A Near-Vertical Slab Tear in the Southeastern Solomon Islands

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Abstract

The Solomon Islands is one of the most seismically active areas in the southern Pacific with high earthquake hazard potential. The regional seismic network, equipped with six broadband seismic stations, was constructed as late as October 2018. On January 27 and 29, 2020, two moderate earthquakes, Mw 6.3 and 6.0, respectively, occurred in the southeastern Solomon Islands. The entire foreshock-main-shock-aftershock sequence was recorded by this seismic network for exploring the seismogenic structures. Based on the spacial distribution of the foreshock-aftershock sequence, the interaction of the subduction and transform zones between the Pacific and the Australia plates could lead to the near-vertical dip-slip tear slab. Confirmed with PREM and the new 1D velocity model for testing the robustness of the earthquake locations, a seismic gap at depths from 25 to 35 km is observed as the "jelly sandwich" rheology of the continental crust of the Australia plate.

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Key Points:

- An optimized local 1D velocity model was determined from the regional seismic network.
- A subduction-to-strike-slip transition system could result in the near-vertical dip-slip tear slab in the southeastern Solomon Islands.
- The “jelly sandwich” rheology of the continental crust of the Australia Plate is observed.

Abstract

The Solomon Islands is one of the most seismically active areas in the southern Pacific with high earthquake hazard potential. The regional seismic network, equipped with six broadband seismic stations, was constructed as late as October 2018. On January 27 and 29, 2020, two moderate earthquakes, Mw 6.3 and 6.0, respectively, occurred in the southeastern Solomon Islands. The entire foreshock-main-shock-aftershock sequence was recorded by this seismic network for exploring the seismogenic structures. Based on the spacial distribution of the foreshock-aftershock sequence, the interaction of the subduction and transform zones between the Pacific and the Australia plates could lead to the near-vertical dip-slip tear slab. Confirmed with PREM and the new 1D velocity model for testing the robustness of the earthquake locations, a seismic gap at depths from 25 to 35 km is observed as the "jelly sandwich" rheology of the continental crust of the Australia plate.

Plain Language Summary

To establish a seismic network is always the first step and essential for studying any researches related to earthquakes, especially in the Solomon Islands, one of the most seismically active areas in the southern Pacific. However, as late as October 2018, the regional seismic network in the southeastern Solomon Islands, equipped with six broadband seismic stations, was constructed because most of the areas are inaccessible. A good 1D local velocity model is crucial for determining earthquake locations. The data set from foreshock-main-shock-aftershock sequence of two earthquakes in 2020 recorded in the seismic network provides a good opportunity for obtaining a 1D velocity model. After the reliable earthquake locations are determined, the spacial distribution of the foreshock-aftershock sequence can provide valuable information about seismogenic structures for better understanding the occurrence of earthquakes. As a result, a near-vertical dip-slip slab of the Australia plate from the subsurface to 120 km with a seismic gap at depths from 25 to 35 km is observed for the first time. This near-vertical tear slab could result from a subduction-to-strike-slip transition system and the seismic gap within the continental crust is related to "jelly sandwich" rheology.

1 Introduction

Previous studies in the Solomon Islands have mainly focused on tectonic evolution (e.g., Yan and Kroenke, 1993; Mann et al., 1998; Petterson et al., 1999; Mann and Taira, 2004; Holm et al., 2016), geology (e.g., Mann et al., 1998; Taylor et al., 2005; Taylor et al., 2008; Chen et al., 2011), and a few related to the crustal and upper mantle structures using ocean-bottom seismometer data set with passive and active sources (e.g., Mann et al., 1996; Phinney et al.,1999; Mann and Taira, 2004; Miura et al., 2004). The subduction systems in the southeastern Solomon Islands have not been documented in detail due to shortages of seismic stations and feasible data for investigating the complex seismogenic, crustal, and upper mantle structures. The complex tectonic setting and geopolitical marginality make the Solomon Islands hardly to be explored, including deploying seismic stations on islets. However, improvement of station coverage, in particular, is one of the most effective observations to answer the seismotectonic debate (e.g., Ku et al., 2020).

The regional seismic monitoring network in the southeastern Solomon Islands was constructed until October 2018 (Fig. 1). On January 27 and 29, 2020, two moderate earthquakes, Mw 6.3 and Mw 6.0, respectively, occurred in the southeastern Solomon Islands. The entire foreshock-main-shock-aftershock sequences were completely recorded by this regional-scale seismic network. These two earthquakes are located in the most active area of the region, which the foreshock and aftershock sequences can provide a unique opportunity to look into the crustal and upper mantle structures of the subduction zones between the Pacific plate (PAP) and the Australia plate (AUP). Here, we report on earthquake distribution for the southeastern termination of the southeastern Solomon Islands subduction zone and also derive a optimized local 1D velocity model utilizing the complete seismic data recorded by the newly seismic network.

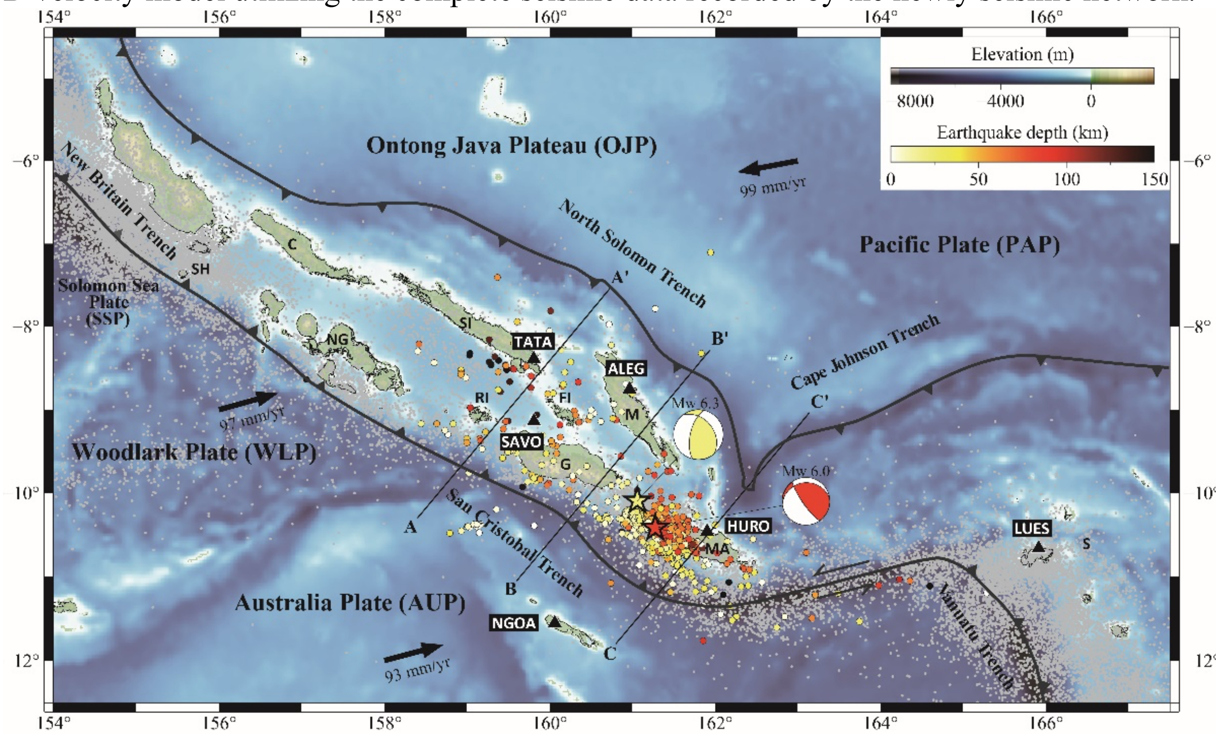

Figure 1. Topography, bathymetry, and regional tectonic setting of the Solomon Islands region. Arrows indicate direction and rate of plate motion of the Australia, Pacific, and Woodlark plates (NUVEL-1A, Demets et al., 1994); heavy lines with triangles represent subduction boundaries; black triangles are broadband seismic stations; yellow and orange stars represent earthquakes occurred on January 27 and 29 from the Incorporated Research Institutions for Seismology (IRIS) catalog; focal mechanisms of the two earthquakes are from GCMT; circles color-coded by depth indicate foreshocks and aftershocks recorded by GNS seismic stations; background seismicity are shown as gray dots and are compiled by the IRIS event catalog for the period 1971-2021; AA', BB' and CC' are the cross sections in Figs. 2-5. SH, Shortland Islands; C, Choiseul; NG, New Georgia Island Group; SI, Santa Isabel; RI, Russell Islands; FI, Florida Islands; G, Guadalcanal; M, Malaita; MA, Makira; SCZ, Santa Cruz Islands.

2 Tectonic setting

The Solomon Islands is located in a complex and active plate boundary where several plates interact with each other, including the PAP, the AUP, and the associated microplates (i.e., the Woodlark plate (WLP) and Solomon Sea plate (SSP)) (Fig. 1) (e.g., Demets et al., 1990, 1994, 2010; Beavan et al., 2002; Miura et al., 2004; Phinney et al., 2004; Taira et al., 2004; Taylor et al., 2005, 2008; Argus et al., 2011; Newman et al., 2011). In the southern Solomon Islands, the WLP and the AUP subduct beneath the PAP forming the New Britain Trench, San Cristobal Trench and

Vanuatu Trench (e.g., Taylor and Exon, 1987; Crook and Taylor, 1994; Taylor et al., 1995; Mann et al., 1998; Taylor et al., 2005). The area surrounding the Solomon Islands and the Santa Cruz Islands contains two subduction-to-strike-slip transition (SSST) regions where a transform zone links two oblique subduction zones (Bilich et al., 2001). In addition, the Ontong Java Plateau of the PAP, the largest and thickest oceanic plateau on Earth, subducts along the North Solomon Trench and the Cape Johnson Trench in the north with slight convergence (e.g., Taylor and Exon, 1987; Yan and Kroenke, 1993; Crook and Taylor, 1994; Mann et al., 1998; Petterson et al., 1999; Mann and Taira, 2004). The Solomon arc is assumed the most representative example of an island arc polarity reversal due to the presence of inwardly double subduction zones resulting in high risk of earthquakes, tsunamis, and volcanic eruptions.

Composed of two chains of islands, the Solomon Islands extends about 1000 km wide which are partitioned into multiple segments by distinct geological or seismological characteristics (e.g., Mann et al., 1998; Taylor et al., 2005; Chen et al., 2011). Nowadays, the active subduction occurs in the southeast of the Solomon Islands along the San Cristobal Trench according to previous seismological investigations from global seismic networks (e.g., Cooper and Taylor, 1987; Mann et al., 1998; Chen et al., 2011). They found that it might be caused by strongly oblique subduction occurring southeast of the region, although the structures of subduction zones is still under debate.

3 Seismic network and data processing

The Institute of Geological and Nuclear Sciences Limited (GNS), New Zealand, deployed six permanent seismic stations in different islets of the southeastern Solomon Islands since October 2018 (Fig. 1). The instruments are equipped with broadband seismometer (Trillium 120PA; Nanometrics Inc., Canada) and 24-bits digital recorder (Q330S; Quanterra Inc., U.S.A.) with sampling rates of 100 Hz. Except for the timing problem of the station LUES, most of the seismic waveforms recorded by the other five stations have good signal-to-noise ratios. To date, this seismic network is maintained by the Ministry of Mines, Energy and Rural Electrification of the Solomon Islands Government.

In this study, we processed two-month continuous seismic waveforms from this seismic network, one month before and after the two main shocks, respectively, to well cover the period of the whole earthquake sequence. The data set is formatted with the daily miniSEED and we used the SeisAn Earthquake analysis software (SEISAN) to establish the event database (Havskov and Ottemoller, 1999). Most of the events occurred close to the seismic network so that we were able to extract numerous high-quality seismic waveforms to pick P- and S-wave arrivals, locate earthquakes and determine magnitudes. We located earthquakes by the HYPOCENTER program (e.g., Lienert et al., 1986) and determined moment magnitude (M_w) by spectral analysis. More details of the waveform analysis procedure are described in Havskov and Ottemoller (2010).

The earthquake catalog contains events detected by at least three stations and has more than one clear S-wave arrival to effectively constrain the depths of earthquakes. The interpolated 1D Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981) was used as the reference model. In total, 730 earthquakes were listed in the preliminary catalog and of which 651 were located within the seismic network. We used the program VELEST (Kissling, 1988, Kissling et al., 1994) to derive a 1D velocity model, which produces the smallest possible uniform error for a set of seismic events with well-constrained locations. We select events within the range of the seismic network with the root-mean-square error in arrival time from 0.5 to 1.0 s to invert a new

1D velocity model. In total, 389 events were selected for inversion to derive the preferred 1D model and then with it we relocated all 730 earthquakes to obtain the final catalog.

4 Results

The background seismicity is extracted from the global earthquake catalog from 1971-2021 compiled by the Incorporated Research Institutions for Seismology (IRIS) (Fig. 2). In 50 years, only ~5100 events in our study area are listed in the IRIS catalog because of poor constraints of station coverage. The hypocenters of the two main shocks, reported by IRIS, distribute apart from depths at 21 and 85 km, respectively (cross-section CC' of Fig. 3). During the same time period, January and February 2020, only 23 earthquakes are listed in the IRIS catalog but 730 are detected from our new data set. Obviously, we detected a significant number of missing events, especially at shallow depths that also appear with steep dip, the same as the deeper events (cross-sections BB' and CC' of Fig. 3). Relatively, in contrast, our results at deep depth show a similarity of high dip angle with background seismicity but are more concentrated at the San Cristobal Trench (cross-sections BB' and CC' of Fig. 3).

Among the 730 events, the standard error of the means in vertical location (ERZ), in horizontal location (ERH), and root-mean-square error in arrival time of event locations are 24.7 $\pm$ 19.15 km, 13.43 $\pm$ 10.8 km, and 0.61 $\pm$ 0.30 s, respectively. The moment magnitudes (M_w) determined in this study mostly range from 2.0 to 4.0. The main earthquake cluster is located between Makira and Guadalcanal (Fig. 1), one of the most active regions in the Solomon Islands, where commonly experiences large earthquakes (Chen et al., 2011). Events in the cluster extend from subsurface to 120 km depth which is similar to the previous studies (Cooper and Taylor, 1985; Mann and Taira, 2004). Three southwest-northeast cross sections nearly perpendicular to the subduction zone show spatial variation of foreshocks and aftershocks from northwest to southeast (Figs. 2 and 3). Two southeastern cross sections close to the main shocks reveal that the event cluster is near-vertical and can be divided into shallow (< 25 km) and deep (35-120 km) parts (cross-sections BB' and CC' of Fig. 3). Although the North Solomon Trench contains fewer earthquakes, the cross sections in the northwest do show two trenches subduct inwardly (cross-sections AA' and BB' of Fig. 3). Fig. 4 presents the cross sections of the relocated earthquakes with the new 1D velocity model. Both the location results with PREM and the new 1D velocity model reveal a steep event cluster, but the new velocity model has low-velocity zone at 10 km depth and slower velocity layer within depths of 25-35 km comparing with PREM (Fig. 5).

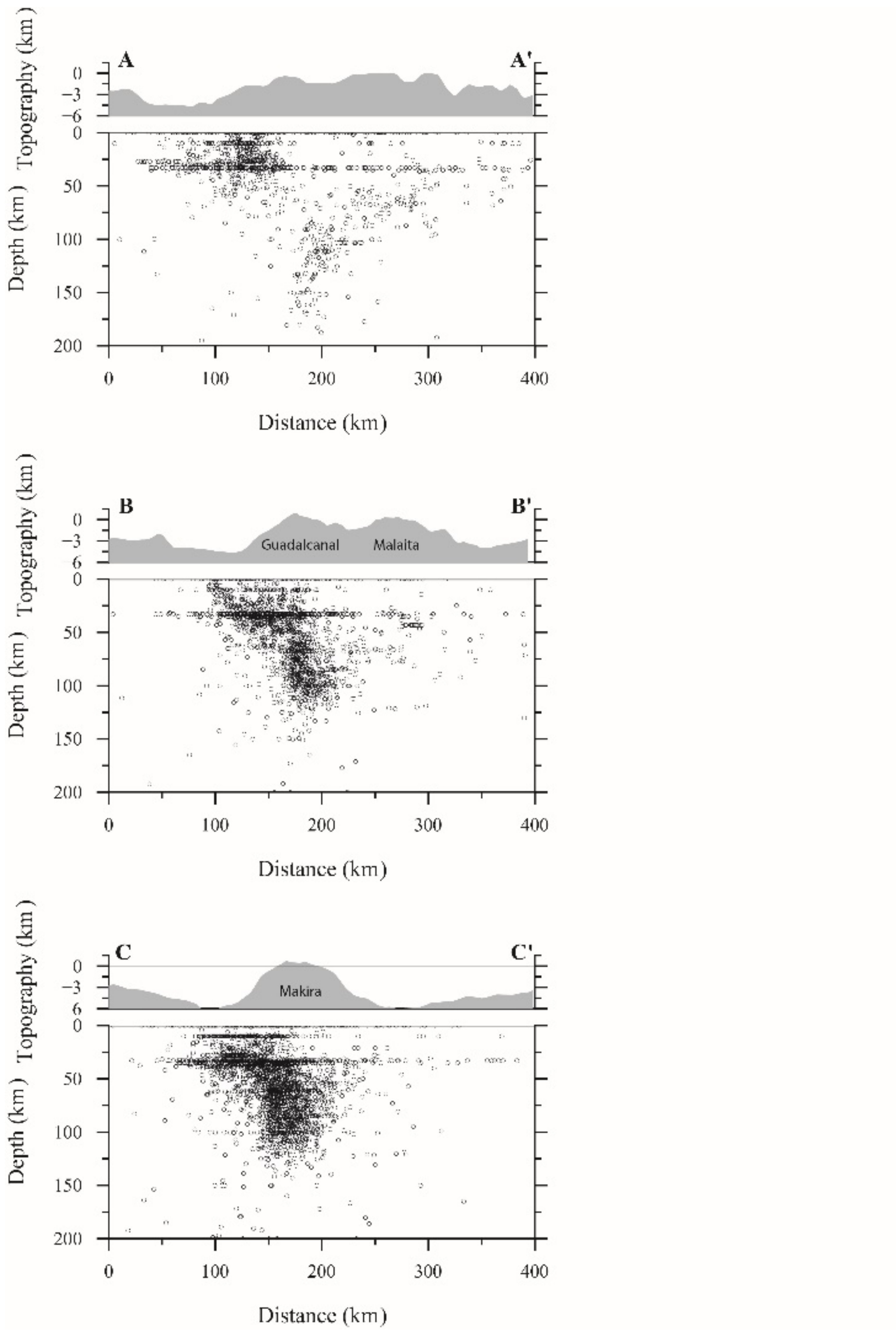

Figure 2. Cross sections of background seismicity around the southeastern Solomon Islands are compiled by IRIS event catalog from the period 1971-2021. Earthquake hypocenters are projected onto the three 200-km-wide transects shown in Fig. 1. Topography of three area is projected on to profiles in the upper panels.

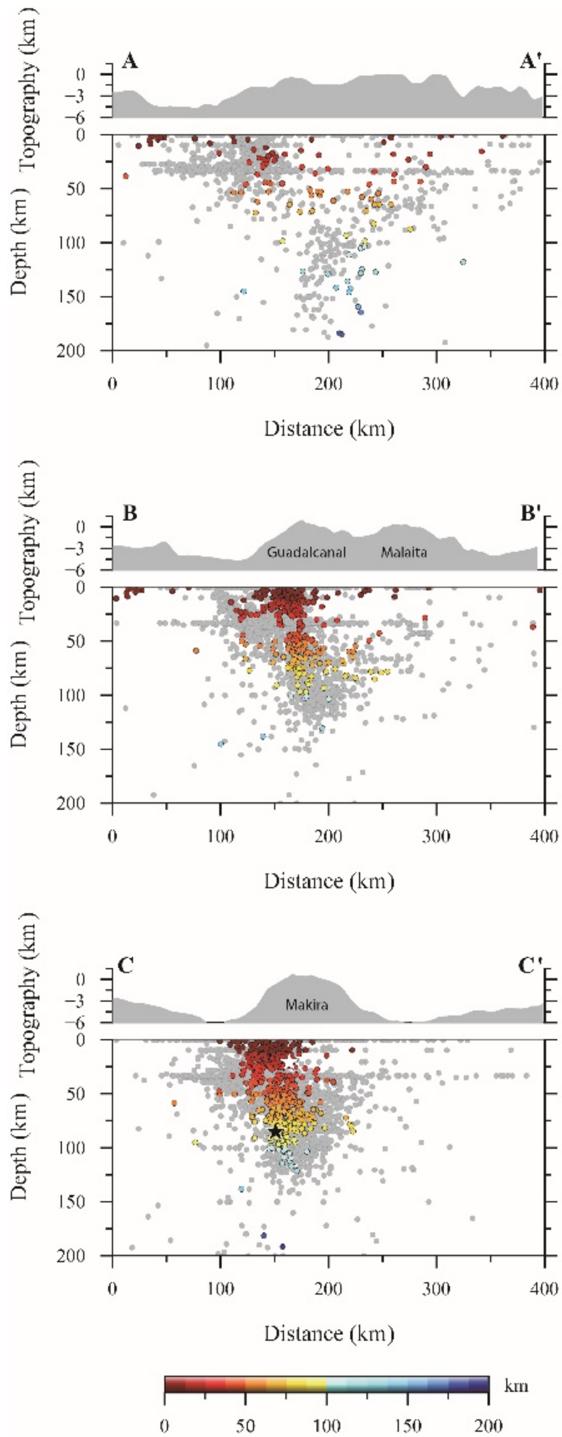

Figure 3. Comparison of earthquake hypocenters in this study and background seismicity. Cross sections with background seismicity (gray dots) and foreshocks and aftershocks (circles color-coded by depth); project lines are shown in Fig. 1; background seismicity is the same as Fig. 2; white and black stars represent January 27 and 29 earthquakes from IRIS event catalog.

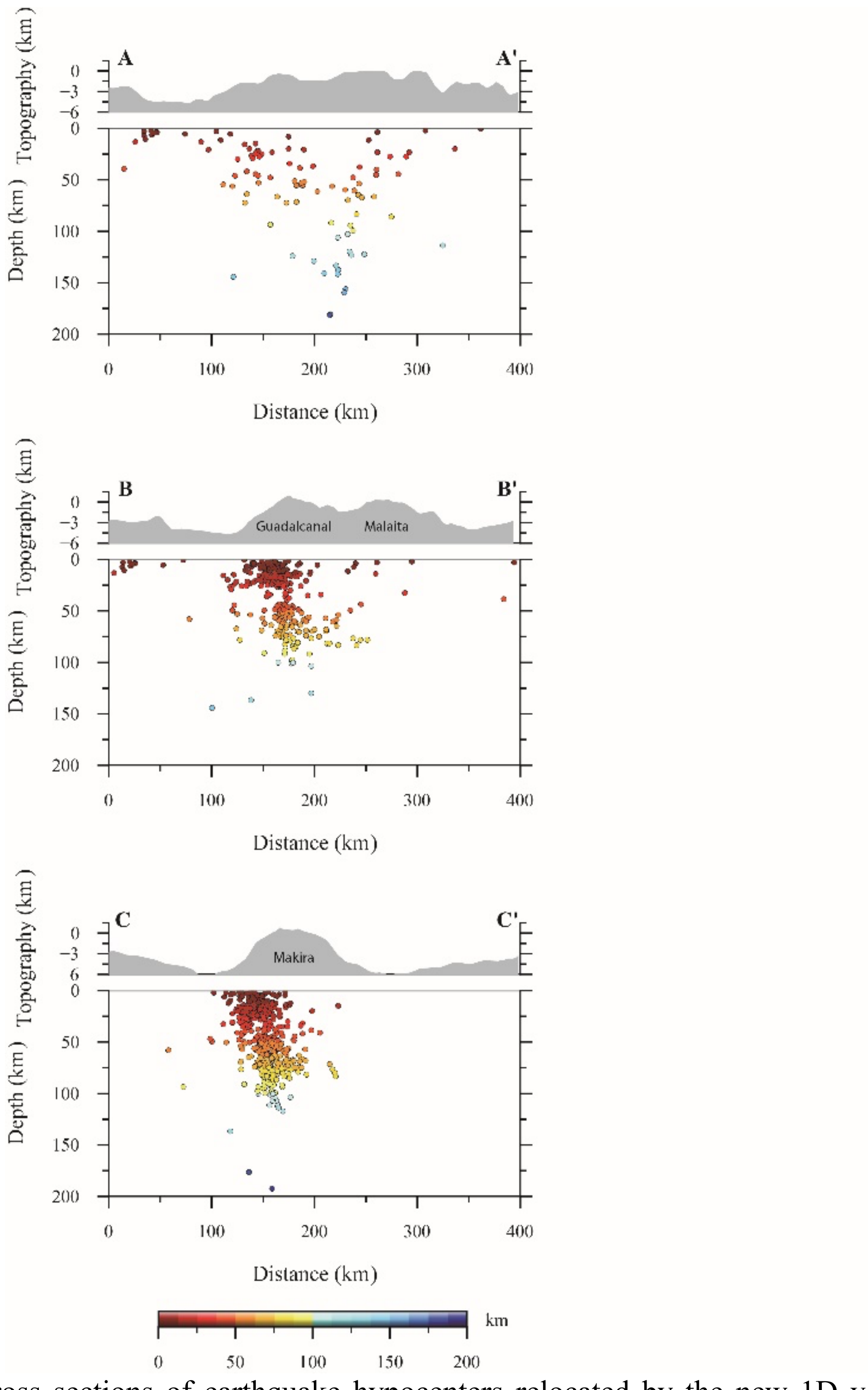

Figure 4. Cross sections of earthquake hypocenters relocated by the new 1D velocity model. Circles color-coded by depth are foreshocks and aftershocks; project lines are shown in Fig. 1.

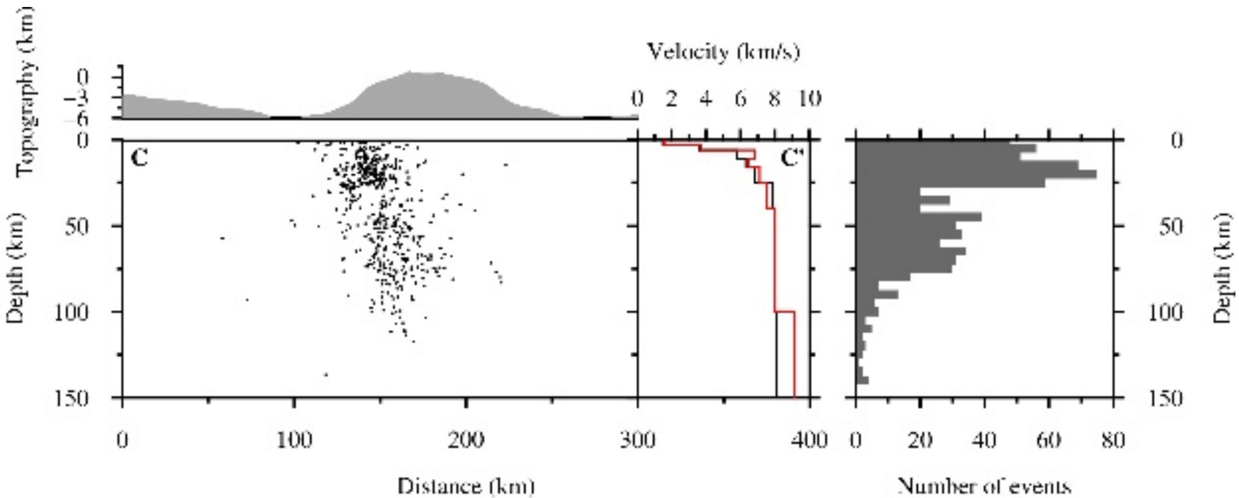

Figure 5. CC' cross section (in Fig. 4) with the seismic cluster relocated by the new velocity model around the southeastern Solomon Islands. The middle panel shows the 1D interpolated PREM (black line) and the new velocity model (red line); the right panel is the event distribution in 5 km depth intervals. Note the seismic gap between 25 km and 35 km depths.

5 Discussions

The Solomon arc, expanding ~1000 km wide, is characterized by diverse fault geometry as well as subduction properties in different segments. The complexity of tectonic setting in the Solomon Islands also makes the behavior of the seismic activities vary along the island chain. With background seismicity from the 1971-2021 IRIS catalog in the Solomon Islands, majority of the earthquakes occurred along the San Cristobal Trench which is much more seismically and volcanically active than that of the early developed subduction zones to the north (Fig. 1). These earthquakes, moreover, mainly distributed between Makira and Guadalcanal, show different structural states from the northwestern side to the southeastern through the hypocenter transects (Figs. 2 and 3). Many studies used seismicity from different global catalogs and time periods to propose the subduction manifestation, including the dip angle and the depth of the two slabs from the San Cristobal Trench and the North Solomon Trench (Cooper and Taylor, 1985; Mann and Taira, 2004; Miura et al., 2004). Cooper and Taylor (1985) and Mann and Taira (2004) gave different points of view from a similar distribution of seismicity between Makira and Guadalcanal that the latter slab angle was much flatter than the former one. However, we have different perspective of the subduction structure beneath the southeastern Solomon Islands from previous studies due to the better quality constrains on the new seismic data set.

Based on our results, we suggest that the event cluster does show as a steep seismogenic structure in the corner zone within the SSST between the Solomon Islands and the Santa Cruz Islands and also could interpret it as the location of near-vertical dip-slip tear within the Australia lithosphere (Fig. 5). This complicated plate configuration as a SSST region, which has been found at least 30 locations on Earth (Bilich et al., 2001), is usually with damaged earthquakes occurred frequently. The seismicity concentrates at the edge of the tear which extends almost vertically from the subsurface to ~120 km. Govers and Wortel (2005) assumed that the intersection between the subduction and the transform propagates through the lithosphere, inducing a tearing transform fragment. They refer to the tearing as a subduction-transform edge propagator (STEP) fault and developed the STEP model to interpret vertical, dip-slip tearing at perpendicular plate boundaries, for example, the northern Tonga (Isacks et al., 1969; Millen and Hamburger, 1998) and the southeast corner of the Caribbean (Molnar and Sykes, 1969; Clark et al., 2008). According to Bilich et al. (2001), the southeastern Solomon Islands is one of the SSST regions where the northeastward subduction of the AUP connects the transition of northeast-southwest transform motion between the PAP and the AUP. We believe that the vertical motions and complex deformation revealed by the seismicity can demonstrate the tear propagation right beneath Makira and Guadalcanal. The suggestion is also consistent with Bilich et al. (2001) that the southeastern Solomon corner zone features a band of mechanisms which nearly reach the strike-slip corner (Fig. 6).

We also observe a seismic gap, both located by PREM (Fig. 3) and the new velocity model (Fig. 4), which is similar to the seismic cluster in the Lesser Antilles of the South American plate and this phonomeon is suggested that the gap is a weak, ductile, lower crustal layer separating a strong upper/middle crustal layer from a strong lithospheric layer (Clark et al., 2008). The seismic gap, known as the “jelly sandwich” rheology (Chen and Molnar, 1983; Watts and Burov, 2003), detaches the subducting and the buoyant pieces of the AUP along a near-vertical tear here. In comparison to significant strength in the dry upper mantle, the weak lower crust would show as the undried granulite in the continental lithosphere (Jackson, 2002). The whole seismogenic deformation is about 100 km wide and extends 120 km through the entire crust and lithosphere and the gap is at 25-35 km depth within the tear.

In order to derive the local 1D velocity model for earthquake location procedures, we use the program VELEST to construct the new velocity model in the southeastern Solomon Islands. In comparison with the interpolated PREM, the seismicity relocated by the new velocity model reveals that the earthquakes at shallow depth (~10 km) become deeper and the cluster also becomes more concentrated. Besides, a new optimized velocity model has a low-velocity layer around 10 km depth and slower velocity from 20-35 km depth. Ku et al. (2020) also observed a low-velocity zone above the Moho in the Western Solomon Islands and they referred it to the lower crustal magma (Dufek and Bergantz, 2005). The distribution of the root-mean-square error in arrival times are more centralized after relocating and that may indicate the new optimized velocity model is more appropriate for this region. However, the cross sections in Fig. 4 show the appearance of earthquakes that relocated with the new velocity model is similar to Fig. 3, which events are located with the interpolated PREM. We can observe the seismic gap at depths of 20-35 km in both results which confirms the authenticity of the seismogenic structure.

Comparing the result with background seismicity, not only do we locate more earthquakes at shallow depth, but we also locate events more concentrated than the prior catalog (Fig. 3). We assume that nearby stations and the interpolated 1D PREM or the new velocity model constrain the quality of the result so that we can locate lots of earthquakes with small magnitude and at shallow depth. Owing to the complete seismic data recorded by the newly seismic network, we interpret the event cluster beneath Makira and Guadalcanal to define the location of active tearing within the Australia lithosphere, at the corner zone between the San Cristobal Trench and transform zone (Fig. 6).

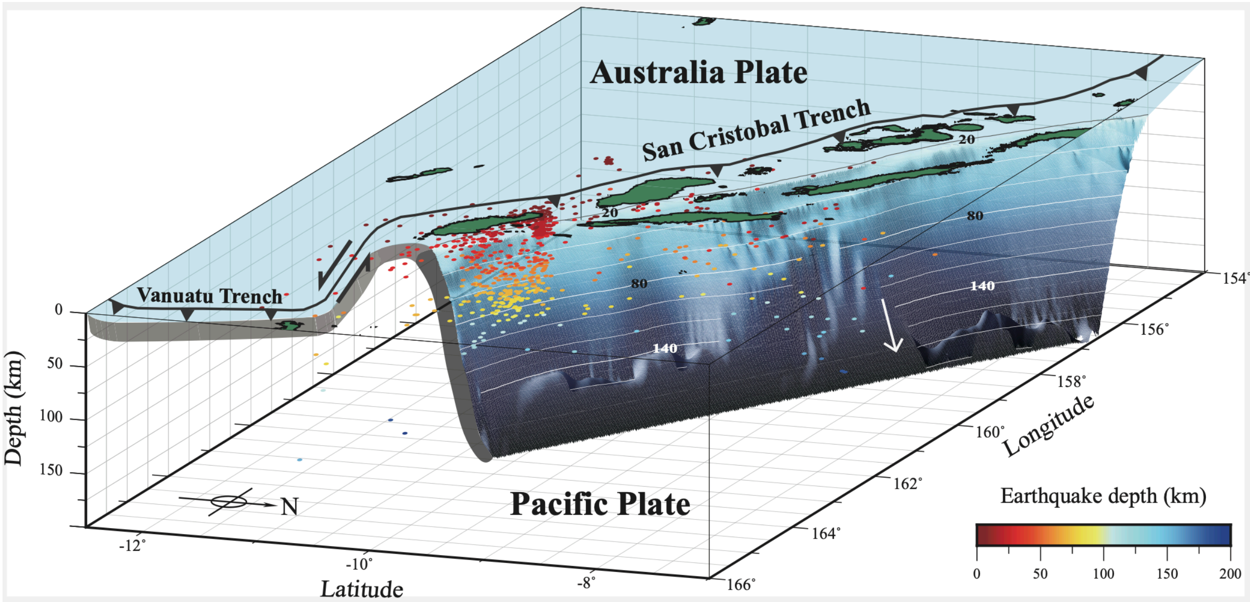

Figure 6. Three-dimensional visualization of the seismic cluster in the southeastern Solomon Islands viewed from northwest. Heavy lines with barbs represent subduction boundaries; solid contour lines are Slab2 – A Comprehensive Subduction Zone Geometry Model (Hayes et al., 2018), contoured every 20 km; earthquake hypocenters (circles) show crustal and mantle seismicity gathers at 100 km-wide seismic cluster, at the edge of the lithospheric tear.

6 Conclusions

In this study, we provide better quality constraints on locating earthquakes with a new optimized local 1D velocity model from the regional seismic network and discover the seismogenic mechanisms and structures in the southeastern Solomon Islands. The earthquake cluster between Makira and Guadalcannal distributes near vertically from subsurface to 120 km depth, which is interpreted as the tear slab within the Australia lithosphere, due to the interaction of subduction and transform zones of the PAP and AUP. A seismic gap observed at depths of 25-35 km sustains a "jelly sandwich" rheology of the continental crust.

Acknowledgments

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Open Research

The seismic data set used in this manuscript is available on https://tecdc.earth.sinica.edu.tw/WAV/2020SolomonIs/ (login with Email: solomon@earth.sinica.edu.tw and password: Islands2023).

Maps were created by using Generic Mapping Tools (GMT) version 6 (Wessel et al., 2019).

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A Near-Vertical Slab Tear in the Southeastern Solomon Islands

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Key Points:

- An optimized local 1D velocity model was determined from the regional seismic network.
- A subduction-to-strike-slip transition system could result in the near-vertical dip-slip tear slab in the southeastern Solomon Islands.
- The "jelly sandwich" rheology of the continental crust of the Australia Plate is observed.

Abstract

The Solomon Islands is one of the most seismically active areas in the southern Pacific with high earthquake hazard potential. The regional seismic network, equipped with six broadband seismic stations, was constructed as late as October 2018. On January 27 and 29, 2020, two moderate earthquakes, Mw 6.3 and 6.0, respectively, occurred in the southeastern Solomon Islands. The entire foreshock-main-shock-aftershock sequence was recorded by this seismic network for exploring the seismogenic structures. Based on the spacial distribution of the foreshock-aftershock sequence, the interaction of the subduction and transform zones between the Pacific and the Australia plates could lead to the near-vertical dip-slip tear slab. Confirmed with PREM and the new 1D velocity model for testing the robustness of the earthquake locations, a seismic gap at depths from 25 to 35 km is observed as the "jelly sandwich" rheology of the continental crust of the Australia plate.

Plain Language Summary

To establish a seismic network is always the first step and essential for studying any researches related to earthquakes, especially in the Solomon Islands, one of the most seismically active areas in the southern Pacific. However, as late as October 2018, the regional seismic network in the southeastern Solomon Islands, equipped with six broadband seismic stations, was constructed because most of the areas are inaccessible. A good 1D local velocity model is crucial for determining earthquake locations. The data set from foreshock-main-shock-aftershock sequence of two earthquakes in 2020 recorded in the seismic network provides a good opportunity for obtaining a 1D velocity model. After the reliable earthquake locations are determined, the spacial distribution of the foreshock-aftershock sequence can provide valuable information about seismogenic structures for better understanding the occurrence of earthquakes. As a result, a near-vertical dip-slip slab of the Australia plate from the subsurface to 120 km with a seismic gap at depths from 25 to 35 km is observed for the first time. This near-vertical tear slab could result from a subduction-to-strike-slip transition system and the seismic gap within the continental crust is related to "jelly sandwich" rheology.

1 Introduction

Previous studies in the Solomon Islands have mainly focused on tectonic evolution (e.g., Yan and Kroenke, 1993; Mann et al., 1998; Petterson et al., 1999; Mann and Taira, 2004; Holm et al., 2016), geology (e.g., Mann et al., 1998; Taylor et al., 2005; Taylor et al., 2008; Chen et al., 2011), and a few related to the crustal and upper mantle structures using ocean-bottom seismometer data set with passive and active sources (e.g., Mann et al., 1996; Phinney et al.,1999; Mann and Taira, 2004; Miura et al., 2004). The subduction systems in the southeastern Solomon Islands have not been documented in detail due to shortages of seismic stations and feasible data for investigating the complex seismogenic, crustal, and upper mantle structures. The complex tectonic setting and geopolitical marginality make the Solomon Islands hardly to be explored, including deploying seismic stations on islets. However, improvement of station coverage, in particular, is one of the most effective observations to answer the seismotectonic debate (e.g., Ku et al., 2020).

The regional seismic monitoring network in the southeastern Solomon Islands was constructed until October 2018 (Fig. 1). On January 27 and 29, 2020, two moderate earthquakes, Mw 6.3 and Mw 6.0, respectively, occurred in the southeastern Solomon Islands. The entire foreshock-main-shock-aftershock sequences were completely recorded by this regional-scale seismic network. These two earthquakes are located in the most active area of the region, which the foreshock and aftershock sequences can provide a unique opportunity to look into the crustal and upper mantle structures of the subduction zones between the Pacific plate (PAP) and the Australia plate (AUP). Here, we report on earthquake distribution for the southeastern termination of the southeastern Solomon Islands subduction zone and also derive a optimized local 1D velocity model utilizing the complete seismic data recorded by the newly seismic network.

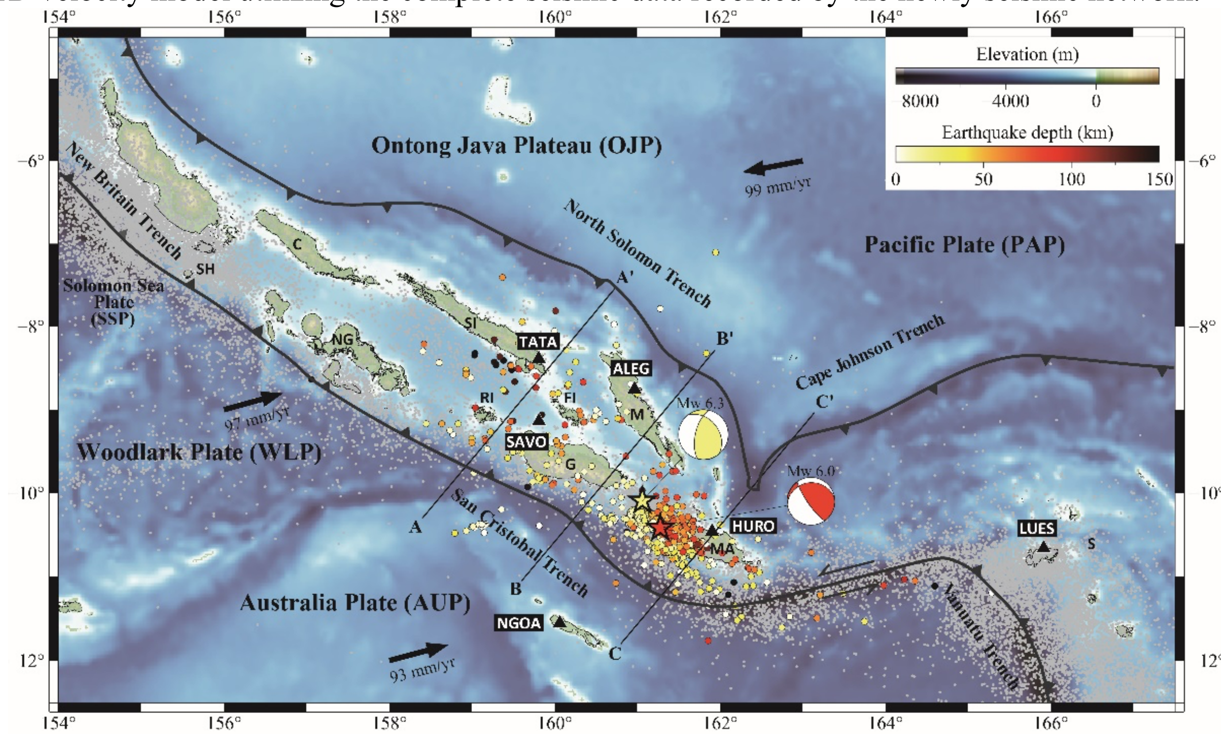

Figure 1. Topography, bathymetry, and regional tectonic setting of the Solomon Islands region. Arrows indicate direction and rate of plate motion of the Australia, Pacific, and Woodlark plates (NUVEL-1A, Demets et al., 1994); heavy lines with triangles represent subduction boundaries; black triangles are broadband seismic stations; yellow and orange stars represent earthquakes occurred on January 27 and 29 from the Incorporated Research Institutions for Seismology (IRIS) catalog; focal mechanisms of the two earthquakes are from GCMT; circles color-coded by depth indicate foreshocks and aftershocks recorded by GNS seismic stations; background seismicity are shown as gray dots and are compiled by the IRIS event catalog for the period 1971-2021; AA', BB' and CC' are the cross sections in Figs. 2-5. SH, Shortland Islands; C, Choiseul; NG, New Georgia Island Group; SI, Santa Isabel; RI, Russell Islands; FI, Florida Islands; G, Guadalcanal; M, Malaita; MA, Makira; SCZ, Santa Cruz Islands.

2 Tectonic setting

The Solomon Islands is located in a complex and active plate boundary where several plates interact with each other, including the PAP, the AUP, and the associated microplates (i.e., the Woodlark plate (WLP) and Solomon Sea plate (SSP)) (Fig. 1) (e.g., Demets et al., 1990, 1994, 2010; Beavan et al., 2002; Miura et al., 2004; Phinney et al., 2004; Taira et al., 2004; Taylor et al., 2005, 2008; Argus et al., 2011; Newman et al., 2011). In the southern Solomon Islands, the WLP and the AUP subduct beneath the PAP forming the New Britain Trench, San Cristobal Trench and

Vanuatu Trench (e.g., Taylor and Exon, 1987; Crook and Taylor, 1994; Taylor et al., 1995; Mann et al., 1998; Taylor et al., 2005). The area surrounding the Solomon Islands and the Santa Cruz Islands contains two subduction-to-strike-slip transition (SSST) regions where a transform zone links two oblique subduction zones (Bilich et al., 2001). In addition, the Ontong Java Plateau of the PAP, the largest and thickest oceanic plateau on Earth, subducts along the North Solomon Trench and the Cape Johnson Trench in the north with slight convergence (e.g., Taylor and Exon, 1987; Yan and Kroenke, 1993; Crook and Taylor, 1994; Mann et al., 1998; Petterson et al., 1999; Mann and Taira, 2004). The Solomon arc is assumed the most representative example of an island arc polarity reversal due to the presence of inwardly double subduction zones resulting in high risk of earthquakes, tsunamis, and volcanic eruptions.

Composed of two chains of islands, the Solomon Islands extends about 1000 km wide which are partitioned into multiple segments by distinct geological or seismological characteristics (e.g., Mann et al., 1998; Taylor et al., 2005; Chen et al., 2011). Nowadays, the active subduction occurs in the southeast of the Solomon Islands along the San Cristobal Trench according to previous seismological investigations from global seismic networks (e.g., Cooper and Taylor, 1987; Mann et al., 1998; Chen et al., 2011). They found that it might be caused by strongly oblique subduction occurring southeast of the region, although the structures of subduction zones is still under debate.

3 Seismic network and data processing

The Institute of Geological and Nuclear Sciences Limited (GNS), New Zealand, deployed six permanent seismic stations in different islets of the southeastern Solomon Islands since October 2018 (Fig. 1). The instruments are equipped with broadband seismometer (Trillium 120PA; Nanometrics Inc., Canada) and 24-bits digital recorder (Q330S; Quanterra Inc., U.S.A.) with sampling rates of 100 Hz. Except for the timing problem of the station LUES, most of the seismic waveforms recorded by the other five stations have good signal-to-noise ratios. To date, this seismic network is maintained by the Ministry of Mines, Energy and Rural Electrification of the Solomon Islands Government.

In this study, we processed two-month continuous seismic waveforms from this seismic network, one month before and after the two main shocks, respectively, to well cover the period of the whole earthquake sequence. The data set is formatted with the daily miniSEED and we used the SeisAn Earthquake analysis software (SEISAN) to establish the event database (Havskov and Ottemoller, 1999). Most of the events occurred close to the seismic network so that we were able to extract numerous high-quality seismic waveforms to pick P- and S-wave arrivals, locate earthquakes and determine magnitudes. We located earthquakes by the HYPOCENTER program (e.g., Lienert et al., 1986) and determined moment magnitude (M_w) by spectral analysis. More details of the waveform analysis procedure are described in Havskov and Ottemoller (2010).

The earthquake catalog contains events detected by at least three stations and has more than one clear S-wave arrival to effectively constrain the depths of earthquakes. The interpolated 1D Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981) was used as the reference model. In total, 730 earthquakes were listed in the preliminary catalog and of which 651 were located within the seismic network. We used the program VELEST (Kissling, 1988, Kissling et al., 1994) to derive a 1D velocity model, which produces the smallest possible uniform error for a set of seismic events with well-constrained locations. We select events within the range of the seismic network with the root-mean-square error in arrival time from 0.5 to 1.0 s to invert a new

1D velocity model. In total, 389 events were selected for inversion to derive the preferred 1D model and then with it we relocated all 730 earthquakes to obtain the final catalog.

4 Results

The background seismicity is extracted from the global earthquake catalog from 1971-2021 compiled by the Incorporated Research Institutions for Seismology (IRIS) (Fig. 2). In 50 years, only ~5100 events in our study area are listed in the IRIS catalog because of poor constraints of station coverage. The hypocenters of the two main shocks, reported by IRIS, distribute apart from depths at 21 and 85 km, respectively (cross-section CC' of Fig. 3). During the same time period, January and February 2020, only 23 earthquakes are listed in the IRIS catalog but 730 are detected from our new data set. Obviously, we detected a significant number of missing events, especially at shallow depths that also appear with steep dip, the same as the deeper events (cross-sections BB' and CC' of Fig. 3). Relatively, in contrast, our results at deep depth show a similarity of high dip angle with background seismicity but are more concentrated at the San Cristobal Trench (cross-sections BB' and CC' of Fig. 3).

Among the 730 events, the standard error of the means in vertical location (ERZ), in horizontal location (ERH), and root-mean-square error in arrival time of event locations are 24.7 $\pm$ 19.15 km, 13.43 $\pm$ 10.8 km, and 0.61 $\pm$ 0.30 s, respectively. The moment magnitudes (M_w) determined in this study mostly range from 2.0 to 4.0. The main earthquake cluster is located between Makira and Guadalcanal (Fig. 1), one of the most active regions in the Solomon Islands, where commonly experiences large earthquakes (Chen et al., 2011). Events in the cluster extend from subsurface to 120 km depth which is similar to the previous studies (Cooper and Taylor, 1985; Mann and Taira, 2004). Three southwest-northeast cross sections nearly perpendicular to the subduction zone show spatial variation of foreshocks and aftershocks from northwest to southeast (Figs. 2 and 3). Two southeastern cross sections close to the main shocks reveal that the event cluster is near-vertical and can be divided into shallow (< 25 km) and deep (35-120 km) parts (cross-sections BB' and CC' of Fig. 3). Although the North Solomon Trench contains fewer earthquakes, the cross sections in the northwest do show two trenches subduct inwardly (cross-sections AA' and BB' of Fig. 3). Fig. 4 presents the cross sections of the relocated earthquakes with the new 1D velocity model. Both the location results with PREM and the new 1D velocity model reveal a steep event cluster, but the new velocity model has low-velocity zone at 10 km depth and slower velocity layer within depths of 25-35 km comparing with PREM (Fig. 5).

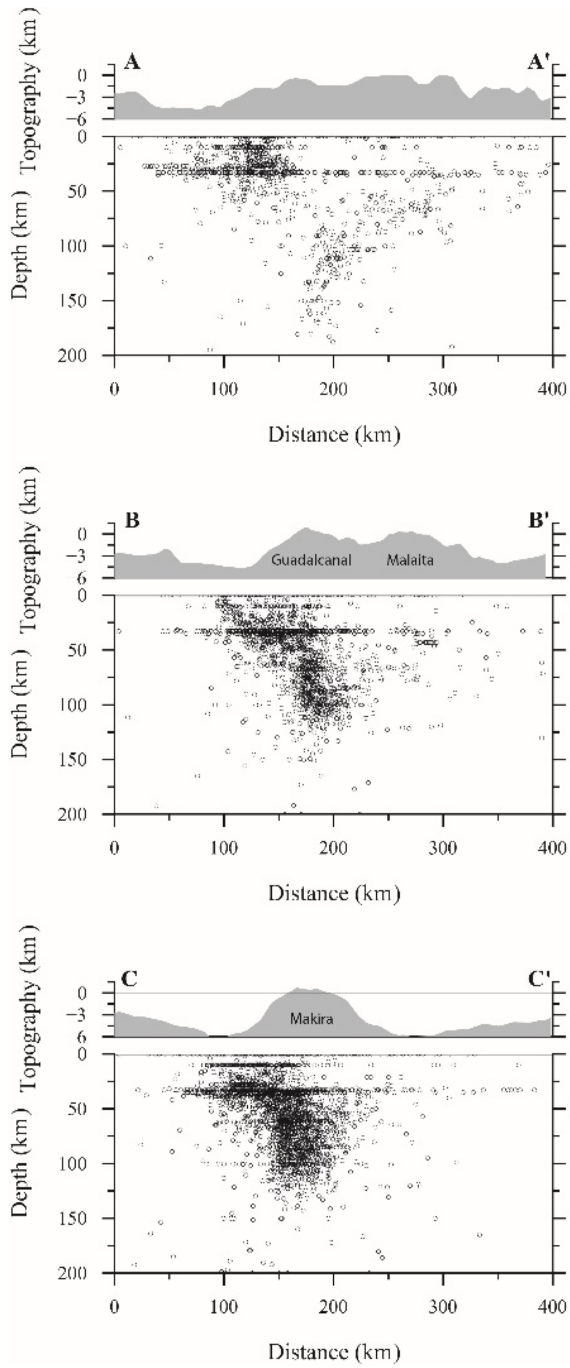

Figure 2. Cross sections of background seismicity around the southeastern Solomon Islands are compiled by IRIS event catalog from the period 1971-2021. Earthquake hypocenters are projected onto the three 200-km-wide transects shown in Fig. 1. Topography of three area is projected on to profiles in the upper panels.

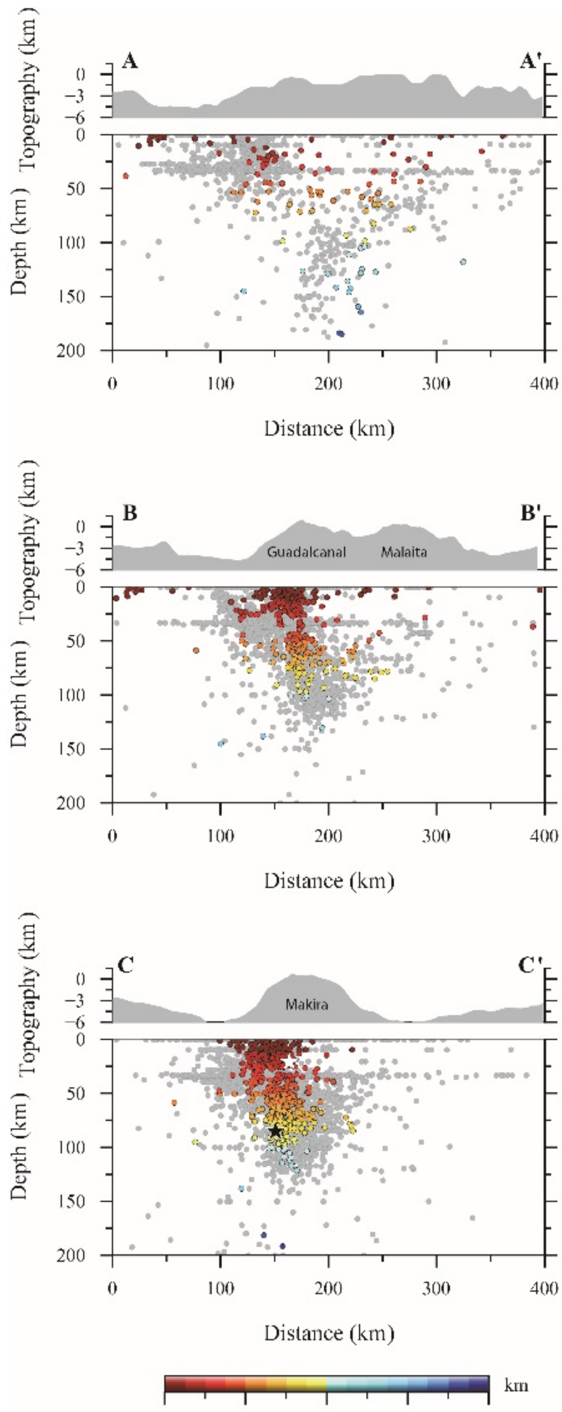

Figure 3. Comparison of earthquake hypocenters in this study and background seismicity. Cross sections with background seismicity (gray dots) and foreshocks and aftershocks (circles color-coded by depth); project lines are shown in Fig. 1; background seismicity is the same as Fig. 2; white and black stars represent January 27 and 29 earthquakes from IRIS event catalog.

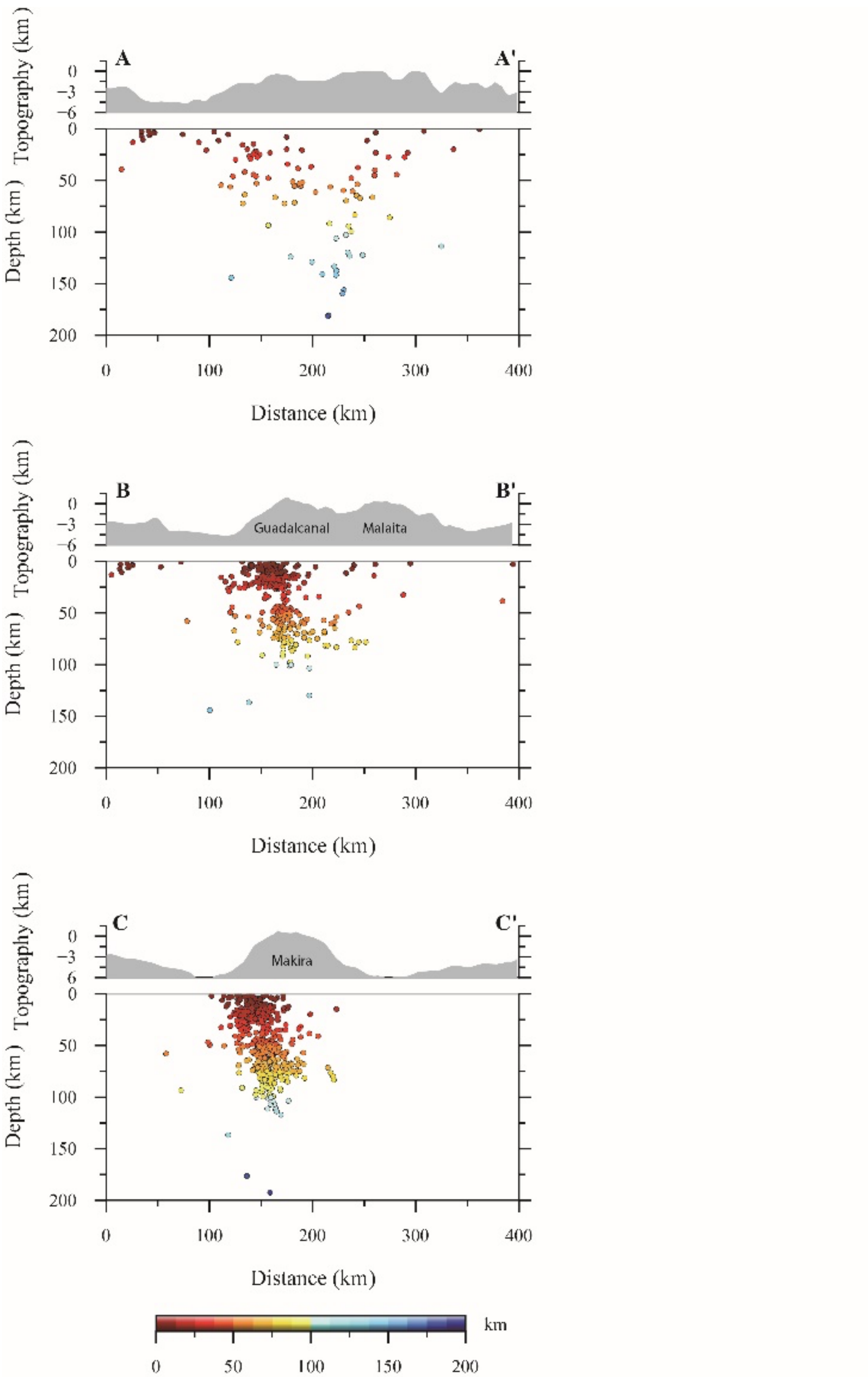

Figure 4. Cross sections of earthquake hypocenters relocated by the new 1D velocity model. Circles color-coded by depth are foreshocks and aftershocks; project lines are shown in Fig. 1.

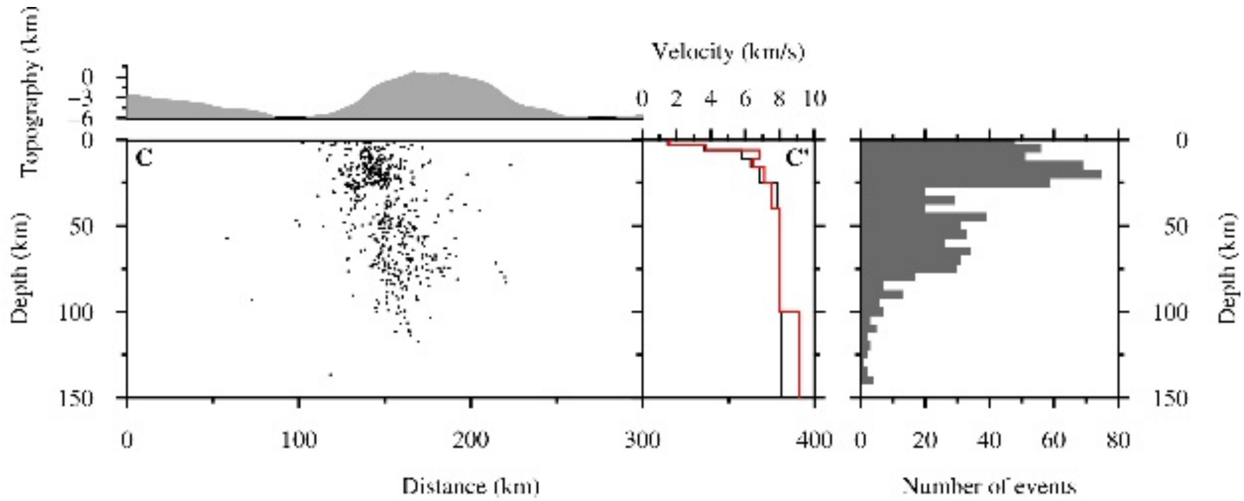

Figure 5. CC' cross section (in Fig. 4) with the seismic cluster relocated by the new velocity model around the southeastern Solomon Islands. The middle panel shows the 1D interpolated PREM (black line) and the new velocity model (red line); the right panel is the event distribution in 5 km depth intervals. Note the seismic gap between 25 km and 35 km depths.

5 Discussions

The Solomon arc, expanding ~1000 km wide, is characterized by diverse fault geometry as well as subduction properties in different segments. The complexity of tectonic setting in the Solomon Islands also makes the behavior of the seismic activities vary along the island chain. With background seismicity from the 1971-2021 IRIS catalog in the Solomon Islands, majority of the earthquakes occurred along the San Cristobal Trench which is much more seismically and volcanically active than that of the early developed subduction zones to the north (Fig. 1). These earthquakes, moreover, mainly distributed between Makira and Guadalcanal, show different structural states from the northwestern side to the southeastern through the hypocenter transects (Figs. 2 and 3). Many studies used seismicity from different global catalogs and time periods to propose the subduction manifestation, including the dip angle and the depth of the two slabs from the San Cristobal Trench and the North Solomon Trench (Cooper and Taylor, 1985; Mann and Taira, 2004; Miura et al., 2004). Cooper and Taylor (1985) and Mann and Taira (2004) gave different points of view from a similar distribution of seismicity between Makira and Guadalcanal that the latter slab angle was much flatter than the former one. However, we have different perspective of the subduction structure beneath the southeastern Solomon Islands from previous studies due to the better quality constrains on the new seismic data set.

Based on our results, we suggest that the event cluster does show as a steep seismogenic structure in the corner zone within the SSST between the Solomon Islands and the Santa Cruz Islands and also could interpret it as the location of near-vertical dip-slip tear within the Australia lithosphere (Fig. 5). This complicated plate configuration as a SSST region, which has been found at least 30 locations on Earth (Bilich et al., 2001), is usually with damaged earthquakes occurred frequently. The seismicity concentrates at the edge of the tear which extends almost vertically from the subsurface to ~120 km. Govers and Wortel (2005) assumed that the intersection between the subduction and the transform propagates through the lithosphere, inducing a tearing transform fragment. They refer to the tearing as a subduction-transform edge propagator (STEP) fault and developed the STEP model to interpret vertical, dip-slip tearing at perpendicular plate boundaries, for example, the northern Tonga (Isacks et al., 1969; Millen and Hamburger, 1998) and the southeast corner of the Caribbean (Molnar and Sykes, 1969; Clark et al., 2008). According to Bilich et al. (2001), the southeastern Solomon Islands is one of the SSST regions where the northeastward subduction of the AUP connects the transition of northeast-southwest transform motion between the PAP and the AUP. We believe that the vertical motions and complex deformation revealed by the seismicity can demonstrate the tear propagation right beneath Makira and Guadalcanal. The suggestion is also consistent with Bilich et al. (2001) that the southeastern Solomon corner zone features a band of mechanisms which nearly reach the strike-slip corner (Fig. 6).

We also observe a seismic gap, both located by PREM (Fig. 3) and the new velocity model (Fig. 4), which is similar to the seismic cluster in the Lesser Antilles of the South American plate and this phonomeon is suggested that the gap is a weak, ductile, lower crustal layer separating a strong upper/middle crustal layer from a strong lithospheric layer (Clark et al., 2008). The seismic gap, known as the "jelly sandwich" rheology (Chen and Molnar, 1983; Watts and Burov, 2003), detaches the subducting and the buoyant pieces of the AUP along a near-vertical tear here. In comparison to significant strength in the dry upper mantle, the weak lower crust would show as the undried granulite in the continental lithosphere (Jackson, 2002). The whole seismogenic deformation is about 100 km wide and extends 120 km through the entire crust and lithosphere and the gap is at 25-35 km depth within the tear.

In order to derive the local 1D velocity model for earthquake location procedures, we use the program VELEST to construct the new velocity model in the southeastern Solomon Islands. In comparison with the interpolated PREM, the seismicity relocated by the new velocity model reveals that the earthquakes at shallow depth (~10 km) become deeper and the cluster also becomes more concentrated. Besides, a new optimized velocity model has a low-velocity layer around 10 km depth and slower velocity from 20-35 km depth. Ku et al. (2020) also observed a low-velocity zone above the Moho in the Western Solomon Islands and they referred it to the lower crustal magma (Dufek and Bergantz, 2005). The distribution of the root-mean-square error in arrival times are more centralized after relocating and that may indicate the new optimized velocity model is more appropriate for this region. However, the cross sections in Fig. 4 show the appearance of earthquakes that relocated with the new velocity model is similar to Fig. 3, which events are located with the interpolated PREM. We can observe the seismic gap at depths of 20-35 km in both results which confirms the authenticity of the seismogenic structure.

Comparing the result with background seismicity, not only do we locate more earthquakes at shallow depth, but we also locate events more concentrated than the prior catalog (Fig. 3). We assume that nearby stations and the interpolated 1D PREM or the new velocity model constrain the quality of the result so that we can locate lots of earthquakes with small magnitude and at shallow depth. Owing to the complete seismic data recorded by the newly seismic network, we interpret the event cluster beneath Makira and Guadalcanal to define the location of active tearing within the Australia lithosphere, at the corner zone between the San Cristobal Trench and transform zone (Fig. 6).

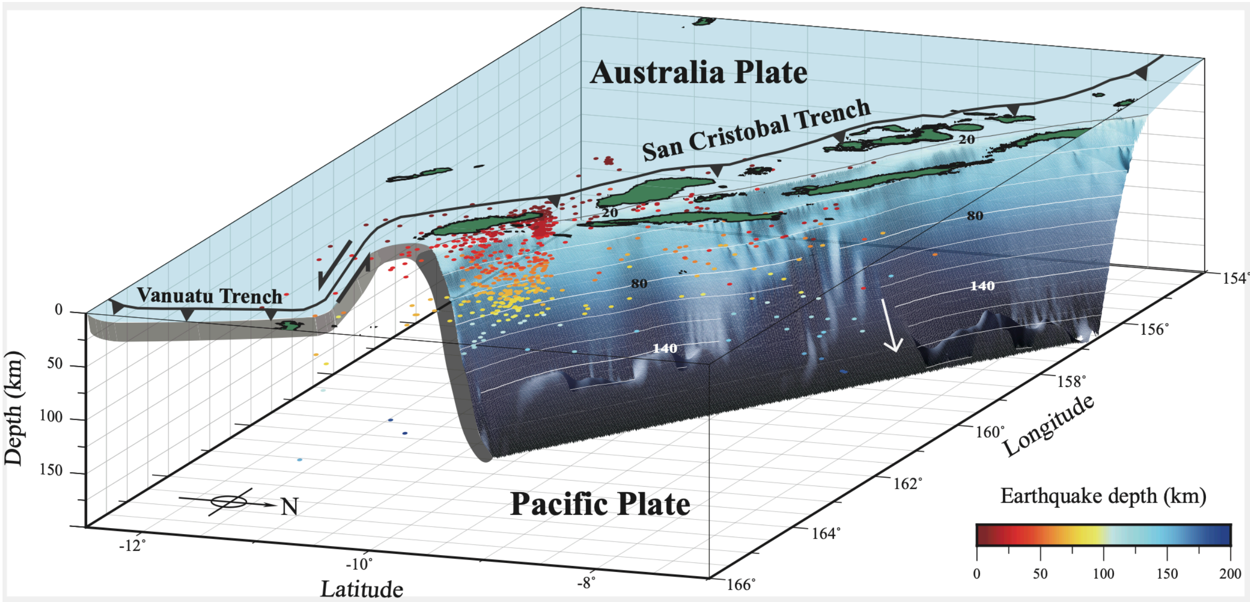

Figure 6. Three-dimensional visualization of the seismic cluster in the southeastern Solomon Islands viewed from northwest. Heavy lines with barbs represent subduction boundaries; solid contour lines are Slab2 – A Comprehensive Subduction Zone Geometry Model (Hayes et al., 2018), contoured every 20 km; earthquake hypocenters (circles) show crustal and mantle seismicity gathers at 100 km-wide seismic cluster, at the edge of the lithospheric tear.

6 Conclusions

In this study, we provide better quality constraints on locating earthquakes with a new optimized local 1D velocity model from the regional seismic network and discover the seismogenic mechanisms and structures in the southeastern Solomon Islands. The earthquake cluster between Makira and Guadalcannal distributes near vertically from subsurface to 120 km depth, which is interpreted as the tear slab within the Australia lithosphere, due to the interaction of subduction and transform zones of the PAP and AUP. A seismic gap observed at depths of 25-35 km sustains a “jelly sandwich” rheology of the continental crust.

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Open Research

The seismic data set used in this manuscript is available on https://tecdc.earth.sinica.edu.tw/WAV/2020SolomonIs/ (login with Email: solomon@earth.sinica.edu.tw and password: Islands2023).

Maps were created by using Generic Mapping Tools (GMT) version 6 (Wessel et al., 2019).

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