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RESEARCH ARTICLE

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Hunt for slow slip events along the Sumatran subduction zone in a decade of continuous GPS data

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Key Points:

- No confirming evidence for slow slip events in continuous data from the Sumatran GPS Array
- Suspicious signals that resemble slow slip events exist but cannot be confirmed
- Slow slip events that are either too small or too large may go undetected

Supporting Information:

- Texts S1–S3 and Figures S1–S31

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Abstract Slow slip events (SSEs) have been observed in GPS time series for many subduction zones worldwide but not in decade-long GPS time series from the Sumatran GPS Array (SuGAr). An outstanding question has been whether SSEs have simply not occurred on the Sunda megathrust or whether they have been obscured by the prodigious number of earthquakes and their ensuing postseismic deformation within the time of geodetic observation. We remove all known tectonic signals from the time series to search for evidence of SSEs. The residuals are essentially flat at the centimeter scale. To search for signals at the millimeter scale we test various filtering and visualization techniques. Despite these efforts, we conclude that it is difficult to confirm that SSEs exist at this scale using the current data, although we do see a few suspicious signals. The lack of evidence for events may reflect SSEs occurring at a magnitude, location, or timescale that renders them undetectable with the current resolution of the SuGAr, that the properties of this megathrust are not conducive to SSEs, or because the megathrust is in an active period of the earthquake cycle.

1. Introduction

Slow slip events (SSEs) detected by geodetic instruments have earned the name "silent earthquakes" because they release tectonic fault strain more slowly than ordinary earthquakes (~1 m/s). At rates of several centimeters per year to several centimeters per day, SSEs slip faster than plate motions but too slowly to generate detectable seismic shaking, allowing them to release accumulated strain with less damage than earthquakes. However, SSEs can also be a hidden danger if the slowly released strain perturbs the surrounding stress field in a way that leads to a catastrophic quake.

SSEs have been detected at many subduction zones worldwide, with their characteristics (e.g., style, size, duration, recurrence interval, and depth) varying widely from place to place [e.g., *Schwartz and Rokosky*, 2007; *Peng and Gomberg*, 2010]. While the list of subduction zones with documented SSEs continues to grow, it presently includes Cascadia [*Dragert et al.*, 2001; *Miller et al.*, 2002], central Japan at Boso [*Ozawa et al.*, 2003], southwest Japan at Nankai [*Hirose et al.*, 1999; *Ozawa et al.*, 2002; *Obara et al.*, 2004] and Ryukyu [*Heki and Kataoka*, 2008; *Nishimura*, 2014], Mexico [*Lowry et al.*, 2001; *Kostoglodov et al.*, 2003], New Zealand [*Douglas et al.*, 2005; *Wallace and Beavan*, 2010], Alaska [*Ohta et al.*, 2006; *Wei et al.*, 2012; *Fu and Freymueller*, 2013], Costa Rica [*Outerbridge et al.*, 2010; *Jiang et al.*, 2012; *Dixon et al.*, 2014], and Ecuador [*Vallée et al.*, 2013]. If we also include subduction zones with preseismic transient slip reported, we add to the list northern Chile and northeast Japan, where preslip but no SSEs in the interseismic period have been yet identified [*Obara*, 2011; *Ito et al.*, 2013; *Ruiz et al.*, 2014; *Schurr et al.*, 2014]. Although afterslip is sometimes also categorized as one type of SSE [e.g., *Schwartz and Rokosky*, 2007], in this paper we use SSEs to refer only to slow slip not triggered by a large seismic event.

Of the areas that have not had SSEs documented, for some (e.g., the Java, Philippine, and Tonga-Kermadec subduction zones) this reflects a simple lack of data. For some, data are available, and this reflects a lack of systematic search (e.g., the Ryukyu subduction zone before *Nishimura* [2014] conducted such a search). And for others, scientists have searched for evidence of SSEs but found none (e.g., the Himalaya [*Ader et al.*, 2012]).

The Sumatran subduction zone used to be an example of having had no SSEs identified, until recently, a postulated very long SSE was discovered in coral microatoll records [*Tsang et al.*, 2015]. Based on a long-term vertical reversal from subsidence to uplift in coral records, this SSE is inferred to have occurred on the Sunda megathrust in the Banyak Islands between 1966 and 1981.

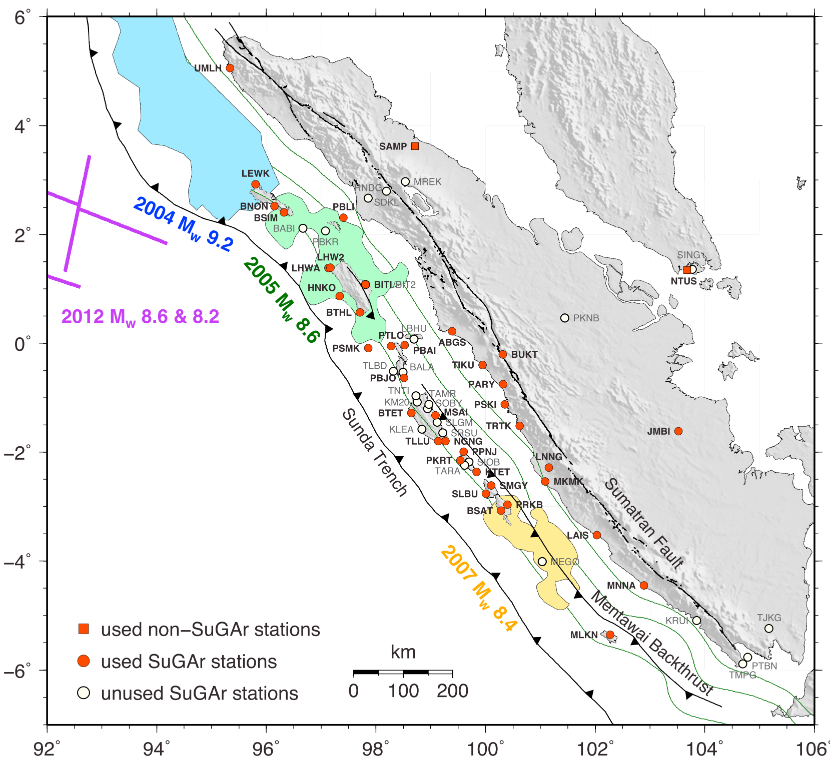

Figure 1. Map of stations in the Sumatran GPS Array (SuGAr). Stations used in this study are marked in red, while stations not used are marked in white. According to the Advanced National Seismic System composite catalog, the map area experienced 5 earthquakes of $M \geq 8$, 11 earthquakes of $7 \leq M < 8$, 86 earthquakes of $6 \leq M < 7$, and 7881 earthquakes of $4 \leq M < 6$ from 2002 to 2014. At least 30 of these events were recorded by the SuGAr in the daily position solutions [*Feng et al.*, 2015]. Colored patches or thick purple lines indicate the estimated rupture patches or segments for the five largest events [*Chlieh et al.*, 2007; *Konca et al.*, 2007, 2008; *Hill et al.*, 2015]. Thin green lines are slab contours at 20 km, 40 km, and 60 km intervals from Slab1.0 [*Hayes et al.*, 2012]. The downdip limit of coupling has been inferred to range from 40 to 60 km depth in previous studies [*Chlieh et al.*, 2008; *Prawirodirdjo et al.*, 2010].

The Sumatran subduction zone has been equipped and monitored with the continuous Sumatran GPS Array (SuGAr) since 2002 [*Feng et al.*, 2015]. Whether the SuGAr has ever recorded any SSEs has become a frequently asked but until now unanswered question. Unfortunately, obtaining an answer is not easy, as the SuGAr is located in one of the most seismically active regions in the world; the SuGAr time series are saturated with coseismic and postseismic signals from many large earthquakes. Removing all these earthquake-related overlapping spatial and temporal signals has been a daunting task, but one that we tackled in *Feng et al.* [2015], in which we developed a technique to robustly and self-consistently remove the tectonic signals from all earthquakes recorded by the SuGAr. Building on our prior work, here we use the residual position time series from that effort to hunt for SSEs along the Sumatran subduction zone.

2. Hunt for Slow Slip Events in Sumatra

To obtain the residual position time series, we added data from 2014 to extend the time series used in *Feng et al.* [2015], who analyzed data from 39 continuous GPS stations (Figure 1) from as early as August 2002 through the end of 2013. Since for this study, we otherwise followed the methods described in *Feng et al.* [2015]; we here only summarize the main steps.

First, we reprocessed the GPS data using the GPS-Inferred Positioning System and Orbit Analysis Simulation Software (GIPSY-OASIS) version 6.2. In order to reduce noise from various delays and loading processes that could mask SSEs in the time series, we made efforts to model most of these noise sources directly in the processing (see the supporting information). On the other hand, in order to preserve as many tectonic signals as possible, we did not apply postprocessing filtering at this stage. Second, by carefully examining the resulting SuGAr time series and comparing them with a seismicity catalog, we identified all recorded earthquakes (30 in total). Third, we fit the north, east, and vertical time series of each station in one optimization procedure to simultaneously estimate known signals that include (1) long-term rates, (2) annual and semiannual signals with constant amplitudes and fixed phases, and (3) coseismic offsets and postseismic decays for the identified earthquakes. Lastly, we removed from the raw position time series all the aforementioned known signals based on our final best fit models to obtain postfit residual position time series.

The obtained postfit residual time series have an average root-mean-square (RMS) scatter of 2.2, 2.4, and 7.7 mm for the north, east, and vertical components, respectively. When plotting the residual time series for all 39 stations together (Figure S1 in the supporting information), we find that they are essentially flat at the centimeter scale. However, when inspecting the closeup views of the residual time series for subsets of the stations (Figures S2–S10), we see many small wiggles and ramps at the millimeter scale. In the interest of better visualizing the pattern of the wiggles and ramps, we filtered the residual time series with a forward-backward Kalman filter and smoother [*Simon*, 2006] and constructed velocity geodograms [*Wernicke and Davis*, 2010] with contrasting colors to represent velocities toward north, east, or up (blue positives) and velocities toward south, west, or down (red negatives) (Figure S11) (details in the supporting information). The velocity geodograms show that most of the positives and negatives are consistent across a substantial portion of the network with some variations in phase and amplitude. The network-wide consistency in positives and negatives indicate spatially correlated noise, often referred to as common-mode error that mainly results from orbital and reference frame errors not of tectonic origin [*Wdowinski et al.*, 1997]. The common-mode error has thus largely obscured our chance of detecting any transient signals of tectonic origin if they are at or below the common-mode noise level.

In an effort to detect potentially obscured tectonic transient signals, we used a common-mode filter to remove the common-mode error [*Davis et al.*, 1999] (details in the supporting information). Similar spatial filtering methods have been used in many other subduction zones to increase the signal-to-noise ratio [e.g, *Dragert et al.*, 2001; *Beavan*, 2005; *Jiang et al.*, 2012]. Such spatial filtering has the inherent risk of introducing artificial signals or removing tectonic signals if they affect stations in a similar manner. To minimize this risk, we first divided the SuGAr network into northern and southern subsets based on differences in the common-mode pattern. We then made sure that the constructed common-mode signal (Figure S13–S14) represented common noise shared by most stations in a subset, not by only several individual stations, so that the common-mode signal was less likely to include sources of tectonic origin and relatively safe to remove. The removal of the common-mode error reduced the average RMS scatter to 1.9, 2.1, and 7.2 mm for the north, east, and vertical components, respectively, with cleaner time series (Figure 2) and significantly suppressed blue and red areas in the velocity geodograms (Figure 3).

3. No Confirmed Evidence for Slow Slip Events in Sumatra

In Figure 2 and its closeup views (Figures S15–S23), we show that the common-mode filtered residual time series for most stations are flat even at the millimeter scale. On the other hand, although many common wiggles and ramps have been removed through common-mode filtering, we still observe small uncommon wiggles and ramps for some stations. These anomalous signals are more pronounced as large blue positives and red negatives in the velocity geodograms (Figure 3). The sources of these anomalous signals could be remaining unmodeled atmosphere and nontidal ocean loading, instrument problems and human activities, or SSEs. To confirm an SSE, we require the signal to be recorded at multiple (preferably three or more) neighboring stations and the sense of direction to be consistent with the motion of SSEs on the megathrust. To be specific, an SSE in Sumatra should start with a horizontal red negative, which represents southwestward motion toward the trench, indicating release of accumulated strain, and end with a horizontal blue positive, which represents the recovery to the previous status. Note that afterslip has been removed from the residual time series, so SSEs here exclusively mean transient slip not triggered by large earthquakes.

Now let us consider individual anomalous signals. We first exclude stations PRKB and TIKU, because they show strange and noisy vertical signals that were likely caused by instrument problems or localized activities. We also exclude stations SAMP and NTUS, because they are located far from the subduction front, so they do not likely record SSEs (Figure 1). But how can we explain the ramps in their filtered residual time series (Figures 2 and 3)? For SAMP, the ramps are related to the gradual failure of the antenna and frequent data gaps; for NTUS, the ramps may be related to unmodeled nontidal ocean loading. SAMP and NTUS remind us not to automatically interpret any anomalous signals as SSEs. Keeping this in mind, we scan through all the filtered time series (Figure 2) for possible SSE signals, with their geodograms (Figure 3) as indicators for anomalies.

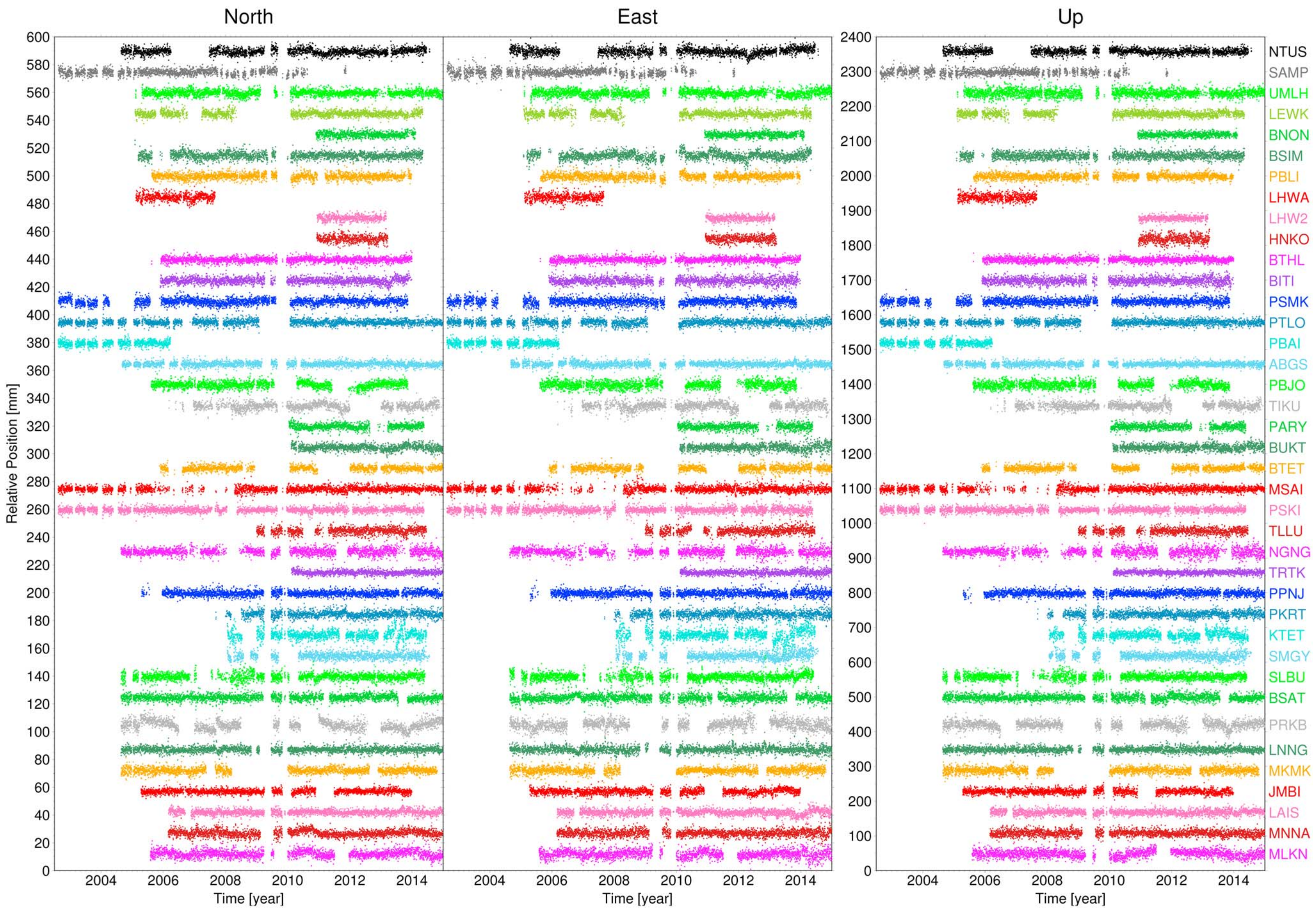

Figure 2. Common-mode filtered residual time series. Stations are plotted roughly from north to south.

In the geodograms (Figure 3), the largest ups and downs appear in the vertical component of station MLKN, which sits alone on Enggano Island. The vertical ups and downs of MLKN are clearly out of phase compared to the rest of the network. It seems that MLKN behaves differently, but we cannot answer if this different behavior is caused by SSEs. The north component of MLKN also shows some ramps, which seem to be correlated with those seen at the nearest station MNNA (Figure S21). Whether this correlation suggests an SSE is unclear without evidence from more stations. Unfortunately, similar to the case of MLKN, most anomalous signals in the filtered time series (Figure 3) appear only at one station or even in one component (e.g., UMLH, LEWK, BSIM, PBJO, BUKT, and MKMK). Therefore, it is difficult to attribute most anomalous signals to SSEs without other independent observations to confirm them.

However, we do find a set of anomalous signals that affected two nearby stations (KTET and SMGY) simultaneously and consistently. For both sites, the suspicious signal started around the middle of 2012 and lasted to the end of the latest data (Figures S22 and S23). In the east component, initial westward motion (red) was followed by motion back to the original (blue) (Figure 3), consistent with the expected motion of an SSE on the Sunda megathrust. The vertical components of KTET and SMGY were oppositely synchronized, with the main motion as uplift at KTET and subsidence at SMGY. Considering the two stations are only 40 km apart, the coherent pattern might be truly an indication of an SSE. Still, based on only two stations, we cannot confirm this hypothesis. Additionally, KTET is particularly noisy during this period of interest (Figures S22 and S23), which reduces the reliability of the data.

In summary, we do not find confirmed evidence for repeating or transient signals of either preseismic or interseismic type at the centimeter scale. At the millimeter scale, SSEs might exist, but it is generally difficult to correlate anomalous signals at multiple stations and confirm them to be real SSEs.

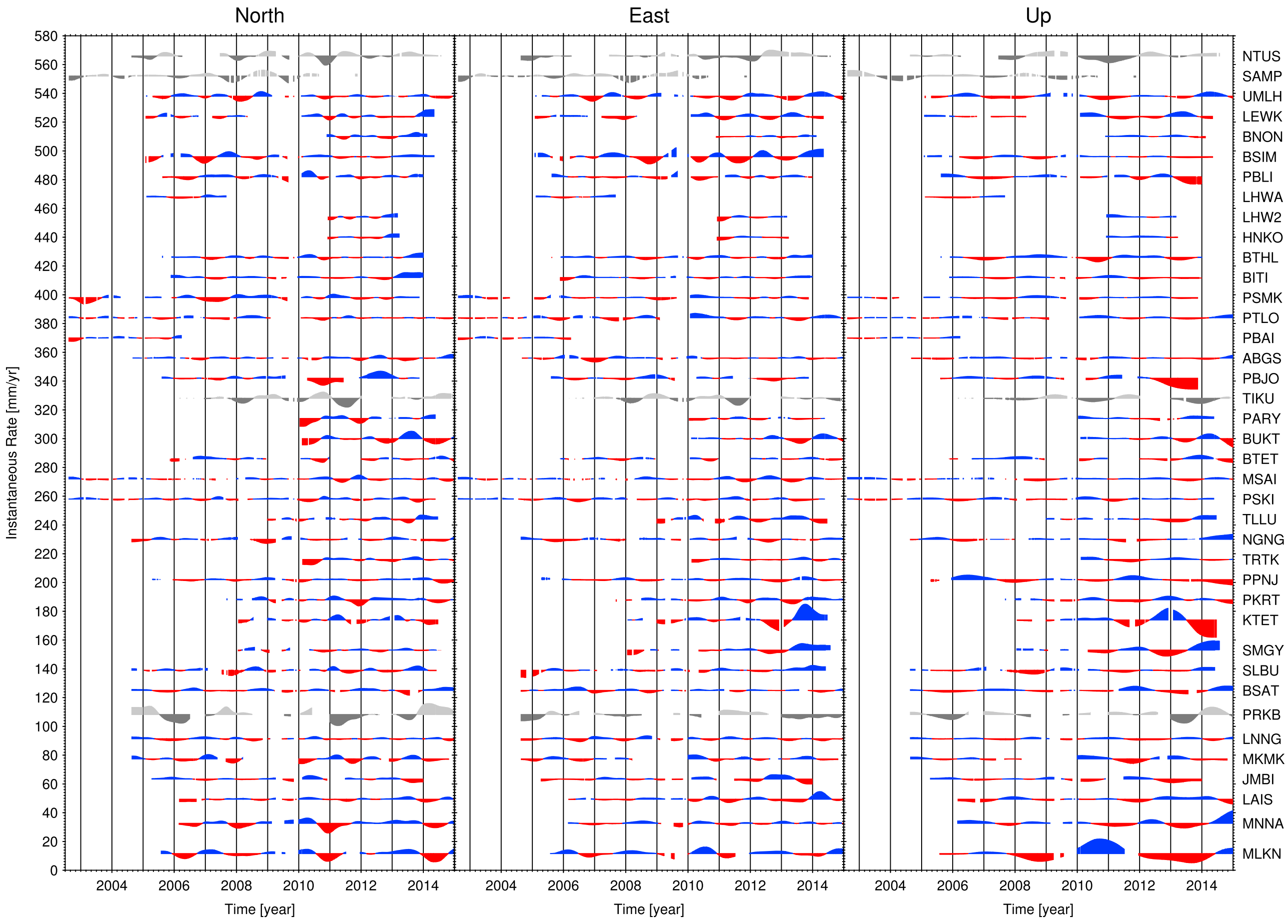

Figure 3. Velocity geodograms for common-mode filtered residual time series.

4. Minimum Sizes of Slow Slip Events That Can Be Observed by the SuGAr

Although the SuGAr network contains a large number of stations, they cover the ∼1700 km length of Sumatra, resulting in relatively large interstation distances. And although the locations of our stations are much closer to the trench than many other subduction zones, thanks to the presence of fore-arc islands, substantial gaps remain in our network in the areas where no islands exist. Resolution, therefore, is a significant concern.

To assess the extent to which our null results could be caused by lack of resolution rather than lack of events, we tested the minimum size of SSEs we would be able to detect at different locations along the Sunda megathrust. Based on the average RMS scatter of the common-mode filtered time series, we first assumed that our stations could resolve only 2 mm horizontal and 7 mm vertical displacements at the minimum. We also assumed that SSEs, if they occurred, were mainly thrust events on the megathrust. We then discretized the Slab1.0 megathrust interface [*Hayes et al.*, 2012] into patches of different sizes. Next, we calculated the minimum dip slip required for each patch to generate an SSE that can be detected by at least three stations among the 39 in our study, using the Okada dislocation model [*Okada*, 1992]. Last, we converted the calculated minimum dip slip to equivalent moment magnitude (M_w) using a rigidity of 30 GPa. While different magnitudes would in reality involve different slip areas, in each of our tests we used the same patch size for all patches. Since the same patch size would not be appropriate for all earthquake sizes, we tested different patch sizes (80×80 km^2, 40×40 km^2, 20×20 km^2, and 10×10 km^2) to gain a more complete view of the minimum size of an event that could be observed.

The results of our tests with different patch sizes show a similar spatial distribution of minimum magnitude with the values changing slightly. One example (40×40 km^2) is given in Figure 4, and the others are available in Figures S25–S27. For comparison, the results for SSEs that can be detected by only one station are also provided in Figures S28–S31. The areas that have the best resolution are beneath and surrounding the fore-arc

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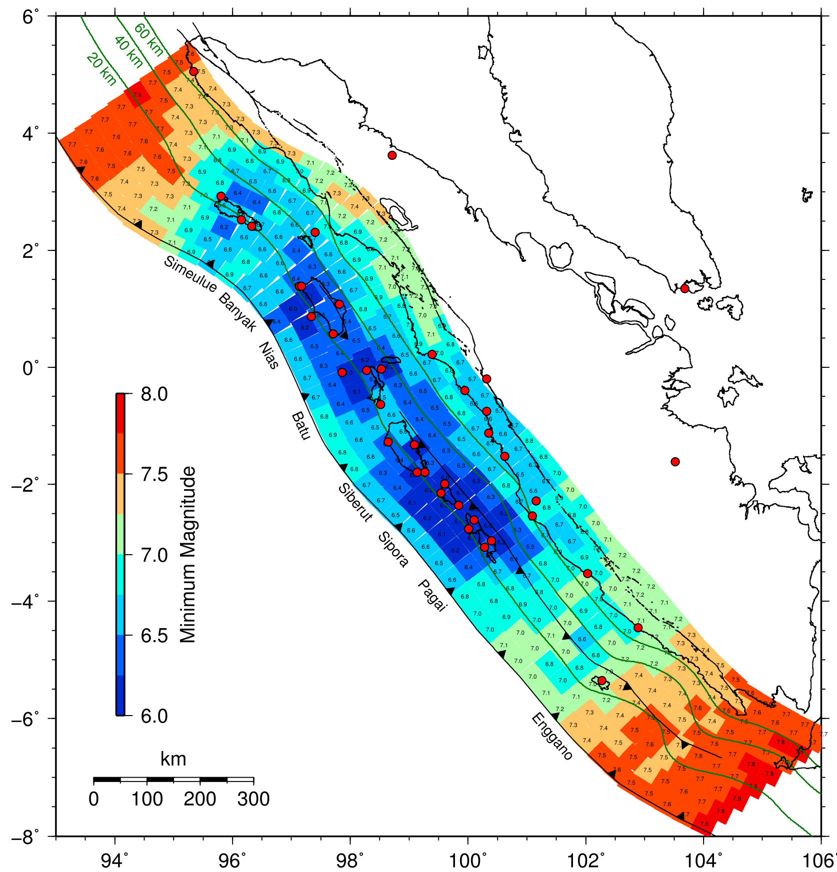

Figure 4. Illustration of the minimum magnitude of SSE event detectable by at least three SuGAr stations at different locations along the Sunda megathrust. Magnitude is calculated based on a rigidity of 30 GPa. Each patch has an area of ~ 40×40 km^2. Additional resolution tests with different patch sizes are available in the supporting information. Green lines are slab contours similar to Figure 1. Black texts near the trench indicate island names.

islands, where most of our stations are located. In those areas, we would be able to resolve SSEs of M_w 6.0–6.5. Far from the network, where fewer fore-arc islands exist, the minimum event would be $M_w > 7.0$. Between the fore-arc islands and the west coast of Sumatra, we have a relatively large observational gap. Unfortunately, this gap encloses the downdip region of past major ruptures (Figure 1) and downdip limit of published coupling maps [*Chlieh et al.*, 2008; *Prawirodirdjo et al.*, 2010], at depths between 40 km and 60 km. In this downdip portion of the seismogenic zone, where SSEs are most commonly observed [e.g., *Wallace and Beavan*, 2010; *Fu and Freymueller*, 2013], the detectable minimum event becomes as large as M_w 6.5–6.7.

Finally, if an SSE occurs immediately after an earthquake, during the period of intense afterslip, it may appear as a modulation of the afterslip signal and therefore would have been removed from the time series. In such a case, afterslip would likely bury an SSE and make it difficult to detect. However, in the later phase of afterslip when the decay is more gradual, a similar event may show as a clear deviation from the afterslip decay. One example of such is a possible SSE imbedded in the afterslip of the 2012 M_w 7.6 Nicoya earthquake [*Malservisi et al.*, 2015].

5. Discussion

The magnitudes of SSEs geodetically observed in subduction zones range between 5.4 [*Sekine et al.*, 2010] and 7.6 [*Fu et al.*, 2015], of which M_w <6.0 have mainly been detected by borehole tiltmeters or strainmeters in Japan [*Obara*, 2011]. Our resolution tests show that events of $M_w \geq 6.5$ could be detectable by the current SuGAr network for a large portion of the Sunda megathrust. Therefore, the SuGAr should be able to detect Cascadia-type SSEs (M_w ~ 6.2–6.8) [*Gomberg et al.*, 2010] in many areas, but such Cascadia-type events are not recorded in the decade of the SuGAr data. Put another way, if Sumatra is similar to Cascadia where SSEs collectively span the entire margin, we should be able to detect some SSEs, but we do not. If Cascadia-type

SSEs are occurring only on areas of the megathrust where the SuGAr has limited resolution, we would not be able to detect them. We also cannot rule out that smaller SSEs like the short-term Nankai-type events (M_w ∼5.4–6.2) [*Sekine et al.*, 2010] occurred here.

Neither can we rule out the possibility that very large SSEs occurred here over the duration of SuGAr observation. With increasing moment magnitude of an SSE, the event duration increases [*Ide et al.*, 2007], and the slip rate decreases [*Meade and Loveless*, 2009]. This makes very large SSEs difficult to detect. For example, *Meade and Loveless* [2009] estimated that a $M_w \geq 8.0$ SSE would last >10 years and would have a slip rate not exceeding 50 mm/yr. Such a slow, long-lasting SSE on the Sunda megathrust would only modify the long-term rates observed by the time series but not reverse the sense of motion as happens for smaller events [*Dragert et al.*, 2001]. We would normally interpret such large events simply as a change in coupling on that area of the megathrust, although it is unclear whether the change of coupling is just a manifestation of very long SSEs. To detect these events, much longer, multidecadal GPS records and/or paleogeodetic data [*Tsang et al.*, 2015] would be required.

We have particularly poor resolution at the southernmost Enggano section, offshore southern Sumatra, due to sparse fore-arc islands here. This is unfortunate as this region appears to have markedly different patterns of seismicity from the rest of the megathrust [see *Feng et al.*, 2015, Figure 1]. Throughout the period of modern instrumentation, the seismicity of the Enggano section has stayed at a relatively high background level, with small to large earthquakes ($M < 8$) but as yet no great earthquakes ($M \geq 8$). It would be interesting if this area is also different in experiencing SSEs. Unfortunately, we have only one station (MLKN) in this region. From our analysis of the residual time series (section 3), we have shown that MLKN did behave differently from the rest of the network, particularly in its vertical component. So it would not be surprising if MLKN has experienced SSEs; it was suggested that a nearby campaign station ENGG changed its rate after the 2000 M_w 7.9 Enggano earthquake [*Prawirodirdjo et al.*, 2010], as did MLKN after the 2007 M_w 8.4 Bengkulu earthquake [*Feng et al.*, 2015].

We have relatively good resolution between Sipora and North Pagai Islands where coherent anomalous signals were found at KTET and SMGY (section 3). This region is in the middle of the Mentawai section, whose southeastern half has broken in multiple discrete patches during several large to great earthquakes [e.g., *Feng et al.*, 2015] and whose northwestern half remains unbroken with an anticipated $M > 8$ earthquake in the coming decades [e.g., *Sieh et al.*, 2008]. If our suspicious signals really indicate an SSE, the location of this event would be in the gap that the great 2007 Bengkulu sequence jumped over and would be very close to the 2008 M_w 7.2 North Pagai earthquake, which was accompanied by a 20 day long earthquake swarm including four $M \geq 6$ events [*Feng et al.*, 2015]. The occurrence of the seismic swarm could suggest that the physical condition of the megathrust between Sipora and North Pagai favors slip released in clusters of smaller events rather than in one single large event. SSEs accompanied by earthquake swarms have been observed in central Japan at Boso [*Ozawa et al.*, 2007] and in New Zealand at Gisborne [*Delahaye et al.*, 2009], and Cape Turnagain [*Wallace et al.*, 2012]; in those locations the physical condition facilitates SSEs as well as earthquake swarms. Perhaps the physical condition of the megathrust between Sipora and North Pagai also favors SSEs, which tend to occur in transition zones where frictional properties change from velocity weakening to velocity strengthening [e.g., *Schwartz and Rokosky*, 2007; *Peng and Gomberg*, 2010]. On the other hand, this SSE, if it is real, might be part of a preseismic process that could evolve into an anticipated $M > 8$ event, as illustrated in 2-D numerical simulations [*Segall and Bradley*, 2012].

If Sumatra does indeed experience only very long SSEs, what might be different to this region compared to other subduction zones that exhibit regular SSEs? In several aspects that we examine, Sumatra is fairly average; the plate convergence rate here is 5–6 cm/yr [*DeMets et al.*, 2010] within the range of ∼3.5 cm/yr (Cascadia) [*DeMets et al.*, 2010] to ∼12.5 cm/yr (southern Ryukyu) [*Heki and Kataoka*, 2008]; the plate age, as an indicator of slab temperature, is 30–70 Ma [*Jacob et al.*, 2014] within the range of <20 Ma (Cascadia) to ∼120 Ma (New Zealand) [*Ide*, 2012]; the incoming sediment reaches a thickness of 3–5 km at the trench off northern Sumatra [*Franke et al.*, 2008; *Klingelhoefer et al.*, 2010; *Shulgin et al.*, 2013] and decreases to 1–2 km at the trench off southern Sumatra [*Singh et al.*, 2011], covering a large portion of the range of trench sediment thicknesses recorded at other subduction zones with SSEs (from 3 to 4 km at northern Cascadia [*Goldfinger et al.*, 2012] to a few hundred meters at Mexico [*Moore and Shipley*, 1988] and Costa Rica [*Shipley and Moore*, 1986]). In some other aspects, we find Sumatra shares similarities with northeast Japan and northern Chile; they all have a shallow average dip of slab (16°), a deep downdip limit of the seismogenic zone (50–53 km) and a wide width of the seismogenic zone (141–162 km) [*Hayes et al.*, 2012]. However, it is unclear if these similar conditions would result in similar characteristics of SSEs.

There are many other factors that cannot be quantified by single numbers but might control whether or not SSEs can occur: the mechanical, frictional, geometrical, or structural properties of the megathrust, or the strength, segmentation, or topography of the overriding plate, or the presence of fluids, etc. In the literature, high fluid pressure has been the most popular explanation for SSE occurrence, as a number of SSE locales have been found coincident with elevated fluids imaged by seismic methods [e.g., *Kodaira et al.*, 2004; *Song et al.*, 2009; *Bell et al.*, 2010; *Kato et al.*, 2010; *Audet and Schwartz*, 2013]. Interestingly, the possible but unconfirmed SSE between Sipora and North Pagai Islands may also coincide with a region of inferred fluid-rich sediments [*Collings et al.*, 2012].

One obvious difference to many other subduction zones is that the observation period of the SuGAr coincides with a very active period in the seismic cycle of Sumatra. How earthquakes and SSEs interact is poorly understood, but there is documented evidence in New Zealand of a M_w 6.3 intraslab earthquake at the Hikurangi subduction zone arresting an ongoing SSE [*Wallace et al.*, 2014]. It has been also suggested that the recurrence interval of SSEs at Boso has been shortened by the 2011 Tohoku earthquake [*Hirose et al.*, 2012; *Ozawa*, 2014]. In addition, coupled with the Sumatran earthquakes of the last decade we have seen that the megathrust here has the frictional properties needed to sustain very high levels of afterslip [*Hsu et al.*, 2006; *Lubis et al.*, 2013; *Gunawan et al.*, 2014]. This afterslip usually occurs updip and downdip of the coseismic rupture patches, in the very areas that SSEs are most likely to occur; perhaps the afterslip here may be relieving the strain that might otherwise be released by SSEs.

Our null results suggest that a combination of different monitoring tools is needed to prove the presence or absence of SSEs along the Sumatran subduction zone. This should include augmenting and strengthening the existing SuGAr network, installing a high-quality seismic network to identify nonvolcanic tremor, low-frequency earthquakes, and very-low-frequency earthquakes and developing seafloor geodesy to extend the coverage.

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