Gempa Nusantara: A database of 7,380 macroseismic observations for 1,200 historical earthquakes in Indonesia from 1546 until 1950

Stacey S. Martin[1, 2 †], Phil R. Cummins[1], Aron J. Meltzner [2, 3]

[1] Research School of Earth Sciences, Australian National University, Canberra, Australia

[2] Earth Observatory of Singapore, Nanyang Technological University, Singapore

[3] Asian School of the Environment, Nanyang Technological University, Singapore

[†] Corresponding author: 7point1@gmail.com; stacey.martin@anu.edu.au

Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

Abstract

We present a new database called Gempa Nusantara which is a collection of 7,380 macroseismic observations for 1,200 historical earthquakes in Indonesia between 1546 and 1950 CE using the European Macroseismic Scale (1998). Scrutinizing preserved original, first-hand private and official documentation from the colonial period in Indonesia, we could examine the completeness of this written record based on the gradual expansion of European influence in the Indonesian Archipelago. As the largest database of uniformly assessed macroseismic intensities ever assembled for Indonesia, our database can correct errors and fill gaps in other contemporary studies of historical Indonesian earthquakes, as well as palaeoseismic studies such as the coral paleo-geodetic record from Sumatra. Remarkably, given the presence of several major active faults, conclusive evidence of earthquake surface rupture during the colonial period was limited to just two events in 1909 and 1933. Our reliance on original materials also allowed us to document extreme co-seismic ground failure in Sumatra in 1936 with striking similarities to those observed on Sulawesi in 2018. From the perspective of seismic hazard in a rapidly urbanizing nation, we show that the frequencies of observed intensities over the duration of our database are correspond with modern seismic hazard curves from recent publications by other authors for twelve Indonesian cities including Jakarta with some notable exceptions such as Ambon and Yogyakarta. In summary, our work on Gempa Nusantara demonstrates how a carefully vetted and well-documented historical record not only compliments studies of seismic hazard but is itself an important standalone tool for the study of earthquake hazards in Indonesia.

Introduction

Indonesia is a sprawling, densely populated country located in a region with high seismicity but poorly understood seismic hazard. The high seismicity is driven by the relative motion of the Sundaland block in the west and other microplates or blocks in the east with respect to the larger Australian, Indian, and Philippine Sea plates (**Figure 1**). Indonesia is the fourth most densely populated country in the world and the fourth largest (*UN*, 2019). It is also rapidly urbanising (*Missen*, 1972; *Firman et al.*, 2007). For example, Jakarta's population was just over 500,000 in 1930, but it is over 10 million today, and it is part of the urban agglomeration of Jabodetabek with a population over 30 million. This makes quantifying the risk exposure from future seismicity critical. To achieve this, a recently developed probabilistic seismic hazard assessment (PSHA) undertaken by *Irsyam et al.* (2020) for Indonesia relied on instrumental earthquake catalogues to estimate seismicity rates. However, the 120-year-long history of instrumental earthquake recording (e.g., *Storchak et al.*, 2013) is often exceeded by the recurrence times of large earthquakes. Therefore, the study by *Irsyam et al.* (2020**)** also incorporated information for large events occurring in the pre-instrumental era by relying on catalogues of historical accounts (e.g., *Newcomb and McCann*, 1987) and palaeoseismic studies (e.g., *Philibosian et al.,* 2014).

Prior to Independence in 1945, Indonesia was colonised for close to four centuries by the Dutch with smaller regional areas under British, Portuguese, or Spanish occupation at various times, and almost all written accounts of pre-instrumental earthquakes are associated with European colonists. Several catalogues of historical Indonesian earthquakes during this period exist (e.g., *du Puy*, 1845; *Wichmann*, 1918, 1922; *Vissier*, 1922; *Soetardi*, 1962; *Soetardjo et al.*, 1985). Of these, the exhaustive multi-lingual compilation by *Wichmann* (1918; 1922) for the period prior to and until 1877 is particularly well known. The Wichmann compendium was summarised by a seminal modern reappraisal of historical seismicity and tsunami activity in Indonesia by *Newcomb & McCann* (1987) and an English translation was recently published by *Harris and Major* (2016). The latter also included a tectonic interpretation of 61 earthquakes documented by *Wichmann* (1918; 1922). Despite this, almost all modern, post *Wichmann* (1918, 1922) catalogues (e.g., *Musson*, 2012; *Albini et al.*, 2014; *Harris and Major*, 2016) rarely if ever consult the primary source material used to compile such catalogs, nor do they provide new information from previously untapped sources such as historical newspapers. Consequently, even these newer catalogues can be affected by inconsistencies that stem from a reliance on unvetted sources and/or the unwitting repetition of errors in earlier catalogues.

Ideally, the historical record should be as complete and continuous as possible in both space and time to reliably estimate the distribution and rates of seismicity associated with historical earthquakes. Despite the existence of the historical earthquake catalogues described above, Indonesia as yet lacks a uniformly assessed database of observations relying as much as possible on original sources. This renders it difficult to perform in-depth quantitative analyses for Indonesia such as the assessment of the recurrence of strong ground motion in dense urbans centres like Jakarta. *Griffin et al.* (2019) have shown that, for several cities in Java, historical accounts of earthquake activity in the colonial period, 1681 to 1877 (*Wichmann*, 1918, 1922; *Harris and Major*, 2016), are consistent with the 2017 Probabilistic Seismic Hazard Assessment (PSHA) computed by *Irsyam et al.* (2020). However, *Griffin et al.* (2019) also note that the short duration of this catalogue for all but the largest events make it difficult to verify the appropriateness of the 2017 PSHA.

For the reasons outlined above, a fresh look at the observations of historical earthquakes in Indonesia is warranted. We therefore re-examined the historical earthquake catalogue in Indonesia with a strong focus on gathering and evaluating original sources. This paper is divided into the main text and supplementary material. We use the main text to discuss our approach to documentation and its completeness in space and time, and then compare our macroseismic observations to previous studies. The new database of macroseismic observations we compiled, called Gempa Nusantara ("Earthquakes of the Indonesian Archipelago" in Indonesian), can be found in the **Supplementary Material (Tables S1, S2)**. Finally, we use these data to compare the annual exceedance frequencies (AEF) of damaging intensities in the Gempa Nusantara database to those estimated by the hazard curves of *Irsyam et al.* (2020) for some of Indonesia's largest cities.

The Gempa Nusantara Database

Our re-evaluated historical macroseismic observations are presented in a new database of earthquakes that we dub the Gempa Nusantara database. The name of our database is derived from a combination of the Bahasa Indonesian (henceforth "bh") words for "*earthquake*" (bh: *gempa bumi*, shortened colloquially to *gempa*) and "*Indonesian archipelago*" (bh: *nusantara*). This database is a comprehensive collection of macroseismic observations we gathered for 1,200 felt earthquakes (indexed in **Table S1**) with 7,380 observations in total (**Figure 1**; **Table S2**). It spans a 404-year period from 1546 until 1950 incorporating the full duration of European (mainly Dutch) colonial rule in Indonesia.

The geographic extent of our database (**Figure 1;** also see **Figure S1**) includes the region from the west coast of the island of Sumatra (≈95° E) to New Guinea (141° E) in the east. Its north-south extent stretches from northern Borneo (≈7.5° N) to the south of Java (≈11° S). We also document shaking that was reported outside the Indonesian Archipelago to ensure completeness of the macroseismic field for selected large earthquakes. These include earthquakes occurring in the Banda Sea region that were felt in northern Australia, events in the region of Sumatra that were felt in parts of the Malay Peninsula, and earthquakes originating in the southern Philippines that were felt in Sulawesi. In this article we refer to specific earthquakes within the Gempa Nusantara database (**Table S1, S2**) with a unique Event Identifier code (e.g., GN-0002 for the 1584 Java earthquake).

We use the 1998 European Macroseismic Scale (EMS-98; *Grünthal*, 1998) to evaluate macroseismic intensity (**Table S2**) displayed as colour-coded filled circles in **Figure 1**. In total, we assign integer intensities at 6,072 locations out of the 7,380 observations that we catalogued. Very damaging shaking intensities (≥8 EMS) were documented at 399 locations including, 32 locations where we assign 10 EMS. Our approach to assigning macroseismic intensities with the EMS-98, to distinguish between building types and damage grades, and to assess ranges and quality indicators (**Table S4**) is detailed in the **Supplementary Material**. In many instances, EMS-98 guidelines cannot be used without adaptation because the local building stock was more vulnerable or employed different traditional or indigenous construction types and/or materials than the European construction on which the EMS-98 was based. Additionally, we consider "*monumental structures*" for intensity evaluation, without which, we believe the long-term record of damaging shaking in parts of Indonesia would be severely handicapped. All assignments that rely on monumental structures are duly flagged in **Table S2**. Critically, we note, that our approach and inferences detailed in the Supplementary Material is not to be misinterpreted as a revision or an update to the EMS-98 but merely outlines how we adapt to the recommendations and terminology from *Grünthal* (1998) to assign intensities in this study.

Our choice of the EMS-98 intensity scale itself marks a shift from the Modified Mercalli Intensity scale (MMI; *Wood & Neumann*, 1931; *Richter*, 1958) in use in Indonesia since 1956 (*Anonymous*, 1957). The MMI scale was meant to replace both the Batavia Intensity Scale (**Supplementary Material**) and the Rossi-Forel Scale (RF) that were used in Indonesia during the colonial period (*Anonymous*, 1957). Sharing a common lineage with the Modified Mercalli Scale (MMI) and Medvedev-Sponheur-Kárník or MSK scale (e.g., *Medvedev et al.*, 1965), the EMS-98 stands apart in its revised form (*Grünthal*, 1998) in that it stipulates non-region-specific definitions and recommended guidelines with which to assess intensity. This leads to more robust intensity assignments at higher levels of shaking (≥ 6 EMS) especially where data on indigenous, traditional, and non-European building typology are meagre or missing, and when modern fragility curves are unavailable. The obvious caveat here is that if intensity assignments saturate at a given level of intensity (see *Ambraseys*, 1963; *Ambraseys and Zátopek*, 1968; *Ambraseys and Bilham*, 2003; *Ambraseys and Douglas*, 2004) the assigned intensities will be lower bounds, in the absence of other diagnostic markers, as that level of shaking would be sufficient to cause higher grades of damage to vulnerable vernacular buildings including complete collapse.

We have attempted to catalogue (**Tables S1 and S2**) all earthquakes for which we could find evidence of damage (which is equivalent to ≥ 5 EMS) except for two earthquakes in Bali on 23 March 1930 (*Anonymous*, 1931) and 2 August 1938 (*Anonymous*, 1940) for which we could not locate macroseismic information. We also include earthquakes that were felt out at sea and those that were unusually widely felt but lower than 5 EMS as large shocks out to sea or in very thinly populated regions could remain uncatalogued. Strongly felt (EMS ≥ 4) earthquakes prior to 1800 described in written materials (see ***Data and Resources***) are also included if we could verify these from original sources recorded in *Wichmann's* (1918) footnotes. We do this to avoid missing large earthquakes outside of the sphere of colonial influence of the Dutch at the time.

Lastly, throughout this article we include non-English text in parentheses (bh: *Bahasa Indonesia*; de: *German*; es: *Spanish*; fr: *French*; nl: *Dutch*) alongside the modern English spelling, e.g., earthquake (nl: *aardbeving* or *aerdbevinge*). In several instances, we have also retained the original spellings (e.g., in German "*ongefehr*" instead of "*ungefähr*") and typography (e.g., in Dutch "*zyn*" instead of "*zijn*") that preceded 20th century language reforms in many of these languages. All moment magnitudes (Mw) reported in this article for instrumental earthquakes are from the ISC-GEM catalogue by *Storchak et al.* (2013).

Archival Materials

We used first-hand accounts and personal correspondence (e.g., *Phoonsen*, 1699), reconnaissance reports (e.g., *Verbeek*, 1898), summaries of damage in epicentral regions (e.g., *Pontoppidan and Shnuif*, 1914) and tabulated felt observations from now out-of-print journals such as *Natuurkundig tijdschrift voor Nederlandsch Indië* to collate observations for our database. The ranges of historical documentary sources, including previously unused or unknown original source, are indicated by filled grey bars in **Figure 2**. The most critical of these primary sources are discussed briefly here (also see **Data and Resources**) with a comprehensive bibliography presented in the **Supplementary Material**.

Prior to 1600, sources were either very few, unreliable, or vague. An earthquake on 29 September 1546 (GN-0001), reported by *Wichmann* (1918), was the earliest we could confirm, aided by 16th century Jesuit missionary correspondence from Halmahera (*Coleridge*, 1886; **Figure 3a**). An older event in 1538 on Ternate (**Figure 3a**) previously thought to be the earliest confirmed seismic event (*Wichmann*, 1918) turned out to be a volcanic eruption upon examination of the Spanish text in question (*de Argensola*, 1609). Other correspondence in the late 1500s (*Jacobs*, 1974) from the region of Ambon and Halmahera also speak of earthquakes but only in passing; for example, a letter written on 4 January 1576 summarising a 26-year sojourn in eastern Indonesia recalled a large earthquake in the Ambon region (**Figure 3a**) on Easter Sunday (*Jacobs*, 1974, p.680) during this period but without stating a calendar year.

In contrast, original sources are better preserved for the Vereenigde Oostindische Compagnie period (VOC; also known as the Dutch East India Company) from 1602 to 1800. We examined the Daily Register (nl: *Dagh-register*) from Casteel Batavia (Jakarta) in manuscript form between 1688 and 1780 along with other transcribed correspondence from the period (e.g., *Niemejer et al.*, 2015). Transcribed versions of the Generale Missiven chronicling correspondence between officials of the VOC in Jakarta and the Heeren VII in Amsterdam between 1610 and 1767 were also examined. Apart from events with clear calendar dates, these also alluded to earthquake damage occurring or being repaired without explicitly recording the date or year of a causative shock (or shocks). For example, *Goor* (2004) includes reports of damage from Buru (**Figure 3a**) and Haruku (**Figure 3a**) in ~1739 (GN-0123), and from Gorontalo (**Figure 3a**) and Ternate in ~1761 (GN-0143; *s'Jacobs*, 2007). We found no further evidence for these events to resolve their calendar date ambiguities or to distinguish if the damage occurred in one or separate earthquakes.

For the sovereign Dutch period that followed, the journal "*Natuurkundig tijdschrift voor Nederlandsch Indië*" (henceforth, NTNI) was a vital source. It is also often referred to as the "*Indonesian journal for natural science*" (bh: *Madjalah ilmu alam untuk Indonesia*) which is a direct translation of the original title. In this journal, *Reiche* (1859), *Versteeg* (1859) and *Weitzel* (1859) republished correspondence on earthquakes appearing in early colonial Javan newspapers between 1800 and 1850. This format continued anonymously between 1850 (*Anonymous*, 1851) to August 1860 (*Anonymous*, 1861) collated under the title "*Berigten van Verschillenden Aard"*. Annual chronological summaries from September 1860 (*Reiche*, 1863) until 1868 (*Bergsma*, 1873a) appeared later. This format was tabulated in 1869 (*Bergsma*, 1873b) and continued with minor changes until 1919 (*Anonymous*, 1920). Important among these was the inclusion from 1890 (*Figee and Onnen*, 1892) of the offset in local time at an observer's position with respect to local time in Jakarta i.e., Batavia Time (GMT + 7h 7m). The cataclysmic eruption of Krakatau in 1883 brought about a renewed interest in geological phenomena, and thereafter, earthquake observations (nl: *aardbevingswaarnemingen*) or "felt reports" were actively sought by the Koninklijk Magnetisch en Meteorologisch Observatorium

(KNMO) in Jakarta (*van Dijk*, 1885; *van Dijk and Poortman*, 1885; *Figee et al.*, 1886). Such observations from individual locations were published until 1919 (*Anonymous*, 1920).

The NTNI addressed the ever-increasing annual rate of felt reports received by the KNMO in 1920 by replacing individual observations with lists of earthquakes alongside the total numbers of felt reports received per event and the highest Rossi-Forel (RF) intensity for each earthquake (*Anonymous*, 1921). These and pre-1920 NTNI lists were then cross-checked by us to look for for damaging events and we supplemented these with additional observations mined from out-of-print colonial newspapers in Bahasa Indonesia or Dutch, digitally or in person (on microfiche, microfilm or in hard copy). For a handful of earthquakes felt beyond the colonial Dutch sphere of influence in Indonesia, we added information from newspapers and scientific sources from neighbouring countries (e.g., *Coronas*, 1899; *Natulaya et al.*, 1985). The colonial newspaper record is remarkably complete with one noteworthy gap occurring during the Japanese occupation of the Indonesian Archipelago during World War II between 1942 to 1945 (**Figure 2**). Sparse information from this period was extracted from Prisoner of War (POW) diaries, and from translated extracts taken from Bahasa Indonesia newspapers (e.g., *Sinar Matahari*) published in Java during the Japanese occupation.

Completeness of the Written Record

The completeness of the annual KNMO observatory lists of felt earthquakes published in the NTNI were impacted by the density of the population and the likelihood that only a subset of these observers would convey an account of their experience to the observatory in Jakarta (*Vissier*, 1920). Globally, the historical record can also be influenced by geopolitics and socioeconomics (*Ambraseys et al.*, 1983; *Hough & Martin*, 2021) and often the best-preserved archival sources in parts of the world such as Haiti (e.g., *Flores et al.*, 2011; *Hough et al.*, 2022) are in the language of the colonizer. Recognising that the historical sources we consider for Indonesia are also colonial, and almost exclusively Dutch, it is necessary to identify and explain any spatiotemporal variations that could exist as colonial power expanded across the archipelago (**Figure 3a**).

We illustrate this by covering the entire region in a grid with a uniform spacing (1° by 1°) and counting the numbers of observations within each grid cell for three distinct chronological periods adapted from *Anonymous* (1938) and *Soedjatmoko et al.* (1965): the VOC period until the onset of the Diponegoro War (1600-1824; **Figure 3b**), the early sovereign Dutch period (1824-1898; **Figure 3c**) and the late sovereign Dutch period (1898-1950; **Figure 3d**). Dutch colonisation was largely driven by economic and political factors (*van Klaveren*, 1953; *Missen*, 1972). This is evident in map-view in **Figure 3b** wherein the geographic distribution of the majority of the pre-1800 earthquakes reports are from western Java and the Maluku region where commercial activity was initially concentrated. This variability in the temporal clustering of macroseismic data underpinned by the expansion of colonial influence is also evident when comparing earthquake intensity reports as a function of time for the Indonesian Archipelago as a whole (**Figure 4a**) with different geographic regions such as Borneo (**Figure 4b**), Java (**Figure 4c**) and the Maluku region (**Figure 4e**). The significant rise in historical earthquake observations in the post–1800 sovereign Dutch period, reflects a critical inflection point in the geopolitical landscape in favour of the Dutch. On Java, for example, the Yogyakarta Sultanate became a vassal of the sovereign Dutch state following the end of the Diponegoro War in 1830 (*Rickleffs*, 1981; **Figure 3a, 4c**). Elsewhere, the Dutch consolidated territory following the cessation of the Padri Wars in central Sumatra in 1838 and by invading the Aceh Sultanate in 1874, and Bali in 1849 and 1906 (*Rickleffs*, 1981). As an outcome of the Treaty of London (also known as the Anglo-Dutch Treaty) of 1824, the Dutch also acquired British "factories" i.e., trading posts such as Fort Marlborough at Bengkulu on Sumatra (**Figure 3a**).

Remote areas such as the interiors of Borneo and western New Guinea are the least well documented in the period we have investigated (**Figure 4b**, **4f**). Colonial expansion on Borneo was stymied by inhospitable conditions and competition from Chinese and Malay interests (*Missen*, 1972; *Rickleffs*, 1981). Despite the remoteness of the Bornean interior, the limited number of historical earthquake observations collated by us (**Table S2**) and by *Martin et al.* (2020a) still appear to reflect the low modern geodetically determined strain rates of ~7 nanostrain/year within the interior of the Sundaland block (**Figure 1**, e.g., *Simons et al.*, 2007; *Mustafar et al.*, 2017). The only exception in Borneo is the region extending from northern Borneo to the Mangkalihat Peninsula (**Figure 3a**) where we have documented several large historical earthquakes. Here, GPS displacements of ~3 mm/yr to ~9 mm/yr have been measured between the Celebes Sea with respect to the Sundaland block (e.g., *Hermawan et al.*, 2010; *Sapin et al.*, 2013). The lack of documentation is starker in western New Guinea (**Figures 3, 4f**), where high rates of modern seismicity have been instrumentally observed (e.g., Okal, 1999; *Storchak et al.*, 2013) and where rates of slip of more than >20mm/yr are inferred geodetically on active faults in the area such as the Sorong Fault (e.g., *Bock et al.*, 2003; **Figure 1**). However, historical earthquake observations from this region are even fewer in number than from Borneo until the start of the 20th century and remained low until 1950.

Unlike southern Sulawesi or the Minahassa Peninsula (**Figure 3a**) that were colonised before or during the early 19th century, central Sulawesi only came under direct Dutch rule by 1908 (*Weber et al.*, 2003; **Figures 3a**, **4g**). Despite an exceptionally high modern slip rate of ~42 mm/yr on the Palu-Koro fault zone (PFZ) in central Sulawesi (*Socquet et al*, 2006; *Watkinson and Hall*, 2017), there is presently very little documentary evidence for large earthquakes associated with it prior to 1906. Anecdotal accounts (see *Abendano*n, 1915), blame an earthquake in the mid-to-late 1800s for liquefaction and a tsunami in Palu Bay with large run-ups (>4m) at Palu (**Figure 3a**) and nearby Donggala, Lero, and Mamboro (**Figure S2**). We located another brief account (*Makassaarsch Handelsblad*, 19 August 1879) of a strong earthquake at Donggala following which the water rose to the floorboards of most houses which were 5-6 feet from the ground floor. We can only infer that it occurred prior to 19 August 1879 i.e., the date of the news account. With this meagre evidence, we cannot reliably connect it with the event in *Abendanon* (1915). An even earlier event is preserved in "*I La Galigo*" which records the Bugis legend of Sawerigading from the 14th century (see *Kern*, 1939). The earthquake and tsunami in "*I La Galigo*", if not myth or metaphor, could represent an even earlier tsunami-generating earthquake in Palu Bay. We unfortunately could not determine calendar dates or other evidence for any of these earthquakes in central Sulawesi, nor could we catalogue other pre-colonial, and pre-19th century earthquakes from this region.

Comparison with the Coral Record

Coral microatoll colonies are found and have been interpreted by palaeoseismologists (white circles in **Figure 5a**) along roughly half (3° N to 3.5° S) off the west coast of Sumatra between latitudes 6° N and 7° S. Potential microatolls sites on the islands of Enggano and Mega (**Figure 5a**) are yet to be explored. This long palaeoseismic coral record is a useful benchmark with which to cross check which events, from a subset of 220 earthquakes (1621 – 1930) from our database, along the entire west coast of Sumatra appear in the coral record. These coral microatolls live near the base of the intertidal zone in the tropics, initially growing as hemispheres that expand radially outward and upward, unconstrained by tidal effects (*Meltzner and Woodroffe*, 2015). This upward growth can be arrested if they grow high enough, or if relative sea level falls low enough due to a climactic signal or from sudden coseismic uplift of the seafloor. The coral colonies' thus exposed uppermost surfaces die of desiccation in what is termed a "*die-down*" while at the same time, parts that remain submerged continue to grow outward. The disrupted pattern of growth rings this produces preserves a record of relative sea level (see *Meltzner and Woodroffe* (2015) for a detailed explanation). In general, this allows coral microatolls to act as natural geodetic instruments and thereby serve as reliable palaeoseismic indicators of the land-level changes caused by great megathrust earthquakes extending several centuries into the past (e.g., *Meltzner et al.*, 2012, 2015; *Philibosian et al.*, 2014, 2017). There are two major sources of megathrust earthquakes in the Sumatran Forearc, which is an iconic example of partitioned, oblique subduction: the Sunda Megathrust, which accommodates arc-normal convergence, and the Sumatran Fault Zone (SFZ), which accommodates arc-parallel motion between the Indian-Australian Plates and the Sunda Block (*Bradley et al.*, 2017). If the long coral record off Sumatra made it possible to distinguish Sunda Megathrust and SFZ earthquakes in the Gempa Nusantara database, it could be an important step forward in understanding earthquake recurrence on both the Sunda Megathrust and the SFZ.

We group earthquakes into four categories (CR1, CR2, CR3 and CR4) described in **Table 1** before comparing these with the interpreted coral record (also see **Table S1**). We could confidently identify just 4 events (CR1, ~2%) up to 1930 in the coral record. These were the earthquakes in 1797 (GN-0196), 1833 (GN-0238), 1843 (GN-0265) and 1861 (GN-0333). For another 17 events (CR 2, ~8%) the spatial distribution of available historical accounts and their absence from the coral record rules out large ruptures on the Sunda Megathrust. The association between coral die-downs and felt earthquakes was ambiguous for 46 events (CR3, ~21%), or in other words, the chronologically timed die-downs might or might not relate to events with similar calendar dates in our database, for example, the newly identified 20 March 1741 earthquake (GN-0125; **Figure 5a**) that damaged buildings at Padang and possibly, Singkil (**Figure 5a**). Adding to the ambiguity are questionable calendar dates such as for an alleged earthquake in Aceh on 3 November 1832 (9 Jumada al-akhir 1248 Al Hijri; GN-0236). We suspect this event could be a large aftershock (GN-0239 or GN-0240) of the 24 November

1833 (9 Jumada al-akhir 1249 Al Hijri) earthquake owing to a Hijri year that we suspect may have been incorrectly recorded in the manuscript source itself (see detailed note in **Table S2**). Surprisingly, none of the remaining 153 events (CR4, ~69%) could be identified in the coral record at all. This leads us to conclude that the preservation of paleo-earthquakes in the coral record is impacted by the distribution (or lack thereof) of coral microatolls living at the time of an earthquake, and the proximity of those microatolls to a megathrust rupture and any vertical deformation (or uplift) the same rupture might produce. This in turn appears to limit the ability to use the coral record to distinguish between Sunda Megathrust and SFZ (or instraslab or non-SFZ crustal fault) earthquakes.

In regions where the coral microatoll colonies are pervasive, the coverage of the coral record is not a complete as it might seem. Near Nias, microatolls dating to the 19th century experienced die-downs as a consequence of coseismic uplift during the 16 February 1861 earthquake (GN-0333). These die-downs would be indistinguishable in the coral record from die-downs resulting from any land-level changes associated with two widely felt aftershocks on 24 February 1861 (GN-0334) and 26 April 1861 (GN-0336), and with two tsunami generating aftershocks on 9 March 1861 (GN-0335) and 1 June 1861 (GN-0339). Also, in the Nias region, historical accounts (*Martin et al.*, 2019) indicate that an island off the southern coast of Simeulue (**Figure 5a**) either experienced local subsidence or severe tsunami erosion because of the 4 January 1907 tsunami earthquake (GN-0697). The best fitting rupture model for the 1907 event is up-dip (*Martin et al.*, 2019, 2020b) and close to the trench front. No corals were found from this period possibly because the reef flats were still elevated above the base of the intertidal zone following the 1861 earthquake; corals recolonized these sites beginning in the 1940s, presumably owing to interseismic subsidence and sea-level rise (*Meltzner et al.*, 2015; **Figure 5b**). Hence, although the 1907 event in the historical record is a megathrust earthquake, it is not present in the coral record. This suggests that large aftershocks and earthquakes whose ruptures are too far up- or down-dip from the area of coral growth will likely go unrecorded even in those regions with a complete coral record. For this same reason, there would also be no coral record for outer-rise earthquakes near the Sunda Trench and for events within the Wharton Basin.

Outside of the region offshore Sumatra stretching from Simeulue in the northwest to the Mentawai Islands in the southeast, a large portion of the Sumatra megathrust off the northern coast of Aceh (between 3º N and 6º N), and the Bengkulu region (**Figure 5a**) to the south (between 3.5º S and 7º S), is unconstrained by coral observations (**Figure 5a**). This makes it difficult to confidently distinguish between Sumatran Fault Zone (SFZ), Sunda Megathrust, non-SFZ crustal fault events or intraslab sources at intermediate depths (**Figure 5c**) in these regions based on very limited documentary even though we suspect some events were on the SFZ. For example, an earthquake on 26 August 1835 (GN-0244) damaged buildings in Padang (*Javasche Courant*, 26 September 1835) and credible accounts indicate it was felt as far away as Georgetown, Singapore and central Java (**Figure 3a**). Though there is no evidence at present for surface rupture on the SFZ in 1835 or other damage on Sumatra, the spatial distribution of shaking is very similar to the intensity distribution of other moderate to large SFZ earthquakes. On the other hand, if the 1835 earthquake was on the Sunda Megathrust there would be no coral record as no microatolls colonies in the Mentawai Islands survived uplift from the 24 November 1833 earthquake (GN-0238) except for a single coral site in the Batu Islands (**Figure 5a**, *Philibosian et al.*, 2014). Therefore, given the documentary and palaeoseismic constraints we face, the source of the 26 August 1835 event (GN-0244) remains a mystery.

Evidence for Historical Surface Ruptures

For onshore faults in populated areas, it might be reasonable to expect surface ruptures to be observed by the local population and recorded in writing. Even though the focus of our study was the collation of macroseismic effects, it was surprising that we only encountered three descriptions of surface rupturing earthquakes.

In the first instance, displacements of triangulation monuments (*filled diamonds* in **Figure 6**) were documented by *Delprat*, (1895) and *Muller* (1895) following the 17 May 1892 Tapanauli earthquake (GN-0574) on Sumatra. Interpreting these observations, *Prawirodirdjo et al*. (2000) computed 4.0m (±0.6m) of right-lateral strike-slip motion on the Angkola segment of the SFZ. Although there appear to have been no direct observations of surface rupture in 1892, a solitary official description that could be interpreted as a surface break was published in the *Sumatra Courant* (18 July 1892). This stated that the worst shock and most of the damage was limited to a line extending from Lubuk Raya (nl: *Loeboe Raja*) past Sorik Marapi (**Figure 6**) to Kelabu (nl: *Klaboe*), along which "the earth was split for many kilometres" (nl: *de bodem palen vèr vaneen gespleten*) within the Angkola Valley. Oddly, *Musson* (2012) places this event on the Sunda Megathrust at 0.8° N and 98° E. This offshore location conflicts with the geodetically determined right lateral slip motion on the SFZ (*Prawirodirdjo et al*., 2000) and damage we have documented in this study.

The only previously known historical surface ruptures on the SFZ in 1926 and 1943 were mapped relying on interviews with local residents (*Untung et al.*, 1985; *Natawidjaja and Kumoro*, 1995). To this small dataset, we add observations from the M_W 7.5 Liwa earthquake on 25 June 1933 (GN-1068). *Berlage* (1934) documented a fissure (**Figure 7**) near the Wai Uluhan stream (~4.937° S, 104.025° E) and near Negeri Ratu (~5.029° S, 104.137° E). However, its onward extent and offsets were unmapped and *Berlage's* (1934) description does not say if it was continuous between the two points that are ~16km apart; from the bridge over the Wai Uluhan stream, it followed the main road to Liwa for ~1km. Additionally, the fissure was ~1m wide (mole track?) near Negeri Ratu and unlike other fissures and cracks from subsidence along the banks of rivers it was mainly on flat land (*Berlage*, 1934). The locations of these observations lie along the trace of the Kumering segments of the SFZ and appear to be the strongest visual clues thus far that co-seismic slip likely occurred on the southern SFZ in 1933. *Berlage* (1934) also reports a co-seismic flood wave (nl: *vloedgolf*) in Lake Ranau and the sinking of ten rice fields (nl: *sawahs*) by half a metre into the lake near the delta of Wai Warduk at Kotabatu (**Figure 7**). His brief description also notes the formation of "cracks and little terraces" (nl: *scheuren en terrasjes*) on the lake shore here. This is suggestive of a lateral spread on the delta but its proximity to the inferred trace of the Kumering segment leads us to question if this too might have been associated with co-seismic faulting in 1933.

The third instance was documented by *Abendanon* (1915) in July 1910 in the Kulawi basin in central Sulawesi on the Palu – Koro Fault zone (PKZ) associated with a M_W 6.8 earthquake on 18 March 1909 (GN-0736). This occurrence is known to modern investigators (e.g., *Daryono & Natawidjaja*, 2019) to which we add additional details. *Abendanon* (1915) described a displacement on the west side of the Naloea River (**Figure S2**) where the western side was higher by ~1m. The "main fissure" (nl: *groote scheur*) was observed to run in a north-south direction from Namo (**Figure S2**) through the villages of Tinabe and Lempé (where the ground in some places subsided ~30 cm) towards Boladangko and over to Pobatua for a length of approximately 7km (also see **Figure S2**). By 1910, the "fissure" was mostly overgrown with a step of ~1m and could be followed for a short distance for which *Abendanon* (1915) approximated a strike of S° 30. The fissure (nl: *aardbevings scheur*) in the Kulawi basin is drawn albeit crudely in *Abendanon's* (1916) map (see **Figure S2**). Its strike across the valley is noticeably at odds with *Abendanon's* (1915) own observation that the "main fissure" ran in a north-south direction. Surface faulting was also observed on the PKZ in the Kulawi basin following the 2018 Palu earthquake (see *Jaya et al.*, 2019; *Wu et al*., 2020). Though we cannot make further inferences without an onsite investigation, including to speculate if the 2018 event re-ruptured the same sections of the fault zone that broke in 1909 in the Kulawi basin, we anticipate these observations highlighted here from 1909 will be beneficial to future field surveys.

On Java, despite a greater population density even historically (see *Nitisantro*, 1970), we did not find conclusive evidence of historical surface rupturing events (pre-1950). It is likely that there may have been surface ruptures on Java that were observed by the local population, but this information was neither recorded nor transmitted to the colonial authorities. A vague account exists for the 1867 Yogyakarta earthquake (GN-0377) from near Ngoto (**Figure 3a**) of a "*great fissure*" (nl: *groote scheur*), 4 *palen* (~6 km) in length that ran through five (unnamed) villages (*van Laar*, 1868). Another uncertain account comes from the 25 October 1875 Java earthquake where the village square (bh: *alun-alun*), in presumably the western part of Kunningan (**Figure 3a**), subsided a few feet along with the trees on it. In both these cases it is hard to say if the description constitutes surface rupturing faults or severe ground failure. We speculate that at least a handful of historical earthquakes might have been associated with known or inferred faults on the island. For example, the intensity distribution of the 12 December 1890 Pati-Juwana earthquake (GN-0560) suggests an association with the Lasem and/or Pati Fault zones. However, not all earthquakes can be associated with mapped faults, such as the 16 November 1847 earthquake sequence west of Cirebon (GN-0278). *Griffin et al.* (2019) note, and we concur, that the highest intensities were observed in a region with no known mapped faults at the time of writing.

Ambiguities in historical accounts can also make it difficult to infer which fault may be associated with a particular event. Accounts of weaker ground motion felt in east Java (*Java-Bode*, 5 January 1853), almost 2000 km from an earthquake on 26 November 1852 in the Banda

Sea region (GN-0293), imply an extensive area of perceptibility. This was among the reasons *Fisher and Harris* (2016) concluded that a great (Mw 8.5) earthquake had occurred in the Banda Sea. But other studies (*Marliani et al.*, 2019; *Cummins et al.*, 2020) have inferred that the accounts from east Java and the Banda Sea area refer to separate, smaller events. Adding to the uncertainty, *Anonymous* (1852) says the shocks in east Java were felt on 26 November (repeated by *Wichmann*, 1918) but later *Anonymous* (1853) citing the Javasche Courant (18 December 1852, v101) says 23 November 1852. Microfiche copies of the Javasche Courant for 18 December 1852 at our disposal were illegible and we acknowledge that a more detailed study is needed to resolve this ambiguity. We tabulate these observations from East Java together with other observations for the 1852 earthquake (GN-0293) but assign a higher uncertainty (G) to the effects at Pasuruan, Sumenap and Surabaya that corresponds to an uncertainty in veracity.

How does Previous Research Compare?

The numbers of earthquakes and macroseismic intensities we present in the Gempa Nusantara database vastly outnumber those in previous studies (e.g., *Soetadi* 1962; *Newcomb & McCann*, 1987). Even rich collections of modern macroseismic intensities (e.g., *van Noten et al.*, 2017; *Rovida et al.*, 2020; *Salditch et al.*, 2020) can be spatially capricious because of geological structure, site conditions, directivity, socioeconomic and cultural factors (e.g., *van Noten et al.*, 2017; *Hough and Martin*, 2021; 2022). The assessment of macroseismic intensity can also be a subjective process more so for historical events which rely on facts and quantities that are not always available (see *Hough and Page*, 2011; *Martin and Hough*, 2016).

With this in mind, we considered our macroseismic intensities alongside published MMI datasets for four well-documented 19th century earthquakes (*Fisher & Harris*, 2016; *Griffin et al.*, 2019; *Cummins et al.*, 2020). Macroseismic intensities from these previous published studies were not converted from one scale to another as a rule (*Ambraseys et al.*, 1983) unless we could re-evaluate them from an original source. At the same time, the mutual equivalence between MMI and EMS-98 (*Musson et al.*, 2010) is acknowledged with the caveat that macroseismic intensity assessments can vary between different observers (see *Szeliga et al.*, 2010; *Hough and Page*, 2011). The difference between integer intensity values at individual locations common to both datasets, that is, Δ Intensity, was calculated (**Figure 8**). We then calculated the absolute median difference (MDIF) of Δ Intensity for each dataset being compared to Gempa Nusantara. Our comparisons display good agreement between the macroseismic intensities in our database and those from *Griffin et al.* (2019; **Figure 8a, 8b**) and *Cummins et al.* (2020; **Figure 8c**) for which MDIF values for Δ Intensity were on average, one unit of intensity. MDIF for Δ Intensity between our data and for data from *Fisher & Harris* (2016; **Figure 8d**) was higher at 1.0 ± 1.4 (1σ). Four of the intensities greater than VII recorded by *Fisher & Harris* (2016) for the 1852 earthquake (GN-0293) were 3 or more intensity units greater than those in our database; the largest being MMI IX for Ambon which the extant documentary data does not support (**Table S2**).

We also cross-checked our tally of events in **Table S1** for any events that appeared, however briefly, in previous earthquake catalogues by *Wichmann* (1918, 1922), *Vissier* (1922), *Soetadi* (1962), *Soetardjo et al.* (1985), *Newcomb and McCann* (1987), *Musson* (2012), *Harris and Major* (2016), and *BMKG* (2019). In **Table S1** (*columns L to S*) we note where these catalogues overlap with Gempa Nusantara, and when available, we also indicate the maximum integer intensities for a given event reported by *Soetadi* (1962), *Soetardjo et al.* (1985), *Harris and Major* (2016) and *BMKG* (2019). We computed the difference (Δ I_{MAX}) between the maximum intensity ($\boldsymbol{I_{MAX}}$) for a given event in Gempa Nusantara (see column F in **Table S1**) and the maximum intensity for a given event obtained in these studies listed in **Table S1** (*columns L to S*). When intensity ranges were recorded, such as MMI VI to MMI VIII (e.g., in

Soetardjo et al., 1985) we considered the median, that is, MMI VII as maximum intensity from that particular study. Only Rossi-Forel (RF) intensities are listed by *Soetadi* (1962); since this would require conversion to EMS-98, which we seek to avoid, they were not considered. No intensities were reported by *Wichmann* (1918, 1922), *Vissier* (1922), or *Musson* (2012) and therefore they were not chosen for comparison. *Newcomb and McCann* (1987) also published intensity maps for 26 Indonesian earthquakes. We do not use these either as they are non-site specific, display large ranges of intensity (MMI I – IV, MMI V – VII, and greater than MMI VIII) and in the case of the 4 January 1907 earthquakes (GN-0687; GN-0688) have been shown to inaccurately depict the earthquake in question (see *Martin et al.*, 2019).

We found the MDIF of Δ I_{MAX} for events reported by *Soetardjo et al.* (1985, S85 (*column O*) in **Table S1**) and *BMKG* (2019, B19 (*column S*) in **Table S1**) in comparison to $\boldsymbol{I_{MAX}}$ in Gempa Nusantara for the same events was 1.069 ± 0.9 (1σ) intensity units and 1.067 ± 0.92 (1σ) intensity units for 109 and 105 common events, respectively (**Figure 9a**). *BMKG* (2019) is virtually identical to *Soetardjo et al.* (1985) with a few intensity values missing or transcribed incorrectly in the former from the latter resulting in slightly different metrics above. The MDIF of Δ I_{MAX} for individual events reported by *Harris & Major* (2016, HM (*column R*) in **Table S1**) with $\boldsymbol{I_{MAX}}$ in Gempa Nusantara was higher at 1.6 ± 1.16 (1σ) units of intensity for 92 common events with maximum intensity values (**Figure 9b**). Our examination of primary source material resulted in $\boldsymbol{I_{MAX}}$ values in Gempa Nusantara that were often much less than those assigned by *Harris and Major* (2016) whose work is based on *Wichmann* (1918); an exception, was the 19 February 1687 earthquake (GN-0079) in Ambon for which we assign 8 EMS while *Harris and Major* (2016) assign MMI IV. In many, if not all, of the other instances we found that the maximum intensity values by *Harris and Major* (2016) above MMI VII were not supported in the primary source material, and in some cases were not supported by descriptions in *Wichmann* (1918) either. As an example, an earthquake on 15 February 1710 at

Ambon (GN-0099) was described by *Valentijn* (1724) as a "strong earthquake in the morning, consisting of three shocks" (nl: *s'morgens een sterke Aardbeving, bestaande in 3 stooten*). *Wichmann* (1918) translates this to: "Morning. Ambon, Three strong shocks" (de: *Morgens. Amboina. Drei starke Stösse*). This meagre information in *Valentijn* (1724) and *Wichmann* (1918), with no indication of actual damage, is insufficient to support MMI IX assigned by *Harris and Major* (2016, p.16).

The subjectivity of individual intensity assignments will be driven by the availability and/or the consideration of original source materials. To emphasise this point we call attention to the 29 December 1820 earthquake (GN-0227) in the Flores Sea. *Wichmann* (1918) reports that at Bulukumba on the south coast of Sulawesi (**Figure 3a**), cannons "hopped (or bounced) on their gun carriages" (de: *hüpften auf ihren Lafetten*). But an earlier Dutch account (*Roorda van Eysinga*, 1830) upon which *Wichmann* (1918) is based says the cannons "shook on their gun carriages" (nl: *op hunne affuiten schudden*). This inconsistency in translation from Dutch to German by *Wichmann* (1918) was later transmitted unknowingly to English as ">1g, cannons hopping" by *Harris & Major* (2016). As a result, ground motions at Bulukumba, were incorrectly thought to imply very strong vertical accelerations. For a different earthquake on Java on 4 January 1840 (GN-0254), *Griffin et al.* (2019) included an observation from Semarang (*Reiche*, 1859; **Figure 10**) interpreted as MMI VII. Revisiting *Reiche* (1859), we conclude that the original account (nl: *De sappeurs zijn, bij het bespeuren eener golvende beweging in de bastions, van de muren naar beneden gesprongen*) does not refer to the collapse of the walls of the under-construction citadel as interpreted by *Griffin et al.* (2019). Instead, it says the military engineering corps (nl: *sappeurs*) jumped down from the walls when they felt it shake with an undulatory motion. This results in a difference of 2 units of intensity between *Griffin et al.* (2019) and our intensity assessment for the same IDP. These observations highlight how errant translations, especially those relying on second-hand material, can produce unreliable input crucial to the later assessment and modelling of hazard (e.g., *Griffin et al.*, 2019; *Irsyam et al.*, 2020).

Frequency of Exceedance for Damaging Shaking

The earliest seismic hazard map we are aware of for Indonesia was developed by H.P. Berlage and C. Brest van Kempen in the 1940s (*Brest van Kempen*, 1942) when the need to understand seismic hazard to mitigate earthquake impacts was recognised (*Brest van Kempen*, 1939; 1942). The first modern seismic hazard maps for Indonesia were developed in the late 1970s (see *Fraser*, 1983) and these were used to inform the Indonesian Building Code in the 1980s (*Surahman et al.*, 2008). The most recently developed probabilistic seismic hazard assessment (PSHA) undertaken by *Irsyam et al.* (2020; **Figure 10**) considered not only subduction-related earthquakes but also used a wide body of geologic and geodetic data on crustal faults, which has significantly increased hazard levels in populated areas. Nonetheless, two limitations of all existing seismic hazard assessments for Indonesia are the paucity of geological studies of active faults in Indonesia and the brevity and incompleteness of existing earthquake catalogues: the earthquake records on which all of these assessments are based are still much shorter than the average recurrence intervals for nearly all faults in the region. A consequence of these limitations may be an underestimation of seismic hazard in parts of Indonesia.

The estimates of macroseismic intensities contained in Gempa Nusantara are independent of the data used to develop the most recent seismic hazard map (*Irsyam et al.*, 2020). They also represent a time period completely different and much longer than that covered by modern seismological and geodetic data. It is therefore useful to test their consistency with the hazard map. **Figure 10** depicts the mean hazard curve for each of the cities displayed in **Figure 10**, along with the associated 2.5% and 97.5% quantile curves that illustrate the range of epistemic uncertainty associated with the choice of ground motion models and earthquake activity parameters used by *Irsyam et al.* (2020). Vs30 estimates from *Wald and Allen* (2007) are incorporated in these curves to characterise site response. No Ground Motion to Intensity Conversion Equation developed specifically for the region of Indonesia existed at the time of writing. Therefore, these PGA curves have been converted to intensity using the relationships of *Worden at al.* (2012) and are compared with the integer intensities in Gempa Nusantara (**Table S2**) for each city. The annual exceedance frequency (AEF) for each intensity level (*open circles in* **Figure 10**) was calculated by counting integer intensity observations at each level of intensity in each city and dividing by the number of years (or interval i.e., "T" in **Figure 10**) prior to 1950 for which these are available; we do not convert alphabetical assignments, for example, "F" for "Felt" to numeric values. The error bars indicate the ranges for the AEF of a given intensity level taking into consideration the minimum and maximum intensity ranges from **Table S2** (*columns M and N*) when these exist. For each city, the AEFs from Gempa Nusantara were then compared to the annual AEFs from the hazard curve. As noted previously we focused on cataloguing as many accounts of damage (≥ 5 EMS) as was feasible. Therefore, the data at or above 5 EMS (dashed vertical lines in **Figure 10**) will be more complete than at lower intensities.

The AEFs computed using historical intensity data shown in **Figure 10** appear to be largely consistent with the hazard curves for half of the cities selected. The exceptions are the cities of Ambon (**Figure 10b**), Banda Neira (**Figure 10d**), Gorontalo (**Figure 10g**), Medan (**Figure 10i**), Padang (**Figure 10j**) and Yogyakarta (**Figure 10m**), which appear to experience intensities 6 EMS or higher with a much greater annual frequency than estimated by the hazard map. This may reflect temporal clustering, especially in the case of Gorontalo and Medan (**Figure 10i**). At Medan, for example, which has an observation interval of only 63 years, and all the intensities greater than 6 EMS were experienced only in the last three decades of this time interval (1920 – 1950). Ambon (**Figure 10b**), Banda Neira (**Figure 10d**), Padang (**Figure 10j**) and Yogyakarta (**Figure 10m**) have longer intervals for which observations were available (T = 318 yr, T = 306 yr, T = 252 yr and T = 132 yr respectively), with intensities greater than 5 EMS consistently observed. Thus, it is possible that Ambon, Banda Neira, Padang and Yogyakarta are proximate to sources of seismicity that are not well characterised in the current seismic hazard map by *Irsyam et al.* (2020).

A large gap persists between the earliest felt earthquake at Banda Aceh on 7 March 1621 (GN-0009) and the next event with an integer intensity value on 8 April 1878 (GN-0454). It is extremely unlikely that no earthquakes were experienced in Banda Aceh for 257 years; the 16 February 1861 Sumatra earthquake (GN-0260) was felt in the city for example. Our AEF calculations are therefore limited to a period from 1878 to 1942 for the city; the stars in **Figure 10c** illustrate how the AEF would be biased if the Banda Aceh record was considered complete for EMS ≥ 5 since 1621.

Observations of strong shaking are important to constrain seismic hazard, but at the other end of the spectrum, weak or moderate ground motions at longer periods can also be damaging at regional distances (~500km) especially to taller structures (e.g., *Singh et al.*, 1988). We documented instances of minor building damage in cities along the west coast of Malaysia and in Singapore (**Figure 1**) from Sumatran earthquakes (e.g., 19 September 1936, GN-1105). In an extreme case, the upper sections of a shipyard chimney were dislodged at Tanjung Rhu in Singapore (*Malay Weekly Mail*, 8 July 1926) from shaking caused by a Sumatran earthquake on 28 June 1926 (GN-0942) at an epicentral distance of ~420km. Similarly, Darwin in northern Australia (**Figure 1**) is regularly shaken by earthquakes originating in the Banda Sea despite being at a distance greater than 600 km from the sources of these shocks (*Allen*, 2021). Of the 67 instances of felt earthquakes in Darwin documented by us between 1874 and 1950, notable occurrences were are the earthquakes on 30 August

1917 (GN-0832) and on 2 November 1950 (GN-1200) when buildings were damaged in the city.

Extreme Ground Motions

The occurrence of high intensities (≥7 EMS) in Gempa Nusantara are few and even fewer at extreme intensities (≥9 EMS) given that Indonesia lies in a tectonic setting capable of producing very large (M_W>8) earthquakes. We concur with *Griffin et al.*, (2019) that intensities above intensity MM VII are almost always accompanied by the widespread collapse of the weak, unreinforced masonry construction typical of the colonial-era in Indonesia. This construction was often modified from European designs but adapted to Indonesian conditions and construction materials (e.g., *Nas*, 2007). In other parts of the world with even weaker building stock, a MMI or MSK intensity exceeding VII or VIII is regarded as a value for intensity saturation (see *Ambraseys*, 1963; *Ambraseys and Zátopek*, 1968; *Ambraseys and Bilham*, 2003; *Ambraseys and Douglas*, 2004) i.e., since everything is destroyed, attempts to assign intensities ≥VII becomes unduly subjective (*Ambraseys and Bilham*, 2003). This is aggravated in parts of the developing world outside Europe where indigenous structures, with or without inherent seismic resistance, are not referred to in any intensity scale (e.g., *Ambraseys and Adams*, 1991; *Aung et al.*, 2019) such as the traditional buildings in Indonesia (e.g., *Taverne*, 1925). Given the mutual equivalence between scales (*Musson et al.*, 2012), this awareness can make it extremely difficult to assign extreme intensities (≥9 EMS) at which many (≥50%) or most (≥75%) A-type and B-type suffer complete (grade 5) collapse (see *Grünthal*, 1998; pp. 20). In an ideal scenario, the quantities and grades of damage to different types of buildings are best determined by ground-based surveys (*Ambraseys & Bilham*, 2003; *Musson & Cecić,* 2012). But this is often unfeasible when studying historical earthquakes

(*Martin & Hough*, 2016) especially if this information went unrecorded, and/or if these occurred outside the sphere of Dutch influence.

Despite these limitations we have assigned intensities 9 EMS at 110 sites and 10 EMS at 43 sites where EMS-98 criteria can be inferred, and when possible, these are supported by reports of people being thrown to the ground or heavy objects being displaced and or interpreted damage Grades 4 or 5 to many or most buildings, especially traditional buildings (bh: *rumah adat*) on Sumatra and Sulawesi. In some instances, the highest intensities are for onshore earthquakes associated with either the Palu-Koro Fault zone (PKZ) or the Sumatran Fault zone (SFZ) such as the 18 March 1909 (GN-0727) and the 24 June 1933 earthquakes (GN-0988) respectively, that resulted in the toppling over and/or destruction of traditional *rumah adats* at locations immediately adjacent to the co-seismic surface ruptures documented on these faults in a previous section. At 92 sites where we document 8 EMS and at another 36 locations where we document 9 EMS, we also assign an upper range of +1 intensity unit, again indicating that shaking could have been stronger at all these locations. Though intensities ≥9 EMS are rare and account less than 2% of the 7,380 intensities in our database, we caution that these are unlikely to have been the only such incidents in Indonesia over the 404-years covered by our database but only those for which a written record has been preserved.

One case of exceptionally violent shaking in an urban setting occurred in the city of Ambon (**Figure 3a**) during the 6 January 1898 earthquake (GN-0609) that corresponds to at least 10 EMS. In the Ambon urban area, credible accounts exist of people being flung a few meters (nl; *sommige eenige meters ver weggeslingerd*) or physically thrown to the ground (e.g., *Van Oldenborgh*, 1898; *Verbeek*, 1898). An eyewitness described being thrown out of his office room and into a bank of flowerpots (*Van Oldenborgh*, 1898). In a separate incident, a woman seated in a chair was thrown to the ground (*De Locomotief*, 22 January 1898). Heavy objects such as cupboards (*De Locomotief*, 22 January 1898) and 60-pound cannons were also bodily shifted (*de Balbian Verster*, 1898). Near the Esplanade (modern Lapandan Merdeka) trees were split from top to bottom (*De Locomotief*, 22 January 1898). At the Sociëteit Endracht on the Esplanade, a piano was ejected onto the street from the interior gallery and billiard balls from the rear gallery were found in the front gallery (*De Nieuwe Vorstenlanden*, 28 January 1898). In post-earthquake reconnaissance, *Verbeek* (1898) himself noted that the posts of sheds within Fort Victoria were shaken out of their stone saddle stones into which they had been nailed with iron bolts. All of these suggest ground motions possibly approached and exceeded 1g within the town of Ambon. Yet another case of extreme shaking was documented at a tea plantation "Tjarennang" (*De Locomotief*, 1 November 1875) near modern Lemaputih (**Figure 3a**) to the west of Kunningan during the 25 October 1875 Java earthquake (EMS 9, GN-0434) where a seated person was thrown off a chair, a herd of cows were thrown to the ground (nl: *een troep koebeesten…. werden op den grond geworpen*) and the "ground waved" (nl: *de grond golfde*).

In addition to being particularly destructive to poorly built structures, strong shaking exacerbates secondary hazards such as liquefaction and landslides. The most extreme example of ground failure related to co-seismic shaking that we could document occurred in 1936 in Sumatra's Karo Highlands with striking similarities to the liquefaction documented in rice-fields in Palu in 2018 (e.g., *Miyajima et al.*, 2019). A M_W 7.2 earthquake on 19 September 1936 (GN-1105) triggered a suspected co-seismic flow slide in agricultural land near Batukarang (**Figure 3a**) to the south-west of Medan. Shaking caused a tract of land between 200m to 300m in width and ~2.5 km in length (~50 to ~75 hectares) with ripe paddy (nl: *vruchtdragende paddi*) to break up with a loud noise, following which, with the water coming to the surface it turned into a mudflow (bh: *banjir loempoer*; nl: *modderbandjir*) that made its way to the river. Seventeen persons working in the rice fields (*De Sumatra Post*, 21 September 1936; *Sinar Deli*, 22 September 1936) succumbed after being engulfed in a "sort of quicksand" (nl: *soort drijfzand*) and only four bodies were recovered (*Deli Courant*, 21 September 1936), two of which were washed downstream (*De Sumatra Post*, 21 September 1936). The sole survivor extricated himself from the "thick mass" (nl: *de breiïge massa*) that formed after clinging to a solid point for safety (*Deli Courant*, 21 September 1936). The land subsided 10m to 15m with a maelstrom of debris including earth and the roots of trees mixed together (*De Sumatra Post*, 21 September 1936). Paddy was visible on pieces of land that were displaced 600m to 1000m (*Deli Courant*, 21 September 1936). Residents of Singgamanik, west of Batukarang, also recall the displacement (bh: *pergeseran*) and collapse (bh: *amblas*) of 10 hectares of rice fields at Juma Pedalong (*Wong*, 2014). The events of 1936 are remembered locally as "Linur Batukarang" (*Wong*, 2014) where "linur" means "earthquake" in the Karo language. We could not identify the exact location of these incidents and the diary of the assistant resident (*Tichelman*, 1936) to Simalungun and the Karo Lands does not provide any further details either. But it is quite likely additional information is yet to be found.

Discussion

Gempa Nusantara is the largest database of historical macroseismic intensities ever assembled for Indonesia, in comparison to previous modern studies (e.g., *Soetadi* 1962; *Newcomb & McCann*, 1987; *Harris and Major*, 2016). The completeness of this record in both space and time is vital to modern seismic hazard assessment. It is also true that the quality of the historical record can itself be influenced by geography, geopolitics, and socioeconomics (e.g., *Missen*, 1972; *Ambraseys et al.*, 1983; *Hittleman et al.*, 2001; *Hough & Martin*, 2021) all of which may or may not influence archival preservation (e.g., *Albini and Rovida*, 2018; *Martin et al.*, 2020a). Our database is also the first study of the Indonesian historical earthquake catalogue since *Newcomb and McCann* (1987) to consult original sources, the majority of which are in European languages. Though this is a necessary initial step, we echo scholars of

Indonesian history (see *Soedjatmoko et al.,* 1965; *Missen*, 1972; *Reid*, 2016) in acknowledging that these data contain an inherent European bias as we have also demonstrated (**Figures 3**, **4**). Therefore, we advocate for future steps to be taken to mirror studies elsewhere (e.g., *Iyengar et al.*, 1999; *Gahalaut et al.*, 2016; *Suárez and García-Acosta*, 2021) that tap local archival sources and indigenous language documentation from Indonesia either by consulting historical newspapers from Indonesia in different local languages (e.g., *Adam,* 1996) or by seeking out unused Babads and fragmentary manuscript materials (e.g., *Fathurahman*, 2010). Historical trade in Indonesia was not restricted to that with Europeans but reflected a wide diversity with both inter-island commerce and interactions with Arab, Chinese, Japanese, and Indian merchants (*Soedjatmoko et al.,* 1965; *Missen*, 1972; *Rickleffs*, 1981). Accounts from these sources may be another untapped resource that could potentially add information to the historical earthquake record in Indonesia and supplement our work on Gempa Nusantara further.

In addition to the vagaries in completeness due to the gradual expansion of colonial European influence in the 18th and 19th centuries, we note that all previous listings and our database contain very limited information for events during the Japanese occupation of the region during World War II. The collection of macroseismic data ceased with the publication of data for 1941 and did not resume until 1948 (*Anonymous*, 1957). Except for a few events such as the 8 – 9 June 1943 Alahang Panjang earthquakes on Sumatra (GN-1167, GN-1168) and the 23 July 1943 central Java earthquake (GN-1169), documentary material for events between 1942 and 1948 known from instrumental records remains elusive. Equally elusive were documentary material in support of large earthquakes of the pre-colonial era. No new evidence was found to support the hypothesis made by *Reid* (2014) that a large tsunami-generating earthquake struck the south coast of Java in the early 17th century. We underline here that our inability to locate new material does not disprove *Reid's* (2014) hypothesis, but simultaneously we also caution future studies from arbitrarily associating this event to others catalogued in Java in the early 1600s without definitive evidence. We also did not find written descriptions of shaking from several large pre-19th century megathrust earthquakes identified in the coral record off Sumatra (see *Philibosian et al.*, 2017).

Though it is important to associate historical observations with specific faults, the dearth of visual and written observations of surface rupturing earthquakes makes this difficult, especially on the Sumatran Fault Zone (SFZ) and on the Palu-Koro Fault Zone (PFZ) with for which geodetic slip rates are as high as ~16 mm/yr (*Bradley et al.*, 2017) and ~42 mm/yr (*Socquet et al.*, 2006), respectively. On the other hand, palaeoseismic studies have identified active faults such as the Lembang (e.g., *Daryono et al.*, 2019) and Pasuruan faults (*Marliani et al.*, 2019) on Java, for which there is no conclusive evidence of damaging earthquakes even over the course of our four-century long database of observations. With the exception of a handful of events discussed in previous sections that could be associated either with onshore faults, including surface ruptures, or slip on the Sunda Megathrust, the vast majority of the 1,200 events in Gempa Nusantara have no definitive association with an active fault include some with extreme ground motion, such as from the 25 October 1875 Java earthquake (GN-0434) and the 6 January 1898 Ambon earthquake (GN-0609). In the Banda Outer Arc region (BOA; **Figure 1**), for example, the 26 November 1852 Banda Sea earthquake (GN-0290), which destroyed Banda Neira (**Figure 3a**) and generated a large tsunami, could have been caused by either a great megathrust earthquake in the outer arc (*Fisher & Harris*, 2016), a large earthquake associated with the recently discovered Banda Detachment (*Pownall et al.*, 2016; *Cummins et al.*, 2020; **Figure 1**), or some other as-yet unknown source.

We note further that non-tectonic, climate drivers such as the Indian Ocean Dipole (IOD) can also produce coral die downs when in a moderate or strong positive phase. The IOD, which is similar to the El Niño – Southern Oscillation (ENSO) in the Pacific Ocean (e.g., *Neelin* *et al.*, 1998), is driven by ocean-atmospheric interactions that influence extreme rainfall patterns and sea level within the Indian Ocean basin (see *Saji et al.*, 1999; *Webster et al.*, 1999). During moderate or positive phases, the IOD can lower mean sea level along the west coast of Sumatra (see *Saji et al.*, 1999 for detailed discussion), causing oceanographically induced die-downs in coral microatolls. These oceanographic die-downs can have a similar amplitude and spatial footprint to tectonic die-downs (*Taylor et al.*, 1987; *Meltzner et al.*, 2010), and could either mask or be confused with modest tectonic uplifts, particularly for events prior to 1846 for which the timing of IOD events is yet unknown. Thus, despite detailed investigations of the coral record for palaeoearthquakes, some earthquakes may not appear in the coral record along the Sunda Megathrust, including outer rise earthquakes and large megathrust ruptures along the trench such as in January 1907 (*Martin et al.*, 2019).

Comparisons between observed intensities from Gempa Nusantara with the Indonesian hazard map (*Irsyam et al.* (2020) similar to that which we present in this study (**Figure 10**) have been made in previous studies for Indonesia (*Griffin et al.*, 2019) and elsewhere (e.g., *Stirling and Peterson*, 2006; *Bozkurt et al.*, 2007; *Salditch et al.*, 2020). We note that although observations in Gempa Nusantara number in the thousands, exceeding those available to *Griffin et al.* (2019), the number of observations at the selected cities discussed in this article is not large, ranging from 82 observations at Jakarta (**Figure 10h**), 28 observations at Surabaya (**Figure 10L**) to 51 at Yogyakarta (**Figure 10m**). These contrast with the over 10,000 observations used by *Bozkurt et al.* (2007) for the Tokyo area in Japan, which allowed a much more detailed study of site response and statistical properties of the intensity observations than we can consider here. Observations of intensity and peak ground acceleration used to derive the *Worden et al.* (2012) intensity prediction equations are sparse above 0.32 g**,** resulting in poor statistical constraint of the model above MMI VIII. This could explain the higher rate of occurrence we estimate for the highest intensities, for example, 10 EMS at Ambon and Banda

Neira, and 9 EMS at Gorontalo, Padang and Yogyakarta, 8 EMS at Bengkulu and Banda Aceh Aceh (**Figure 10**), compared with published hazard curves from *Irsyam et al.* (2020). We note that some of the high-intensity observations are associated with damage to "monumental structures" ("M" in **Table S3**) for which the actual intensities may have been higher. The amplification (or deamplification) of ground motions in fluvial and volcano-sedimentary basins such as Yogyakarta, and the complex interaction of these basins with critical reflections with the Moho and other subsurface structures could also be reflected in our intensities. As for the Indonesian hazard map, no Indonesia-specific ground motion prediction equation was available to *Irsyam et al.* (2020), it could also be that ground motion is poorly characterised in places such as Surabaya, from where fewer higher intensity observations are available. Additionally, unlike the well-constrained seismic coupling on faults such as the Sumatran Fault Zone (e.g., *Natawidjaja*, 2017), many other faults in Indonesia are thought to be active but with slip rates that are poorly constrained by either geodetic or geologic data. Such faults were identified in the seismic hazard analysis of *Irsyam et al.* (2020), but pending further studies to constrain slip rates these were assigned a very low slip rate of 0.1 mm/yr. It is highly plausible that at least some of these faults do have appreciable slip rates. For example, the GPS study of *Koulali et al.* (2017) suggests that oblique convergence is likely accommodated by slip rates of several mm/yr along faults near the northern coast of Java, like the Kendeng and Baribis Thrusts. These and/or other faults might be associated with the damaging shaking we have documented in our database.

In conclusion, we reiterate that the study of historical earthquakes is highly relevant to the cataloguing and analysis of seismic hazards. As we have shown in this study, historical seismology supplements and fills in the gaps left unanswered by other scientific approaches such as palaeoseismology and instrumental observation. This emphasizes the need for the study of such "unscientific" materials (*Ambraseys*, 1971; *Hough*, 2001). Underestimating or ignoring such datasets will undermine our collective efforts to understand the science of earthquakes and safeguard the world we live in.

Data and Resources

Supplemental Material for this article includes the Gempa Nusantara database in Tables S1 – S3 in an Excel Spreadsheet as well as our approach to intensity assignment, a brief description of the Batavia Scale and Figure S1 and S2. The compilation of this database was a single-handed effort by the lead author lasting the better part of a decade and despite every well-meant effort, errors could have still been unknowingly introduced. Therefore, future updates to any of these materials will be made available via GitHub (https://github.com/7point1/GempaNusantara, last accessed 15 September 2022). The out-of-print journal "*Natuurkundig tijdschrift voor Nederlandsch Indië*" is digitally available via the Koninklijk Instituut voor Taal-, Land- en Volkenkunde (KITLV) collections at the Universiteit Leiden (https://digitalcollections.universiteitleiden.nl, last accessed 15 September 2022). The "*Generale missiven van gouverneurs-generaal en raden aan heren XVII der Verenigde Oostindische Compagnie*" from 1610 to 1767 and other transcribed correspondence from the later sovereign Dutch period can be found via the digital collections of the Koninklijke Nederlandse Akademie van Wetenschappen at Huygens ING (http://resources.huygens.knaw.nl, last accessed on 15 September 2022). Additional VOC manuscripts are available at the Sejarah Nusantara database (https://sejarah-nusantara.anri.go.id/, last accessed on 15 September 2022). Out of print newspapers can be accessed via the online collections of the Biblioteca Nacional Digital Brazil (http://bndigital.bn.gov.br/, last accessed on 15 September 2022), the British Library (https://www.britishnewspaperarchive.co.uk, last accessed on 15 September 2022), the Global Press archive (https://gpa.eastview.com/, last accessed on 15 September 2022), the Koninklijke

Bibliotheek (http://www.delpher.nl, last accessed on 15 September 2022), the National Library of Singapore (http://eresources.nlb.gov.sg/main/, last accessed on 15 September 2022), and the National Library of Australia (https://trove.nla.gov.au/newspaper/, last accessed on 15 September 2022). Early 19th century periodicals are also available digitally via the Digizeitschriften (http://www.digizeitschriften.de/, last accessed on 15 September 2022), Münchener Digitalisierungszentrum at the Bayersche Staatsbibliothek (https://www.digitale-sammlungen.de, last accessed on 15 September 2022), the Österreichischen Nationalbibliothek (http://digital.onb.ac.at, last accessed on 15 September 2022) and Universität Bielefeld (www.ub.uni-bielefeld.de, last accessed on 15 September 2022). Written materials from internees at WW2 Prisoner of War camps on Java and Sumatra can be found via the NIOD (*Nederlands instituut voor oorlogsdocumentatie) Instituut voor Oorlogs-, Holocaust- en Genocidestudies*. https://www.niod.nl/, last accessed on 15 September 2022). *Wong* (2014) describing the Linur Batakarang incident in the Karo Highlands in Sumatra in 1936 can be found at this link (https://www.kompasiana.com/billwong/552b06d5f17e613264d623a9/kisah-linur-batukarang-tahun-1936, last accessed on 15 September 2022). Additional material only available in hard copy (paper, microfiche, or microfilm) was consulted in person at libraries in Australia, Singapore, and in the Netherlands. Population statistics were obtained from Badan Pusat Statistik (https://www.bps.go.id, last accessed on 15 September 2022). Topographic data were downloaded from the Indonesian Geospatial Portal (https://tanahair.indonesia.go.id/, last accessed on 15 September 2022) and GEBCO (https://www.gebco.net/, last accessed on 15 September 2022)). All external hyperlinks recorded in this paper point to verified sources of information in 2022 but given the dynamic nature of the worldwide web we cannot guarantee these in the future.

Acknowledgments

The authors acknowledge the traditional owners of the lands upon which this research was conducted and pay our respects to their traditions and their elders, past, present and emerging. We thank Koen van Noten, an anonymous reviewer and the associate editor, Ricardo Taborda, for constructive feedback on this manuscript. We also thank Emily Hammond and Annastasia Pratt for the handling of the publication process. We specifically wish to thank the Earth Observatory of Singapore (EOS) founding Director Prof. Kerry Sieh for his support for this project. This article has benefitted from interactions with and assistance from Trevor Allen, Peter Baxter, Linda Chua, Elaine Devan, Brendan Duffy, Oman Fathurahman, Domenico Di Giacomo, Lina Handayani, Susan Hough, Iwan Hermawan, Elizabeth Oliver, Ryan Pranyanto, Anthony Reid, François Sapin and Christina Widiwijayanti. The patience and co-operation of staff at the libraries listed here is sincerely appreciated: the Australian National University libraries (*Canberra*), the International Institute of Social History (*Amsterdam*), the British Library (*London*), Institute of Southeast Asian Studies (Yusof Ishak Institute, *Singapore*), Koninklijke Bibliotheek (*The Hague*), the Nanyang Technological University libraries (*Singapore*), the National Library of Australia (*Canberra*), the National Archives of Australia (*Canberra*), the National Library of Singapore (*Singapore*), and the National University of Singapore library (*Singapore*). Figures were generated using Generic Mapping Tools (GMT), the Matplotlib (3.5.1) and Numpy (1.21.5) libraries in Python (v. 3.9), and Quantum GIS (v3.22.6). SSM and AJM were financially supported by the Earth Observatory of Singapore and by the National Research Foundation (NRF) Singapore and the Singapore Ministry of Education (MoE) under the Research Centres of Excellence initiative. SSM was also supported by the Australian National University (ANU) Research Scholarship (738/2018). AJM was also supported by the National Research Foundation (NRF) Singapore under its NRF Fellowship scheme (Award NRF-NRFF11-2019-0008). This is Earth Observatory of Singapore contribution number 283.

References

Abendanon, E.C. (1915), "Midden-Celebes-Expeditie: Geologische en geographische doorkruisingen van Midden-Celebes," **2**, *Koninklijk Nederlandsch Aardrijkskundig Genootschaap*, Leiden, pp. 835 – 836, pp. 871 – 878 (in Dutch).

Abendanon, E.C. (1916), Plates 12 and 13, in Atlas to "Midden-Celebes-Expeditie: Geologische en geographische doorkruisingen van Midden-Celebes 1909 – 1910", *Koninklijk Nederlandsch Aardrijkskundig Genootschaap* (in French and Dutch).

Abram, N., M. Gagan, J. Cole, W.S. Hantoro and M. Mudelsee (2008), Recent intensification of tropical climate variability in the Indian Ocean, *Nature Geoscience*, **1, pp.** 849 – 853, doi: 10.1038/ngeo357.

Adam, A. (1996), The vernacular press and the emergence of modern Indonesian consciousness (1855 – 1913), *Studies on Southeast Asia*, **17**, 206 p.

Albini, P.,and A. Rovida (2018), Earthquakes in southern Dalmatia and coastal Montenegro before the large 6 April 1667 event, *Journal of Seismology*, **22** (2/3), doi: 10.1007/s10950-018-9730-4.

Albini, P., R.W. Musson, A. Rovida. M. Locati, A. Gomez Capera, and D. Viganò (2014), The global earthquake history, *Earthquake Spectra*, **30**, 2, pp. 607 – 624, doi: 10.1193/122013EQS297.

Allen, T.I. (2021), A far-field ground motion model for the North Australian Craton from plate-margin earthquakes, *Bulletin of the Seismological Society of America*, doi: 10.1785/0120210191.

Ambraseys, N. (1963), The Buyin-Zara (Iran) earthquake of September 1962; a field report. *Bulletin of the Seismological Society of America,* **53**, pp. 705 – 740, doi: 10.1785/BSSA0530040705.

Ambraseys, N. (1971), Value of historical records of earthquakes, *Nature*, **232**, pp. 375 – 379, doi: 10.1038/232375a0.

Ambraseys, N.N., and A. Zátopek (1968), The Varto Űstükran (Anatolia) earthquake of 19 August 1966 – Summary of a field report, *Bulletin of the Seismological Society of America*, **58**, 1, pp. 47 – 107, doi: 10.1785/BSSA0580010047.

Ambraseys, N.N., and R. Bilham, (2003), Earthquakes and Associated Deformation in Northern Baluchistan 1892–2001, *Bulletin of the Seismological Society of America*, **93**, 2, pp. 1573 – 1605, doi: 10.1785/0120020038.

Ambraseys, N.N., and C.P. Melville (1982). A history of Persian earthquakes, Cambridge University Press, 219 p.

Ambraseys, N.N., and R.D. Adams (1991), Reappraisal of major African earthquakes, south of 20°N, 1900-1930, *Natural Hazards*, **4**, pp. 389 – 419, doi: 10.1007/BF00126646.

Ambraseys, N.N., and J. Douglas (2004), Magnitude calibration for north Indian earthquakes, *Geophysical Journal International*, **159**, pp. 165 – 206, doi: 10.1111/j.1365-246X.2004.02323.x.

Ambraseys, N., E. Banda, J. Irving, D. Mallard, C. Melville, T. Morse, R. Muir-Wood, D. Muñoz, L. Serva, D. Shilton, E. Surinach, and J. Vogt (1983), Notes on historical seismicity, *Bulletin of the Seismological Society of America*, **73**, 6, pp. 1917 – 1920.

Anonymous (1851), Berighten van verschillenden aard, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **1**, pp. 86 – 87, 153 – 154, 303, 463 – 464. (in Dutch).

Anonymous (1852), Berighten van verschillenden aard, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **3**, p. 860 (in Dutch).

Anonymous (1853), Berighten van verschillenden aard, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **4**, p. 199 (in Dutch).

Anonymous (1920), Vulkanische verschijnselen en aardbevingen in den Oost Indischen Archipel waargenomen gedurende het jaar 1919, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **80**, 3, pp. 199– 259 (in Dutch).

Anonymous (1921), Vulkanische verschijnselen en aardbevingen in den Oost Indischen Archipel waargenomen gedurende het jaar 1920, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **81**, 2, pp. 89 – 123 (in Dutch).

Anonymous (1931), Vulkanische verschijnselen en aardbevingen in den Oost Indischen Archipel waargenomen gedurende het jaar 1930, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **91**, 3, pp. 414 – 451 (in Dutch).

Anonymous (1938), Atlas van tropisch Nederland, Published by the Koninklijk Nederlandsch Aardrijkskundig Genootschap in cooperation with den Topografischen Dienst in Nederlandsch-Indië, The Hague. 17 p.

Anonymous (1940), Aardbevingen in den Oost Indischen Archipel waargenomen gedurende het jaar 1938, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **100**, 1, pp. 38 – 75 (in Dutch).

Anonymous (1957), Earthquakes in Indonesia for the years: 1948 – 1955, *Ministry of Communications, Meteorological and Geophysical Institute*, Series A, No. 45, 72 p.

Aung, L.T., S. Martin, Y. Wang, S. Wei, M. Thant, K.N. Htay, H.M. Aung, T.Z. Kyaw, S. Min, K. Sithu, T. Naing, E.H.N. Myo, T.H. Oo, S. N. Khaing, G. Suresh, W. Chen, P. M. Maung, and V.K. Gahalaut (2019). A comprehensive assessment of ground motions from two 2016 intra-slab earthquakes in Myanmar, *Tectonophysics*, **765**, 146 – 160, doi: 10.1016/j.tecto.2019.04.016.

Bergsma, P.A. (1873a), Aardbevingen in den Oost Indischen Archipel gedurende het jaar 1868 (vervolgd op de aanteekeningen in vol. 31, p.412), *Natuurkundig tijdschrift voor Nederlandsch Indië*, 32, 1, pp. 25 – 27 (in Dutch).

Bergsma, P.A. (1873b), Aardbevingen in den Oost Indischen Archipel gedurende het jaar 1869, *Natuurkundig tijdschrift voor Nederlandsch Indië*, 32, 1, pp. 119 – 127 (in Dutch).

Berlage, H.P. (1934), De aardbeving in Zuid-Sumatra van 25 Juni 1933 (waarnemingen in het epicentrale gebied), *Natuurkundig tijdschrift voor Nederlandsch Indië*, **94**, 1, pp. 15 – 36 (in Dutch).

Bock, Y., L. Prawirodirdjo, J.F. Genrich, C.W. Stevens, R. McCaffrey, C. Subarya, S.S.O. Puntodewo and E. Calais (2003), Crustal motion in Indonesia from Global Positioning System measurements, *Journal of Geophysical Research*, **108**, 2367, B8, doi: 10.1029/2001JB000324.

Bozkurt, S. B., R.S. Stein, & S. Toda (2007). Forecasting probabilistic seismic shaking for greater Tokyo from 400 years of intensity observations. *Earthquake Spectra*, 22, 3, pp. 525 – 546, doi: 10.1193/1.27535.

Bradley, K., Feng, L., Hill, E. M., Natawidjaja, D. H., & Sieh, K. (2017). Implications of the diffuse deformation of the Indian Ocean lithosphere for slip partitioning of oblique plate convergence in Sumatra, *Journal of Geophysical Research*, 122, 572–591, doi: 10.1002/2016JB013549.

Brest van Kempen, C.P. (1939), Het bouwen in seismisch gebied, *De Ingenieur in Nederlandsch Indië*, **6**, 9, pp. 197 – 214 (in Dutch).

Brest van Kempen, C.P. (1942), Aardbevingen, *Natuurwetenschappelijk Tijdschrift voor Nederlandsch Indië*, **102**, 1, pp. 1 – 9 (in Dutch).

BMKG (2019), Katalog gempabumi signifikan dan merusak (1821-2018).

Coleridge, H.J. (1886), The life and letters of Saint Francis Xavier, London, **1**, p. 388.

Coolhaas, W. Ph. (1975), Generale missiven van gouverneurs-generaal en raden aan heren XVII der Verenigde Oostindische Compagnie (1686 – 1697), 5, Rijks Geschiedkundige Publicatiën (Grote Serie 150), The Hague, **99**, pp. 202 – 206, p. 388, p. 413, p. 442.

Coronas, J., (1899), Terremotos de Zamboanga de 21 septiembre 1897, La actividad séismica en el Archipiélago Filipino durante el año 1897, Observatario de Manila, Manila, pp. 47 – 92 (in Spanish).

Cummins, P.R., I.R. Pranantyo, J.M. Pownall, J.D. Griffin, I. Meilano and S. Zhao (2020), Earthquakes and tsunamis caused by low-angle normal faulting in the Banda Sea, Indonesia. *Nature Geoscience*, **12**, pp. 312 – 318, doi: 10.1038/s41561-020-0545-x.

Daryono, M. D.H. Natawidjaja, B. Sapiie, and P.R. Cummins (2019), Earthquake geology of the Lembang Fault, West Java, Indonesia, *Tectonophysics*, **751**, pp. 180 – 191, doi: 10.1016/j.tecto.2018.12.014.

Daryono and Natawidjaja (2019). Surface rupture of the 1909 event (M7) on Palukoro Fault in tropical forest of Central Sulawesi, Indonesia, Proceedings of the HAGI-IAGI-IAFMI-IATMI Joint Convention 2019, Yogyakarta, 4p.

Delprat, Th. (1895), Effects of earthquakes in Sumatra, *Nature*, **52**, pp. 129 – 130.

de Argensola, L.B. (1609), Conquista de Las Islas Molucas, Madrid, p. 55 (in Spanish).

du Puy, J. (1845), Een paar aanteekeningen met omtrent vuurbergen en aardbevingen op Sumatra, *Tijdschrift voor Neerlandsch Indië*, **7**, 3, pp. 110 – 116 (in Dutch).

Fatuhrahman, O. (2010), Katalog naskah dayah Tanoh Abee, Aceh Besar, published in co-operation with Tokyo University of Foreign Studies (TUFS), Penerbit Komunitas Bambu, Masyarakat Pernaskahan Nusantara (Manassa), PPIM UIN Jakarta and PKPM Aceh, Jakarta, Indonesia, 374 p. (in Indonesian).

Figee, S. and H. Onnen (1892), Vulkanische verschijnselen en aardbevingen in den Oost Indischen Archipel waargenomen gedurende het jaar 1890, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **51**, 3, pp. 318 – 359 (in Dutch).

Figee, S., H. Onnen, and J.A. Schuurman (1886), Circulaire gezonden aan H.H. medewerkers tot het verzamelen van aardbevingswaarnemingen, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **45**, 2, pp. 233 – 234 (in Dutch).

Firman, T., B. Kombaitan, and P. Pradono (2007), The dynamics of Indonesia's urbanisation: 1980 – 2006, *Urban Policy and Research*, **25**, 4, pp. 433 – 454, doi: 10.1080/08111140701540752.

Fisher, T.L. and R.A. Harris (2016), Reconstruction of 1852 Banda Arc megathrust earthquake and tsunami, *Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards*, **83**, 1, pp. 667 – 689, doi: 10.1007/s11069-016-2345-6.

Flores, C.H., U.S. ten Brink, W. Bakun (2011). Accounts of Damage from Historical Earthquakes in the Northeastern Caribbean, to Aid in the Determination of their Location and Intensity Magnitudes, USGS Open File Report (2011-1133), 199, doi: 10.3133/ofr20111133.

Fraser, I.A.N (1983), A new draft code for seismic design of buildings in Indonesia, *Bulletin of the New Zealand National Society of Earthquake Engineering*, **16**, 3, pp. 247 – 254.

Gahalaut V.K., S.S. Martin, D. Srinagesh, S.L. Kapil, G. Suresh, S. Saikia, V. Kumar, H. Dadhich, A. Patel, S.K. Prajapati, H.P. Shukla, J.L. Gautam, P.R. Baidya, S. Mandal, & A. Jain (2016), Seismological, geodetic, macroseismic and historical context of the 2016 Mw 6.7 Tamenglong (Manipur) India earthquake, *Tectonophysics*, **688**, pp. 36 – 48, doi: 10.1016/j.tecto.2016.09.017.

Griffin, J, N. Nguyen, P. Cummins and A. Cipta, A (2019). Historical earthquakes of the Eastern Sunda Arc: Source mechanisms and intensity-based testing of Indonesia's national seismic hazard assessment. *Bulletin of the Seismological Society of America*, **109**, 1, pp. 43 – 65, doi: 10.1785/0120180085.

Grünthal, G. (Editor) (1998), The European Macroseismic Scale EMS-98, Conseil de l'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, **15**, Luxembourg, 101 p.

Hall, R. (2014), The origin of Sundaland, *Proceedings of the Sundaland resources 2014 MGEI Annual Convention*, Palembang, Indonesia. 28 p.

Harris, R, and J. Major (2016) Waves of destruction in the East Indies: The Wichmann catalog of earthquakes and tsunami in the Indonesian region from 1538 to 1877, *Geological Society, London*, Special Publications, **441**, pp. 9 – 46, doi: 10.1144/SP441.2.

Hermawan, I., (2010), Sismotectonique des failles actives en Indonésie, vue par Géodésie Spatiale, Doctoral Thesis, L'Université Pierre et Marie Curie, 131 p (in French).

Hesse, E. (1687), Ost-Indische Reise beschreibung, Dresden, pp. 124 – 125 (in German).

Hittleman, A.M., P.A. Lockridge, L.S. Whiteside, and J.F. Lander (2001), Interpretive pitfalls in historical data, *Natural Hazards*, **23**, pp. 315 – 338, doi: 10.1023/A:1011144703109.

Hough, S.E. (2001), On the scientific value of "unscientific" data, *Seismological Research Letters*, **71**, 5, pp. 483 – 485, doi: 10.1785/gssrl.71.5.483.

Hough, S.E., and M. Page (2011), Toward a consistent model for strain accrual and release for the New Madrid Seismic Zone, central United States, *Journal of Geophysical Research*, 116, p. B03311, doi: 10.1029/2010JB007783.

Hough, S.E., and S.S. Martin (2021), Which earthquake accounts matter? *Seismological Research Letters*. **92**, 2A, pp. 1069 – 1084, doi: 10.1785/0220200366.

Hough, S.E., and S.S. Martin (2022), Reply to “Comment on ‘Which earthquake accounts matter?’ by S.E. Hough and S.S. Martin” by D.J. Wald, *Seismological Research Letters*. **93**, 1, pp. 506 – 511, doi: 10.1785/0220210142.

Hough, S.E., S.S. Martin, S. Symithe and R. Briggs (2022). Exploring rupture scenarios for the 3 June 1770 Haiti earthquake, *Bulletin of the Seismological Society of America*, (*in press*).

Hurukawa, N., B.R. Wulandari and M. Kasahara (2014), Earthquake history of the Sumatran Fault, Indonesia, since 1892, derived from relocation of large earthquakes, *Bulletin of the Seismological Society of America,* **104,** 4, pp. 1750 – 1762, doi: 10.1785/0120130201.

Irsyam, M., P.R., Cummins, M. Asrurifak, L.Faizal, D.H. Natawidjaja, S. Widiyantoro, I. Meilano, W. Triyoso, A. Rudiyanto, S. Hidayati, M. Ridwan, N.R. Hanifa, and A.J. Syahbana (2020), Development of the 2017 national seismic hazard maps of Indonesia, *Earthquake Spectra*, **36**, 1, doi: 10.1177/8755293020951206.

Iyengar, R.N., D. Sharma and J.M. Siddiqui (1999). Earthquake history of India in medieval times, *Indian Journal of History of Science*, **34**, 3, pp. 181 – 237.

Jacobs, H. (1974), Documenta Malucensia (1542 – 1577), *Institutum Historicum Societatis Iesu*, Rome, 758 p.

Jaya, A., O. Nishikawa and S. Jumadil (2019), Distribution and morphology of the surface ruptures of the 2018 Donggala-Palu earthquake, central Sulawesi, Indonesia, *Earth, Planets and Space*, **71**, 114, doi: 10.1186/s40623-019-1126-3

Kern, R.A. (1939), “I La Galigo: Catalogus der Boegineesche tot den I La Galigo-cyclus behoorende handschriften”, Leiden University, Leiden (in Dutch).

Kreemer, C., G. Blewitt and E.C. Klein (2014). A geodetic plate motion and Global Strain Rate Model, *Journal of Geophysical Research*, **15**, 10, pp. 3849 – 3889, doi: 10.1002/2014GC005407.

Marliyani, G.I., J.R. Arrowsmith and H. Helmi (2019), Evidence form multiple ground-rupturing earthquakes in the past 4,000 years along the Pasuruan Fault, East Java, Indonesia: Documentation of active normal faulting in the Javan Backarc, *Tectonics*, **38**, pp. 1489 – 1506, doi: 10.1029/2018TC005255.

Martin, S.S. and S.E. Hough (2016), Reply to, "Comment on 'Ground Motions from the 2015 Mw 7.8 Gorkha, Nepal, Earthquake Constrained by a Detailed Assessment of Macroseismic Data' by Stacey Martin, Susan E. Hough and Charleen Hung" by Andrea Tertulliani, Laura Graziani, Corrado Castellano, Alessandra Maramai, Antonio Rossi, *Seismological Research Letters*, **87**, 4, pp. 369 – 377, doi:10.1785/0220160061.

Martin, S.S., and S.E. Hough (2022), The 8 April 1860 Jour de Pâques earthquake sequence in southern Haiti, *Bulletin of the Seismological Society of America*, doi: 10.1785/0120220016.

Martin, S.S., L. Li, E. Okal, J. Morin, A. Tetteroo, A. Switzer, K. Sieh (2019), Reassessment of the 1907 Sumatra "tsunami earthquake" based on macroseismic, seismological and tsunami observations, and modelling, *Pure and Applied Geophysics*, **176**, pp. 2831 – 2868, doi: 10.1007/s00024-019-02134-2.

Martin, S.S., Y. Wang, M. Muzli, and S. Wei (2020a). The 1922 Peninsula Malaysia Earthquakes: Rare intraplate seismicity within the Sundaland block in Southeast Asia, *Seismological Research Letters,* **91**, 5, pp. 2531 – 2545, doi: 10.1785/0220200052.

Martin, S.S., L. Li, E. Okal, J. Morin, A. Tetteroo, A. Switzer, K. Sieh (2020b), Correction to: Reassessment of the 1907 Sumatra "tsunami earthquake" based on macroseismic, seismological and tsunami observations, and modelling, *Pure and Applied Geophysics*, **177**, pp. 5641 – 6542, doi: 0.1007/s00024-020-02588-9.

Medvedev, S. V., W. Sponheuer, and V. Kárník (1965), Шкала Сейсмической Интенсивности MSK 1964 (*Seismic Intensity Scale Version MSK 1964, in Russian*), *Akademii Nauk SSSR Geofiz. Kom.*, Moscow, 280.

Meltzner, A.J., and C.D. Woodroffe (2015), Coral Microatolls, in I. Shennan, A.J. Long and B.P. Horton (eds), *Handbook of Sea-level Research*, John Wiley & Sons, Ltd., Chichester, UK, pp. 125 – 145.

Meltzner, A. J., K. Sieh, H.-W. Chiang, C.-C. Shen, B. W. Suwargadi, D. H. Natawidjaja, B. Philibosian, R. W. Briggs, and J. Galetzka (2010), Coral evidence for earthquake recurrence and an AD 1390–1455 cluster at the south end of the 2004 Aceh–Andaman rupture, *Journal of Geophysical Research*, **115**, B10402, doi: 10.1029/2010JB007499.

Meltzner, A. J., K. Sieh, H.-W. Chiang, C.-C. Shen, B. W. Suwargadi, D. H. Natawidjaja, B. Philibosian, and R. W. Briggs (2012), Persistent termini of 2004- and 2005-like ruptures of the Sunda megathrust, *Journal of Geophysical Research*, **117**, B04405, doi:10.1029/2011JB008888.

Meltzner, A.J., K. Sieh, H-W. Chiang, C-C. Wu, L. L.H. Tsang, C-C. Shen, E. M. Hill, B.W. Suwargadi, D. H. Natawidjaja, B. Philibosian, R.W. Briggs (2015), Time-varying interseismic strain rates and similar seismic ruptures on the Nias–Simeulue patch of the Sunda megathrust, *Quaternary Science Reviews*, **122**, pp. 258 – 281, doi: 10.1016/j.quascirev.2015.06.003.

Missen, G.J. (1972), Viewpoint on Indonesia – A geographical study, Thomas-Nelson, Melbourne, 359 p.

Miyajima, M., H. Setiawan, M. Yoshida, Y. Ono, K. Yusuke, K. Kosa, I.S. Oktaviana, Martini, and Irdhiani (2019), Geotechnical damage in the 2018 Sulawesi earthquake, Indonesia, *Geoenvironmental Disasters*, **6**, 6, pp. 1 – 8, doi: 10.1186/s40677-019-0121-0.

Muller, J.J.A. (1895), De Verplaatsing van eenige triangulatie-pilaren in de residentie Tapanoeli (Sumatra) tengevolge van de aardbeving van 17 Mei 1892, *Verhandelingen der Koninklijke Akademie van Wetenschappen te Amsterdam*, **3**, 2, 26 p.

Musson, R. M. W. (2012), A provisional catalogue of historical earthquakes in Indonesia, Earth Hazards and Systems Programme Open Rept. OR/12/073, 22 pp.

Musson, R. M. W, and I., Cecić (2012), Intensity and Intensity Scales, New Manual of Seismological Observatory Practice 2 (NMSOP-2), GFZ Potsdam, 1-41, doi: h10.2312/gfz.nmsop-2_ch12.

Mustafar, M.A., W.J.F. Simons, F. Tongkul, C. Sitarapod, K. Omar and P. Visser (2017), Quantifying deformation in North Borneo with GPS. *Journal of Geodesy,* **91**, pp. 1241 – 1259, doi: 10.1007/s00190-017-1024-z.

Nas, P. (2007)(ed). The past in the present: Architecture in Indonesia, Leiden, 286 p.

Natawidjaja, D.H., and Y. Kumoro (1995), Gempa bumi tektonik daerah Bukit-Tinggi-Muaralabuh: Hubungan segmentasi sesar aktif dengan gempa bumi tahun 1926 dan 1943, *Proceeding seminar sehari geoteknologi dalam industrialiasi*, pp. 50 – 75, Bandung (in Indonesian).

Natulaya, P., S. Sodsri, and E.P. Arnold (1985), Series on Seismology: Volume II – Thailand, *Southeast Asia Association of Seismology and Earthquake Engineering*, 403 p.

Neelin, J.D., D. Battisti, A.C. Hirst, F-F. Jin, Y. Wataka, T. Yamagata and S.E. Zebaik (1998), ENSO theory, *Journal of Geophysical Research – Oceans*, **103**, C7, pp. 14261 – 14290, doi: 10.1029/97JC03424.

Newcomb, KR, and W.R. McCann (1987) Seismic history and seismotectonics of the Sunda Arc. *Journal of Geophysical Research*, 92, B1, pp. 421 – 439, doi: 10.1029/JB092iB01p00421.

Niemeijer, H.E., Th. Van den End, and G.J. Schutte (2015), Bronnen betreffende Kerk en School in de Gouvernementen Ambon, Ternate en Banda ten tijde van de VOC, 1605-1791, 264, **1,** 1, 's Gravenhage, 576 p (in Dutch).

Nitisantro, W. (1970), Population trends in Indonesia, Cornell University Press, Ithaca, 266 p.

Philibosian, B., K. Sieh, J-P. Avouac, D.H. Natawidjaja, H-W Chiang, C-C Wu, H. Perfettini, C-C Shen, M.R. Daryono, B.W Suwargadi (2014), Rupture and variable coupling behavior of the Mentawai segment of the Sunda megathrust during the supercycle culmination of 1797 to 1833, *Journal of Geophysical Research – Solid Earth*, **119**, pp. 7258– 7287, doi: 10.1002/2014JB011200.

Philibosian, B., K. Sieh, J-P. Avouac, D.H. Natawidjaja, H-W Chiang, C-C Wu, C-C Shen, M.R. Daryono, H. Perfettini, B.W Suwargadi, Y. Lu and X. Wang (2017), Earthquake supercycles on the Mentawai segment of the Sunda megathrust in the seventeenth century and earlier, *Journal of Geophysical Research - Solid Earth*, **122**, pp. 642 – 676, doi: 10.1002/2016JB013560.

Phoonsen, B. (1699), Copie van een Brief uit Batavia, op den 10ten February 1699, door den Herr B. Phoonsen aan Mevrouw Lestevenon geschreven, *Europische Mercurius*, Amsterdam, **10**, 2, pp. 173 – 175 (in Dutch).

Pontoppidan, H. and S. Snuif (1914), Verslag over de aardbeving op 26 Juni 1914 in die residentie Benkoelen, *Jaarboek van het mijnwezen in Nederlandsch-Indië*, Verhandelingen, 43, 2, pp. 78 – 89 (in Dutch).

Pownall, J. M., R. Hall, & G.S. Lister (2016). Rolling open Earth's deepest forearc basin, *Geology*, **44**, 11, pp. 947 – 950, doi: 10.1130/G38051.1.

Prawirodirdjo, L, Y. Bock, J.F. Genrich, S.S.O. Puntodewo, J. Rais, C. Surabaya, and S. Sutisna (2000), One century of tectonic deformation of the Sumatran fault from triangulation and Global Positioning System surveys, *Journal of Geophysical Research – Solid Earth*, **105**, B12, pp. 28343 – 28361, doi: 10.1029/2000JB900150.

Reiche, M. Th. (1859), Berighten over aardbevingen en berguitbarstingen vermeld in de Javasche Couranten van 1831 tot 1840, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **18**, pp. 245 – 282 (in Dutch).

Reiche, M. Th. (1863), Aanteekeningen omtrent de aardbevingen en andere natuurverschijnselen waargenomen in den Indischen Archipel, gedurende het laatste gedeelte van 1860 en het jaar 1861 verzameld, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **25**, 1, pp. 108 – 137 (in Dutch).

Reid, A. (2016), Two hitherto unknown Indonesian tsunamis of the seventeenth century: Probabilities and context, *Journal of Southeast Asian Studies,* **47**, 1, pp. 88 – 108.

Richter, C.F. (1958). Elementary Seismology, W.H. Freeman, San Francisco.

Ricklefs, M.C. (1981), A history of modern Indonesia since c. 1200, Stanford University Press, 512 p.

Roorda van Eysinga, P.P. (1830), Verschillende reizen en lotgevallen van S. Roorda van Eysinga, Amsterdam, 189 p (in Dutch).

Rovida, A., M. Locati, R. Camassi, B. Lolli, and P. Gasperini (2020), The Italian earthquake catalogue CPTI15. *Bulletin of Earthquake Engineering*, **18**, 7, pp. 2953 – 2984, doi: 10.1007/s10518-020-00818-y.

Saji, N.H., B.N. Goswami, P.N. Vinayachandran and T. Yamagata (1999), A dipole mode in the Indian Ocean, *Nature*, **401**, pp. 360 – 363, doi: 10.1038/43854.

Salditch, L., M. Gallahue, M.C. Lucas, J. Neely, S.E. Hough, and S. Stein (2020), California Historical Intensity Mapping Project (CHIMP): A consistently interpreted dataset of seismic intensities for the past 162 years and implications for seismic hazard maps, *Seismological Research Letters*, **91**, 5, pp. 2631 – 2650, doi: 10.1785/0220200065.

Sapin, F., I. Hermawan, M. Pulellier, C. Vigny, J-C. Ringenback (2013). The recent convergence on the NW Borneo Wedge - a crustal-scale gravity gliding evidenced from GPS, *Geophysical Journal International*, **193**, pp. 549 – 556, doi: 10.1093/gji/ggt054.

Simons, W. J. F., A. Socquet, C. Vigny, B. A. C. Ambrosius, S. Haji Abu, Chaiwat Promthong, C. Subarya, D. A. Sarsito S. Matheussen, P. Morgan and W. Spakman (2007), A decade of GPS in Southeast Asia: Resolving Sundaland motion and boundaries, *Journal of Geophysical Research*, **112**, B06420, doi: 10.1029/2005JB003868.

Singh, S.K., E. Mena, and R. Castro (1988). Some aspects of source characteristics of the 19 September 1985 Michoacan earthquake and ground motion amplification in and near Mexico City from strong motion data, *Bulletin of the Seismological Society of America,* **78***, 2,* pp. 451 – 477, doi: 10.1785/BSSA0780020451.

Socquet, A., Simons, W., Vigny, C., McCaffrey, R., Subarya, C., Sarsito, D., et al. (2006). Microblock rotations and fault coupling in SE Asia triple junction (Sulawesi, Indonesia) from GPS and earthquake slip vector data. Journal of Geophysical Research, 111(B8), B08409, doi: 10.1029/2005JB003963.

Soedjatmoko, M. Ali, G.J. Resink and G. Kahin (1965)(eds), An introduction to Indonesian Historiography, Cornell University Press, Ithaca, 427 p.

Soetadi, R. (1962), Seismic zones in Indonesia, *Geophysical Notes*, **2**, Departemen perhubungan udara – Djawatan meteorologi dan geofiski, Jakarta, pp. 3 – 10.

Soetardjo, M. Untung, E.P. Arnold, R. Soetadi, S. Ismail, and E.K. Kertapati (1985), Indonesia, Series on Seismology: Volume V – Indonesia, *Southeast Asia Association of Seismology and Earthquake Engineering*, 199 p.

Stirling, M., and M. Petersen (2006). Comparison of the historical record of earthquake hazard with seismic-hazard models for New Zealand and the continental United States, *Bulletin of the Seismological Society of America*, 96, 6, pp. 1978 – 1994, doi: 10.1785/0120050176.

Storchak D. A., D. D. Giacomo, I. Bondár, E. R. Engdahl, J. Harris, W. H. K. Lee, A. Villaseñor, and P. Bormann (2013). Public release of the ISC-GEM global instrumental earthquake catalogue (1900–2009). *Seismological Research Letters*, **84,** 5, pp. 810 – 815, doi: 10.1785/0220130034.

Surahman, A., I.W. Sengara and W. Merati (2008), Probabilistic seismic hazard assessment and structural performance against seismic actions, *International conference on Earthquake Engineering and Disaster Mitigation*, Jakarta.

Suárez, G., and V. García-Acosta (2021). The first written accounts of Pre-Hispanic earthquakes in the Americas, *Seismological Research Letters*, **92**, 6, pp. 3856 – 3864, doi: 10.1785/0220210161.

Szeliga, W., S.E. Hough, S. Martin, and R. Bilham (2010). Intensity, magnitude, location, and attenuation in India for felt earthquakes since 1762, *Bulletin of the Seismological Society of America*, **100**, pp. 570 – 584, doi: 10.1785/0120080329.

Taylor, F.W., C. Frohlich, J. Lecolle, and M. Steckler (1987), Analysis of partially emerged corals and reef terraces in central Vanuatu arc: Comparison of contemporary coseismic and nonseismic with Quaternary vertical movements, *Journal of Geophysical Research*, **92**, pp. 4905 – 4933, doi: 10.1029/JB092iB06p04905.

Tichelman, G.L. (1936), Dagboeken, met opmerkingen 23 Augustus – 17 Juli 1937, Nationaal Archief, Den Haag, Collectie 133 G.L. Tichelman, nummer toegang 2.21.097.01, inventarisnummer 37 (in Dutch).

Untung, M., N. Buyung, E. Kertapati, Undang, and C.R. Allen (1985), Rupture along the Great Sumatran fault, Indonesia, during the earthquakes of 1926 and 1943, *Bulletin of the Seismological Society of America*, **75**, 1, pp. 313 – 317.

van Dijk, P. and J.J. Poortman (1885), Circulaire gezonden aan alle personen, die hunne medewerking bij de waarneming van aardbevings-verschijnselen hebben togezegd, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **44**, 3, 277 – 279 (in Dutch).

van Dijk, P. (1885), Voorloopige instructive omtrent de waarneming van aardbevings-verschijnselen, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **44**, 3, 280 – 292 (in Dutch).

van Noten, K., T. Lecocq, C., Sira, K.G. Hinzen, T. Camelbeeck (2017). Path and site effects deduced from merged transfrontier internet macroseismic data of two recent M4 earthquakes in northwest Europe using a grid cell approach, *Solid Earth* **8**, pp. 453 – 477, doi: 10.5194/se-8-453-2017.

van Klaveren, J.J. (1953), The Dutch colonial system in the East Indies, Rotterdam,

van Oldenborgh, J. (1898), Verslag inzake de aardbeving van 6 Januari 1898, Correspondence on 17 January 1898 from the resident of Ambon (Van Oldenborgh) to the governor-general (Van de Wijck), No. 94. Afschrift, National Archief, Koloniën 2.10.02, 5288, vb. 19 juli 1898 no. 12 (in Dutch).

Valentijn, F. (1724), Oud- en nieuw Oost-Indiën, 2, Dordrecht – Amsterdam, p. 275.

Verbeek, R.D.M. (1898), Kort verslag over de aardbeving te Ambon of 6 Januari 1898, Batavia, 46 p (in Dutch).

Versteeg, W.F. (1859), Berighten over aardbevingen en berguitbarstingen vermeld in de Javasche Couranten van 1841 tot 1850, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **18**, pp. 283 – 342 (in Dutch).

Vissier, S.W. (1922), Inland and submarine epicentre of Sumatra and Java earthquakes, Verhandelingen 9 (complement tot Verhandelingen 7), *Koninklijk Magnetisch en Meteorologisch Observatorium te Batavia*, Batavia, pp. 1 – 14.

Vogel, J.W. (1704), Zehnjahrige Ost-Indische Reise Beschreibung, Altenburg, pp. 264 – 266 (in German).

Wald, D., and T. Allen (2007). Topographic slope as a proxy for seismic site conditions and amplification, *Bulletin of the Seismological Society of America*, **97**, 5, pp. 1379 – 1395, doi: 10.1785/0120060267.

Watkinson and Hall (2017), Fault systems of the eastern Indonesian triple junction: evaluation of Quaternary activity and implications for seismic hazards, *Geological Society of London*, Special Publications, **441**, pp. 71 – 120, doi: 10.1144/SP441.8.

Weber, R., W. Kreisel, and H. Faust (2003), Colonial interventions on the cultural landscape of Central Sulawesi by "Ethical Policy": The impact of the Dutch rule in Palu and Kulawi Valley, 1905—1942, *Asian Journal of Social Science*, **31**, 3, pp. 398 – 434.

Webster, P.J., A.M. Moore, J.P. Loschnigg and R.R. Leben (1999), Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98, *Nature*, **401,** pp. 356 – 360, doi : 10.1038/43848.

Wichmann, A. (1918), Die Erdbeben des Indischen Archipels bis zum Jahre 1857, *Verhandelingen der Koninklijke Akademie van Wetenschappen te Amsterdam (Tweed Sectie)*, **20**, 4, 193 p., Amsterdam (in German).

Wichmann, A. (1922), Die Erdbeben des Indischen Archipels von 1858 bis 1877, *Verhandelingen der Koninklijke Akademie van Wetenschappen te Amsterdam (Tweed Sectie)*, **22**, 5, 209 p., Amsterdam (in German).

Weitzel, A.W.P. (1859), Berighten over aardbevingen en berguitbarstingen vermeld in de Bataviasche Kolonial Courant, de Java-Gouvernement Gazette, De Bataviasche

Courant en de Javasche Courant, van 1810 tot 1830, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **18**, pp. 152 – 244 (in Dutch).

Worden, C. B., M. Gerstenberger, D.A. Rhoades, and D.J. Wald (2012). Probabilistic relationships between ground-motion parameters and modified Mercalli intensity in California, *Bulletin of the Seismological Society of America*, **102**, 1, pp. 204 – 221, doi: 10.1785/0120110156.

Wood, H.O. and F. Neumann (1931), Modified Mercalli intensity scale of 1931, *Bulletin of the Seismological Society of America*, **21**, pp. 277 – 283.

Wong, B. (2014), Kisah Linur Batukarang Tahun 1936, Kompasiana.

Wu, D, Z. Ren, J. Liu, J. Chen, P. Guo, G. Yin, H. Ran, C. Li, and X. Yang (2020), Coseismic surface rupture during the 2018 Mw 7.5 Palu earthquake, Sulawesi Island, Indonesia. *GSA Bulletin,* **133** (5-6): 1157–1166. doi: /10.1130/B35597.1

Author Affiliations

Stacey S. Martin (SSM)
Research School of Earth Sciences (RSES)
Australian National University (ANU)
142 Mills Road, Canberra 2601
Australia
7point1@gmail.com; stacey.martin@anu.edu.au
(*Formerly Earth Observatory of Singapore (EOS), Singapore*)

Phil R. Cummins (PRC)
Research School of Earth Sciences (RSES)
Australian National University (ANU)
142 Mills Road, Canberra 2601
Australia
phil.cummins@anu.edu.au

Aron J. Meltzner (AJM)
Earth Observatory of Singapore (EOS)
Nanyang Technological University (NTU)
50 Nanyang Ave, Block N2-01a-15,
Singapore 639798
meltzner@ntu.edu.sg

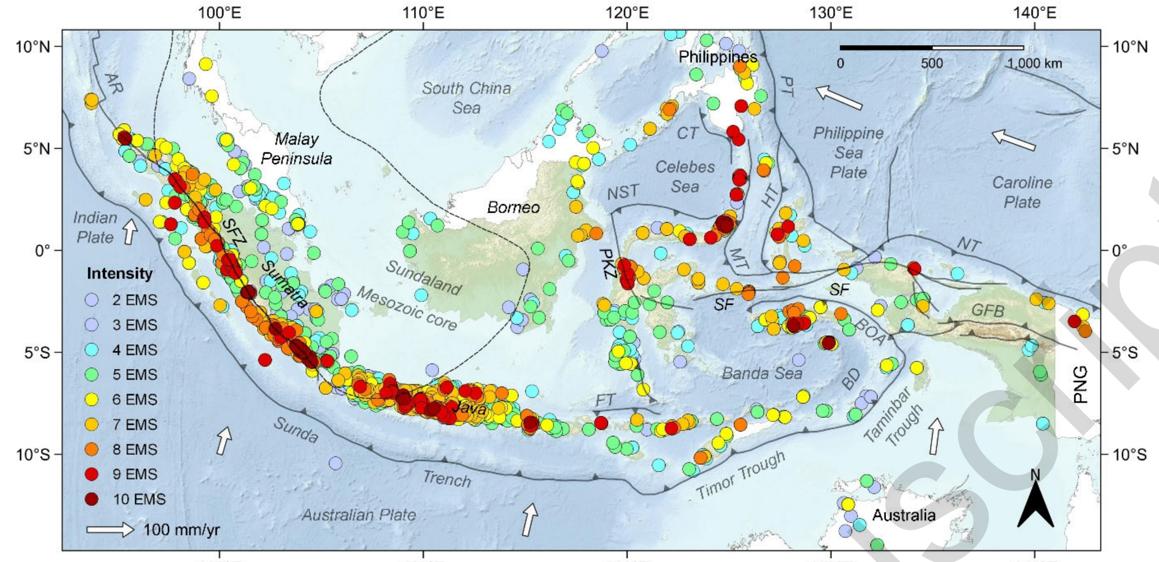

Figure 1: Intensity observations (*coloured circles*) from the Gempa Nusantra database overlain on a simplified tectonic map of Indonesia. Dashed line is the outline of the Mesozoic core of the Sundaland block from *Hall* (2014). Toothed lines show convergence between major tectonic plates and blocks. We use the model by *Kreemer et al.* (2014) to calculate and display plate motion vectors with respect to the Sundaland block. (AR: Andaman Ridge; BD: Banda Detachment; BOA: Banda Outer Arc; CT: Cotabato Trench; FT: Flores Thrust; GFB: Guinea Fold and Thrust Belt; HT: Halmahera Trench; MT; Molluca Trench; NST: North Sulawesi Trench; NT: New Guinea Trench; PNG: Papua New Guinea; SF: Sorong Fault zone).

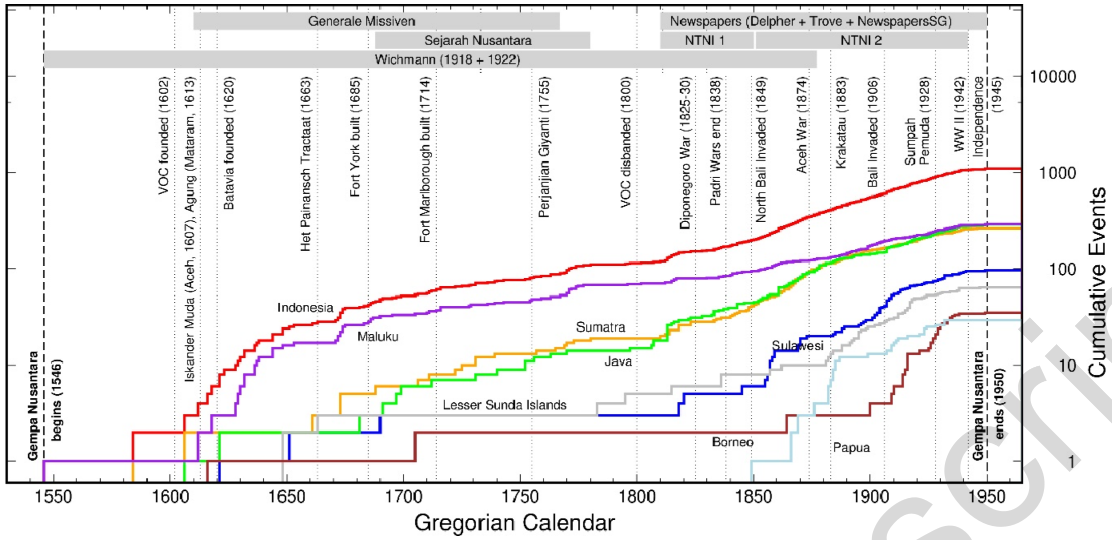

Figure 2: Cumulative distribution of events catalogued in the Gempa Nusantara database for all of Indonesia (*red*); note the logarithmic scale on the vertical axis. Cumulative events separated into major geographic regions, i.e., Borneo (*brown*), Java (*green*), Maluku (*purple*), Papua (*light blue*), Sulawesi (*dark blue*), Sumatra (*orange*) and the Lesser Sunda Islands (*grey*) are also shown. The chronological ranges of principle historical documentations (*horizontal grey bars*) are shown on top. We also indicate the occurrence of major events (e.g., Declaration of Independence in 1945) that directly or indirectly impacted the collation of historical earthquakes in Indonesia. (NTNI = *Natuurkundig tijdschrift voor Nederlandsch Indië*).

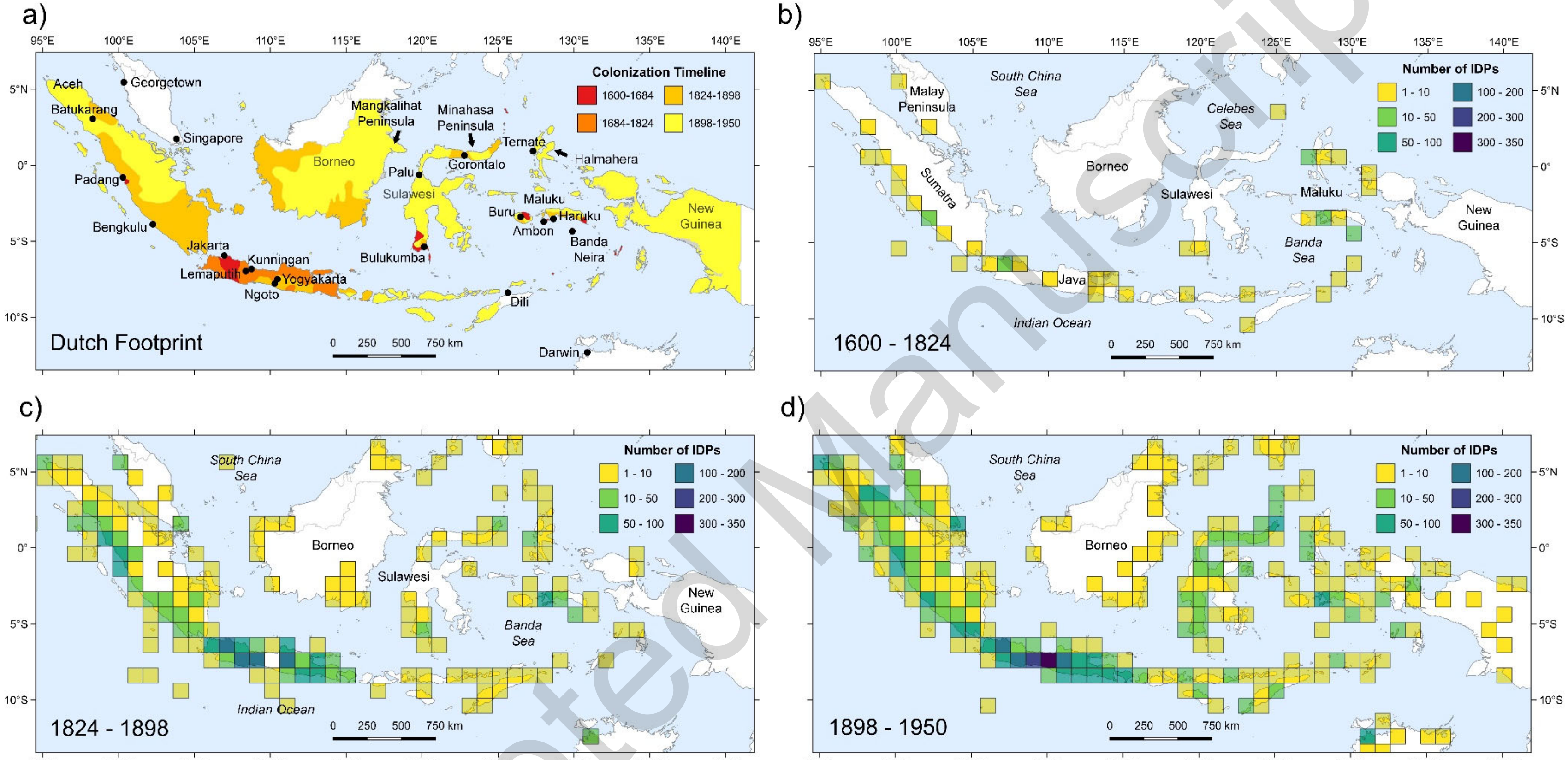

Figure 3: a) Expansion of Dutch political control in Indonesia (modified after *Soedjatmoko et al.*, 1965) from 1600 to 1950. Distribution of felt observations (*coloured boxes*) in three discrete time windows, **b)** VOC period to the onset of the Diponegoro War, **c)** early sovereign Dutch and **d)** late sovereign Dutch period, that correspond with distinct periods of the expansion of Dutch rule in the Indonesian Archipelago.

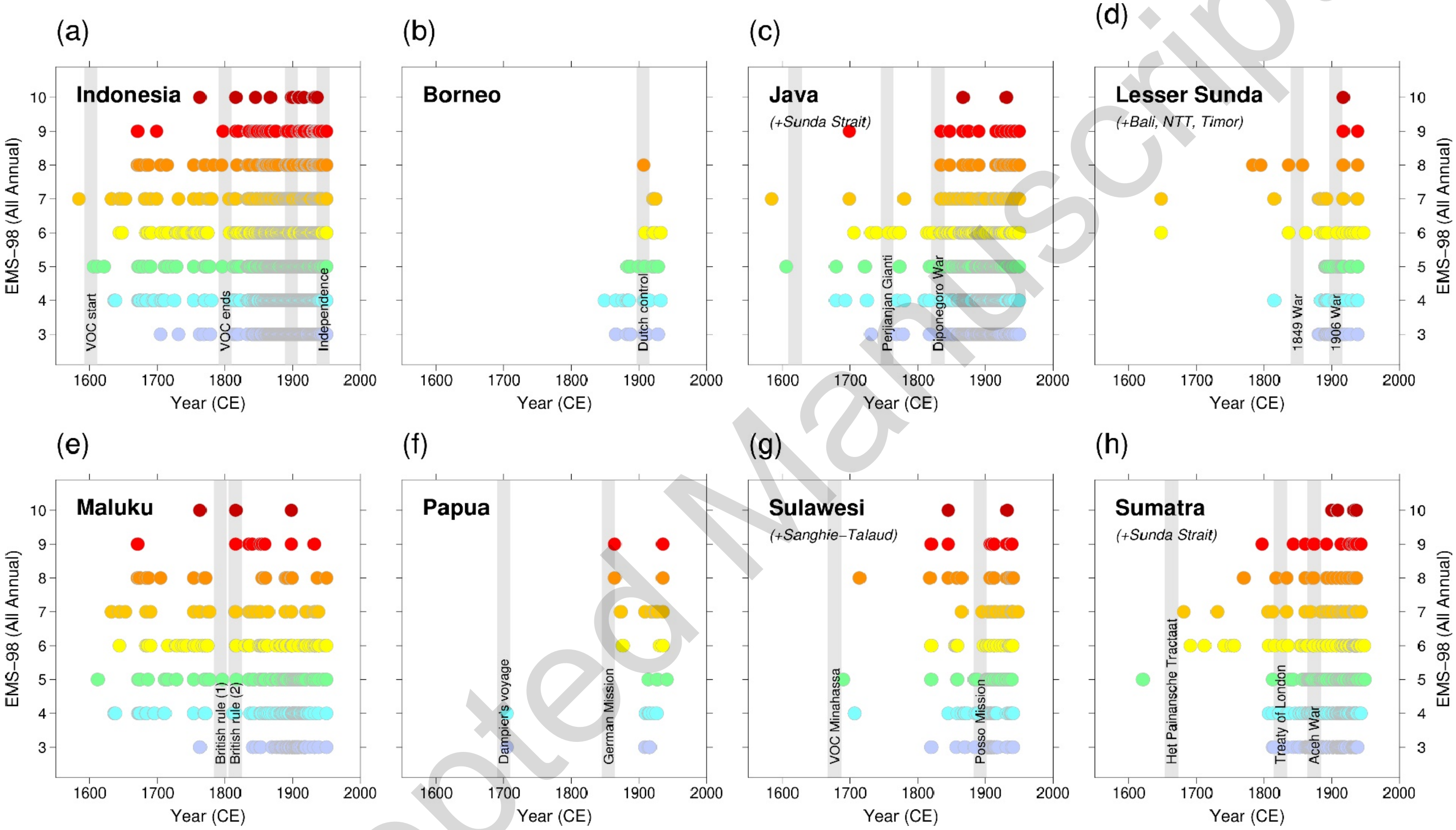

Figure 4: Macroseismic intensity displayed as function of time (1546 to 1950) for all of Indonesia (a), Borneo (b), Java (c), the Lesser Sunda Islands (d), North and South Maluku region (e), Papua (f), Sulawesi (g) and Sumatra (h). Grey bars indicate important historical events in each region. Coloured symbols utilise the same colour scale as in **Figure 1**.

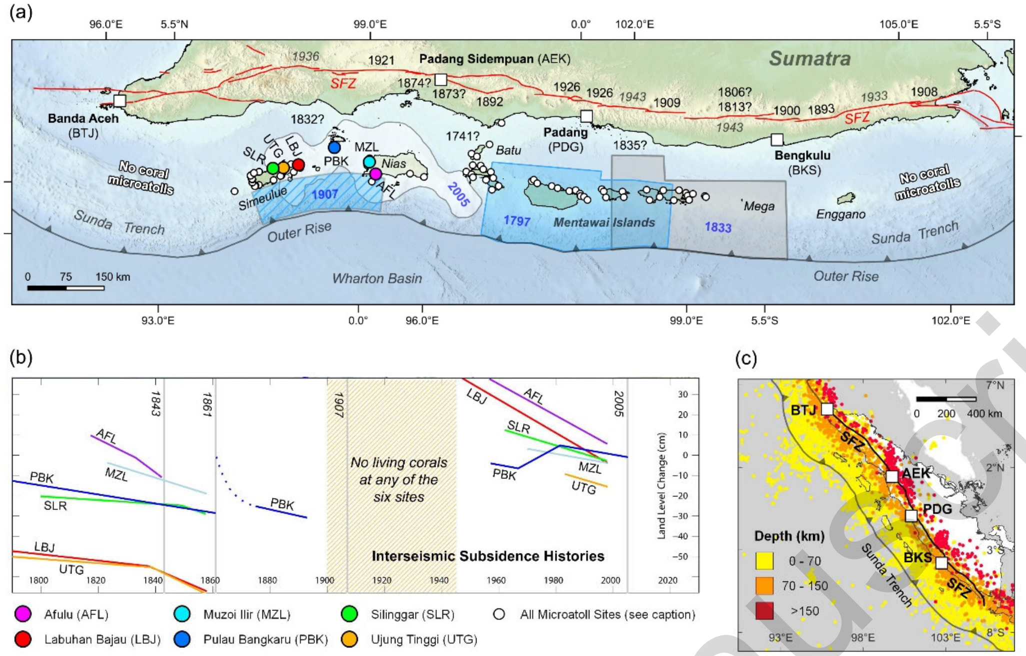

Figure 5: (a) Geodetically modelled rupture of the 2005 earthquake from *Konca et al.* (2008; *white shaded area*) and the rupture of the 1907 earthquake (*blue shaded with hash lines area*) based on forward modelling of tsunami observations by *Martin et al.* (2019) are shown. Inferred rupture patches of the 1797 and 1833 earthquakes from *Natawidjaja et al.* (2006) are shown as filled blue and grey polygons respectively. All coral microatolls intepreted by *Meltzner et al.* (2012, 2015) and *Philibosian et al.* (2014, 2017) are shown as small white circles. Coloured circles are corals intepreted by *Meltzner et al.* (2015). Years indicate historical earthquakes associated with the Sumatran Fault Zone (SFZ) by *Sieh and Natawidjaja* (2000); years after 1930 are shown in italics. Year with question marks (1835) indicate events for which the source fault is unknown as discussed in the text. **Figure (b)** Coloured circles are coral microatolls interpreted by *Meltzner et al.* (2015) and correspond to the same coloured circles in **Figure 5a**. **Figure 5b** displays histories of interseismic vertical deformation for ~200 years (adapted from *Meltzner et al.*, 2015) at the same six sampling sites shown on the map. After coseismic uplift in 1861, microatolls at most sites died entirely, and by 1900 the lone surviving microatoll at PBK had also died for unknown reasons. As a consequence of the gap in coral observations

between ~1900 and ~1940 (*orange hashed lines*), any vertical displacements from the 1907 earthquake or others during this period were not recorded which indicates a period when coral microatolls were yet to recolonize the reefs after uplift in 1861. **Figure 5c** shows seismicity from *Storchak et al.* (2013).

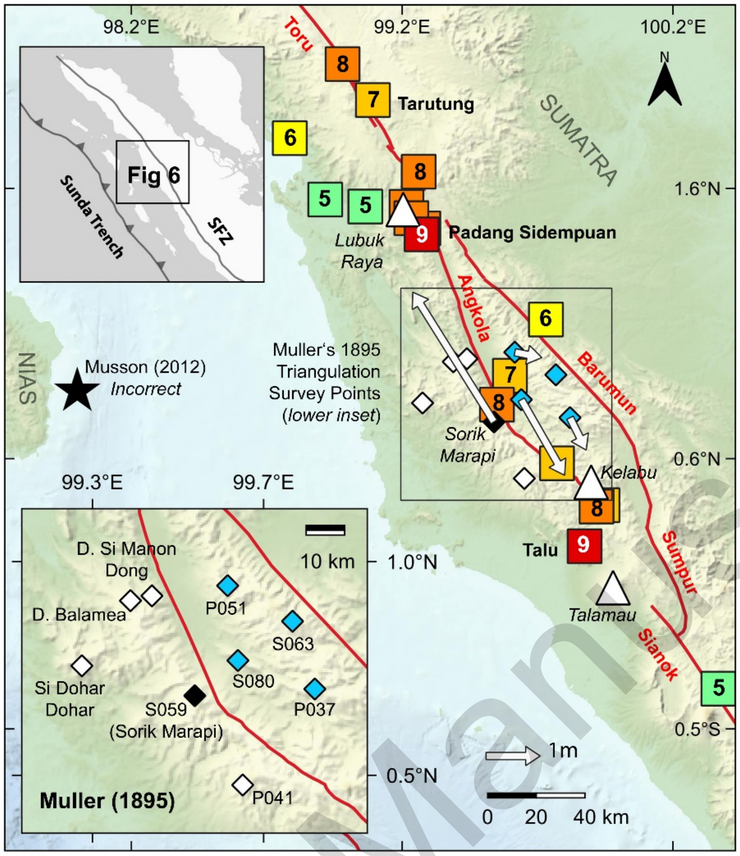

Figure 6: Macroseismic (*coloured squares*) and geodetic observations (*diamonds*) for the 17 May 1892 earthquake in northern Sumatra. Mapped fault segments from *Irsyam et al.* (2020) are shown in red following the naming convention from *Sieh and Natawidjaja* (2000) and selected mountain peaks are indicated by white triangles. White arrows indicate the geodetically computed displacements by *Prawirodirdjo et al.* (2000). The lower inset figure shows the locations of triangulation survey points (*Muller*, 1895) as diamonds with colours indicating displacement to the north-west (*black diamonds*) or to the south-east (*blue diamonds*). Sites with no displacements (P041) and those not considered by *Prawirodirdjo et al.* (2000) are shown as white diamonds. Codes for triangulation survey locations are the same as in *Prawirodirdjo et al.* (2000). Selected mountain peaks (*white triangles*) are also displayed. We also indicate the location of this event from *Musson* (2012); see text for discussion. Colour scheme for macroseismic observations is the same as in **Figure 1**.

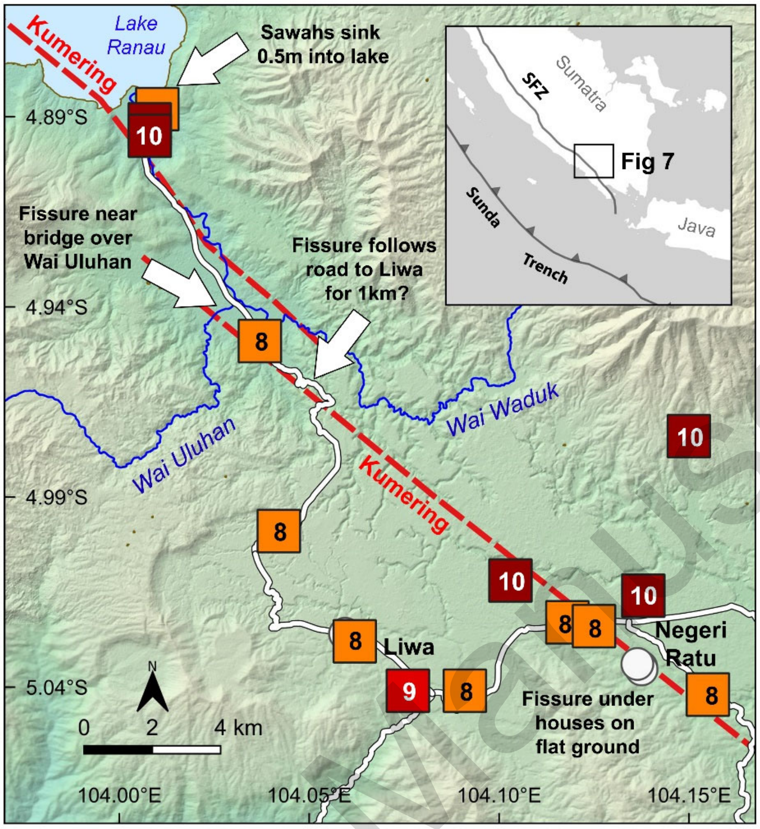

Figure 7: Locations and brief descriptions from *Berlage* (1934) that suggest surface rupture was observed at three locations on the Kumering segment of the SFZ during the 1933 Liwa earthquake on Sumatra. Unlike the other locations described by *Berlage* (1934), the exact location of the inferred rupture following the road between the Wai Uluhan bridge and Liwa is uncertain. On this figure we mark the most likely location given that this is the only stretch of the road to Liwa that runs along the fault trace. Dashed red lines indicate the approximate fault traces from *Irsyam et al.* (2020) and colour scheme for macroseismic observations (*coloured squares*) is the same as in **Figure 1**. The location of the subsided rice fields (nl: *sawahs*) is also shown.

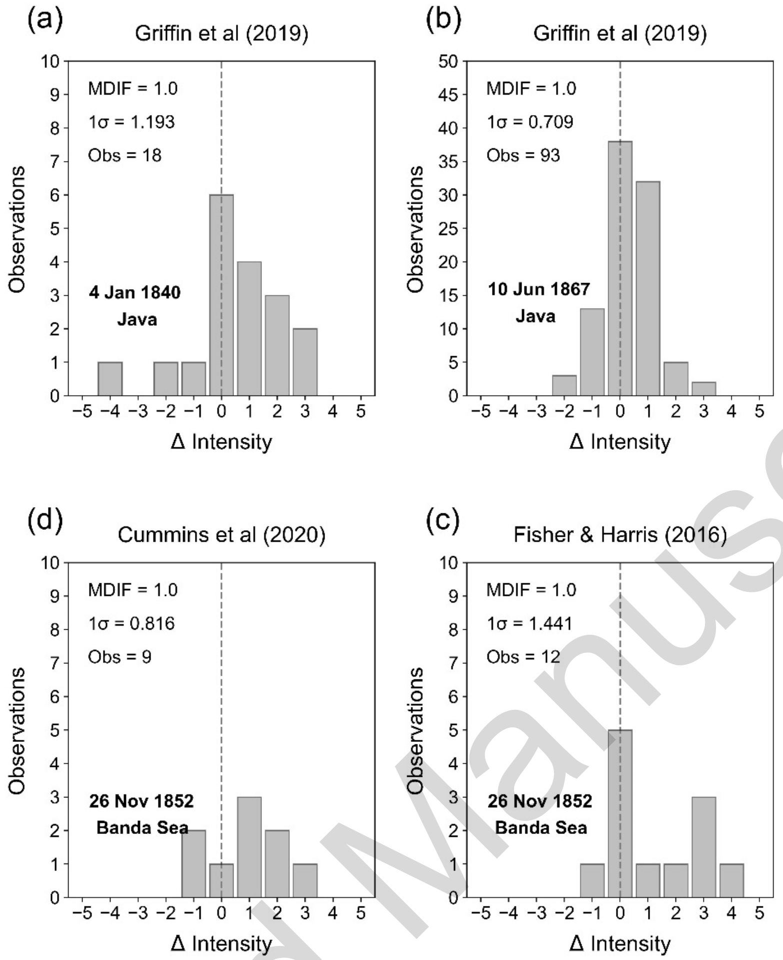

Figure 8: The distribution of the absolute median difference (MDIF) in intensity (Δ Intensity (*grey bars*) between observations from our study for four historical earthquakes (**Figures 8a – 8d**) compared to intensities from *Fisher & Harris* (2016), *Griffin et al.* (2019) and *Cummins et al.* (2020) at identical geographic locations. Each plot displays MDIF, its standard deviation and the number of points considered (Obs) for a given event. The grey line indicates one-to-one correspondence.

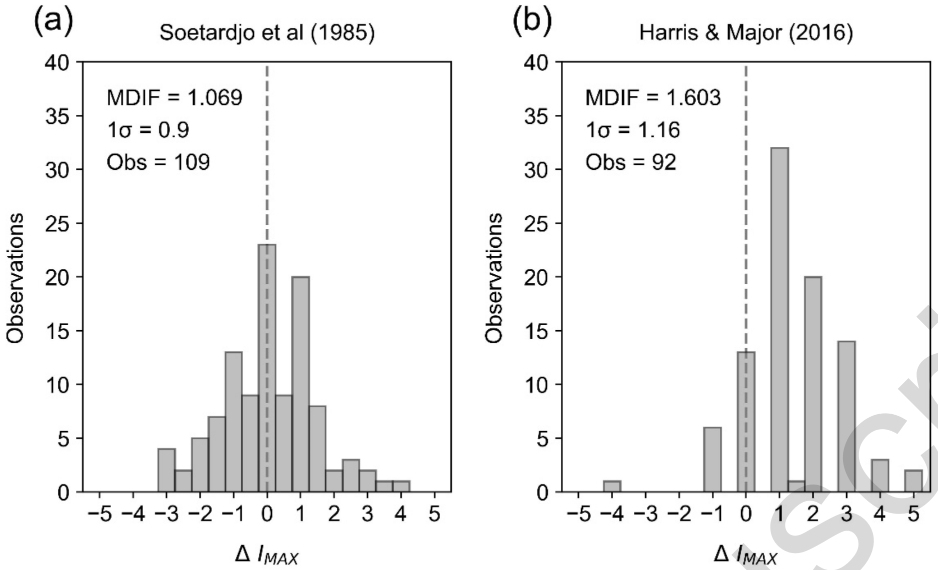

Figure 9: The distribution of the absolute median difference (MDIF) of I_{MAX} (ΔI_{MAX}) between the maximum intensity per event from our study (**Figures 8a – 8b**) compared to older maximum intensity per event from *Soetardjo et al.* (1985) and *Harris and Major* (2016). Each plot displays MDIF, its standard deviation and the number of common points considered (Obs). The grey line indicates one-to-one correspondence.

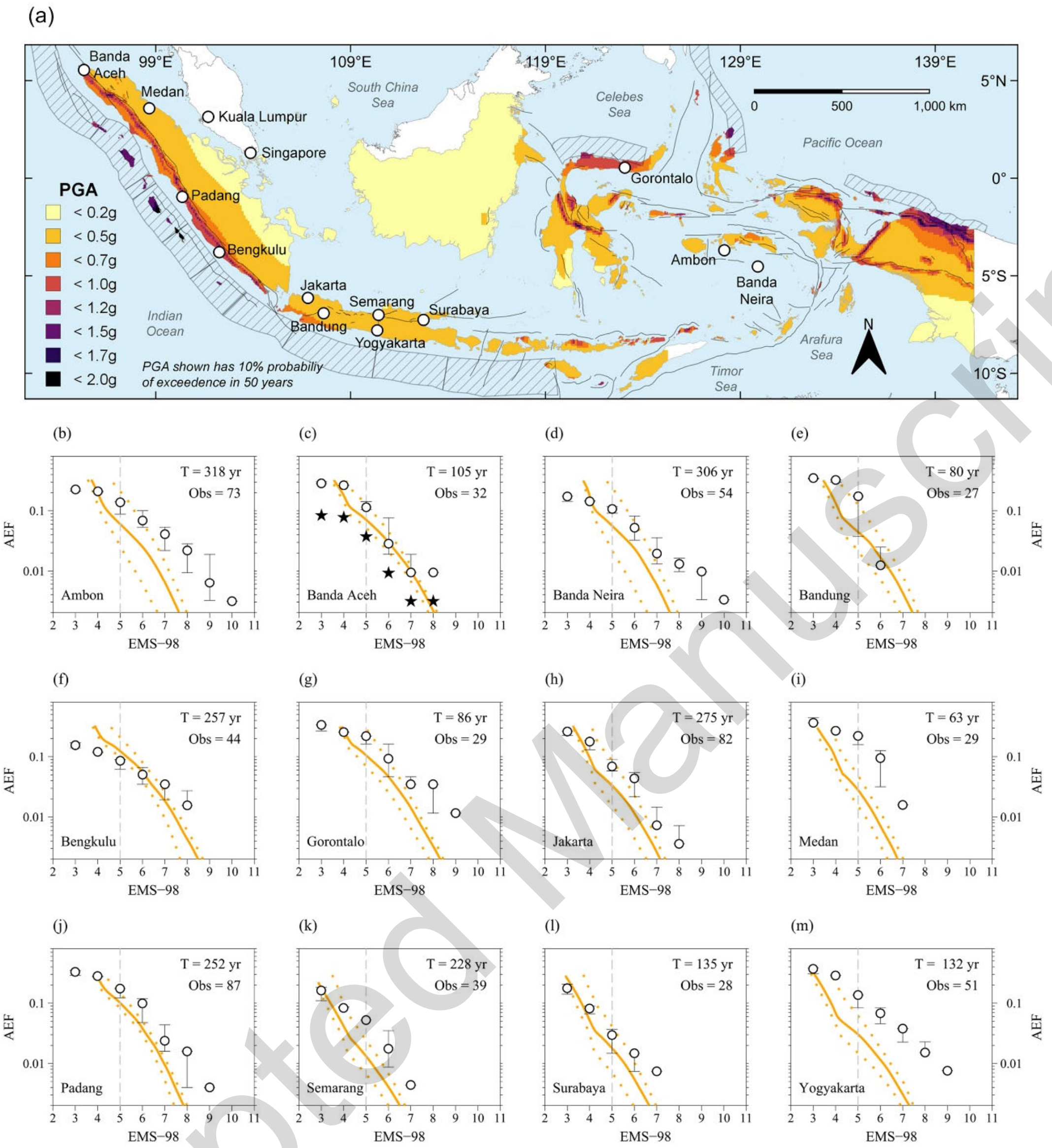

Figure 10a: Seismic hazard map for Indonesia from *Irsyam et al.* (2020) expressed in terms of peak ground acceleration (PGA) that has a 10% probability of exceedance in 50 years. Active structures (*black lines*) and subduction megathrusts (*hashed band*) used by *Irsyam et al.* (2020) in the computation of this map are also displayed. Locations discussed in the text are marked by while circles. **Figures 10b-10m**, Annual exceedance frequencies (AEFs) for twelve locations in Indonesia. Solid orange line represents the mean hazard curve for each location with the 2.5% and 97% quantile curves (*dotted orange lines*) representing the epistemic

uncertainties. Open circles show the AEF for each intensity level with error bars indicating the upper and lower range of each AEF based on any intensity ranges in **Table S2**. For Banda Aceh, *stars* indicate how the AEF would be biased if the Banda Aceh record was considered complete for EMS ≥ 5 since 1621, as discussed in the text. Dashed vertical line indicates 5 EMS (T= time; Obs = number of observations).

Gempa Nusantara: A database of 7,380 macroseismic observations for 1,200 historical earthquakes in Indonesia from 1546 until 1950

Stacey S. Martin, Phil R. Cummins, Aron J. Meltzner

Supplementary Material

Contents

Supplementary Material 1 – Gempa Nusantara (Tables S1 – S3)

The entire database i.e., Tables S1, S2 and S3 can be found in file titled "**Gempa_Nusantara_v1.xlsx**" accompanying this BSSA paper. This file (including any future updates) can also be found at https://github.com/7point1/GempaNusantara

Supplementary Material 2 – Approach to Intensity Assessment

We use the 1998 European Macroseismic Scale (EMS-98; *Grünthal*, 1998) to evaluate macroseismic intensity (**Table S2**) displayed as colour-coded filled circles in **Figure 1**. Our approach to assigning macroseismic intensities with the EMS-98, to distinguish between building types and damage grades, and to assess uncertainty (**Table S3** *at the end of this Supplementary Section*) is detailed here. Critically, we note, that our approach and inferences detailed here are ***not to be misinterpreted*** as a revision or an update to the EMS-98 but merely outlines how we adapt to the recommendations and terminology from *Grünthal* (1998) to assign intensities in this study. In many instances, EMS-98 guidelines cannot be used without adaptation because the local building stock was more vulnerable or employed different traditional or indigenous construction types and/or materials than the European construction on which the EMS was based.

Choice of Intensity/Macroseismic Scale

Our choice of the EMS-98 intensity scale marks a shift from the Modified Mercalli Intensity scale in Indonesia (MMI; *Wood & Neumann*, 1931; *Richter*, 1958). The MMI scale was meant to replace both the Batavia Intensity Scale (**Supplementary Material 3**) and the Rossi-Forel scales that were used in Indonesia prior to 1956 (*Anonymous*, 1957). Both the MMI and the EMS-98 scales are successors to older intensity scales such as the Mercalli-Cancani-Sieberg scales (MCS; *Sieberg*, 1912) developed with European conditions in mind. *Taverne* (1925) recognised the MCS as being inadequate with which to characterise damage to the local indigenous building stock on Java. Many modern users outside Europe, especially those in nations formerly colonised by Europe, opt for the seemingly less controversial MMI scale unaware of the MMI scale's common European origins. Nonetheless, the EMS-98 stands apart in its revised form (*Grünthal*, 1998) in that it stipulates non-region-specific diagnostic indicators and recommended guidelines with which to assess intensity. Compared to the MMI, the ability to incorporate non-European construction materials and styles before estimating the quantities and types (referred to as "grades") of damage ensures thorough use of as much of the original observations at hand as possible. This leads to more robust intensity assignments at higher levels of shaking (≥ 6 EMS) especially where data on indigenous, traditional, and non-European building typology are meagre or missing, and when modern fragility curves are unavailable.

General Intensity Diagnostics

At non-damaging levels of shaking (< 5 EMS) we consider diagnostic indicators, that is, definitions or guidelines for each level of intensity (*Grünthal*, 1998) with adjective and adverb modifiers such as “not heavy” (nl: *niet hevig*) or “heavy” (nl: *hevig*), “moderate” (nl: *middlematig*), “more or less” (nl: *meer op minder*), “quite” (nl: *vrij*; nl: *tamelijk*), “repeated” (nl: *herhaalde*) and “very” (nl: *zeer*). We also used percentage counts from *Medvedev et al.* (1965) to distinguish between “few” (≤ 5%), “many” (up to 50%), and “most” (up to and greater than 75%). Adverb distinctions such as “few” (nl: *een paar*; nl: *weinig*), “many” (nl: *veel*), and “most” (nl: *meest*) are necessary in keeping with the statistical nature of EMS-98 (*Grünthal*, 1998; *Tertulliani et al.*, 2016), but we reiterate *Martin & Hough’s* (2016) observation that both modern and historical documentary sources can often be devoid of these.

At damaging intensities (≥ 5 EMS) the adaptability of the EMS-98 allows it to be confidently used to determine intensities when building construction was discussed (*also see subsequent section*) in some detail (e.g., *Abendenanon*, 1915; *Stehn*, 1925) and/or the percentages of buildings destroyed or damaged were recorded (e.g., *Taverne*, 1925; *Berlage*, 1934). In such cases, we determine an EMS-98 intensity based on a combination of diagnostic indicators which also include a combination of damage grades, building vulnerability, and the quantity of damage (*Grünthal*, 1998). Damage grades 1 to 5 (*Grünthal*, 1998) were associated with descriptions indicating “insignificant” (nl: *niet belangrijk*) or “minor damage” (nl: *licht*; grades 1 to 2), “partial” (nl: *gedeeltelijk)* collapse or “no longer inhabitable” (nl: *niet meer bewoonbaar*; grades 3 to 4), or “complete” collapse or collapsed to the ground (nl: *totaal*; grade ≥ 4).

In an ideal scenario, the quantities and grades of damage to different types of buildings are best determined by ground-based surveys (*Ambraseys & Bilham*, 2003; *Musson & Cecić,* 2012). But this is unfeasible when studying historical earthquakes (*Martin & Hough*, 2016). Building on the previous point, we also acknowledge the observation made by *Ambraseys & Bilham* (2003) that the distinction between “damaged” (nl: *beschadigd*), “collapsed” (nl: *storten in*) and “destroyed” (nl: *verneild*; nl: *zerstort*) is rarely preserved in written or published historical documentation. For example, the distinction between the complete collapse of walls from the loss of gables or masonry veneers alone is rarely made. To address these unknowns, we cautiously associate explicit reports of insignificant damage,

damage to walls without collapse, and the collapse of houses (unknown, partial, or complete) with a gradual increase in intensity values from 5 EMS to 8 EMS.

The highest intensities (10 EMS) were assigned in very rare instances when accounts categorically described exceptionally violent ground motions (e.g., Ambon earthquake on 6 January 1898). These assignments were based on eyewitness accounts that recalled the inability to stand or walk and being forcibly thrown to the ground. Whenever possible, these assignments were also supported by documented damage to buildings (many or most of grade ≥ 4) and/or if heavy objects were bodily moved or thrown around.

Estimation of Building Types and Vulnerability Classes

Variations in local construction can be accommodated when using the EMS-98 by adjusting the vulnerability class. Documentary accounts often only recorded rudimentary building types, namely, masonry (nl: *steenen*), or wooden (nl: *houten*) structures. Therefore, extracting damage grades from historical data will be subjective. To account for this uncertainty, all of our intensities ≥ 5 EMS are appropriately assigned lower qualities ("B" to "H"; **Table S3**). Unable to irrefutably identify most individual buildings or to decipher their health or state of preservation (or lack thereof) at the time of a given seismic event we broadly categorise these buildings into vulnerability classes A and B respectively (*Grünthal*, 1998; pp. 14). In these, and all subsequent cases discussed in this section we acknowledge the uncertainties in our values by adding a range of ±1 unit of intensity wherever appropriate in **Table S2**.

The term "*inlandsche woningen*" was often invoked to describe traditional "native" structures known colloquially in Indonesia as the *rumah adat* (bh) or *rumah tradisional* (bh). The Dutch term fails to account for the widespread diversity in architectural and construction styles across Indonesia (e.g., *Sumintardja*, 1978; *Dawson & Gillow*, 1994). In rural Sumatra (including Nias) and Sulawesi, these buildings have a mortised post-and-lintel structure with wooden or bamboo walls and a thatched roof (*Dawson & Gillow*, 1994) and are built on posts or stilts that rest on, but are not attached to, flat stones (nl: *neuten*). In the literature at hand, we also encountered other wooden or bamboo structures in parts of north Maluku and Sulawesi, some of which were built above water on poles (nl: *paalwoningen*), particularly in communities by the sea (bh: *perkampungan laut*).

The wooden structures in Sumatra and Sulawesi are flexible when subjected to lateral seismic loads but can be compromised during very strong ground motions that cause the timber posts to move off the "*neuten*" or to fail from age or neglect resulting in some form of structural failure. Historical descriptions (e.g., *Abendenanon*, 1915) often used the words "shifted" (nl: *verschoven*) or "toppled over" (nl: *omgevallen*) instead of the more common "caved in" (nl: *storten in*) without elaborating further whether these buildings bodily fell over, or completely collapsed. Assuming vulnerability class B (see *Grünthal*, 1998) we used these to infer a damage Grades of 4 to 5 if the account said a building "toppled over" or "caved in", to infer a minimum intensity of 8 EMS; higher values were assigned depending on the number of structures affected (many = 9 EMS; most/all = 10 EMS).

Traditional rural homes in Java were simple square structures on a raised base with a thatched or tiled roof supported by wooden posts and walls of woven bamboo or brick reflecting the affluence of the owner (*Dawson & Gillow*, 1994; *Nas*, 2007). The structures described on Java and, north Maluku, and those in *perkampungan laut*, were easily shaken out of plumb (nl: *scheefstaan*) or collapsed. Assuming vulnerability class A-B (see *Grünthal*, 1998) and inferring Grades 3 to 4 (for out of plumb) and Grades 4 to 5 (for collapsed), we infer a minimum intensity of 7 EMS and 8 EMS respectively, and higher values depending on the number of structures sustaining Grades 4 to 5 (most = 9 EMS; all = 10 EMS).

In urban settings, masonry structures incorporated Chinese, Hindu-Buddhist, Islamic or European influences in architecture (see *Nas*, 2007). Structures built during the VOC period and in the early 19th century were largely masonry with influences (and sometimes material) from the Netherlands (*Nas*, 2007). In colonial enclaves, masonry construction either exactly mimicked designs and layouts from Europe (*Nas*, 2007) or were of a unique tropical colonial *Indische* style; the latter incorporated architectural features such as better ventilation, larger verandas, and larger pyramidal and steeply pitched roofs to adapt to the hot, humid, and wet tropical climate (e.g., *Nas*, 2007). These enclaves were surrounded by additional masonry buildings in the Chinese and Arab quarters (e.g., *Nas*, 2006). We assessed these structures as vulnerability class B (*Grünthal*, 1998). A few reports from western New Guinea were also forthcoming from observers in bivouacs (nl: *bivaak*) but we do not use these to assign intensity.

In records prior to the 19th century from eastern Indonesia, the only damage often recorded was to monumental buildings that included defensive structures such as VOC redouts (bh: *benteng*). The

EMS-98 scale cautions against the singular use of "*monumental structures*" for intensity evaluation (*Grünthal*, 1998). These are structures of societal, economic, symbolic or cultural significance that tend to be sturdier than the prevalent building stock or are structures that are more likely to be damaged owing to their structural or non-structural complexity (*Grünthal*, 1998, p. 53). Reiterating *Grünthal* (1998), we note that, even when available, it was impossible for us to account for any possible exaggeration of damage to elicit higher financial compensation by VOC officials, or to gauge damage to other structures in the vicinity, in particular traditional dwellings whose survival (or lack thereof) might not have been deemed of any importance to the VOC. However, we are also of the opinion that to ignore these reports would severely handicap the long-term record of damaging shaking in eastern Indonesia. The wide diversity in construction styles and materials used in these structures, and the small number of descriptive observations, prevented us from classifying damage grades separately as has been done by previous studies, for example, in Iran (e.g., *Ambraseys and Melville*, 1983) and in Myanmar (*Aung et al.*, 2019). The 17th and 18th century descriptions of damage to these defensive structures in particular, sometimes indicated whether the bastions or the battlements of these buildings were cracked (grade ≤ 3) or destroyed (grade ≥ 4). To these we tentatively assigned 6 EMS or 7 EMS, respectively, with what we deemed an appropriate uncertainty (±1 unit of intensity). Some redouts in the region also had non-masonry canopies (see illustrations in *Valentijn*, 1724). We record a lower intensity (6 EMS) to reports of unspecified damage to redoubts considering the difficulty in determining what part of the structure was damaged or the health of the structure in general. All intensity values derived from these and other descriptions of impacts to monumental buildings have an "M" appended to their respective quality indicator in **Table S2** to clearly distinguish them from the rest of the dataset. This provides future studies the opportunity to either include or exclude these points of observation in case of differing points of view.

Non-Integer and Other Intensity Diagnostics

Accounts that were devoid of descriptive diagnostics are marked as "felt" (F). These include instances when an earthquake was "felt" (nl: *gevoeld*) or was "observable" (nl: *waarneembare*), where only "vibrations" (nl: *trillingen*) or "shocks" (nl: *schuddingen*) were reported, and when vague anecdotal evidence was forthcoming, for example, a "serious earthquake" (nl: *erg aardbeving*) had occurred. Maritime reports (e.g., *Rudolph.,* 1887; 1895) of "seaquakes" felt onboard ships in the open ocean (nl:

zeebevingen; nl: *zeeschuddingen*) are also duly flagged (S). As advised by *Vogt et al.* (1994), these were not assessed for intensity.

We did not assess secondary effects such as ground failure, liquefaction, landslides, and damage to paddy fields (nl: *sawahs*) as these can occur at a wide range of intensity (*Grünthal*, 1993). Their independent usage to determine intensity, particularly in the absence of other diagnostics of intensity, is to be strongly avoided (*Vogt et al.*, 1994; *Musson et al.*, 2010). We also do not include intensity values from published isoseismal maps or other previous studies in our database (*Ambraseys et al.*, 1983); the only two exceptions are *Martin et al.* (2019) and *Martin et al.* (2020), led by the lead author of this present study and which followed the same approach as in this study. Intensities were also not converted between intensity scales (*Ambraseys et al.*, 1983) but we are conscious of the congruence between MMI and EMS-98 (*Musson et al.*, 2010).

Intensity Ranges and Uncertainties

Lastly, quantitative minimum and maximum intensity ranges are recorded for each IDP in **Table S2** in the columns titled “EMS-lower” and “EMS-upper”. The only exceptions (NA) in these columns are in the case of non-integer flags, that is, “felt” (F), “damage” (D), “seaquake” (S), and “tsunami” (T). IDP’s are also alphabetically (“A” to “H”) weighted for quality (*Musson*, 1998); “A” represents a high or good quality while “H” indicates a poorer quality assessment (see **Table S3)**.

Uncertainty	Reason for Uncertainty	This study
0	None	A
1	Reliability of Intensity Value (R)	B
2	Location uncertainty (L)	C
3	R + L	D
4	Veracity of Observation (V)	E
5	R + V	F
6	L + V	G
7	R + L + V	H
-	Monumental buildings (M)	+M
-	Multiple Events (X)	+X

Table S3: Qualitative integer uncertainties in IDP values based on the reliability of assigned intensity or location, or the veracity of the available information from *Musson* (1998). We also indicate the letters that we associate with the integer values from *Musson* (1998). We also append two additional criteria to indicate uncertainties due to intensities based on monumental buildings and damage from multiple events.

These qualities are based on i) how reliable the intensity assessment was, ii) the spatial resolution of a given geographic location, iii) the veracity of available data, or different combinations of the preceding three qualitative uncertainties (*Musson*, 1998). For a handful of Dutch reports, locations were vague such as within an island group or in higher order administrative divisions such as regencies (nl: *regentschappen*; bh; *kabupaten*), departments (nl: *afdeelingen*) or subdepartments (nl: *onderafdeeling*), districts, and occasionally in dependencies (nl: *onderhoorigheden*) such as for Aceh or Sulawesi. For all of these a location uncertainty of "C" was assigned or an appropriate letter, when in combination with other qualitative uncertainties. Intensities assigned to multiple, closely spaced earthquakes or those based on damage to "monumental" structures (*discussed previously*) were assigned "X" and "M" flags respectively that are appended to other alphabetical qualities (**Table S3**).

Supplementary Material 3 – The Batavia Intensity Scale

Prior to 1956, the Rossi-Forel Scale (*de Rossi*, 1883) and the Batavia Intensity Scale were used in Indonesia during the colonial period. Early attempts were made by the colonial Dutch administration to standardise the collection of macroseismic diagnostics (*van Dijk*, 1885), particularly, following the 1883 eruption of Krakatau, when specific directives (*van Dijk and Poortman*, 1885; *Figee et al.*, 1886) with detailed advice (*van Dijk*, 1885) were issued.

Intensity	Description	Translation
I	Zwakke trilling, door velen gevoeld	Weak vibrations, felt by many.
II	Matig, door iedereen gevoeld; rinkelen van glaswerk, rammelen van deuren en ramen	Moderate, felt by everyone; glasswork rattles, doors and windows rattle.
III	Vrij sterk, slapenden worden wakker; hangklokken blijven stilstaan; deuren en ramen slaan open en dicht	Quite strong, sleeping people awakened; pendulum clocks stand still; doors and windows open and shut.
IV	Sterk, schilderijen vallen van de wanden, lichte meubels vallen om, licht scheuren van pleisterwerk	Strong, pictures fall from walls, light furniture falls over, light/slight cracks in plasterwork.
V	Zeer sterk, muren scheuren, stukken pleister en pannen vallen naar beneden, kasten slaan om	Very strong, walls crack, pieces of plaster and (roof) tiles fall down, cupboards fall over.
VI	Steenen huizen storten in, houten huizen vallen an de neuten	Masonry houses collapse, wooden houses fall off their staddle stone supports.
VII	Algemeene verwoesting	General destruction

Table S4: Intensity levels of the Batavia State (*Anonymous*, 1920) with its diagnostics in Dutch with a translation into English.

Observers were instructed to include in their reports of seismic disturbances their “locality” (nl: *plaatsbepaling*), “date, time, duration” (nl: *tijdsbepalling*; nl: *duur*), “direction (nl: *richting*), “intensity” (nl: *intensiteit*; nl: *kracht*) and “nature, remarks (nl: *bijkomende verschijnselen*). Observer assigned RF intensities briefly appeared in the NTNI until 1897, no intensity scale was formally used by the Observatory until the introduction of the “Batavia Scale” in 1919 (*Anonymous*, 1920).

Later annual summaries from 1920 until 1938 (*Anonymous*, 1940), converted these intensities to Rossi-Forel or RF intensities. This scale was almost always listed alongside the Rossi-Forel scale. The “Batavia” scale has been largely forgotten and is even missing from a history of early macroseismic scales (*Davison*, 1921; 1933). We do not utilise this scale in our intensity assessments or in any of our analyses but record it here (**Table S4**) for the sake of completeness and out of scientific interest.

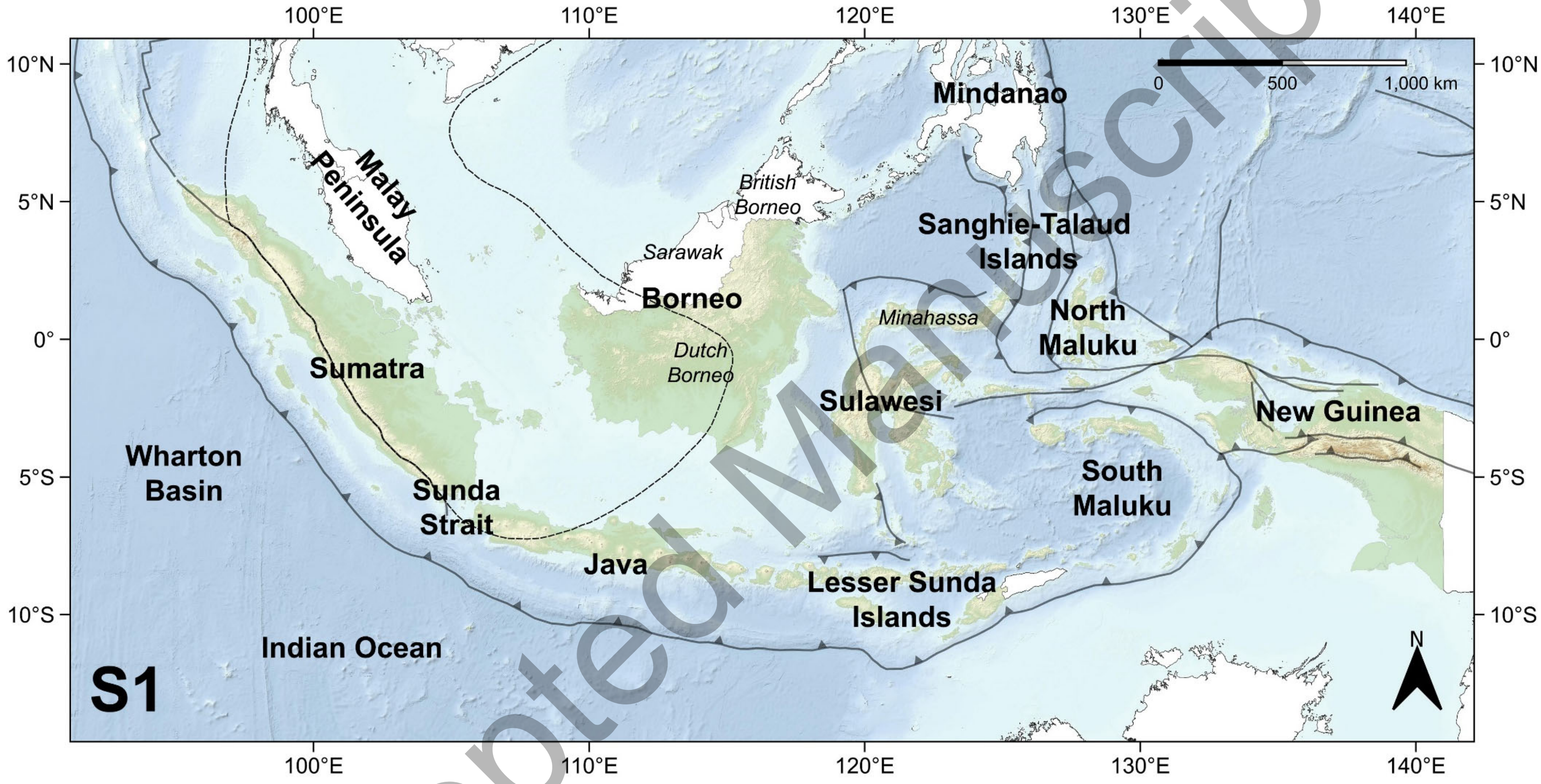

Figure S1: Zones used in the naming of events in Column B (**Table S1, S2**)

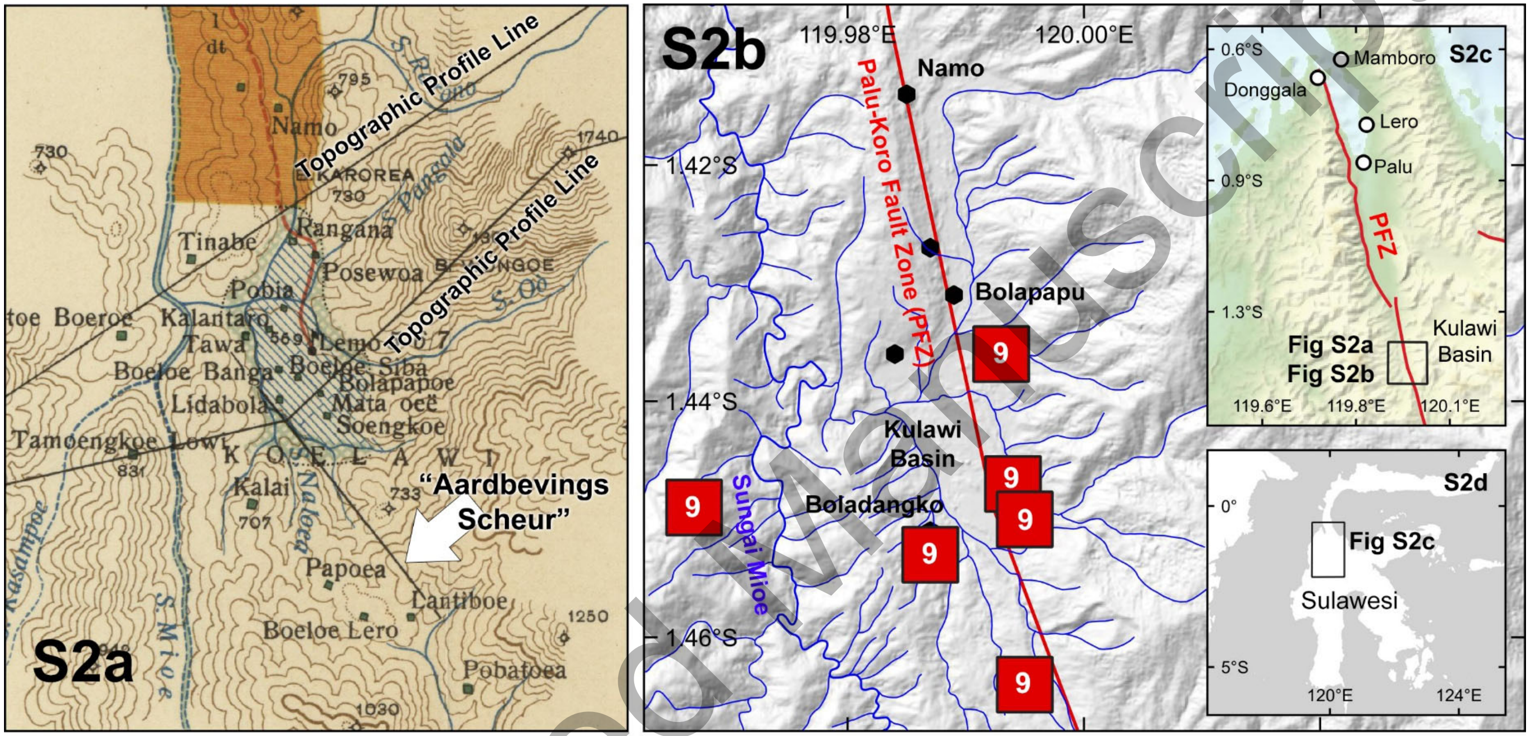

Figure S2: Location of the surface rupture from the 1909 Sulawesi earthquake (GN-0736) from *Abendanon* (1916). In **Figure S2a**, linear black line indicated by a white arrow shows the approximate location of the "earthquake fissure" (nl: *aardbevings scheur*) as drawn by *Abendanon* (1916). **FigureS2b** shows the same region with drainage and 2018 observation locations (filled diamonds) from *Jaya et al* (2019) for the 2018 Palu earthquake as well as intensity observations (red numbered squares) from the 1909 earthquake. **Figures S2c** and **S2d** indicate approximate locations of **Figure S2a**. Image in **Figure S2a** is cropped to the Kulawi basin but a full and high-resolution image from *Abendanon* (1916) is available in the public domain from the National Library of Australia (https://nla.gov.au/nla.obj-230968818). (PKZ = Palu-Koro Fault zone).

References

Abendanon, E.C. (1915). “Midden-Celebes-Expeditie: Geologische en geographische doorkruisingen van Midden-Celebes,” **2**, *Koninklijk Nederlandsch Aardrijkskundig Genootschaap*, Leiden, pp. 835 – 836, pp. 871 – 878 (in Dutch).

Abendanon, E.C. (1916), Plates 12 and 13, in Atlas to “Midden-Celebes-Expeditie: Geologische en geographische doorkruisingen van Midden-Celebes 1909 – 1910”, *Koninklijk Nederlandsch Aardrijkskundig Genootschaap* (in French and Dutch).

Albini, P., R.W. Musson, A. Rovida. M. Locati, A. Gomez Capera, and D. Viganò (2014), The global earthquake history, *Earthquake Spectra*, **30**, 2, pp. 607 – 624.

Ambraseys, N.N., and R. Bilham (2003). Earthquakes and Associated Deformation in Northern Baluchistan 1892–2001, *Bulletin of the Seismological Society of America*, **93**, 2, pp. 1573 – 1605.

Ambraseys, N.N., and C.P. Melville (1982). A history of Persian earthquakes, Cambridge University Press, 219 p.

Ambraseys, N., E. Banda, J. Irving, D. Mallard, C. Melville, T. Morse, R. Muir-Wood, D. Muñoz, L. Serva, D. Shilton, E. Surinach, and J. Vogt (1983). Notes on historical seismicity, *Bulletin of the Seismological Society of America*, **73**, 6, pp. 1917 – 1920.

Anonymous (1920), Vulkanische verschijnselen en aardbevingen in den Oost Indischen Archipel waargenomen gedurende het jaar 1919, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **80**, 3, pp. 191 – 259 (in Dutch).

Anonymous (1940), Aardbevingen in den Oost Indischen Archipel waargenomen gedurende het jaar 1938, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **100**, 1, pp. 38 – 75 (in Dutch).

Anonymous (1957), Earthquakes in Indonesia: 1948 – 1955, Series A, No. 45, *Department of Communications, Meteorological and Geophysical Institute*, Jakarta, 72p.

Aung, L.T., S. Martin, Y. Wang, S. Wei, M. Thant, K.N. Htay, H.M. Aung, T.Z. Kyaw, S. Min, K. Sithu, T. Naing, E.H.N. Myo, T.H. Oo, S. N. Khaing, G. Suresh, W. Chen, P. M. Maung, and V.K. Gahalaut (2019). A comprehensive assessment of ground motions from two 2016 intra-slab earthquakes in Myanmar, *Tectonophysics*, **765**, 146 – 160, doi: 10.1016/j.tecto.2019.04.016.

Berlage, H.P. (1934). De aardbeving in Zuid-Sumatra van 25 Juni 1933 (waarnemingen in het epicentrale gebied), *Natuurkundig tijdschrift voor Nederlandsch Indië*, **94**, 1, pp. 15 – 36 (in Dutch).

de Rossi, M.S. (1883), Programma dell'Osservatorio ed archivio geodinamico presso il Regio Comitato geologico d'Italia con istruzioni per gli osservatorii e descrizioni d'instrumenti, Rome. Pp. 66 – 68.

Davison, C. (1921), Scales of seismic intensity – Supplementary paper, *Bulletin of the Seismological Society of America*, **11**, 2, pp. 95 – 130.

Davison, C. (1933), On scales of seismic intensity and on the construction and use of isoseismal lines, *Bulletin of the Seismological Society of America*, **24**, 4, pp. 158 – 166.

Dawson, B., and J. Gillow (1994). The traditional architecture of Indonesia, Thames and Hudson, New York, 192 p.

Figee, S., H. Onnen, and J.A. Schuurman (1886), Circulaire gezonden aan H.H. medewerkers tot het verzamelen van aardbevingswaarnemingen, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **45**, 2, pp. 233 – 234 (in Dutch).

Grünthal, G. (Editor) (1998). The European Macroseismic Scale EMS-98, Conseil de l'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, **15**, Luxembourg, 101 p.

Harris, R, and J. Major (2016) Waves of destruction in the East Indies: The Wichmann catalog of earthquakes and tsunami in the Indonesian region from 1538 to 1877, *Geological Society, London*, Special Publications, **441**, pp. 9 – 46.

Hough, S.E., and S.S. Martin (2021), Which earthquake accounts matter? *Seismological Research Letters*. **92**, 2A, pp. 1069 – 1084.

Martin, S.S. and S.E. Hough (2016). Reply to, "Comment on 'Ground Motions from the 2015 Mw 7.8 Gorkha, Nepal, Earthquake Constrained by a Detailed Assessment of Macroseismic Data' by Stacey Martin, Susan E. Hough and Charleen Hung" by Andrea Tertulliani, Laura Graziani, Corrado Castellano, Alessandra Maramai, Antonio Rossi, *Seismological Research Letters*, **87**, 4, pp. 369 – 377, doi:10.1785/0220160061.

Martin, S.S., L. Li, E. Okal, J. Morin, A. Tetteroo, A. Switzer, K. Sieh (2019), Reassessment of the 1907 Sumatra "tsunami earthquake" based on macroseismic, seismological and tsunami observations, and modelling, *Pure and Applied Geophysics*, **176**, pp. 2831 – 2868.

Martin, S.S., Y. Wang, M. Muzli, and S. Wei (2020). The 1922 Peninsula Malaysia Earthquakes: Rare intraplate seismicity within the Sundaland block in Southeast Asia, *Seismological Research Letters,* **91**, 5, pp. 2531 – 2545.

Medvedev, S. V., W. Sponheuer, and V. Kárník (1965). Шкала Сейсмической Интенсивности MSK 1964 (Seismic Intensity Scale Version MSK 1964, in Russian), Akademii Nauk SSSR Geofiz. Kom., Moscow, 280.

Musson, R. M. W. (1998). Intensity assignments from historical earthquake data: issues of certainty and quality, *Annali di Geofsica*, **41**, 1, 79-91.

Musson, R. M. W. (2012), A provisional catalogue of historical earthquakes in Indonesia, Earth Hazards and Systems Programme Open Rept. OR/12/073, 22 pp.

Musson, R. M. W, and I., Cecić (2012). Intensity and Intensity Scales, New Manual of Seismological Observatory Practice 2 (NMSOP-2), GFZ Potsdam, 1-41, doi: h10.2312/gfz.nmsop-2_ch12.

Musson, R.M.W., G. Grunthal, and M. Stucchi (2010). The comparison of macroseismic intensity scales, *Journal of Seismology*, **14**, p. 413 – 428.

Nas, P. (2007)(ed). The past in the present: Architecture in Indonesia, Leiden, 286 p.

Richter, C.F. (1958). Intensities and isoseismals, Elementary Seismology, W.H. Freeman, San Francisco, pp. 135 – 149.

Rudolph, E. (1887). Ueber Submarine Erdbeben en Eruptionen, *Beiträge für Geofisik: Zeitschrift für physikalische Erdkunde*, **1**.

Rudolph, E. (1895). Ueber Submarine Erdbeben en Eruptionen (Zweite Beitrag), *Beiträge für Geofisik: Zeitschrift für physikalische Erdkunde*, **2**, pp. 537 – 667 (in German).

Stehn, Ch. E. (1925). De aardbeving van Maos op 15 Mei 1923, Vulkanologische en Seismologicsche Mededeelingen, 8, pp. 22 – 28 (in Dutch).

Sumintardja, J. (1978). Kompendium sejarah arsitektur, Bandung, 218 p.

Taverne, N.J.M. (1925). De aardbevingen van Wonosobo op 12 November en 2 December 1924, *Vulkanologische en Seismologicsche Mededeelingen*, **8**, pp. 1 – 21.

Tertulliani, A., L. Graziani, C. Castellano, A. Maramai, & A. Rossi (2016). Comment on “Ground Motions from the 2015 Mw7.8 Gorkha, Nepal, Earthquake Constrained by a Detailed Assessment of Macroseismic Data” by Stacey S. Martin, Susan E. Hough, and Charleen Hung, *Seismological Research Letters*.

van Dijk, P. (1885), Voorloopige instructive omtrent de waarneming van aardbevings- verschijnselen, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **44**, 3, 280 – 292 (in Dutch).

van Dijk, P. and J.J. Poortman (1885), Circulaire gezonden aan alle personen, die hunne medewerking bij de waarneming van aardbevings-verschijnselen hebben togezegd, *Natuurkundig tijdschrift voor Nederlandsch Indië*, **44**, 3, 277 – 279 (in Dutch).

Valentijn, F. (1724). Oud- en nieuw Oost-Indiën, 1, Dordrecht – Amsterdam, p. 331 – 332.

Vogt, J., R.M.W. Musson and M. Stucchi (1994). Seismogeological and hydrological criteria for the New European Macroseismic Scale (MSK-92), *Natural Hazards*, **10**, pp. 1 – 6.

Wood, H.O. and F. Neumann (1931). Modified Mercalli intensity scale of 1931, *Bulletin of the Seismological Society of America.* **21**, pp. 277 – 283.