

1    **The 2021 South Sandwich Island  $M_w$  8.2 earthquake: a slow event**  
2    **sandwiched between regular ruptures**

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8    **Key Points**

- 9    ● The South Sandwich Island  $M_w$  8.2 earthquake appears to have extended deep depth, yet  
10    displayed tsunami earthquake-like features.
- 11    ● Inversions including long-period data revealed a  $M_w$  8.16 slow subevent at shallow depth,  
12    connecting regular deep ruptures at the ends.
- 13    ● The hybrid of deep and shallow ruptures represents an extreme example of the broad spectral  
14    behaviors of subduction zone earthquakes.

## **Abstract**

We determined the rupture sequence of the Aug 12, 2021  $M_w$  8.2 South Sandwich Island earthquake which, according to the reports from the National Earthquake Information Center, appears to be a complex sequence in both time and space. Notable tsunamis were recorded by tide gauges at global distances. Given the complexity of this event, we used a multiple subevent inversion method that can accommodate complex variations of fault geometry, location, depth, and temporal characteristics of the event. We found that the rupture initiated as a regular deep thrust earthquake; it then triggered a shallow dominantly slow subevent extending ~200 km to the south, and ended with 2 other regular subevents. The total duration is ~260s, unusually long for an  $M_w$  8.2 event. Our result is qualitatively consistent with other moment tensor solutions and the observed  $m_B$ - $M_w$  and  $M_S$ - $M_w$  relations, and provides a more quantitative space-temporal pattern of this unusual sequence.

## **Plain Language Summary**

The 2021 August South Sandwich Island  $M_w$  8.2 earthquake was a surprise, because it was initially reported as a magnitude 7.5 event at a deep depth (47 km) but generated a global-spreading tsunami that would only be expected for a larger and shallower event. By using seismic data with period as long as 500s, we revealed a hidden  $M_w$  8.16 shallow slow event that happened between clusters of regular ruptures in the beginning and end. Although the slow event contributed 70% of the seismic moment, lasted three minutes, and ruptured a 200-km section of the plate interface, it is essentially invisible at short or intermediate periods, which explains its anomalously low body-wave and surface-wave magnitudes. The 2021 South Sandwich Island earthquake represents an extreme example of the broad spectral behaviors of subduction zone earthquakes and calls for attention in the research and warning of similar events.

## 1 Introduction

Large megathrust earthquakes on the subduction interface extend from near-trench to depths and display very different depth-varying slip behaviors [Lay *et al.*, 2012]. Large earthquakes that rupture the shallowest portion of the subduction interface (<15km) can generate devastating tsunamis, but they appear to rupture slowly with inefficient excitation of short-period seismic waves disproportionately to their seismic moment and tsunami. These earthquakes are “tsunami earthquakes” [Kanamori, 1972]. At deeper depths (15~50km), large thrust earthquakes have faster rupture velocities and stronger radiation of short-period seismic energy with inefficient tsunami generation. Their contrasting rupture characteristics are well interpreted by two distinct types of fault properties; the slow slip of shallow tsunami earthquakes is commonly attributed to weak sediments, while the brittle failures of unstable fault patches explain the fast deeper earthquakes.

On August 12, 2021, a great earthquake ( $M_w > 8$ ) struck the South Sandwich Island region of the south Atlantic Ocean (Fig. 1a). This event occurred close to the South Sandwich trench, where the South American plate subducts beneath the South Sandwich plate at a velocity of 7 cm/year [Pelayo and Wiens, 1989]. A remarkable observation of this earthquake is its far reaching-tsunamis. The tsunamis spread to the north Atlantic, Pacific, and Indian Oceans, where tide gauges measured peak amplitudes of ~20 cm at over 10,000 km distance from the source (Fig. S1). Although modeling these tide gauge observations is challenging because of the lack of detailed bathymetry data between the source and gauges, the observed tsunamis at global distances appear to suggest that the South Sandwich Island earthquake could be categorized as a regular shallow tsunamigenic earthquake.

However, the South Sandwich Island earthquake seems to have extended to large depths with a complex temporal history. The early report (PDE) from the National Earthquake Information Center (NEIC) of the US Geological Survey listed 2 events within 3 minutes: 1. NEIC1, At

18:32:52 (UTC) (25.03 °W, 57.68 °S, Depth=47.2 km,  $M_w=7.5$ ) and 2. NEIC2, At 18:35:17 (25.26 °W, 58.38 °S, Depth=22.8 km,  $M_w=8.1$ ). In this paper, we call collectively the earthquake sequence which started at 18:32:52 (UTC) and lasted for about 300s, the 2021 South Sandwich Island earthquake, and we refer the 1<sup>st</sup> (NEIC1) and 2<sup>nd</sup> (NEIC2) events as the foreshock and the mainshock, respectively. The Global Centroid Moment Tensor Project (GCMT) [Ekström *et al.*, 2012] reported 2 events: 1. GCMT1 (202108121832A, centroid time: 18:35:25,  $M_w=8.3$ , 24.34 °W, 59.48 °S, Depth=20.0 km) and 2. GCMT2 (202108121835A, centroid time: 18:36:13,  $M_w=7.9$ , 25.15 °W, 60.47 °S, 15.1 km). USGS NEIC also reported a moment tensor solution at the centroid time around 18:36 with  $M_{wc}=7.98$  and depth=10 km with an alternative solution with  $M_{ww}=8.13$  and depth=35.5 km (more details in supporting table S1). Given the variability of these solutions, we attempted W-phase inversion. Because of the complex interference of the waveforms of several events, only with a very narrow long-period pass band (0.00125 to 0.002 Hz, i.e., 500 to 800 s), we could obtain a solution that can fit long-period waveforms satisfactorily for 40 stations (more details in supporting text S1, Fig. S2-3).

The depths reported by different catalogs range from 10 to 50 km, and the hypocenters scatter around the Slab 2.0 [Hayes *et al.*, 2018] interface (Fig. 1b). This is probably caused by difficulty in locating the events accurately, due to the complex interference of seismic waves from the foreshock and mainshock. Nevertheless, the deeper depths of the South Sandwich Island earthquake appear to contradict the shallow slip inferred from the global-spreading tsunami. While detailed rupture analyses would be needed to understand this disparity, it is difficult to define a physical fault plane for slip inversions due to the diverse locations and focal mechanisms from different sources (Fig. 1). In addition, the aftershocks extend ~400km along the curved subduction zone, making a planar fault unphysical. Thus, we need to analyze the rupture properties of this earthquake with flexibility in fault geometries, while maintaining the depth-dependent complexities.

In this study, we first investigate the overall spectral characteristics of the event. Then, we determine the kinematic rupture process with a multiple subevent inversion of broad-band seismic waveforms, and evaluate the contributions of subevents and discuss their relationships.

## **2 General Spectral Characteristics**

Given the complex rupture characteristics of the 2021 South Sandwich Island earthquake, we first investigate this event using 3 magnitude scales,  $m_B$ ,  $M_S$ , and  $M_w$ . Although  $m_B$  and  $M_S$  are old somewhat qualitative parameters, they are available for global earthquakes and useful for understanding the spectral characteristics of the South Sandwich Island sequence in global context. To the first order,  $m_B$ ,  $M_S$ , and  $M_w$  represent the spectral amplitudes of the sequence at about 4s, 20s, and 200s or even longer period.

### **2.1 $m_B$ vs. $M_w$ relationship**

For the measurement of  $m_B$ , we used the method described in Kanamori and Ross [2019] which follows the method developed by Gutenberg and Richter [1956]. We used the vertical component P-wave recorded at 54 global network stations (epicentral distance of  $30^\circ$ - $80^\circ$ , Fig. S4). The medians of station  $m_B$  are 6.87 and 7.10 for the foreshock and the mainshock, respectively. Fig. 2a compares the  $m_B$ - $M_w$  relationship for these events with the  $m_B$  values of about 3,000 events with  $M_w \geq 6$  for a period from 1988 to 2018 taken from Kanamori and Ross [2019]. The  $m_B$  data for the global events shown by small dots represent the range for ensemble of global events. The  $m_B$  for the mainshock is probably the upper bound because the time window for the  $m_B$  measurements contains some energy from the foreshock, only 145s earlier. The  $m_B$  values for the foreshock and the mainshock are 0.4 and 0.6  $m_B$  unit, respectively, smaller than the average

global  $m_B$ - $M_w$  trend; this indicates that these events, especially the mainshock, are deficient in short-period energy.

## 2.2 $M_S$ vs. $M_w$ relationship

We made a similar comparison of  $M_S$  vs.  $M_w$  relationship. We computed  $M_S$  using 20 s surface waves from 483 global seismic stations (distance range of  $30^\circ$ - $120^\circ$ ), and measured the peak ground motion amplitudes. Since the surface waves of the foreshock and mainshock overlap, we could not measure  $M_S$  for each event separately, and obtained just one  $M_S=7.68$  (Fig. S5). Compared with the empirical global  $M_S$ - $M_w$  relationship [Di Giacomo *et al.*, 2015] from the ISC  $M_S$  dataset [ISC, 2021], the observed  $M_S$  is 0.5 smaller than the average trend (Fig. 2b).

The smaller  $m_B$  and  $M_S$  than the global average trends indicate depleted seismic energy release at short periods and slow rupturing characteristics [Kanamori, 1972; Kanamori and Ross, 2019]. As shown in Fig. 2a-b, the South Sandwich Island earthquake is among the biggest outliers from the general trend. Other anomalous events similar to the South Sandwich Island earthquake includes the 1992 Nicaragua  $M_w$  7.6, the 1994 Java  $M_w$  7.8, the 1996 Peru  $M_w$  7.5, the 2006  $M_w$  7.7 Java, and the 2010  $M_w$  7.8 Mentawai Island earthquakes, all of which are well-known shallow slow tsunami earthquakes. This similarity suggests that the South Sandwich Island earthquake probably involved a substantial slow rupture component at the shallow subduction interface.

## 3 Multiple subevent inversion

To image the detailed rupture process of the earthquake, we applied the multiple subevent inversion method. Our subevent inversion algorithm represents a complex rupture with multiple simpler sources, each of which can have different timings, locations, source durations and focal

mechanisms [Jia *et al.*, 2020a; Jia *et al.*, 2020b; Ross *et al.*, 2019; Zhan *et al.*, 2014]. This simple parameterization allows flexible representation of time history and fault geometries, thereby capturing the first-order spatiotemporal rupture complexities. Our subevent method is particularly suitable for describing the South Sandwich Island earthquake which contains at least two major events in 3 minutes and involves potential fault geometry variations along the curved South Sandwich trench. As the possible slow rupture may propagate long distance with strong directivity effects, we introduce a finite subevent with a unilateral Haskell rupture model with a constant rupture velocity [Haskell, 1964]. In this study, we use the Haskell model only for the long duration ( $>100$ s) subevent with potentially significant rupture directivity. We applied a Markov Chain Monte Carlo inversion in a Bayesian framework, and increased the number of subevents iteratively until the waveforms fit well (supporting text S2 for more details).

We collected 58 teleseismic (distance of  $30^{\circ}$ - $90^{\circ}$ ) P velocity and displacement records, 43 teleseismic SH displacement records, and 12 three-component regional (distance within  $40^{\circ}$ ) full waveforms in displacement (Fig. S6) for the subevent inversion. We removed their instrumental responses, and filtered the P and SH waves between 0.005-0.05 Hz for modeling short period features. For the regional full waves, we used them in two datasets with different filter bands. One of them with a 0.002-0.02 Hz passband represents intermediate period waves, and the other with 0.002-0.0033 Hz, long period motions. This combination of short, intermediate and long period bands allows mapping the ruptures of different length scales simultaneously. The teleseismic Green's functions are calculated combining the propagator matrix method and plane wave approximation [Kikuchi and Kanamori, 1991; Qian *et al.*, 2017], using the CRUST 2.0 [Laske *et al.*, 2001] model at the source region and the IASPEI91 model [Kennet, 1991] at other places. The regional full-wave synthetics are computed with a frequency-wavenumber integration algorithm [Zhu and Rivera, 2002], using the PREM model [Dziewonski and Anderson, 1981].

Our subevent model consists of 5 subevents that span ~300 km along the trench (Fig. 3, supporting table S2). We fixed the first subevent at the NEIC  $M_w$  7.5 event hypocenter. Data fittings (Fig. 3b, Fig. S7) and model uncertainties (Fig. S8) suggest that the source parameters are well constrained. The rupture begins with two short-duration subevents E1 (centroid time  $\tau_c=13$  s after the origin time, duration  $d_c=23$  s,  $M_w$  7.2) and E2 ( $\tau_c=36$  s,  $d_c=19$  s,  $M_w$  7.2), which in total ( $M_w$  7.4) generally represents the NEIC  $M_w$  7.5 foreshock. They have close locations and similar shallow dipping thrust focal mechanisms (average strike/dip/rake= $157^\circ/18^\circ/82^\circ$ ), but the centroid depth of E1 is deep (39 km) while E2 is shallow (7 km), suggesting an up-dip rupture propagation along the plate interface. They are located near a patch of dense aftershock seismicity (Fig. 3a).

Concurrent with the rupture initiation represented by E1-E2 in the first 50 s, the subevent E3 ( $\tau_c=90$  s,  $M_w$  8.16) emerged and continued for ~180 s. E3 contributes the most seismic moment of the South Sandwich Island earthquake, and its moment rate function (Fig. 3c) has a remarkably smaller aspect ratio (peak moment rate over duration,  $1.2 \times 10^{17}$  N-m/s<sup>2</sup>) than regular subevents E1-E2 (average of  $3.3 \times 10^{17}$  N-m/s<sup>2</sup>). As a Haskell source, E3 initiates close to the locations of E1-E2, and unilaterally propagates towards the south with a slow velocity (~1 km/s) and a long fault length (~180 km). E3 is located at 14 km depth with an uncertainty of  $\pm 5$  km (Fig. S8), and it has a very shallow-dipping thrust mechanism (strike/dip/rake= $134^\circ/4^\circ/22^\circ$ ), although the strike and rake angles are not well constrained due to the shallow dip angle (Fig. S9). The shallow slow slip of E3 presumably transfers the stress along the slab, which explains the downdip dense aftershock seismicity as well as the triggered outer-rise earthquakes (Fig. 3).

The rupture terminated with the final two subevents E4 ( $\tau_c=195$  s,  $d_c=26$  s,  $M_w$  7.6) and E5 ( $\tau_c=226$  s,  $d_c=50$  s,  $M_w$  7.7) at 250-300 km south of the epicenter. They occurred about 3 minutes after the rupture initiation. E4 and E5 are also shallow dipping thrust subevents (average strike/dip/rake= $206^\circ/23^\circ/106^\circ$ ), but their strike angles are ~50 degrees rotated clockwise from E1-E2. This rotation is consistent with the geometry of the curved South Sandwich Island trench.



Their locations are close to the downdip high-density aftershock patch (Fig. 3). This spatial pattern is similar to that for the other two major slip asperities (E1-E2 and E3). The depth of E4 (25 km) is significantly deeper than E5 (9 km), indicating coexisting megathrust slip at different depth domains. Moment rate functions of E4-E5 display similar aspect ratios (average of  $5.3 \times 10^{17}$  N-m/s<sup>2</sup>) to E1-E2, indicating that E4 and E5 are, unlike E3, more like regular ruptures.

The low aspect ratio, slow rupture velocity, overall shallow depth, and shallow-dipping mechanism of E3 suggest that it is a “slow earthquake” at the shallow subduction interface. This feature can be most prominently demonstrated in Fig. 4. The regular subevents E1, E2, E4 and E5 contribute almost all of the short and intermediate period waveforms, while E3 barely excited short and intermediate period signals (Fig. 4a-4c, Fig. S10). In contrast, E3 generated large long-period waves, comparable to the sum of all other subevents (Fig. 4d, Fig. S10). The diminished short period excitation explains the smaller-than-average  $m_B$  and  $M_S$  of E3 (Fig.2).

Fig. 3c compares the overall rupture sequence determined by our multiple subevent inversion with the events determined by other methods. The sequence starts with E1 which is the foreshock (NEIC1). The long duration subevent E3 connects the short duration subevents E1-E2 at the beginning and E4-E5 at the end, forming a continuous megathrust rupture process. This approximately corresponds to the long-duration GCMT1 ( $M_w$  8.3) in the middle of the rupture extent (Fig. 1). The GCMT2 ( $M_w$  7.9, half duration=24 s), with the centroid time 48 s later than GCMT1 probably overlaps with GCMT1 in time, and roughly corresponds to E4-E5 at the southern tip with rotated strike angles (Fig. 1). The W-phase solution, which is similar to the NEIC  $M_{ww}$ , probably represents a very long-period component of the latter half of the sequence (Fig. 1, Fig. S2).

#### **4 Discussion and conclusions**

The 2021 South Sandwich Island ( $M_w$  8.2) earthquake is a complex multiple event, including a slow subevent E3 connecting other regular thrust subevents at the beginning and the end. The slow subevent E3 contributes 70% of the total seismic moment of the sequence. The large moment and the relatively shallow depth of E3, with weak short-period seismic radiation, make this sequence as a whole look like a tsunami earthquake. The total duration of the whole sequence (E1 to E5) is about 260s; thus, the centroid time shift, 130s, estimated from the half duration is anomalously long on the centroid time delay vs.  $M_w$  scaling relation obtained by [Duputel *et al.*, 2013], as shown by Fig. 5. The 2002 Guerrero earthquake [Kostoglodov *et al.*, 2003] and the 2006 Java earthquake [Ammon *et al.*, 2006], both of which are slow tsunami earthquakes, share a similar trend on Fig. 5. Thus, the South Sandwich Island earthquake appears to be a hybrid of deep rupture and slow tsunamigenic slip; this explains the somewhat unusual combination of the relatively large depth and the globally-observed tsunami.

Although the shallowest subduction interface is often considered seismically inactive due to the velocity-strengthening frictional properties [Scholz, 1998], some large tsunami earthquakes were found to host major slip at near-trench depths [Kanamori and Kikuchi, 1993; Lay *et al.*, 2011]. However, the slow component of the South Sandwich Island earthquake may have a broader depth extent than the traditional tsunami earthquakes. The slow subevent E3 has an overall shallow centroid depth of 14 km, which explains its global-spreading tsunamis and the two large ( $\sim M_w$  7) outer-rise aftershocks (Fig. 1) due to the possible stress transfer at shallow subduction interface [Sladen and Trevisan, 2018]. However, it is probably not confined in the near-trench depths like other tsunami earthquakes, but could have extended to deeper domains, which is consistent with absence of observation of devastating tsunami. The deeper slip could trigger slow rupture by dynamic weakening [Ma, 2012; Noda and Lapusta, 2013], making the slip span over a broad depth range. However, the detailed depth distribution of the slow subevent remains unclear

and difficult to resolve, because of the tradeoff between seismic moment, dip angle and depth [Tsai *et al.*, 2011]. This requires further investigations.

In summary, the 2021 South Sandwich Island  $M_w$  8.2 earthquake involves a complex depth-varying rupture process. The complex interaction of deep regular slip and shallow slow subevent explains somewhat contradicting combination of the deep subevents, the tsunami earthquake-like features with diminished short-period seismic radiation and the global-spreading tsunamis. This highlights the importance of accurately mapping the slow components of megathrust earthquakes over a broad frequency band for reliable tsunami warning.

## Acknowledgments

We thank the IRIS for providing public access ([http://ds.iris.edu/wilber3/find\\_event](http://ds.iris.edu/wilber3/find_event)) to all the seismic data. We thank the IOC of UNESCO for providing public access (<http://www.ioc-sealevelmonitoring.org/>) to the tide gauge data. This work is supported by USGS grant G19AP00030.

## Data Availability Statement

All figures are plotted using GMT (<https://www.generic-mapping-tools/>) and MATLAB (<http://www.mathworks.com/>) software. Seismic data are available on the IRIS Wilber 3 page ([https://ds.iris.edu/wilber3/find\\_stations/11455082](https://ds.iris.edu/wilber3/find_stations/11455082)). Tide gauge data are available on the IOC sea level page (<http://www.ioc-sealevelmonitoring.org/list.php>).

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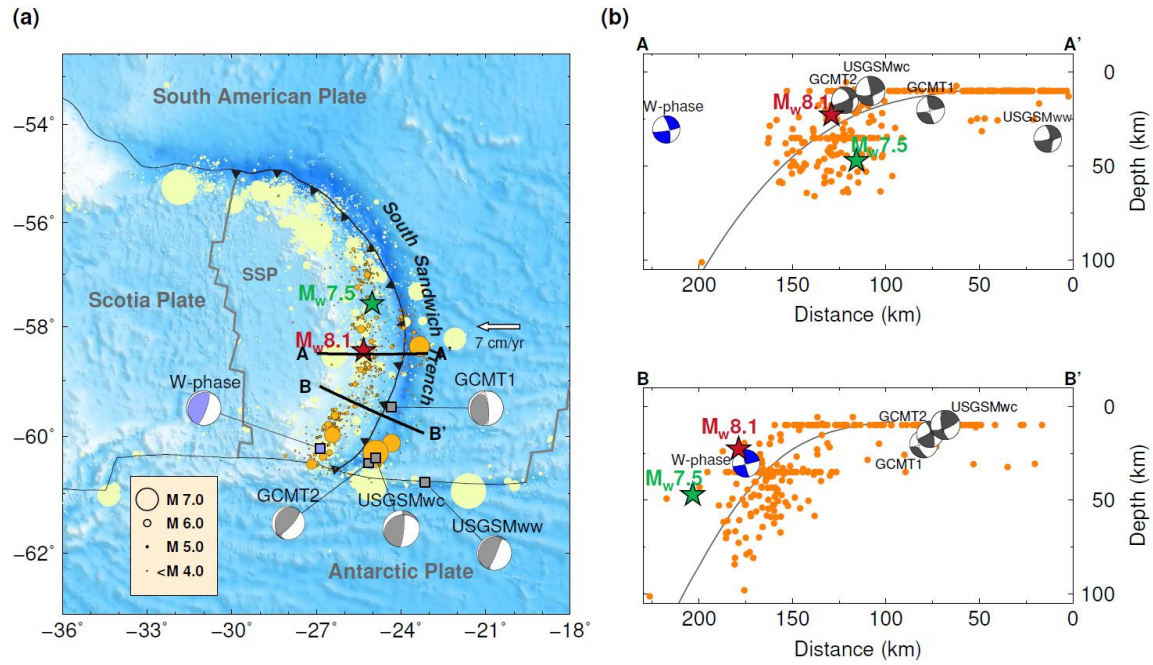
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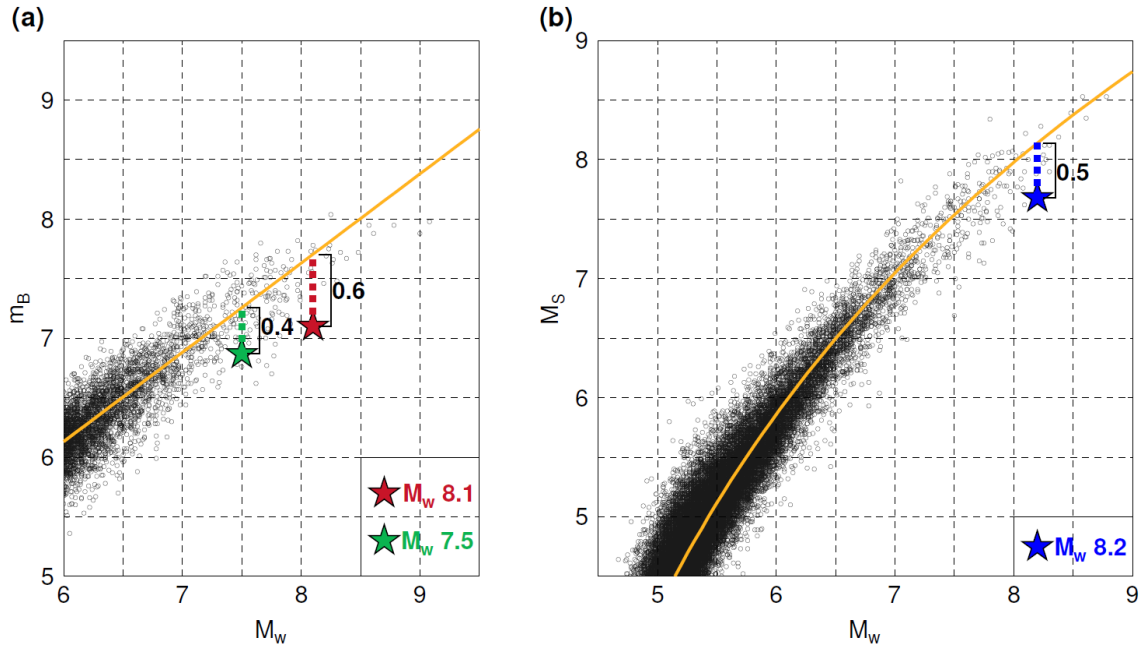
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## 323 Figures

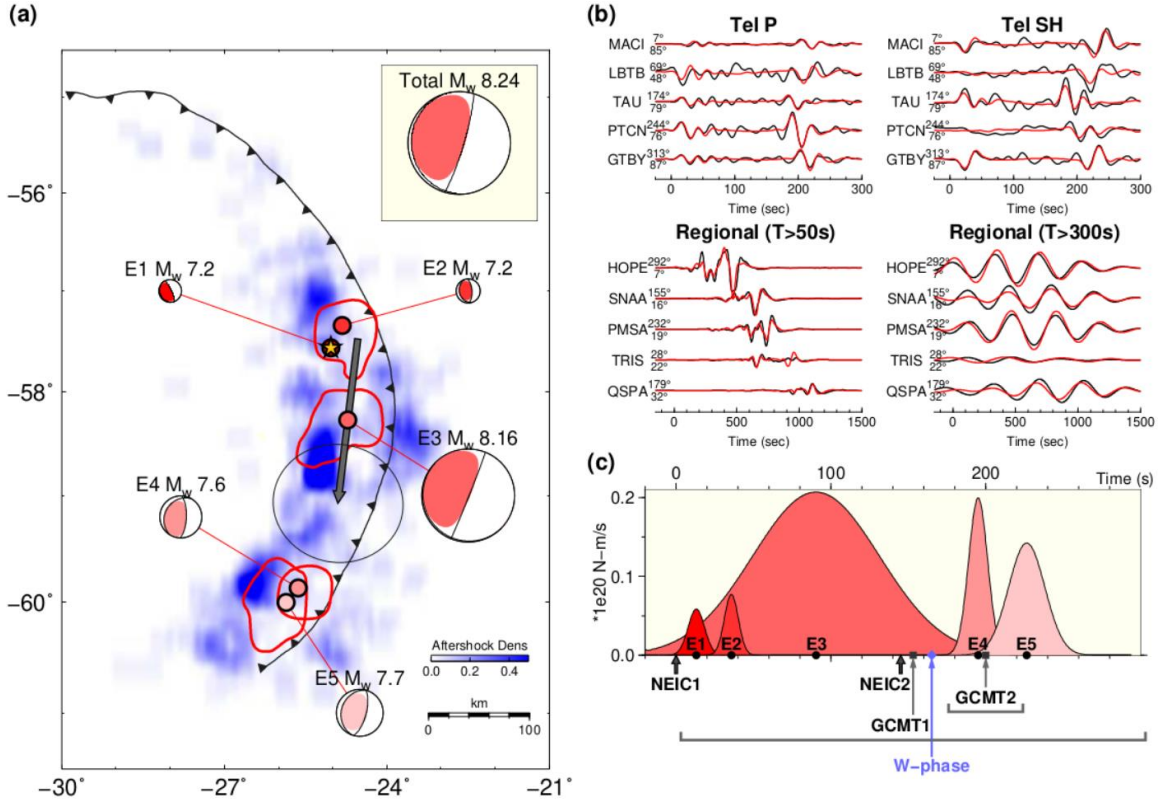


**Figure 1.** Overview of the tectonic setting and seismicity. (a) Tectonics of the South Sandwich region. The M<sub>w</sub> 7.5 foreshock (green star) and the M<sub>w</sub> 8.1 mainshock (red star) occurred close to the South Sandwich Trench, where the South America Plate subducts under the South Sandwich Plate (SSP). Yellow circles show the background seismicity according to the ISC catalog. Orange circles indicate the aftershocks within two weeks of the South Sandwich event. The beachballs display our W-phase moment tensor (in blue), USGS NEIC M<sub>wc</sub>, M<sub>w</sub>, and two Global CMT solutions (in gray). (b) Cross-sections along the black line segments in (a). The orange dots indicate the aftershocks within 100 km of the profiles. The black line represents the Slab 2.0 interface. Beachballs and stars are the same as (a), but for cross section views.



**Figure 2.**  $m_B$  and  $M_s$  measurements for the South Sandwich Island sequence. (a) Body wave magnitude  $m_B$  for the  $M_w 7.5$  foreshock (green star) and the  $M_w 8.1$  mainshock (red star). The solid yellow line indicates the general trend,  $m_B = 0.75 M_w + 1.63$  [Kanamori and Ross, 2019], which is regressed from the database of global earthquakes for the period 1988-2018 (black circles). (b) Surface wave magnitude  $M_s$  for the sequence. The solid yellow line shows the empirical relation,  $M_w = \exp(-0.222 + 0.233 M_s) + 2.863$ , regressed from the historical earthquakes (black circles) in the GCMT catalog [Di Giacomo et al., 2015].





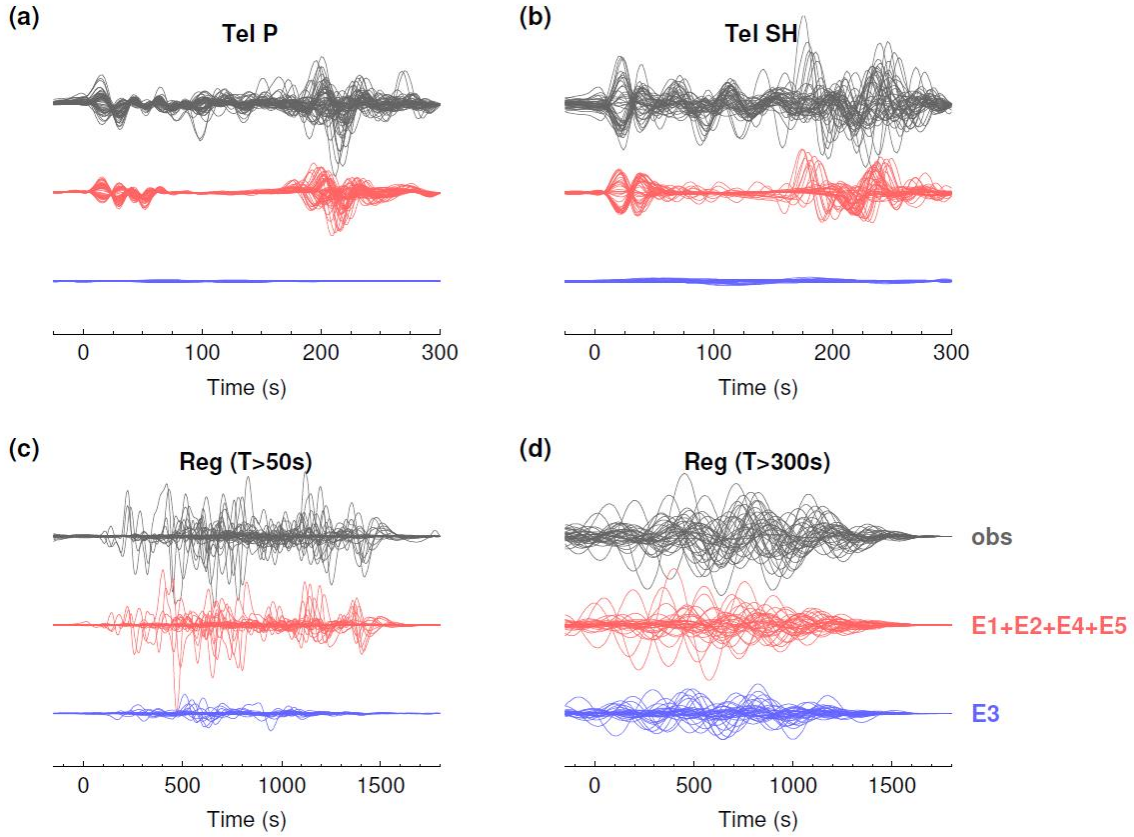
**Figure 3.** Rupture process of the South Sandwich Island sequence. (a) Subevent locations (red dots) and focal mechanisms (red beachballs). Yellow star indicates the hypocenter, collocated with the first subevent E1. The red contours show 95% confidence limits of the subevent locations. The gray arrow at E3 indicates its rupture directivity, and its length reflects rupture length. The black contour at the arrow end shows the 95% confidence limit of the rupture length and direction of E3, assuming the back end as the starting point. The aftershock density is displayed by the blue background color. The inset box shows the summation of subevent moment tensors. (b) Representative data (black) and synthetic (red) waveform fits for teleseismic P and SH waves (0.005-0.05 Hz), vertical component intermediate period (0.002-0.02 Hz) and long period regional (0.002-0.0033 Hz) full waves. The numbers leading the traces are azimuths and distances. (c) Moment rate functions for all subevents. The black circles indicate subevent centroid times. The dark arrows point to two NEIC event origin times. Gray squares and blue

357 diamond indicate centroid times of the GCMT and W-phase solutions, and the underneath solid  
358 lines denote the corresponding source durations.

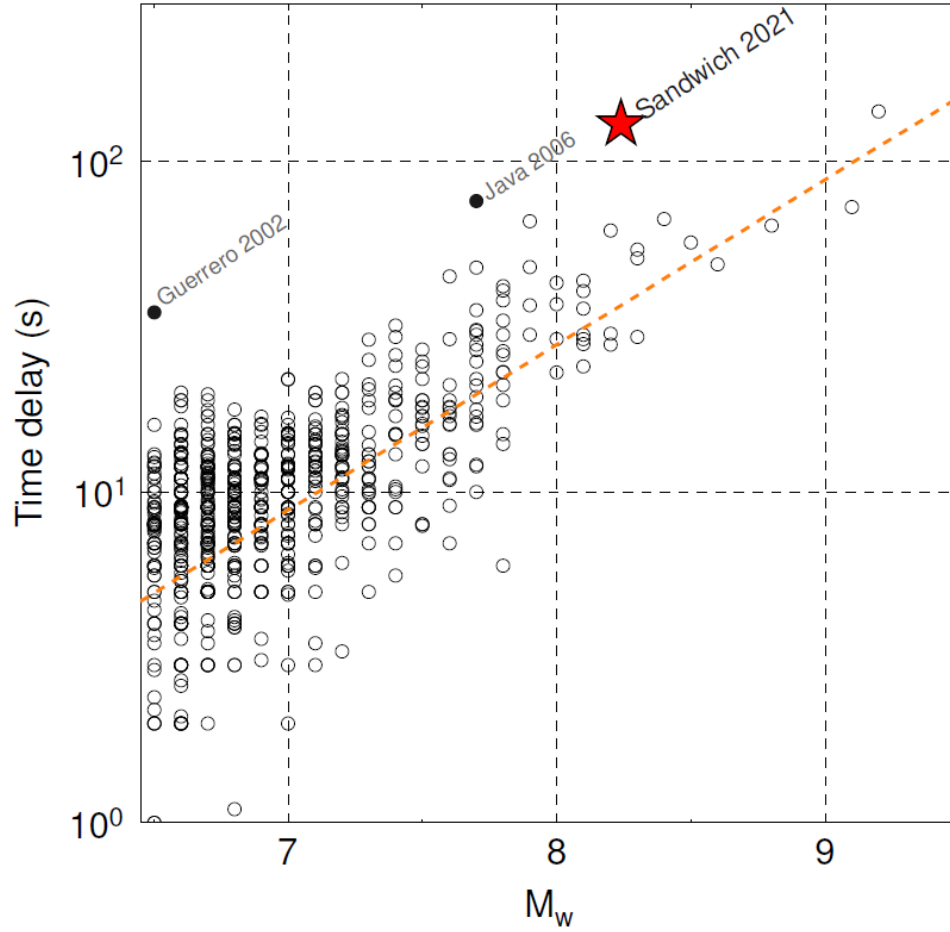
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**Figure 4.** Waveform contributions from two groups of subevents. The observed data for all stations are plotted together in black lines. The total contribution from regular subevents E1, E2, E4, E5 are in red lines. The synthetics of the slow subevent E3 are indicated by blue lines. (a) P waves. (b) SH waves. (c) Intermediate period (0.002-0.02 Hz) and (d) long period (0.002-0.0033 Hz) regional full waveforms.



**Figure 5.** Relation between time delay (half duration) and  $M_w$  for the South Sandwich Island event (red star). Black circles represent the time delays of historical events from the W-phase measurements, the orange dashed line indicates an exponential relationship using the stress parameter of 0.37 MPa [Duputel et al., 2013].