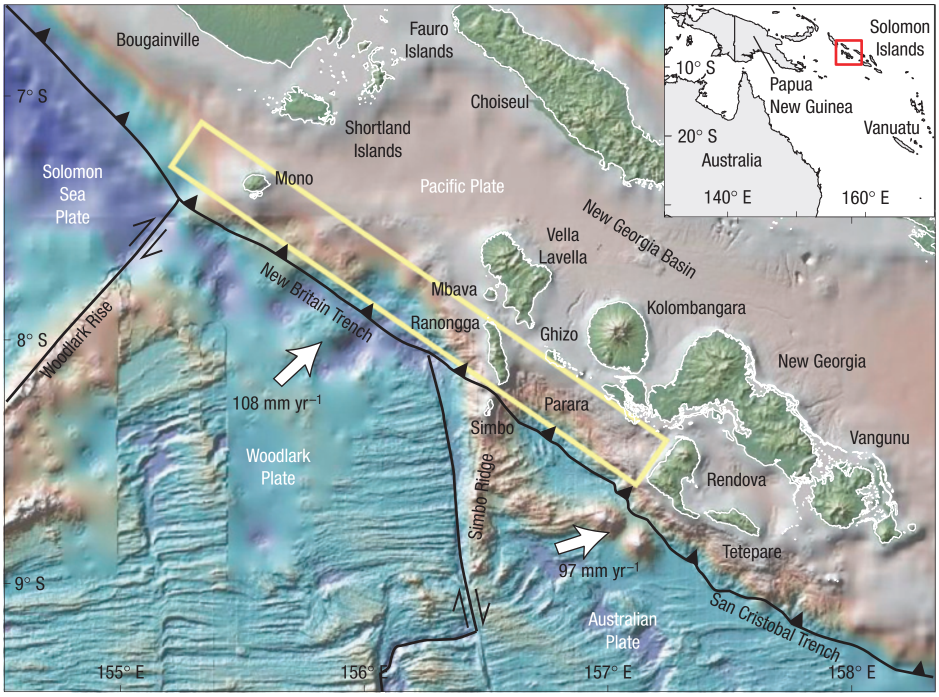

Figure 1 Plate tectonic setting and bathymetry[23,24] of the western Solomon Islands. The yellow rectangle indicates the model fault plane and approximate rupture zone for the M_W 8.1 earthquake of 1 April 2007. Note that rupture crosses the triple junction where the Woodlark, Australian and Pacific Plate boundaries intersect. For the 1 April earthquake, observations of uplifted and subsided coastlines, as well as tsunami heights on islands surrounding the rupture zone, are consistent with uplift produced by 5 m slip along a rectangular fault with dimensions of 30 km × 245 km, centroid depth of 15 km and a dip of 38°.

Figure 2 Geologic evidence of co-seismic vertical motions. a, Solution notch on Parara Island. The white band just above the water level is coralline algae that have died and bleached owing to $\sim$0.5 m of uplift accompanying the 1 April 2007 earthquake. The lower solution notch was actively eroding before 1 April and microatolls indicate that this coastline was subsiding before 1 April. It is likely that this notch developed over multiple cycles of interseismic subsidence and co-seismic uplift. **b**, Photo of exposed coral reef on southern Ranongga where there was co-seismic coastal uplift of 2.36 ± 0.14 m.

Following the 1 April earthquake, our team arrived on 16 April and visited 11 major and numerous small islands where we used reef corals and other coastal features to measure vertical displacements. We mostly used coral microatolls, which function as natural tide gauges that enable us to determine vertical motions to within $\sim$10 cm. Under suitable conditions, some coral species grow upward and horizontally; thus, when sea level is stable, the corals form horizontal upper surfaces that are controlled by extreme low tide levels. Subsequent subsidence (or uplift) produces further upward growth (or stepped die-downs) along the microatoll edges. In Vanuatu[12,13] and in Indonesia[14,15], we have interpreted these features to infer the amount and geographic extent of vertical motions caused by recent and prehistoric earthquakes. In the Solomons, our field efforts focused on

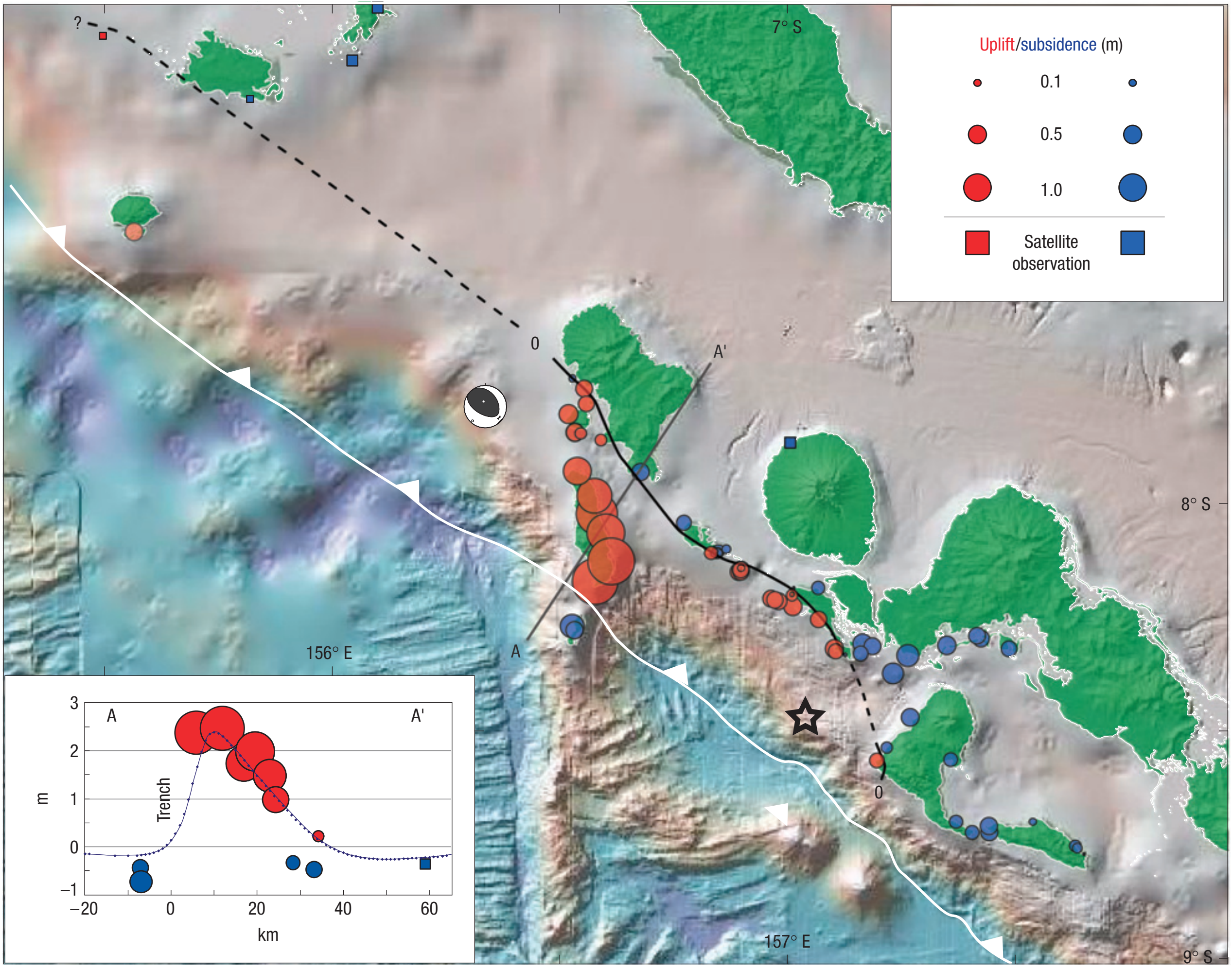

Figure 3 Vertical motions produced by the 1 April 2007 earthquake. Red circles indicate uplift; blue circles indicate subsidence; size is scaled to the amount of vertical displacement. The star is the US Geological Survey epicentre for the 1 April main shock; the beachball indicates the centroid moment tensor focal mechanism and centroid location[27]. The inset compares vertical motions along a transect A–A′ with motions calculated for 5 m slip along the rectangular fault in Fig. 1.

measuring uplift and identifying the boundary between uplift and subsidence on the forearc; for sites in the far field, we used paired before/after Advanced Spaceborne Thermal Emission and Reflection Radiometer images following established methods[16] (see Supplementary Information, Tables S1–S3).

We observed uplift on all of Ranongga and Mbava Islands as well as the southern coasts of Parara, Ghizo and Vella Lavella Islands (Figs 1, 3 and Supplementary Information, Figs S1–S3). The greatest uplift, 2.46 ± 0.14 m, was on the southern part of Ranongga. Uplift on Ranongga decreases northward to ∼1 m at its northern end, continues along the trend of the underthrusting Simbo ridge across Mbava Island and ends on southern Vella Lavella Island. The line of zero vertical change, or hingeline, intersects the southern coasts of Vella Lavella, Ghizo and Parara. The hingeline also shows that rupture was restricted to the portion of the megathrust shallower than ∼15 km that had previously been interpreted as aseismic on the basis of microearthquake data[17]. Clearly abandoned pre-1 April high-tide lines and local eyewitness reports limit uplift of Rendova to a small area near the southwestern corner, providing a firm southeastern rupture boundary.

A broad swath of subsidence is located north of the uplift and includes much of New Georgia, Kohinggo, Kolombangara and Vella Lavella Islands. The subsidence trough reaches a maximum of 0.66 ± 0.14 m between Kohinggo and New Georgia, where flooding has led to extensive coastal damage during high tides. Long-term uplift rates of ∼1 mm yr^{-1} along much of the co-seismically subsided volcanic arc suggest that subsidence from 2007-type events may be more than fully recovered before the next rupture[9,10]. Rendova and Tetepare, located just east of the 1 April epicentre, subsided even though they are along strike with the rupture, their southern coasts are only ∼15 km from the trench and they have rapid mean Holocene uplift rates[9,10]. Near the western end of the aftershock zone, satellite data (see Supplementary Information, Table S2) showed that Mono Island uplifted at least 0.12 m, Shortland Island was stable or subsided slightly and the Fauro Islands and southeastern Bougainville subsided tens of centimetres.

Our field observations and measurements place useful quantitative constraints on models of the 1 April 2007 rupture zone. Subsidence of Tetepare and uplift of only the southwestern corner of Rendova indicate that the fault rupture began just west of the structurally controlled coast of Rendova[8] and extended northwestward. Uplift of several metres on the southern coast of Ranongga suggests that slip may have extended up to the trench floor here. The fact that damaging tsunamis were recorded on

Choiseul indicates that the rupture extended along the trench from Vella Lavella nearly to Bougainville where there is no island shielding Choiseul from the trench, a total distance of ∼245 km. The observations of subsidence on Simbo, significant uplift on Ranongga, Mbava, Vella Lavella, Ghizo and Parara Islands and subsidence on northern Vella Lavella and northern Ghizo Islands require that the zone of slip is confined within the region between the trench and a nearly parallel line ∼35 km to the northeast through Vella Lavella, Ghizo and Parara Islands. However, at Ranongga and along a projection of its trend to southern Vella Lavella, the uplift zone widens to ∼45 km. The northwestern termination of rupture approximately coincides with the intersection of the Woodlark Rise and the New Britain Trench, a strike–slip boundary between the Woodlark and Solomon Sea plates (Fig. 1).

To provide a simple evaluation of co-seismic slip on the megathrust, we compare our field observations with predictions from the analytical solution for vertical surface deformation produced by slip on a rectangular fault embedded within an elastic half-space[18]. The simplest fault model with an overall match to the field observations and the reported focal mechanism (see the Methods section) is for a thrust with 5 m of slip along a rectangular fault with dimensions 245 km by 30 km dipping 38° down towards the northeast, and extending along the trench from offshore southwest Rendova Island approximately to Bougainville (Fig. 1). This model matches the amount and pattern of uplift on Ranongga and reproduces the abrupt transitions from subsidence–uplift–subsidence observed on Simbo–Ranongga–Vella Lavella (Fig. 3); it slightly underestimates the maximum subsidence observed on Simbo and in the backarc.

There are no coastal uplift observations to constrain the width and depth of the fault between Vella Lavella and Mono and whether it ruptured up to the trench floor there. However, tsunami modelling using seafloor uplifts produced by the fault shown in Fig. 1 (see the Methods section) predicts significant tsunami run-ups on Choiseul as well as Simbo, Ranongga, Ghizo and Vella Lavella, consistent with what occurred. This and the presence of numerous aftershocks occurring between Vella Lavella and Bougainville indicate that the rupture extended across this entire region and terminated in the vicinity of the Woodlark rise boundary between the Woodlark and Solomon Sea plates.

An important implication of the uplift observations and simple elastic modelling is that they show the earthquake ruptured across a triple junction on the subducting plate and inferred boundaries between major tectonic blocks on the overriding plate. Yet, the rupture terminated near the Woodlark rise, a second subducting triple junction. The 1960 $M_W = 9.5$ Chile rupture terminated at the subducting boundary between the Nazca and Antarctic plates, and no previously known historical earthquakes have ruptured across adjacent subducting plates. This has been interpreted as strong evidence that major structural boundaries on subducting and/or overriding plates control great megathrust ruptures[19–21]. In the Solomons, the 1 April 2007 earthquake clearly ruptured across the Simbo Ridge ridge-transform boundary separating the subducting Woodlark and Australian plates even though this boundary accommodates differential motion of 60–72 mm yr^{-1} (refs 22–24). Furthermore, a boundary on the overriding plate just west of Vella Lavella previously inferred on the basis of bathymetric variations and aftershock zones did not arrest rupture on the underlying megathrust[8]. The 1 April 2007 earthquake demonstrates the shortcomings in predicting megathrust rupture segment boundaries purely on the basis of structural features on the subducting and overriding plates. It also suggests that quantitative models of stress regimes near adjacent subducting plates need to incorporate interplate stresses and consider the rheological and dynamic conditions within the underlying mantle that may apply tractions to both subducting plates.

Southeastward of the 1 April 2007 rupture zone, subsidence of Rendova and Tetapare and the occurrence of aftershocks here may be a cause for concern, because both suggest an increase in elastic strain accumulation at the rupture boundary. It is thus possible that the adjacent rupture enhanced static stress here and that this strongly coupled boundary is still locked. Most of the people on islands in and around New Georgia live and work along the coasts and may be adversely affected if a future earthquake here causes a tsunami. Elsewhere in the Solomons, there have been notable instances in 1919–20, 1931, 1939, 1945–46, 1971, 1974, 1975 and 1995 of two or more earthquakes with magnitudes of 7.2–8.1 occurring as pairs or multiplets separated by intervals of hours to months[25,26].

METHODS

For the slip and geometry of the rectangular fault we used to model vertical deformation, we assumed a dip (38°) and scalar moment (1.6×10^{21} N m) in agreement with the quick global centroid moment tensor[27] reported by Columbia University, a rigidity μ of 30 GPa, an along-arc length of 245 km in agreement with observed uplift and subsidence and a centroid depth of 15 km. Slip is thus 5 m for a fault of width 30 km. To model relative tsunami heights at coastal locations produced by slip on this fault, we used the standard half-space solution[18] for ocean floor displacements and a finite-difference program that accurately calculated propagation and wave heights for water depths exceeding 100 m.

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Author contributions

F.W.T., R.B. and C.F. are responsible for tectonic and seismological interpretations; F.W.T., R.B., A.B., A.K.P. and D.B. carried out the field investigations; M.H. and C.F. developed the tsunami model; A.J.M. provided satellite-derived observations of vertical motions and tide model calculations.