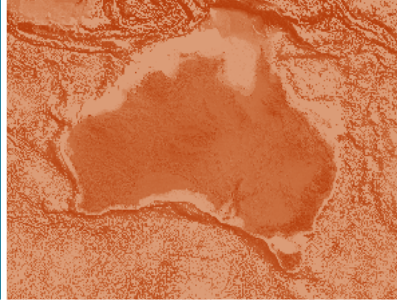
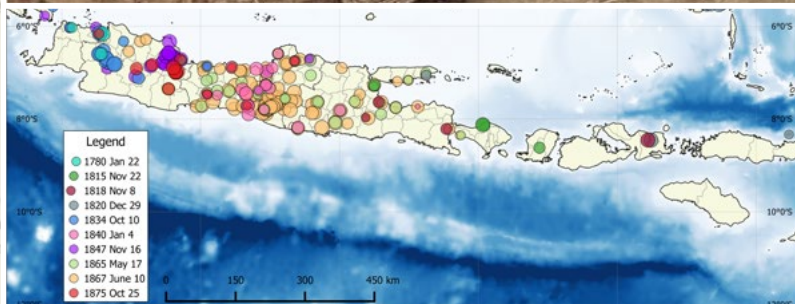
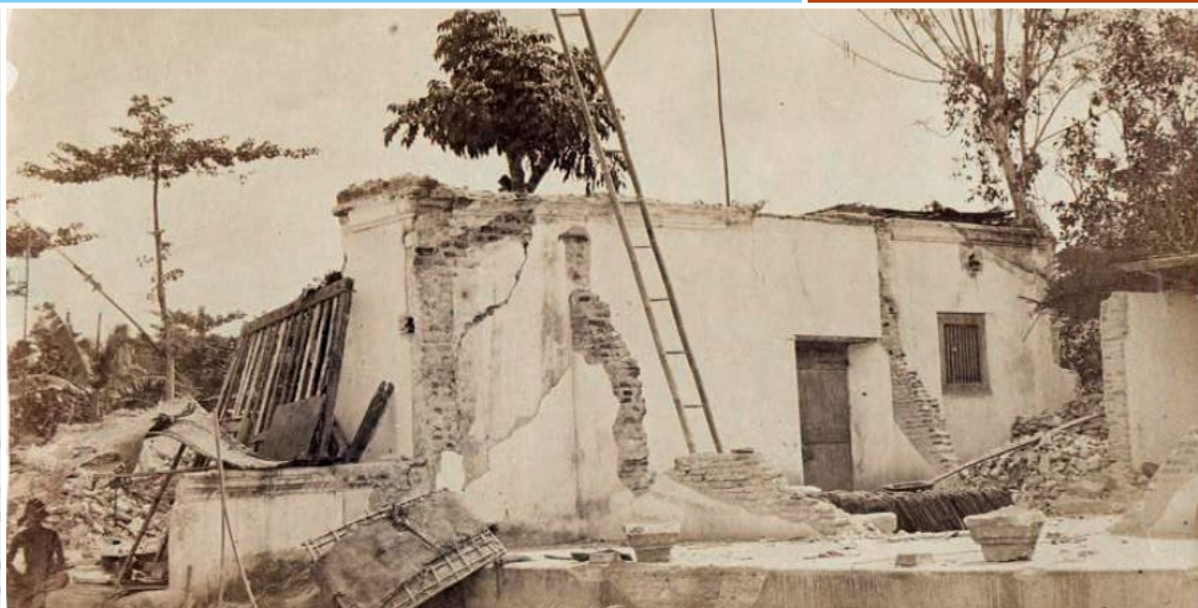




AARDBEVINGEN
IN DEN INDISCHEN ARCHIPEL,
GEDURENDE HET JAAR 1867,
DOOR
dr. P. BERGSMA.
I. JAVA en MADOERA.
BATAVIA.
10^{den} Juni, circa 4^u 10^m des voormiddags, is
lichte aardbeving gevoeld. Verscheidene
ven stilstaan. Aan de gasfabriek heeft me
n dat een der gashouders 25 Ned. duim
g, terwijl uit de kuip van den gashouder
ort werd, het meest aan de westzijde overlo
t water in de kuip weder tot rust gekom
et dat er ongeveer 8 duim water uitgestor

BUITENZORG.
10^{den} Juni, des voormiddags circa 4^u 15^m
beving gevoeld.

PREANGER-REGENTSCHAPPEN.
10^{den} Augustus zijn ten 7^u 55^m des namid
ng twee vrij hevige horizontale schokken
van Z. naar N. gevoeld; de beweging duu
ut.



Record 2015/23 | GeoCat 83909

Indonesia's Historical Earthquakes

Modelled examples for improving the national hazard map

Ngoc Nguyen, Jonathan Griffin, Athanasius Cipta and Phil R. Cummins

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Modelled examples for improving the national hazard map

GEOSCIENCE AUSTRALIA
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Ngoc Nguyen^{1,2}, Jonathan Griffin², Athanasius Cipta¹ and Phil R. Cummins^{1,2}



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1. Research School of Earth Sciences, ANU College of Physical and Mathematical Sciences, Australian National University
2. Geoscience Australia

Department of Industry, Innovation and Science

Minister for Resources, Energy and Northern Australia: The Hon Josh Frydenberg MP

Assistant Minister for Science: The Hon Karen Andrews MP

Secretary: Ms Glenys Beauchamp PSM

Geoscience Australia

Chief Executive Officer: Dr Chris Pigram

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Executive Summary

With a population of over 250 million people, Indonesia is the fourth most populous country in the world (United Nations, 2013). Indonesia also experiences more earthquakes than any other country in the world (USGS, 2015). Its borders encompass one of the most active tectonic regions on Earth including over 18 000 km of major tectonic plate boundary, more than twice that of Japan or Papua New Guinea (Bird, 2003). The potential for this tectonic activity to impact large populations has been tragically demonstrated by the 2004 Sumatra earthquake and tsunami. In order to inform earthquake risk reduction in Indonesia, a new national earthquake hazard map was developed in 2010 (Irsyam et al., 2010). In this report historical records of damaging earthquakes from the 17th to 19th centuries are used to test our current understanding of earthquake hazard in Indonesia and identify areas where further research is needed. In this report we address the following questions:

- How well does our current understanding of earthquake hazard in Indonesia reflect historical activity?
- Can we associate major historical earthquakes with known active faults, and are these accounted for in current assessments of earthquake hazard?
- Does the current earthquake hazard map predict a frequency and intensity of shaking commensurate with the historical record?
- What would the impact of these historical earthquakes be if they were to reoccur today?

To help answer questions like these, this report collates historical observations of eight large earthquakes from Java, Bali and Nusa Tenggara between 1699 and 1867. These observations are then used to:

- Identify plausible sources for each event;
- Develop ground shaking models using the OpenQuake Engine (GEM Foundation, 2015);
- Assess the validity of the current national seismic hazard map; and
- Estimate fatalities were the historical events to occur today using the InaSAFE (InaSAFE.org, 2015) software.

In order to mitigate the impact of earthquakes it is necessary to understand where earthquakes can occur, how big they can be and how often they occur. This understanding of earthquake sources can inform probabilistic seismic hazard assessment to support earthquake resistant building codes. This information can also be used to develop earthquake ground shaking scenarios to inform disaster planning and preparedness.

The recurrence intervals of large earthquakes on a particular fault can be hundreds of years. Therefore, analysis of historical records of earthquakes can complement the record of instrumentally recorded earthquakes. Observations from historical events can help identify the location of active faults and the timing of the last great event. This leads to a better understanding of the geological processes that have shaped the current landscape and the likelihood of future earthquakes to recur in a particular location.

The analysis in this report demonstrates that:

- Most of Java experienced high intensity ground shaking (MMI >5) due to earthquakes between 1699 and 1867.
- Intralab earthquakes may contribute more to Java's earthquake hazard than previously thought.
- The present understanding of active faults in Java is incomplete. Presently unmapped active faults are required to explain some of the observed events.
- The current (2010) national seismic hazard map may underestimate the frequency of high intensity shaking, most notably for the megacity of Jakarta, Indonesia's capital.
- The maximum magnitude of the Flores Thrust may be larger ($\sim M_w$ 8.4) than previously thought (M_w 8.1) in order to explain the 1820 Bulukumba tsunami in southern Sulawesi.
- Many of the historical events, if they re-occurred today, could kill 10 000s of people and potentially displace 10s millions more. It is estimated that a repeat of the 1699 earthquake in Jakarta could kill approximately 100 000 people, although there is considerable uncertainty associated with such estimates.

This contribution to the understanding of Indonesia's seismic activity aims to inform future revision of Indonesia's national seismic hazard map and to provide a database of historically based earthquake scenarios for disaster management planning.

1. Introduction

1.1 Modelling Historical Earthquake Events

Indonesia, the fourth most populous country in the world, is situated in one of the world's most seismically active regions. Over 48 000 earthquakes with $M \geq 4$ were recorded between 1799 and 2010 (Putra et al., 2012). As such, it is critical that Indonesia's seismic hazard map is as accurate as possible. This report aims to contribute to the improvement of the next national hazard map via three main objectives:

1. to create a database of earthquake scenarios based on historical events from Java, Bali and Nusa Tenggara for future planning;
2. to assess the validity of the current national seismic hazard map for Java; and
3. to identify historically active faults which may have been overlooked or unidentified in the previous hazard map (Irsyam et al., 2010) and faults which need further investigation.

The opportunity to investigate Indonesia's historical seismic activity arose from the translation of *Die Erdbeben des Indischen Archipels bis zum Jahre 1857* (The earthquakes of the Indian Archipelagos until the year 1857) (Wichmann, 1918) and *Die Erdbeben des Indischen Archipels von 1858 bis 1877* (The earthquakes of the Indian Archipelagos from 1857 to 1877) (Wichmann, 1922) from German to English by Harris and Major (in press). Selected earthquakes with informative reports of large-scale damage from Wichmann's catalogues were evaluated using the Modified Mercalli Intensity (MMI) scale. Possible fault sources for these events were identified based on our knowledge of the tectonics of Java and the macroseismic intensity distribution. The OpenQuake software was then used to simulate possible earthquakes on these faults in order to identify the most plausible source(s) for each historical event. The resulting ground shaking simulations were used to discuss the validity of Indonesia's current national seismic hazard map. They also provide scenarios that can be used for disaster management planning, allowing consideration of the impacts were such an event to occur today.

Special focus has been placed on Java because more than 57% of Indonesia's population is concentrated in Java (World Bank, 2015). Fourteen scenarios are proposed by matching modelled MMI with observed MMI for eight earthquake events (some have multiple scenarios) based on the available historical evidence (Table 1.1). Events that were also investigated but were not modelled include earthquakes occurring in 1757, 1818, 1865 and 1875. Further information about observed MMI for modelled events can be found in Appendix A; additionally further information about MMI for events not modelled are in Appendix B.

Table 1.1 Summary of historical earthquakes modelled using OpenQuake for this report.

Year	Date	Region Affected	Proposed Fault Source/ Mechanism	Modelled M_w
1699	January 5	Java and Sumatra	Intraslab, Megathrust	8.0, 9.0
1780	January 22	West Java and Sumatra	Baribis thrust, crustal fault, intraslab	7.0, 7.0, 8.0
1815	November 22	Java, Bali, Lombok	Back-arc thrust	7.3
1820	December 29	Java, Flores and Sulawesi	Flores thrust	8.4
1834	October 10	West Java	Baribis thrust, crustal fault, intraslab	7.0, 7.0, 7.7
1840	January 4	Central and East Java	Strike-slip	6.5
1847	November 17	West and Central Java	Strike-slip	7.5, 7.6
1867	June 10	Java and Bali	Intraslab	7.7

Population growth in Indonesia has increased from ~178.5 million in 1990 to ~240.5 million in 2010 (World Bank, 2015). Many major cities in Java have over 100 people per 100 metre squared including, but not limited to, Jakarta (>200), Bandung (>200), Cirebon (>200), Magelang (~180), Malang (~150), Surabaya (~150), Yogyakarta (~130), Semarang (~100), and Bogor (~100); all of which have experienced $MMI \geq 7$ events in the past (Figure 1.1). Accordingly, total number of displaced persons and fatality estimates are modelled in InaSAFE for each proposed scenario in Section 4.

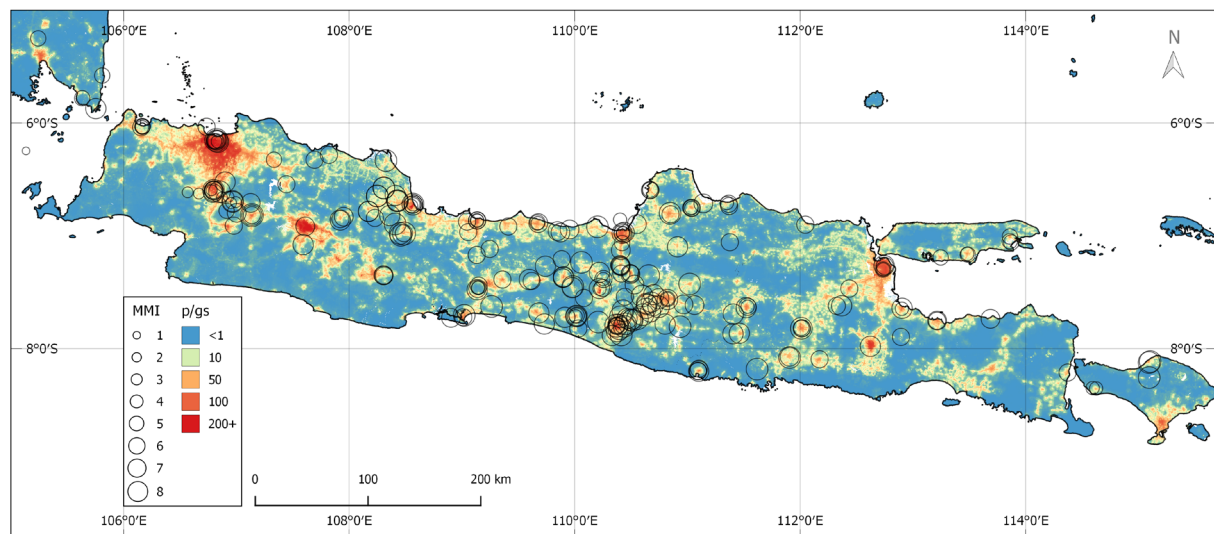


Figure 1.1 Estimates of persons per grid square (p/gs) (~100 m at the equator) in for Java for 2015 (adjusted to match United Nations' projections by Gaughan et al., 2013)), with observed MMI from all events modelled. Data from WorldPop (2015).

1.2 Regional Tectonic Setting

The tectonic evolution and present-day stress regime control active faulting in Java. West and Central Java form part of the core of the Sunda Block (Sundaland) while East Java (along with West Sulawesi) are continental fragments thought to have rifted off north-west Australia before being accreted to the Sunda Block about 90 Ma (Hamilton, 1979; Hall, 2011). A structural trend running SW-NE, referred to as the Luk-Ulo suture (Pulunggono and Martodjojo, 1994; Metcalfe, 2011), is interpreted as the boundary between the Sundaland core and East Java however the exact location of this feature is interpreted differently by different authors.

As the Australian plate's northward movement accelerated around 45 Ma (Veevers, 2006), subduction of oceanic crust along the southern coast of Java began (Hall, 2011) and has continued to the present day, creating a north-south directed maximum stress and generating the late Neogene Sunda Orogeny (Simandjuntak and Barber, 1996). This stress field has generated E-W trending structures as thrust and fold belts, and re-activated SW-NE and SE-NW structures as strike-slip features (Pulunggono and Martodjojo, 1994). Inherited N-S structural features in West and Central Java are considered inactive (Pulunggono and Martodjojo, 1994). In addition to these shallow crustal structures, damaging earthquakes also occur on the subduction megathrust and within the subducting slab.

Along with the sinistral SW-NE trending Luk-Ulo Suture, a number of authors have proposed a conjugate dextral SE-NW strike-slip structure, referred to as the Pamanukan-Cilacap Fault. Together these two structures create a wedge in Central Java (Satyana, 2007).

Despite there being many damaging earthquakes noted in the historical record, there is still much uncertainty regarding the location, activity rates and faulting style of the main active crustal faults in Java. Reasons for this include active volcanism, high erosion rates, dense tropical vegetation and intensive agriculture that limit the preservation potential of surface rupture features. Subduction is normal to the trench, in comparison with Sumatra, where oblique convergence partitions strain between the subduction zone and the Great Sumatran Fault. On Java, crustal deformation is more widely distributed across inherited structural features meaning that slip-rates of individual faults are low compared with the Great Sumatran Fault, reducing their geomorphic expression. Therefore although many faults have been identified (Table 1.2), there is little consensus in the literature regarding shallow crustal seismogenic sources in Java. The following section describes the evidence that has been proposed for active crustal faults in Java.

1.2.1 Shallow active faults

1.2.1.1 Cimandiri Fault

The Cimandiri Fault (Figure 1.2, fault A) extends from Pelabuhan Ratu Bay (Sukabumi Regency) in the southwest to Cianjur or Bandung Regency in the northeast. The Cimandiri Fault is primarily a sinistral strike-slip fault, however an oblique normal component has been suggested to explain uplift of the southern block relative to the northern block (Martodjojo, 1984; Anugrahadi, 1993; Dardji et al., 1994).

Kertapati (2006) used geological observations to estimate a slip rate of 2 mm/year at a 30° dip. Supartoyo (2014) considered the Cimandiri Fault to be active and divided this fault into 3 segments. On the contrary Hall et al. (2007) suggest the fault is not active. The Cimandiri fault has been proposed as the source of destructive earthquakes on 15 February 1844 (Soetardjo et al., 1985), 28 November 1879 (Irsyam et al., 2010), 14 January 1900 (Soetardjo et al., 1985), 15 December 1910 (Soehaimi, 2011), 26 November 1973 (Supartoyo and Surono, 2009), 10 February 1982 (Soehaimi, 2011), and 12 July 2000 (Soehaimi, 2008, 2011).

1.2.1.2 Lembang Fault

The Lembang fault (Figure 1.2, fault B) is 24 km in length, extending from west to east approximately 20 km north of Bandung city. Kertapati (2006) estimated the Lembang fault's slip rate to be 2 mm/year, whilst Meilano et al. (2012) estimated 6 mm/year of geodetic slip and locking at 3-15 km depth. Recent events attributed to the Lembang fault include the M_w 3.3 earthquake in Cisarua (West Bandung Regency) on August 28, 2011 (Afnimar et al., 2015). The earthquake caused damage to 103 houses and 370 villagers were evacuated (Badan Geologi, 2013). Notable aftershocks occurred on 3rd and 4th of September 2011. Prior to this, a M_w 2.9 earthquake had occurred on July 21 of the same year (Afnimar et al., 2015). The Lembang fault has been known to produce large earthquakes, for example $\sim M_w$ 6.8 about 2 000 years ago (Afnimar et al., 2015), and has the potential to produce large ($M_w > 6.5$) earthquakes every 400-600 years (Horspool et al., 2011). The last large event ($\sim M_w$ 6.6) occurred approximately 500 years ago (Afnimar et al., 2015).

1.2.1.3 Cilacap, Pamanukan-Cilacap or Citanduy Fault

A SE-NW trending strike slip structure is present near the boundary between Central and West Java (Figure 1.2, fault C). This structure extends to the NW from the southern coast near Cilacap, however its northern expression is unclear. It may connect with the Baribis Fault (Martodjojo, 1984; Simandjuntak and Barber 1996) or alternatively may cut across and offset this feature. This is considered to be an active fault and earthquakes at Majalengka, Brebes and Pekalongan have been attributed to it.

1.2.1.4 Baribis-Kendeng Thrust

The Baribis-Kendeng Thrust (Figure 1.2, fault D and E) has been proposed as a major thrust and fold structure extending across Java from the Sunda Strait in the west to East Java, the Bali basin and even linking to the Flores Thrust. However, the strike-slip Cimandiri and Citanduy Faults cut across the Baribis-Kendeng Thrust in West and Central Java and therefore it is not clear that this is one structure. Some interpretations instead have the eastern end of the Baribis Fault trending to the southeast from near Kadipaten (Majalengka Regency) linking to the Citanduy Fault and extending towards Cilacap (Martodjojo, 1984). Conversely, the Kendeng Thrust may extend west to link with the Cimandiri Fault. The Kendeng Fold-Thrust belt is expressed geomorphologically in East Java by the presence of E-W trending belt of hills (Irsyam et al., 2010).

1.2.1.5 Pati and Lasem Faults

The Lasem (Kertapati and Saputra, 2010; Zulfakriza et al., 2014) (Figure 1.2, fault F) and Pati (Susilo and Adnan, 2013) (Figure 1.2, fault G) faults are both located to the northeast of Semarang along the same structural lineament as the Central Java Structural Lineament. The Pati Fault is thought to be responsible for the 1890 Pati earthquake that resulted in a number of fatalities (Supartoyo and Surono, 2008). Irsyam et al. (2010) gave the Lasem fault a maximum magnitude of 6.5 and a maximum magnitude of 6.8 for the Pati fault.

1.2.1.6 Opak Fault

The Opak fault (Figure 1.2, fault H) has been defined along a SSW-NNE 32 km long trace with a slip rate of 2.4 mm/year and maximum magnitude of M_w 6.8 in the 2010 revision of Indonesia's national earthquake hazard map (Irsyam et al., 2010). The M_w 6.3 earthquake on 27 May 2006 in Yogyakarta has been attributed to the Opak fault. However, research conducted by Tsuji et al. (2009) and Setijadji et al. (2007) revealed that the earthquake was caused by reactivation of a Tertiary fault located approximately 10 km to the west and parallel to the Opak fault. This fault dips to the west and may therefore have a reverse slip component in addition to a sinistral strike-slip movement.

1.2.1.7 Central Java Structural Lineaments (Muria-Kebumen Fault or Luk-Ulo Suture)

Java's basement rock is exposed along the Luk-Ulo Suture (Metcalf, 2006, 2011). This fault (or more probably, fault zones) is the suture between the Sundaland core and East Java (Figure 1.2, fault L). While many authors place a structure here in interpreting the tectonics of Java, it is unclear whether this structure is active and whether any deformation is spread over a broader fault zone. Satyana (2007) suggests the wrench fault system is composed of a primary left lateral Muria-Kebumen fault and a complimentary right lateral Pamanukan-Cilacap fault (Figure 1.2, fault M). The structure aligns with the Lasem and Pati faults northeast of Semarang.

1.2.1.8 Other Faults

A number of other smaller faults have been proposed by various authors, for which little is known. These are summarised in Table 1.2.

Table 1.2 Other known active faults in Java. Where historical earthquakes have been proposed to occur on these faults, they are noted.

Name	Slip rate (mm/yr)	Type	Length (km)	M _{max}	Earthquake
Kedung Rejo ^{a)}	0.023	WN	7.0	5.3	
Kedung Tunggal ^{a)}	0.018	SS	4.0	5.4	
Kali Suru ^{a)}	0.029	WR	5.0	5.6	
Kali Balong ^{a)}	0.030	WR	4.0	5.6	
Kalinyamatan ^{a)}	0.016	SS	7.0	5.6	
Kayu Manik ^{a)}	0.020	WN	7.0	5.5	
Gua Tritip ^{a)}	0.027	R	6.0	5.6	
Ranggas ^{a)}	0.023	WN	20.0	5.6	
Gunung Tempur ^{a)}	0.023	WR	20.0	5.3	
Semarang ^{a)}					1856 Semarang (MMI 8) 1821 Jepara (MMI 8)
Bumiayu ^{a)}					
Citarik ^{b)}					1833 Jakarta, 1852 Bogor
Cisadane ^{c)}		SS			
Ciliwung ^{c)}		SS			
Kali Bekasi ^{c)}		SS			

Note: SS – strike-slip, R – reverse, WR – wrench-reverse, WN – wrench-normal, ^{a)} Irsyam et al. (2010), ^{b)} Sidarto (2008), ^{c)} Moechtar (unpub.).

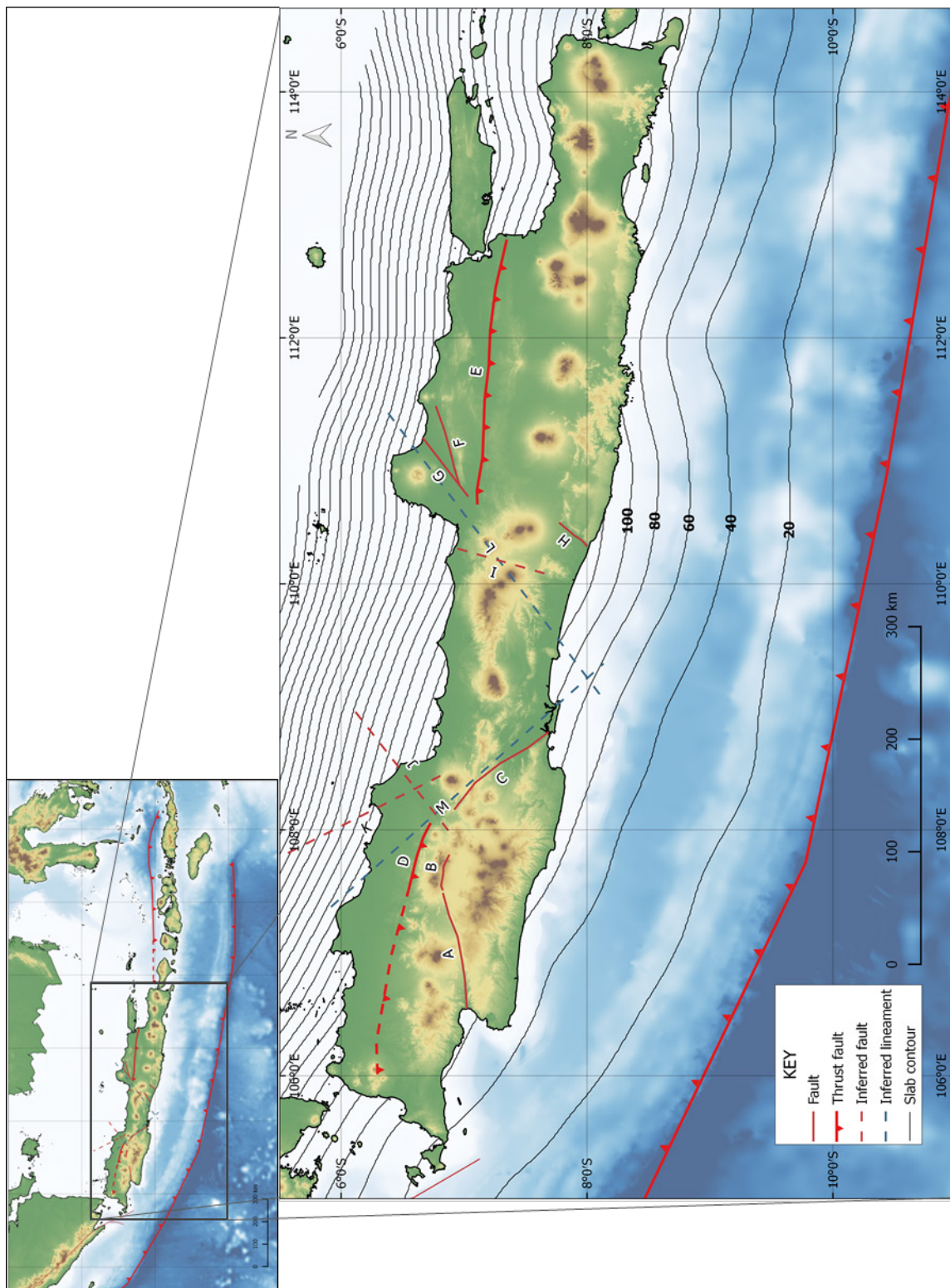


Figure 1.2 Major structural features and faults used in this study for Java, Bali and Nusa Tenggara. In overview map, the Sunda trench continues south of Sumatra to south of Sumba. The Great Sumatran Fault spans the entire length of Sumatra and the Flores fault runs from the Flores Basin to the Bali Basin. Faults in inset map: A – Cimandiri (Dardji et al., 1994), B – Lembang (Meilano et al., 2012), C – Cilacap, Pamanukan-Cilacap or Citanduy (Satyana, 2007), D – Baribis (adapted from Simandjuntak and Barber (1996)), E – Kendeng (adapted from Simandjuntak and Barber (1996)), F – Lasem (Zulfakrizza et al., 2014), G – Pati (Susilo and Adnan, 2013), H – Opak (Susilo and Adnan, 2013), I – 1840 inferred fault (this record), J and K – 1847 inferred faults (this record), L and M – Central Java Structural lineaments (Satyana, 2007); L – Muria-Kebumen lineament or Luk-Ulo Suture, M – Pamanukan-Cilacap fault.

1.3 Administrative Divisions

Reports of damage often come from historically important towns or cities and/or from a *Residency* or *Regency*¹. The historical reports of earthquake damage from the Regencies and/ or Residencies are biased by the distribution of government officials and economic assets. The northern side of the island has been occupied since the 1600s because of safe ship ports (Figure 1.4). The main trading port on Java was at Batavia during the 1600s and 1700s, then at Surabaya in the 1800s. In 1808, Daendels began the construction of *De Grote Postweg* (the Great Post Road) (Figure 1.5); a military road connecting regencies from Banten to Besoki allowing goods and services to be delivered within the week (Cribb, 2010).

On the south coast, the main ports are at Cilacap and Pacitan but are generally not as frequented as the north side because it is open to the ocean (Raffles, 1817). Hence, the southern coastal region was less important economically. Consequently, earthquake damage reports in Preanger Residency are minimal and incomplete (Figure 1.5). In addition, The Sultans of Surakarta and Yogyakarta governed a large portion of the southern side of the island. Accordingly, there is no continuity of information between *Vorstenlanden* (Princely states) in comparison to the rest of Dutch controlled Java.

The names of historic locations are used according to the references cited with modern location names in brackets where possible. Note that the names of historical locations may vary according to different references.



Figure 1.3 Map of the administrative divisions from 1832 to 1866 for Java (Cribb, 2010).

¹ Today, Java is divided into six provinces (Banten, Jakarta, West Java, Central Java, Yogyakarta, and East Java) and over 100 regencies. Historically, these administrative divisions originate from the establishment of 10 *Landrostambten* or *Prefectuur*, (re-termed *Residencies* by Raffles), by Herman Willem Daendels (Dutch Governor-General from 1808-1811) (De Kat Angelino, 1931). Each residency was divided into districts or regencies; and all regencies were divided into divisions (present-day districts) (De Kat Angelino, 1931). The administrative divisions of Java subsequent to the British invasion and governance by Sir Thomas Stamford Raffles (1811-1815), who erected another 6 Residencies (De Kat Angelino, 1931), and the years following restoration of Dutch rule were highly unstable and not very well catalogued. By 1832 the administrative boundaries had become relatively static (Figure 1.3). Japara, Buitenzorg (Bogor), Krawang and Banjoewangi were initially designated as Regencies. Patjitan (Pacitan) was an *Assistant-Resident* and all others were Residencies (Cribb, 2010). In 1849, Banjoewangi became *Assistant-Resident*. In 1855, Probolinggo separated from Besoeki, and in 1857 Madoera (Madura) separated from Soerabaja (Surabaya). In 1867, Buitenzorg was merged with Batavia, and Patjitan came under Madioen (Madiun) administration (Cribb, 2010).

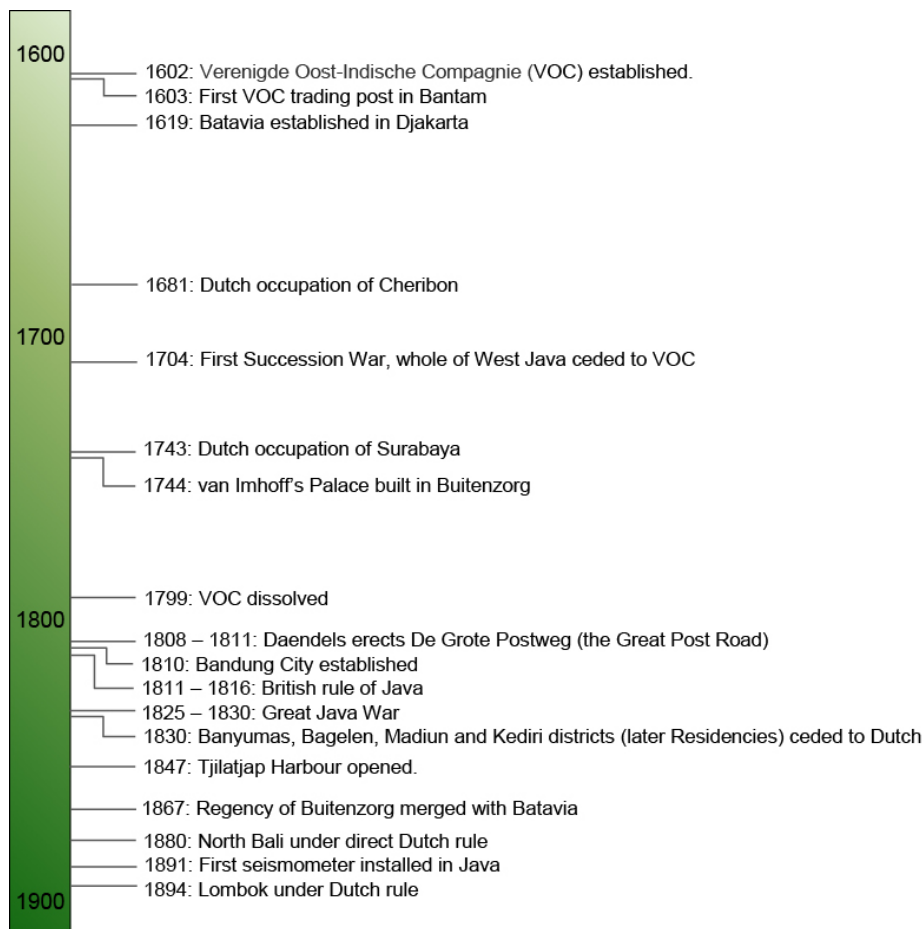


Figure 1.4 Timeline of key events in Java, Bali and Nusa Tenggara from 1600-1900.

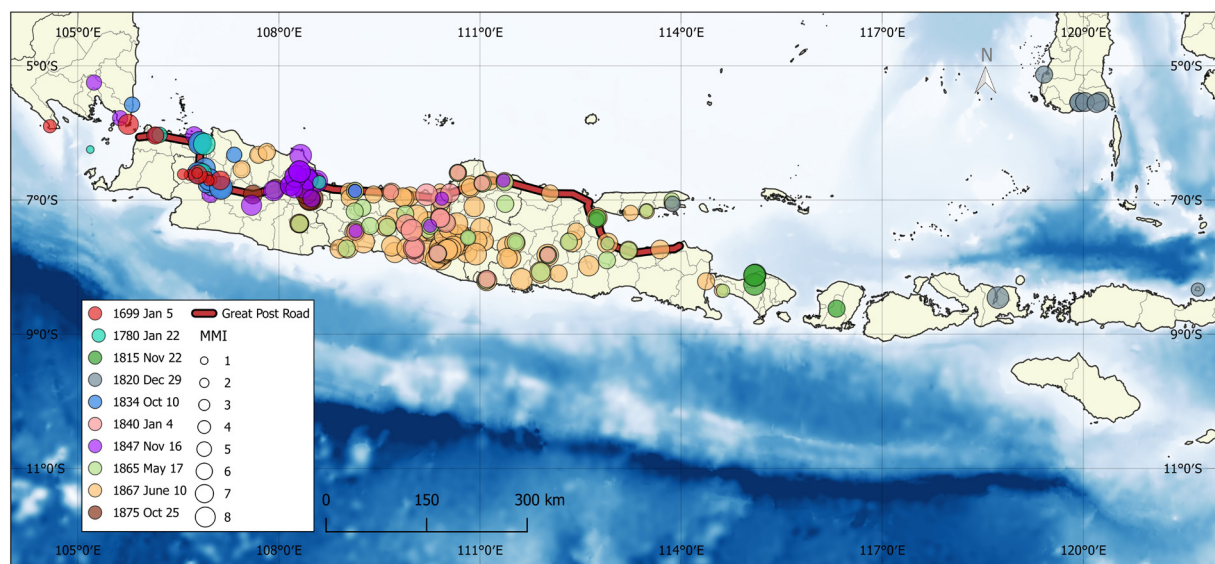


Figure 1.5 Distribution of observed MMI from 1600 to 1900 for events investigated in Java, Bali and Nusa Tenggara.

2. Modelling Historical Earthquake Events

2.1 Methodology

2.1.1 Estimation of Modified Mercalli Intensity

The Modified Mercalli Intensity (MMI) scale used here is that of Richter (1958), which is an abridged form of earlier scales introduced by Sieberg (1923) and Wood and Neumann (1931). It has been assumed that buildings and structures in Java, Bali and Nusa Tenggara were not designed to withstand earthquakes for the interval investigated. Therefore, structures were classified as Masonry Type C (neither reinforced nor designed against horizontal forces) and Type D (weak materials; low standards of workmanship) (Richter, 1958). Consequently, where considerable structural damage, partial or total building collapse has been reported, an MMI 8 was assigned (Table 2.1). In most cases therefore we are unable to assign $\text{MMI} > 8$, although it is possible that ground shaking stronger than MMI 8 occurred.

Table 2.1 Summary of the Modified Mercalli Intensity Scale.

Intensity	Damage
I	Not felt except by a very few under especially favourable conditions.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted.

Source: U.S. Geological Survey (2013)

2.1.2 Earthquake Simulation

2.1.2.1 Modelling Parameters

In this study, we convert Psuedo-spectral Acceleration (PSA) at 1 second period to MMI using Atkinson and Kaka (2007). All modelled MMI conversions were mapped at 2 km resolution using the equations:

$$MMI = C_1 + C_2 \log \gamma \text{ for } \log \gamma \leq \log \gamma(I5) \quad (1)$$

$$MMI = C_3 + C_4 \log \gamma \text{ for } \log \gamma \geq \log \gamma(I5) \quad (2)$$

where C_1 is 3.23, C_2 is 1.18, C_3 is 0.57, C_4 is 2.95, $\log \gamma(I5)$ is 1.50, for PSA at 1 second, with the standard deviation of the above regression being 0.84. Note that this conversion introduces additional uncertainties into our analysis.

Fault surface rupture length (SRL) was calculated using equation 3 from Wells and Coppersmith (1994) for all events except December 29, 1820.

$$M = a + b \times \log(SRL) \quad (3)$$

where a is 5.16 for strike slip or 4.86 for normal faults and b is 1.12 for strike slip or 1.32 for normal faults.

Wells and Coppersmith's (1994) equation for calculating SRL for reverse faults is based on a small sample set, of which the largest reverse fault was a M_w 7.4. Accordingly, SRL for the 29 December, 1820 event, was calculated using the equation:

$$M_w = a + b \times \log(L) \quad (4)$$

where a is 4.868, b is 1.932, and L is length (Strasser et al., 2010).

Slab 1.0 (Hayes et al., 2012) was used to model fault ruptures for interface and intraslab earthquakes.

2.1.2.2 Ground Motion Prediction Equations

A specific ground motion prediction equation (GMPE) does not exist for Indonesia, although expansion of the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) strong motion network should make this possible in the near future. A number of GMPEs were preselected for the Global Earthquake Model's (GEM) (see Di Alessandro et al. (2012) for an overview of GEM) OpenQuake Engine (Pagani et al., 2014; Silva et al., 2014) using the selection criteria outlined by Douglas et al. (2012) and Stewart et al. (2012). The use of one GMPE over another may produce very different results, as seen in Figure 2.1.

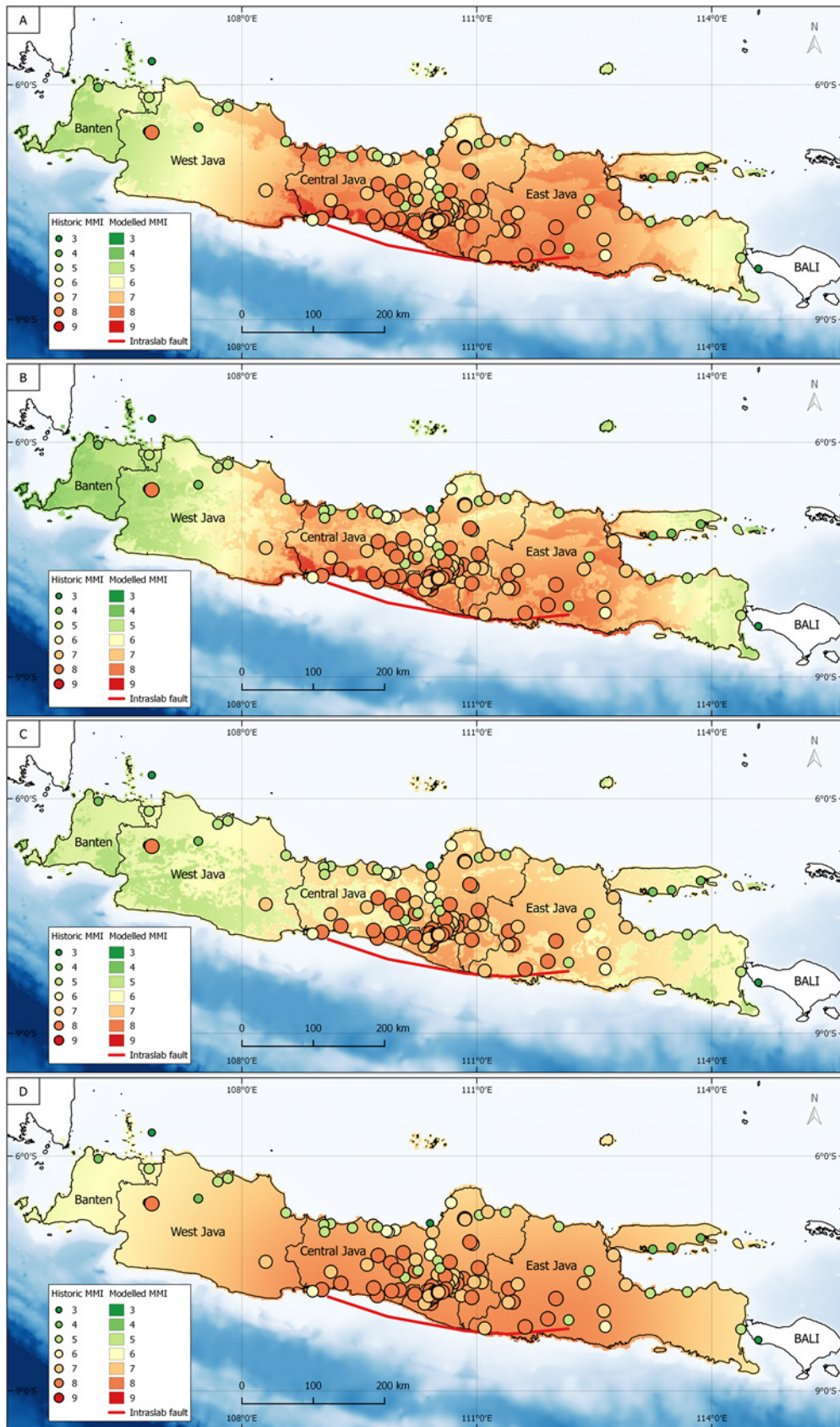


Figure 2.1 Modelled MMI results (M_w 7.7) using the GMPEs A) ZhaoEtAl2006SSlab, B) AtkinsonBoore2003SSlab, C) LinLee2008SSlab, and D) YoungsEtAl1997SSlab for June 10, 1867.

Although the GMPE by Zhao et al. (2006) for intraslab earthquakes provides the best match to observed MMI for June 10, 1867, it is not a perfect fit (Figure 2.1 A). Modelled intensity results are between MMI 7 and 8 on the southern coast of Central Java decreasing slowly northwards, matching historical MMI. However, attenuation remains low and regions further away from the fault, such as Banten and Madura, are over estimated. In comparison, the GMPE by Atkinson and Boore (2003) for intraslab earthquakes has higher attenuation (Figure 2.1 B), resulting in lower MMI for regions further away, matching observed MMI, but producing lower MMI for regions close to the fault source. The GMPE by Lin and Lee (2008) (Figure 2.1 C) produced low intensity (MMI 6-7) where intensity was historically high (MMI 7-8), and the reverse is seen when the GMPE by Youngs et al. (1997) (Figure 2.1 D) is used. A comparison of GMPEs developed using data from other regions of the world to strong motion data from Indonesia was done by Rudyanto (2013). Based on Rudyanto's (2013) assessment, which is consistent with our current observations, we use GMPEs outlined in Table 2.2.

Table 2.2 Source type and correlating ground motion prediction equations used.

Source types	Ground motion prediction equations used in OpenQuake
Crustal faults – Strike slip, normal, reverse	BooreAtkinson2008 (Boore and Atkinson, 2008) ChiouYoungs2008 (Chiou and Youngs, 2008)
Subduction – interface (megathrust)	ZhaoEtAl2006SInter (Zhao et al., 2006)
Subduction – intraslab	ZhaoEtAl2006SSlab (Zhao et al., 2006) AtkinsonBoore2003SSlab (Atkinson and Boore, 2003)

2.1.2.2 Site Amplification

Ground shaking may vary considerably between nearby areas exposed to the same seismic source due to amplification of seismic waves by different soil properties. Average shear wave velocity in the upper 30 m of the earth (V_{S30}) is commonly used as a proxy for the amplification properties of soil at a site. Although it provides incomplete characterisation of site effects, it is a useful proxy in the absence of a more detailed site assessment (Zhao, 2011). Proxy methods can be used to estimate regional average V_{S30} in areas where field measurements are limited. Estimated V_{S30} values (Figure 2.2) are incorporated directly into GMPEs that include this term in their functional form. For GMPEs that do not incorporate V_{S30} in their functional forms, sites are classified into the National Earthquake Hazards Reduction Program (NEHRP) site classes and associated with amplification factors at each site (Borcherdt, 1994).

Matsuoka et al. (2006) propose V_{S30} is an empirical function of morphology (elevation, slope and the distance from hills/mountains) and geology (type and age of lithology). A study of Probabilistic Seismic Hazard Assessment (PSHA) for Sulawesi shows that V_{S30} derived from geomorphological data correctly estimates site class at approximately 25% of sites measured by the H/V method (Cipta et al. in press). In contrast, a proxy method based only on topographic slope (e.g. Wald and Allen (2007)) is correct for only 15% of measured sites. More specifically, topographic slope best predicts site class C while the geomorphologic method is more accurate for site class D (Cipta et al. in press). Noting that there is also considerable uncertainty in the use of H/V measurements as a basis for estimating site effects (Ghasemi et al., 2009; Zhao, 2011), site amplification remains a major source of uncertainty.

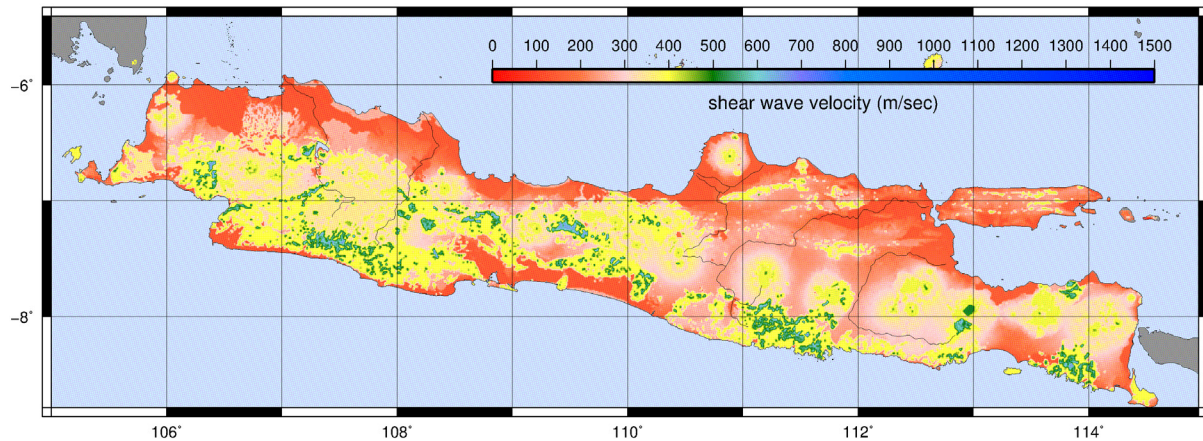


Figure 2.2 Java's shear wave velocity in the upper 30 metres (V_{s30}) of soil, estimated using the technique by Matsuoka et al. (2006).

2.1.2.3 Root mean squared error calculations

As a simple measure of the difference between the observed MMI observations and our modelled results we calculate the Root Mean Square Error (RMSE) as:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (MMI_{O_i} - MMI_{M_i})^2} \quad (5)$$

where MMI_{O_i} and MMI_{M_i} are respectively the observed and modelled MMI at the i th site and n is the total number of sites.

2.1.3 Limitations

2.1.3.1 MMI Estimations

The estimation of MMI values for a historical earthquake event is limited by several factors. Firstly, the MMI scale is based on observation. As a result, it is only applicable in locations where there were humans to observe the event (as seen in Figure 1.5). In addition, the observation of perceived damage depends on the building materials and the type of soil it was built on. However, these factors are not in the historical record, and therefore we must make assumptions about building quality. Consequently, an unknown error exists that cannot be quantified.

Secondly, the historical data is biased in numerous ways. For example, the data is based on what was deemed important to record by Dutch authorities at the time, particularly structures of economic or political value. Individual reports are also biased by perception; an earthquake of the same magnitude may be perceived differently in different locations depending on the frequency in which earthquakes occur in different regions. Historical reports tend to report the most intense damage, meaning our estimate of MMI for an entire town may be biased by the sites of strongest amplification and/or most vulnerable buildings. Also, for some events where multiple hazards have occurred, for example, an earthquake that causes a landslide generating a tsunami, the damage reported is often undifferentiated from their causes, making it difficult to assign an MMI.

The data used to model the historical event is limited by the information used. Errors may arise where details become inaccurate because of multiple translations. Additionally, there may be other information or reports, which may be in other languages, that we are unaware of or do not have access to.

Lastly, the names of most locations in Indonesia have changed by varying degrees. Although the majority are placed with confidence, the accuracy of approximate locations for some historical villages cannot be guaranteed.

2.1.3.2 Ground motion prediction models

In developing plausible source models for the events studied herein, we use GMPEs that have been developed using global strong motion databases without any data from Java in particular. Adding further to this uncertainty, our estimates of site amplification are based on a proxy method developed using data from Japan. Cipta et al. (in press) has shown that this method estimates site amplification classes correctly in about 25% of cases for Sulawesi, however no comparisons have been done using field measurements from Java. In addition, this is applied at a 2 km resolution, and therefore we may not capture local regions of particularly high amplification, for example alluvial plains along rivers and streams. If we underestimate site amplification we may therefore overestimate the magnitude of the source earthquake in order to match the observed intensities.

2.2 Historical Events

2.2.1 January 5, 1699

2.2.1.1 Historical Account

One of the most significant historical earthquake events in the 17th century striking Java occurred on 5 January 1699, when Batavia (Jakarta) experienced "an earthquake so heavy and strong that nothing comparable had ever been known to have occurred here, the movement having lasted with severe shakes and shocks for about three quarters of an hour" (Coolhaas VI: 49-50, translation by Reid 2012). In Batavia (Figure 2.3), 21 houses, 29 barns and at least 28 lives were lost (Phoonsen, 1699, translation by Reid 2012). Significant collapse of buildings were also reported in Lampong (Lampung), Sumatra, and some damage was also reported from Bantam.

In addition to aftershocks that lasted several days, the earthquake caused a number of landslides around Mount Salak, near Buitenzorg (Bogor) (Nata and Witsen, 1700). These landslides disrupted the main rivers flowing into Batavia posing challenges to transportation and access to clean drinking water.

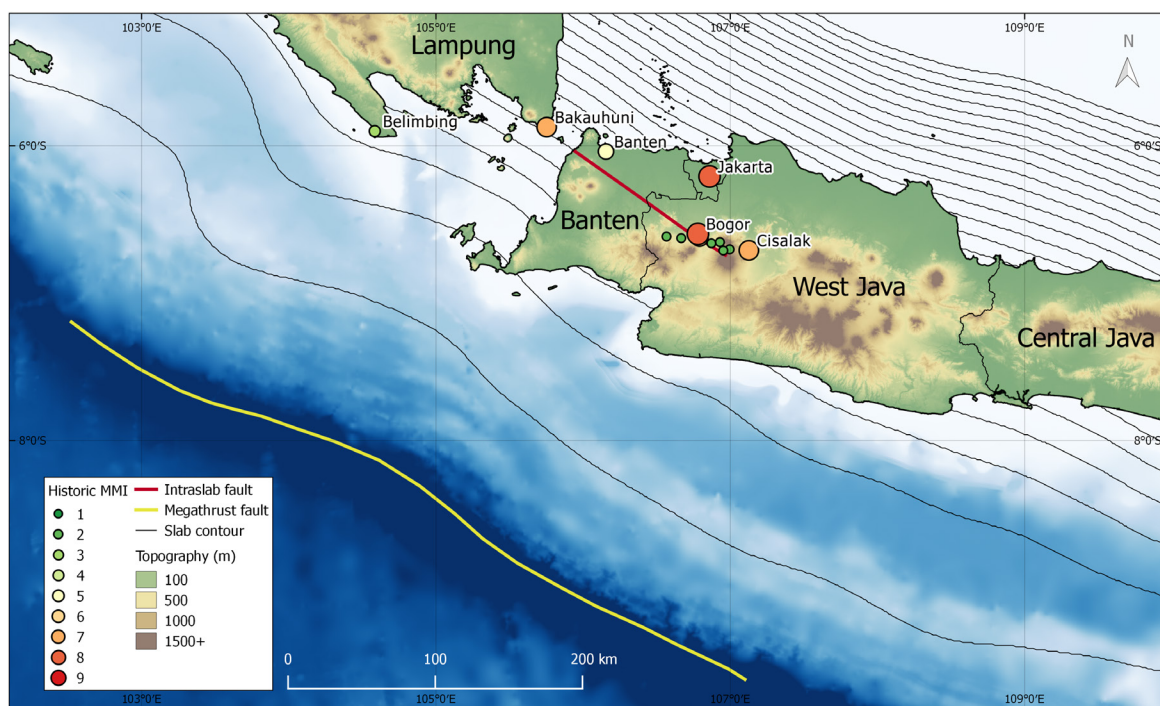


Figure 2.3 Distribution of observed MMI based on historical evidence, and fault trace used to model ground motion shaking for 5 January 1699. Slab contour at 20km intervals starting from the Sunda trench.

2.2.1.2 Scenarios

The widespread nature of the damage (in Batavia (Jakarta), Buitenzorg (Bogor), Bantam (Banten) and Lampung (Lampung)), indicates that the source was either a large magnitude, deep earthquake located somewhere between Cisalak and Lampung or a megathrust event. Musson (2012) and Albini et al. (2013) have assigned a moment magnitude (M_W) of 7.5 to this event, however they suggest it could have been larger. Hence, we modelled a M_W 8.0 in the intraslab in Scenario A (Table 2.3) and a M_W 9.0 megathrust event in Scenario B (Table 2.4).

Table 2.3 Model parameters for January 5, 1699, Scenario A: Intraslab.

Ground Motion Prediction Equation	AtkinsonBoore2003SSlab
Moment Magnitude	8.0
Earthquake rupture co-ordinates	105.913° -6.078° 106.967° -6.742°
Earthquake rupture length	138 km
Hypocentre/ Depth	105.913° -6.078°/ 120 km
Rake	-90°
Dip	45°

Table 2.4 Model parameters for January 5, 1699, Scenario B: megathrust.

Ground Motion Prediction Equation	ZhaoEtAl2006SInter
Moment Magnitude	9.0
Earthquake rupture co-ordinates	102.523° -7.894° 107.100° - 9.62078°
Earthquake rupture length	575 km
Hypocentre/ Depth	105.064° -7.894°/ 10 km
Rake	90°
Dip	30°

2.2.1.3 Result and Discussion

In Scenario A, the intraslab event (Figure 2.4), results in seismic intensities of MMI 9 at Jakarta, Cisalak, Bantam, Buitenzorg and Lampong, which were reported to have suffered heavy damage. The intraslab event resulted in very high intensity (MMI 9) in north Banten Province, Bandung, and the north coast from the Sunda Strait to Karangampel (Indramayu Regency) (Figure 2.4). Those areas were not recorded as affected but it is possible that those areas suffered from strong shaking due to local conditions. North and central parts of Banten Province are composed by pyroclastic materials, and Quaternary loose materials that can amplify seismic waves. Bandung city and the north coast are characterised by other soft rocks, such as lacustrine deposits in Bandung and alluvial deposits along the north coast.

Normal faulting is very common for intraslab earthquakes. In this scenario, the northern side of the fault subsided. Although the northern, hanging-wall side of the fault experienced higher intensities, this was mainly due to the topographically-derived site response having higher amplification there. However, these steep areas are composed of loose pyroclastic material so that landslides could be triggered by strong shaking (MMI 8) which is consistent with the historical record. The RMSE for Scenario A is 2.9.

The damage from this event was distributed over a wide area, with significant damage occurring between Bogor and Lampung (Sumatra). Additionally, many landslides were reported near Bogor. Although large intraslab earthquakes at 100 km depth are infrequent, they do occur and are destructive as seen in Chile on January 25, 1939. The epicentre of the Chilean earthquake (M_s 7.8) was at 80-100 km depth and produced very strong shaking (MMI 9) over a very wide area (Beck et al., 1998).

Scenario B (Figure 2.5) results were of intermediate intensity (MMI 6-7) over the whole of western Java, except in the mountain ranges and south coast. In the mountain ranges, from west of Bogor to south of Cirebon, through north of Cianjur, north of Bandung basin and Majalengka, the intensity varies from MMI 5 to MMI 6 (Figure 2.5). Although areas affected in the mountain ranges are closer to the fault source than the north coast, this area experienced less shaking. Compared to the north coast, which is composed of predominantly Holocene alluvium, the mountain ranges are composed of older undifferentiated volcanic material (Badan Geologi, unpub.) that is stiffer than loose sediment of the Holocene; hence, the north coast has higher V_{s30} values (Matsuoka et al., 2006). The RMSE for Scenario B is 3.0.

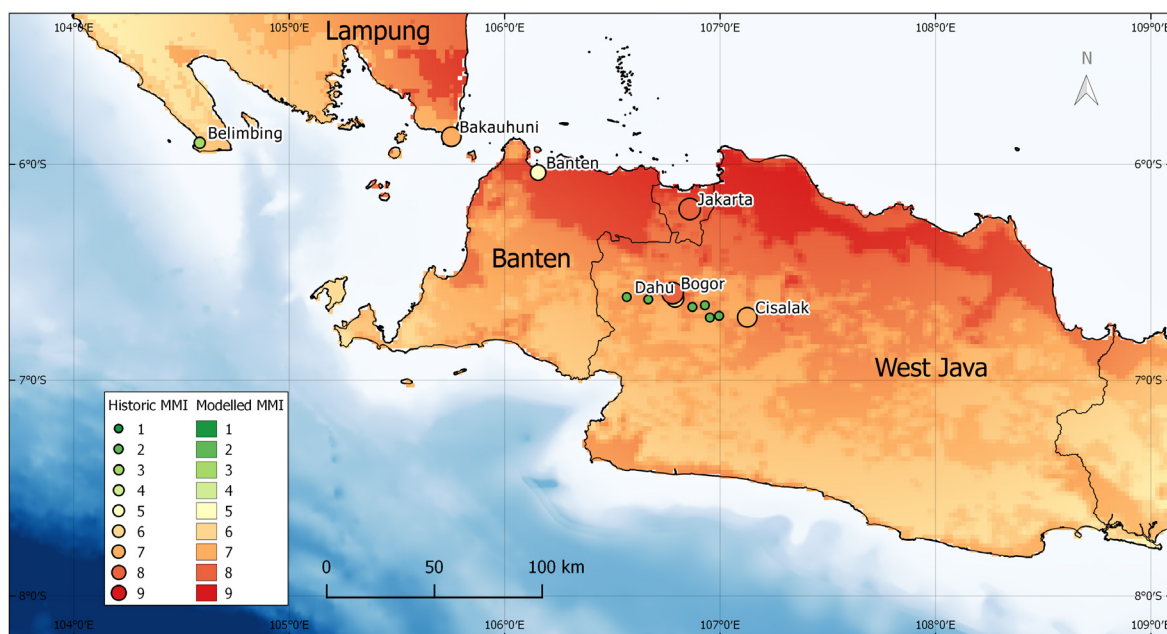


Figure 2.4 Modelled MMI results using parameters outlined in Table 2.3 (intraslab) for January 5, 1699.

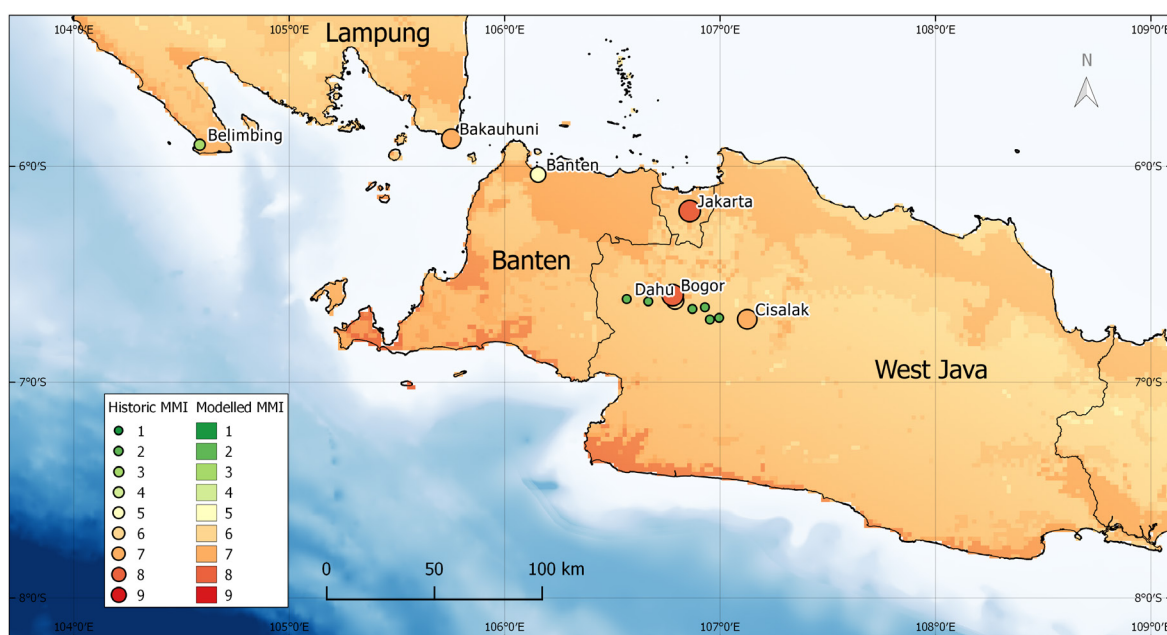


Figure 2.5 Modelled MMI results using parameters outlined in Table 2.4 (megathrust) for January 5, 1699.

Since the south and west coast are the closest areas to the fault source, this area suffers from higher intensity (MMI 8). Effects of site amplification due to local geology may be the reason for high modelled intensity in this area. Young alluvial and young marine sedimentary deposits dominate along the west and south coasts (Badan Geologi, unpub.). The uncompacted rocks have low shear-wave velocity, which amplify ground shaking.

Historical data shows that Batavia (Jakarta) and south of Buitenzorg (Bogor) had suffered from great shaking and caused building collapse, casualties and landslides. Results from Scenario B produced MMI 7, which is considered to cause only slight damage. By comparing intensity results from Scenario

A (intraslab) and Scenario B (megathrust) to intensity from historical data, it is most likely that the 1699 earthquake was an intraslab event.

2.2.2 January 22, 1780

2.2.2.1 Historical Account

This earthquake is considered as one of the largest ever to have hit Java (Musson, 2012; Albini et al., 2013). However, there is very little mention of it in the seismic hazard literature. Ground shaking was felt over the whole of Java and south-eastern Sumatra; it was felt most strongly in West Java (Figure 2.6). Ground shaking caused 27 sheds and houses to collapse in *Zandsee* and *Moorish gracht* (canal) (Wichmann, 1918), located in present-day Central Jakarta where Jakarta Cultural Centre is now standing. It was reported that ‘a mighty bang’ was heard from Mount Salak 2 minutes after the quake and Mount Gede ‘smoked’ (Harris and Major, in press). Meanwhile Bantam (Banten) suffered from strong vibrations. Weak vibrations were also felt in Cheribon (Cirebon), and a seaquake was observed by the ship *Willem Frederik*, which was at the entrance to the Sunda Strait (Wichmann, 1918). Albini et al. (2013) estimate the earthquake could have been M_w 8.5 or larger.

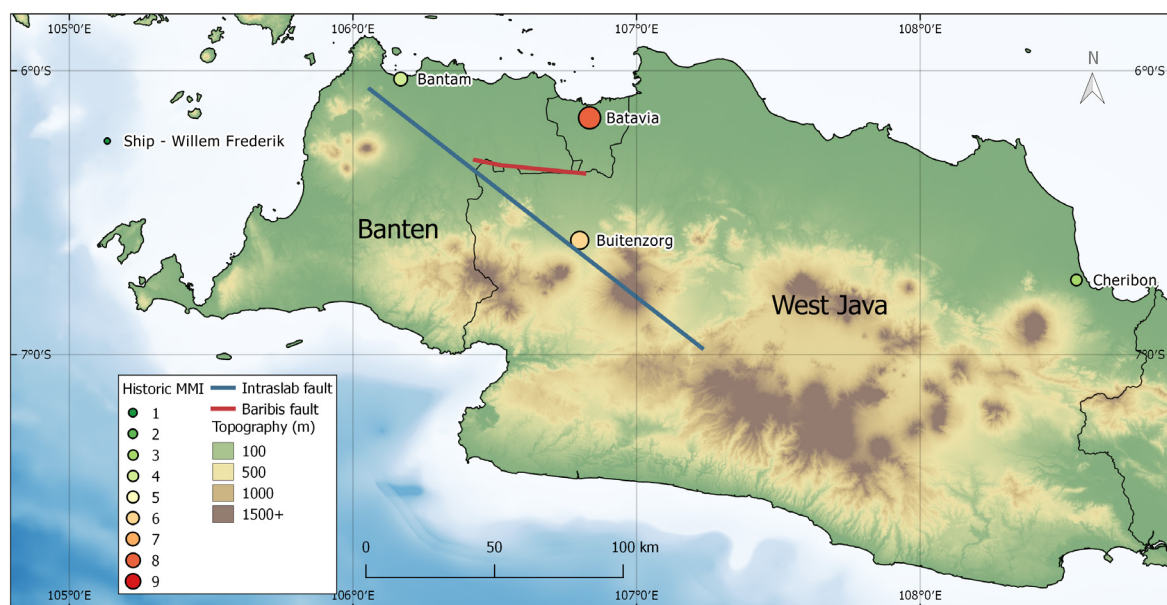


Figure 2.6 Distribution of observed MMI based on historical evidence, and faults used to model ground motion shaking for January 22, 1780.

2.2.2.2 Scenarios

Based on the high intensities felt at Batavia and Buitenzorg, the event was likely to be either on the Baribis fault (which lies between the two localities) or it was an intraslab event to cause damage over a wide area. The Baribis fault (Figure 1.2) is located on the northern part of Java island, and spans from Purwakarta Regency to Baribis hills in Majalengka Regency (van Bemmelen, 1949). The Baribis fault is dipping 31° to the south and has a slip rate of 1 mm/year (Hutapea and Mangape, 2009). Simandjuntak and Barber (1996) and Simandjuntak (1992) claimed that the Baribis-Kendeng Fault can be traced from the Sunda Strait eastwards across Java and into the Bali Basin, connecting into the Flores Thrust, north of Flores, and may continue eastward as Wetar Thrust. This major Java back thrust is considered active since the Late Neogene.

Active faulting on the eastern part of the Baribis fault can be seen from a destructive earthquake in Majalengka Regency on July 6, 1990 (Soehaimi, 2008). This magnitude 5.8 earthquake's hypocentre was at 6.55°S and 108.20°E at 14 km depth (Supartoyo and Surono, 2009). The earthquake destroyed and damaged more than 150 houses, and killed 1 villager and injured 7 people at Anggarwati, the closest village to the epicentre (Associated Press, 1990). However, significant earthquakes have not yet been recorded in the western part of the fault, closer to Jakarta. Nevertheless, we propose a M_w 7.0 thrust event on the western part of the Baribis fault in Scenario A (Table 2.5). Two other scenarios, Scenario B: crustal fault (Table 2.6), and Scenario C: intraslab (Table 2.7), were also simulated for this event.

Table 2.5 Model parameters for Scenario A: Baribis thrust.

Ground Motion Prediction Equation	BooreAtkinson2008
Moment Magnitude	7.0
Fault type	Reverse
Earthquake rupture co-ordinates	106.530° -6.340° 106.840° -6.390°
Earthquake rupture length	45 km
Hypocentre/ Depth	106.750° -6.440° / 12 km
Rake	90°
Dip	45°

Table 2.6 Model parameters for Scenario B: crustal fault

Ground Motion Prediction Equation	BooreAtkinson2008
Moment Magnitude	7.0
Fault type	Strike-slip
Earthquake rupture co-ordinates	106.530° -6.340° 106.840° -6.390°
Earthquake rupture length	45 km
Hypocentre/ Depth	106.853° -6.463° / 70 km
Rake	0°
Dip	90°

Table 2.7 Model parameters for Scenario C: intraslab

Ground Motion Prediction Equation	AtkinsonBoore2003SSlab
Moment Magnitude	8.0
Earthquake rupture co-ordinates	106.060° -6.065° 107.230° -6.977°
Earthquake rupture length	165 km
Hypocentre/ Depth	106.721° -6.378° / 160 km
Rake	-90°
Dip	45°

2.2.2.3 Results and Discussion

There is limited data recorded for this event, however, it is estimated that Batavia (Jakarta), Buitenzorg (Bogor), Bantam (Banten) and Cheribon (Cirebon) suffered from ground shaking with intensity MMI 8, 7, 6 and 3 respectively. There is not enough data to determine intensity at Mount Gede and Mount Salak, south of Bogor. In Scenarios A and B, maximum intensity of MMI 8 was experienced in Batavia, Buitenzorg and Bantam which, excluding Batavia, is overestimated. These simulations also gave similar estimated intensity in Cheribon, while historical data reported smaller intensity (Figure 2.7 and Figure 2.8).

The intraslab scenario, M_w 8.0 at 160 km depth, resulted in an overestimation of intensity compared to the historical data. The outcomes produced high intensity (MMI 8 or higher) along most of the north coast, which is composed of alluvium, from north Jakarta to Cirebon. The northern coast of Banten Province experienced modelled intensity of MMI 7-8. From west of Jakarta to Banten (Bantam) city, the area is predominantly composed of flood plain deposits (Figure 2.9).

In Scenario C, the intraslab model, the Southern Mountain ranges in central Banten and West Java is hit by ground shaking with intensity varying from MMI 6 to MMI 7. The southern flank of the Southern Mountain ranges are composed of coral, igneous rock and Tertiary formations, which experienced ground shaking up to MMI 6. Although this area is closer to the hypothetical fault trace of Scenario C than the north coast, ground shaking is less intense because of site amplification; soft sediment, which is found on the north coast, amplifies seismic wave. Amplification is expected to be smaller in the area composed by hard rock or stiff soil.

The modelled results from Scenario C overestimated intensity compared to the observed intensity. And although Scenario A and Scenario B both provide a good prediction for Jakarta and Bogor, Scenario A is preferred as the fault source of the 1780 event because Scenario B overestimates intensity more than Scenario A for Bantam and Cheribon. The RMSE for Scenarios A, B and C are 2.1, 3.5, and 2.6 respectively.

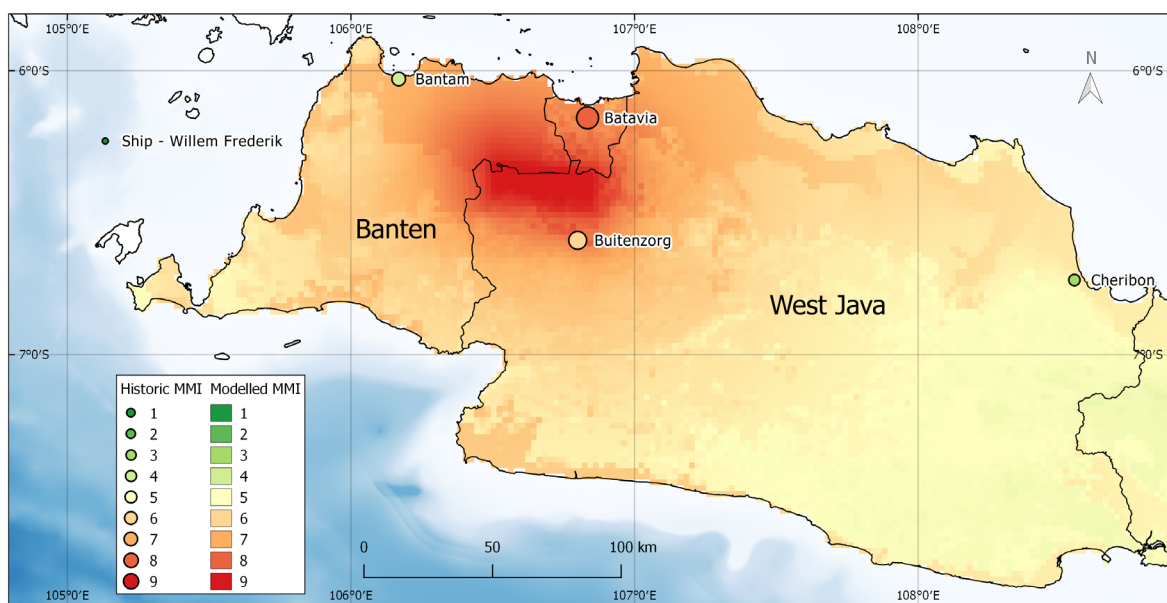


Figure 2.7 Modelled MMI results using parameters outlined in Table 2.5 (Baribis thrust) for January 22, 1780.

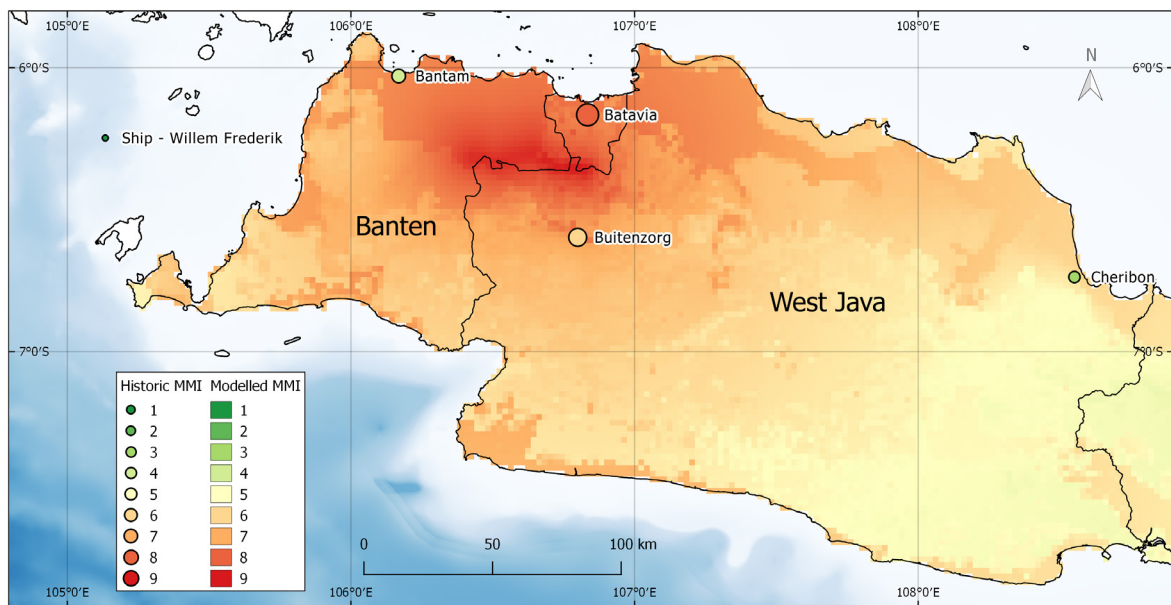


Figure 2.8 Modelled MMI results using parameters outlined in Table 2.6 (crustal fault) for January 22, 1780.

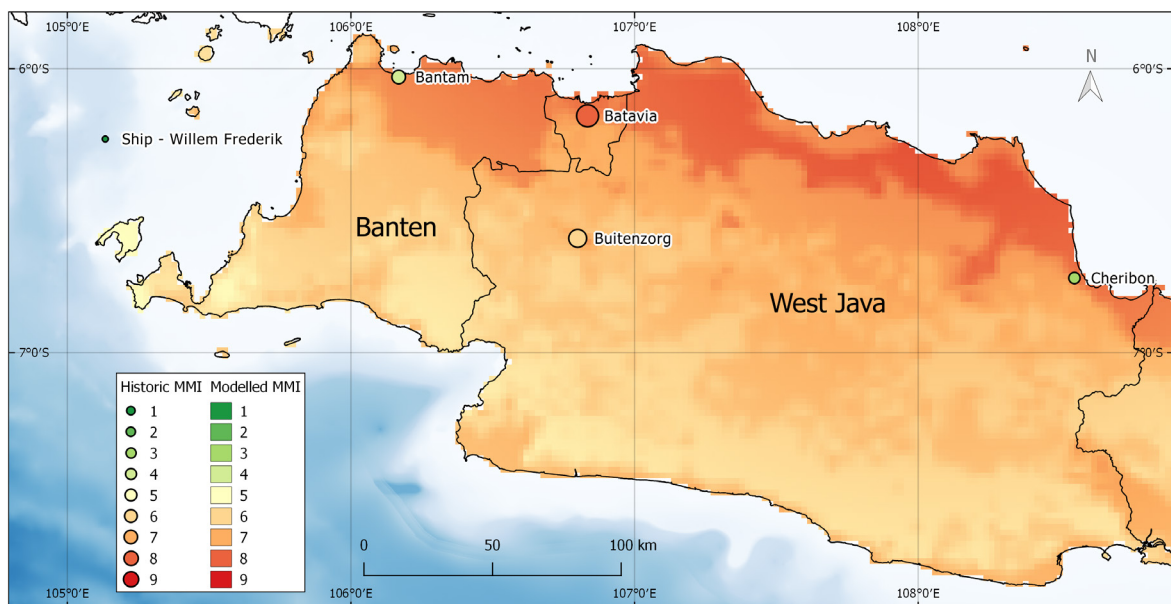


Figure 2.9 Modelled MMI results using parameters outlined in Table 2.7 (intraslab) for January 22, 1780.

2.2.3 November 22, 1815

2.2.3.1 Historical Account

On November 22, 1815, a violent earthquake was reported on the island of Bali (Wichmann, 1918). At Boleeliang (Buleleng) (Figure 2.10), violent quakes began at about 10 p.m. local time and persisted for almost an hour (*Java Government Gazette* 16 December 1815, p. 3). Then a tremendous explosion was reported to have come from the coastal mountains. As a consequence of the mountain explosion, a landslide was generated, burying entire villages and killing 10 253 people in Singa Radja (Singaraja) and Boleeliang (Vriesman, 1884). A tsunami followed which killed over 1 200 people (*Java Government Gazette* 16 December 1815, p. 4). At 11 p.m. in Sourabaya (Surabaya), on the same evening, earthquakes were felt, lasting nearly 30 seconds (*Java Government Gazette* 16 December 1815, p. 3). Furthermore, a “very strong earthquake” was felt on Lombok (Zollinger, 1847).

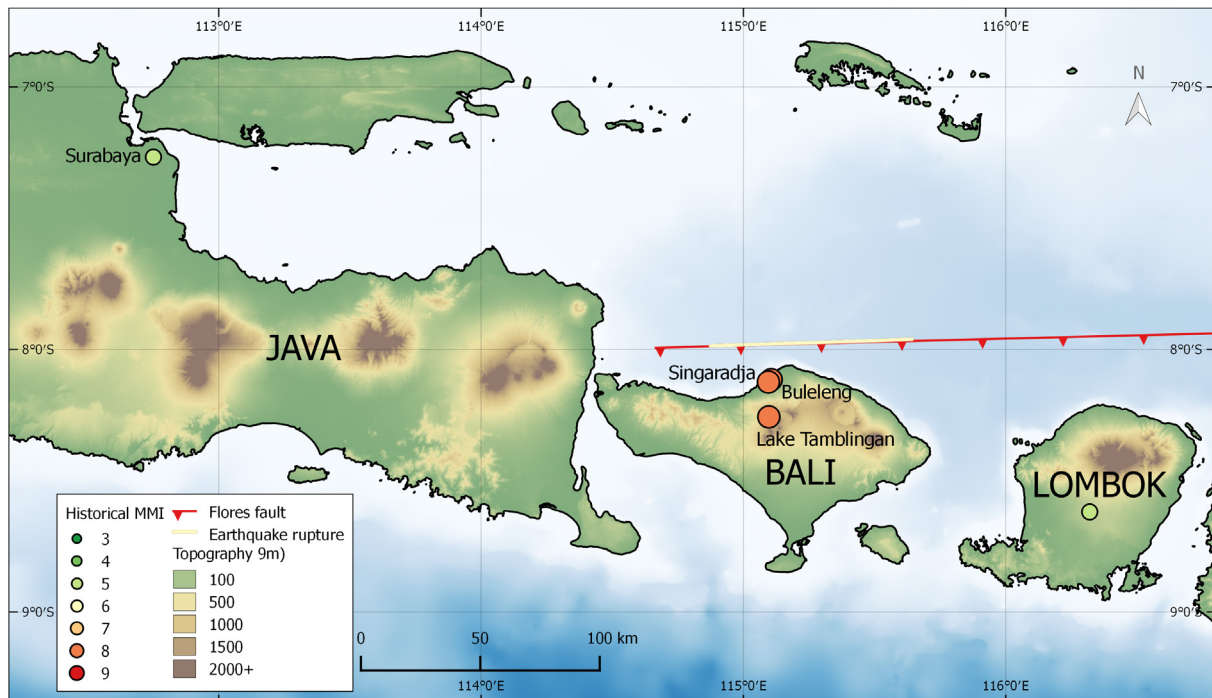


Figure 2.10 Distribution of observed MMI based on historical evidence, and Flores thrust zone with section of earthquake rupture for November 22, 1815 highlighted.

2.2.3.2 Scenario

Thrusting of the back-arc was first reported by Hamilton (1977; 1979). However, Hamilton's (1979) interpretation of the Flores fault extends from north of central Flores in the Flores Basin to north of central Sumbawa. Using digital seismic reflection profiles, Silver et al. (1983) propose the Flores fault extends further west into the Bali Basin. However, the Flores fault loses surface expression north of Lombok, and is argued to be present on the basis of complex folds in the Bali Basin (Silver et al., 1983). Furthermore, since 1991, all shallow (< 250 km) earthquakes with hypocentres in Bali and north of Bali were thrust events (Widiyantoro and Fauzi, 2005). Recent modelled convergence rates of 5.6 mm/year from Global Positioning System (GPS) measurements also support this (Susilo et al., 2014). Due to the ambiguity of the faulting north of Bali, the term Flores thrust zone (FTZ) is used here. The FTZ is a zone of thrusting that involves more than one related fault, mapped on the surface, with the assumption that the faults are connected at depth (Silver et al., 1986). The FTZ may be

connected with the Kendeng thrust fault in East Java, which in turn may be connected to the Baribis thrust fault (Simandjuntak & Barber 1996). In this report, scenarios for November 22, 1815 and December 29, 1820, have been modelled with the FTZ extending from the Flores Basin to the Bali Basin (Figure 2.10).

Between 1962 and 1984, eleven earthquakes with $M_w > 5.5$ occurred on the FTZ, eight of which occurred in the Bali Basin (McCaffrey and Nabelek, 1987). All eight events were shallower than 26 km (McCaffrey, 1988), and dip between 13° and 35° (McCaffrey and Nabelek, 1987). Using these boundaries, a series of earthquake simulations were modelled. The best-fit scenario, that is, modelled MMI most similar to historical MMI, was a M_w 7.3 at 10 km depth with a 30° dip (Table 2.8).

Table 2.8 Model parameters used for November 22, 1815.

Ground Motion Prediction Equation	ZhaoEtAl2006SInter
Moment Magnitude	7.3
Fault type	Reverse
Earthquake rupture co-ordinates	114.874° -7.996° 115.642° -7.971°
Earthquake rupture length	85 km
Hypocentre/ Depth	115.176° -7.987°/ 10 km
Rake	90°
Dip	30°

2.2.3.3 Results and Discussion

Modelled intensity results are between MMI 8 and 9 on the central north and eastern side of Bali, decreasing to MMI 7 and 8 on the southern half of the island, 'with the lowest MMI, between 6 and 7, occurring in western Bali (Figure 2.11). The lower MMI on the western tip of Bali is likely a result of distance from the hypocentre. For the majority of the island of Lombok, the modelled MMI is between 5 and 6, except along the central west coast where the modelled MMI is between 6 and 7, a result of site amplification. At Surabaya, modelled intensity is approximately MMI 5, matching that of the assigned historical MMI. The RMSE calculation for this event is 0.7.

An alternative source for this event would be from an intraslab fault in the Java trench however, there is insufficient historical data to test this scenario. It is also possible that the FTZ is located further north and another thrust or strike-slip fault runs parallel to the Flores back arc thrust fault (see interpretations by McCaffrey (1988)).

It is unclear if the tsunami was caused by a flank collapse or if a volcanic eruption had occurred on Bali. There is a high correlation between earthquake events and increased volcanic activity within the Indonesian region (Eggert and Walter, 2009), which can occur on the same day (Hill et al., 2002). Therefore, the possibility of volcanic induced earthquake activity cannot be ruled out.

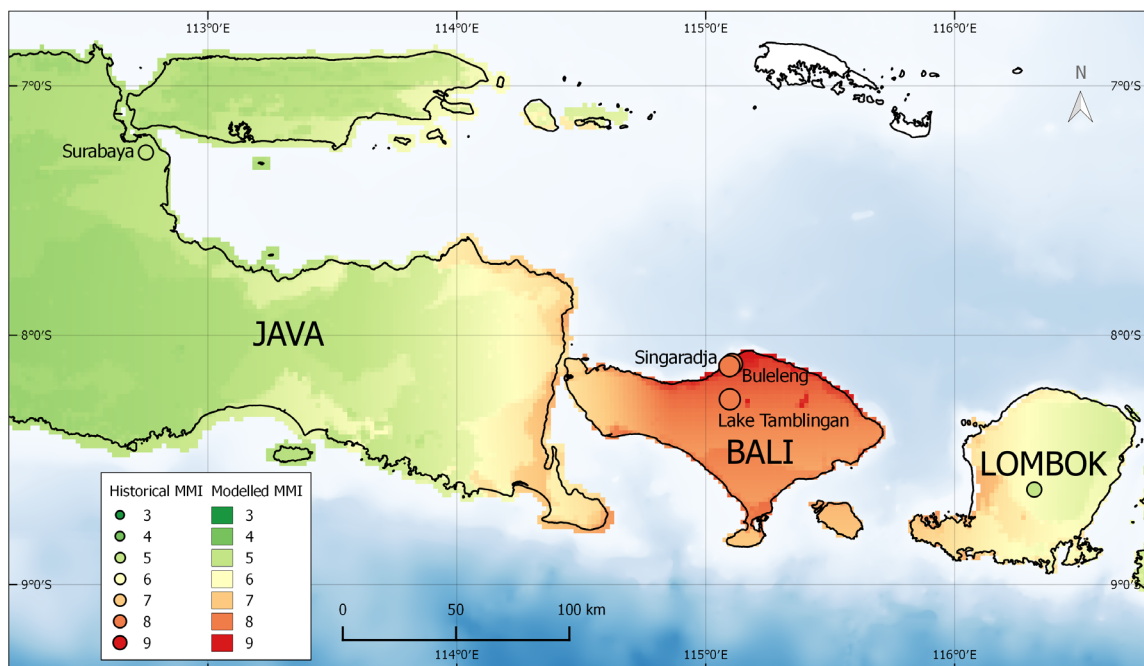


Figure 2.11 Modelled MMI results using parameters outlined in Table 2.8 for November 22, 1815.

2.2.4 December 29, 1820

2.2.4.1 Historical Account

On December 29, 1820, an earthquake occurred which generated large tsunami run-up in several locations, stretching from Sumenep (Java) to several localities along the southern coast of Sulawesi (Figure 2.12). At Bima (Sumbawa), the earthquake lasted over two minutes, followed by a strong tsunami which flung anchored ships in the bay far inland, uprooted houses and trees, and caused the collapse of many stone structures (Reinwardt, 1858). After the flood wave, mud covered the land and houses. Some people were killed by the collapse of buildings. Fissures formed in the ground, and many homes became uninhabitable, including that of the King of Bima (Reinwardt, 1858).

At Makassar (Makassar) on Sulawesi, the earthquake lasted two and a half minutes (*Bataviashe Courant* 28 April 1821, p. 1). It was also felt in other places on the south coast of Celebes (Sulawesi). A tsunami followed which destroyed villages from Bontain (Bonthain) in the west to Boelekombā (Bulukumba) in the east, including the villages of Terang-Terang and Nipa-Nipa (Roorda van Eysinga, 1830).

At Boelekombā (southern Sulawesi), the earthquake lasted approximately four to five minutes (Roorda van Eysinga, 1830). Fort Boelekombā was reported to have fluctuated to and fro whilst 6-pounder (c. 2.7 kg) cannons on the bastions hopped from their mountings (Wichmann, 1918). The earthquake was accompanied by a 18-24 m wave, which inundated 350-450 m inland (Roorda van Eysinga, 1830). Multiple vehicles were flung from the beaches into rice fields, and the barracks of the fort was destroyed. As a result of the tsunami, 400-500 persons died (Roorda van Eysinga, 1830).

At Sumanap (Sumenep, Madura Island), the earthquake lasted a minute and was followed by large waves of great force at 3 p.m. After half an hour, the river gently flooded (*Bataviasche Courant* 20 January 1821, No. 3). No damage was reported from the earthquake, however some small ships were damaged as a result of the tsunami. The earthquake was also felt on the island of Polaeë (Palu Island), off the coast of Flores (Reinwardt, 1858).

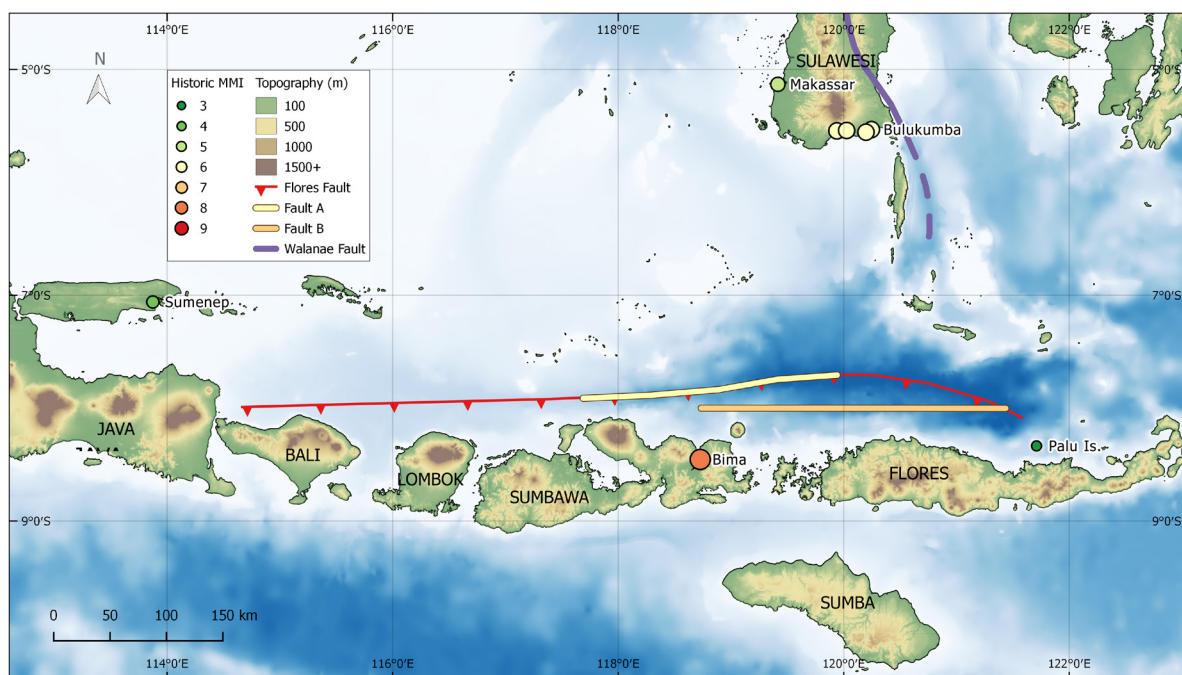


Figure 2.12 Distribution of observed MMI based on historical evidence, and Flores back-arc thrust fault zone with section of modelled earthquake rupture highlighted for December 29, 1820. Purple dashed line is Walanae Fault's inferred extent.

2.2.4.2 Scenarios

Harris and Major (in press) propose the Walanae fault to be the fault source for this event, based on the height of tsunami inundation and the duration the earthquake at Belekomba (Bulukumba). As shown in Figure 2.12, the Walanae fault runs NW-SE between southern Sulawesi and Flores, and is thought to accommodate mostly sinistral strike-slip motion, although it may have a thrust component. An earthquake on the Walanae fault may produce strong ground shaking and possibly a large tsunami at Belekomba. Although earthquake duration is reportedly longer at Belekomba and Makassar than Bima and Sumanep, this may be influenced by a number of factors such as soil depth in the sedimentary basin and human perception.

Harris and Major (in press) do not discuss whether the 1820 earthquake could have occurred along the Flores back-arc thrust, even though this could better explain the strong shaking and tsunami inundation observed at Bima on Sumbawa. Active back arc thrusting of the Flores fault occurs beneath the volcanic arc dipping at 30° (McCaffrey and Nábělek, 1984). Assuming the hypocentre of the earthquake was on the FTZ, multiple magnitude events were modelled using this boundary condition. The scenario with the best outcome (i.e. modelled MMI with the closest matching results to historical MMI) was a M_w 8.4 with a hypocentre at 30 km depth (Table 2.9). However, outcomes from tsunami modelling using Clawpack's GeoClaw V.5.3.0 (The Clawpack Development Team, 2015), indicate that the fault must be further east, for example an earthquake rupture along Fault B (Table 2.10), to produce a tsunami as high as 10 m. While this is only about half the reported height of 18–24 m, these reports are vague – e.g., whether they refer to run-up or tsunami height is unclear. However, according to the historic account by Roorda van Eysinga (1830), villagers had to swim or float to safety as houses and roofs floated by. Hence, we are assuming that, even when exaggerated, it was probably higher than 10 metres.

Table 2.9 Model parameters for Fault A for December 29, 1820.

Ground motion prediction equation	ZhaoEtAl2006SInter
Moment Magnitude	8.4
Fault Type	Reverse
Fault co-ordinates	117.695° -7.915° 119.950° -7.710°
Earthquake rupture length	250 km
Hypocentre/ Depth	118.890° -7.835°/ 30 km
Dip	30°
Rake	90°

Table 2.10 Model parameters for Fault B for December 29, 1820.

Ground motion prediction equation	ZhaoEtAl2006SInter
Moment Magnitude	8.4
Fault Type	Reverse
Fault co-ordinates	118.735° -8.0° 121.440° -8.0°
Earthquake rupture length	300 km
Hypocentre/ Depth	120.0° -8.0°/ 10 km
Dip	35°
Rake	90°

2.2.4.3 Results and Discussion

Modelled MMI results for a M_w 8.4 at 30 km depth (Fault A) occurring on the Flores fault would result in high intensity (MMI 8-9) across most of Sumbawa and western Flores (Figure 2.13). If an earthquake rupture occurred along Fault A, then Makassar, Bulukumba, and Bonthain would experience MMI 6, matching historical reports. However, the model overestimates the intensity for Sumenep, and probably for Palu Island too. The intensity modelled at Sumenep is MMI 5 rather than the MMI 4 that was observed. On the other hand, Palu Island may have experienced the MMI 6 that was modelled, but there is not enough historical data to support this. Reports that the earthquake was felt on Palu Island do not shed light on the extent of the earthquake's intensity. There are no reports of the amount of damage (if any) west of Bima and as such, the moment magnitude may have been larger than modelled.

If the earthquake occurred farther to the east, on Fault B (Figure 2.14), then modelled shaking intensity at Bonthain and Bulukumba is less than was historically reported, that is, MMI 5.8 as opposed to MMI 6.1 as modelled in Fault A. The RMSE for Fault A is 1.4, whereas the RMSE for Fault B is 1.8. Outcomes from tsunami modelling show that 34 m of thrust movement on Fault B could produce a tsunami as large as 10 m just offshore Bulukumba (Figure 2.15). It is not implausible that such high slip may have occurred at least in the eastern part of Fault B where it is required to produce a tsunami commensurate with that observed.

The idea that an earthquake along the Flores back-arc thrust could affect Sulawesi is supported by a more recent event. In 1992, December 12 a M_w 7.9 (focus depth = 16 km) earthquake struck Flores, generating a 25 m high tsunami killing more than 2 000 people (Beckers and Lay, 1995). The event was felt with intensity MMI 4 near Makassar, Sulawesi.

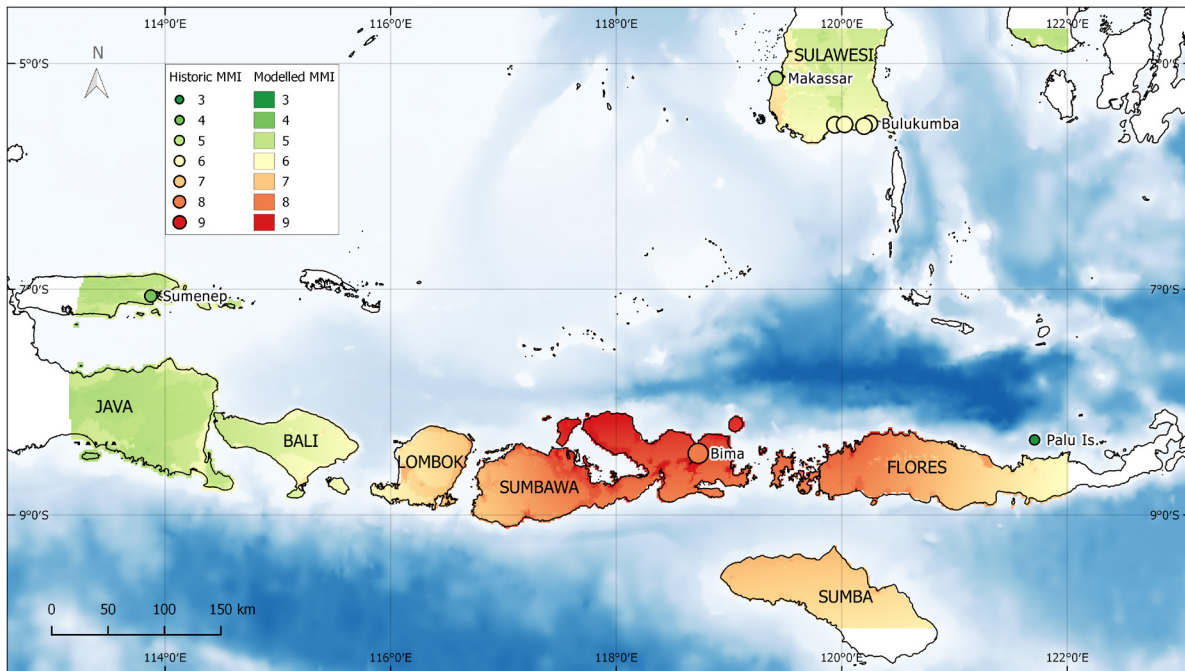


Figure 2.13 Modelled MMI results using parameters outlined in Table 2.9 for December 29, 1820.

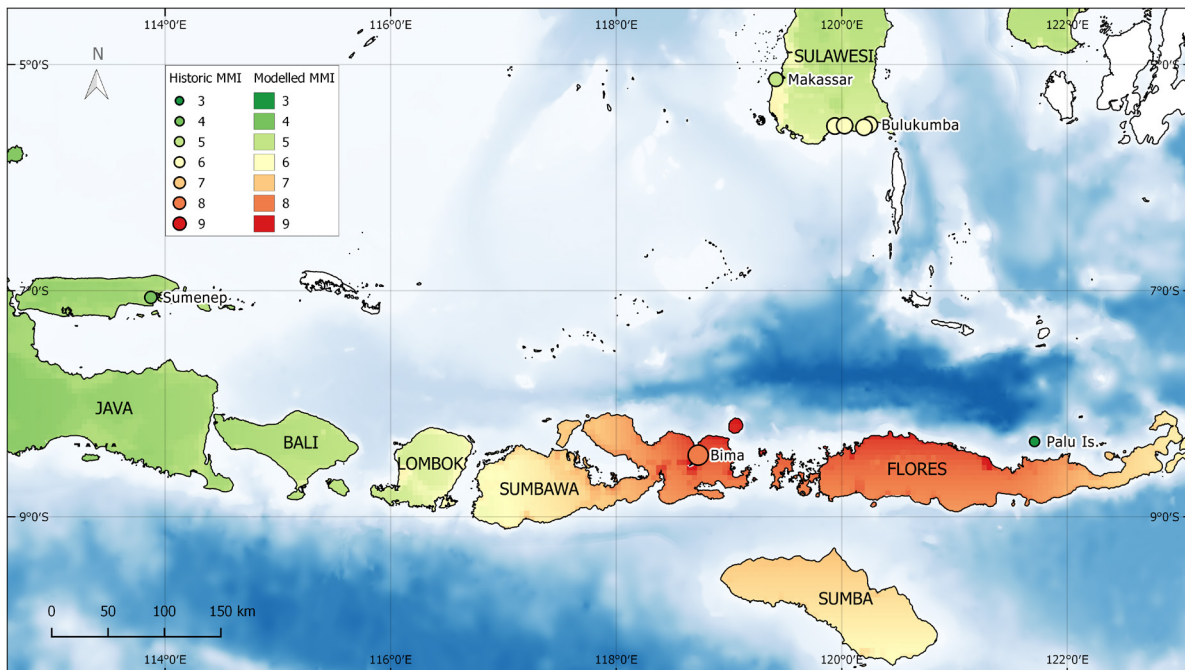


Figure 2.14 Modelled MMI results using parameters outlined in Table 2.10 for December 29, 1820.

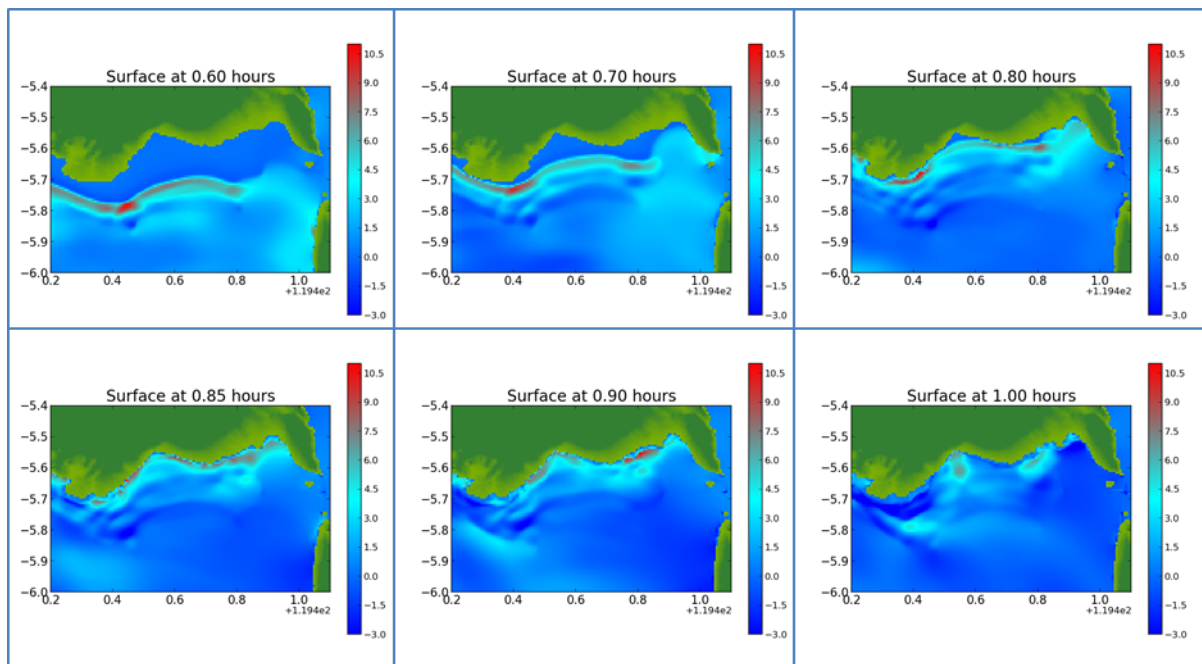


Figure 2.15 Tsunami heights (metres) arriving at southern Sulawesi at time intervals 0.6, 0.7, 0.8, 0.85, 0.9 and 1 hour after initial fault rupture.

A similar event occurred on Bima when it was damaged by a severe earthquake and tsunami again on November 28, 1836 (M_w 7.5 (Musson, 2012)). Again, the earthquake was also felt in Makassar, suggesting the fault source was highly active. Furthermore, Bima experienced an earthquake in 1818 that may be linked with a widespread earthquake that occurred on 8 November, over East Java, and a volcanic eruption that occurred on the same day. Thus, there may be a pattern of stress release from left to right along the Flores back-arc thrust. This is evidenced by an event in 1815, one that occurs in 1818 and then another one further east in 1820.

Note that the tsunami arrival time in Sumenep (3 p.m., 5 hours after the earthquake) may not be reliable because Indonesia's time zones were systematised in *circa* 1912, on the basis of 6 time zones for all of Indonesia. Prior to this, every location in Indonesia had its own time zone, and there was no uniformity (Reid, pers. comm. 2015). Modelling of a tsunami on the Flores back-arc thrust resulted in a tsunami arriving at Sumanep as early as 2 hours after the earthquake, but for the case of Fault B there was a larger, second wave that arrived about 5 hours after the earthquake.

2.2.5 October 10, 1834

2.2.5.1 Historical Account

A series of small shaking events on the night of October 10, 1834, were preceded by a 'great concussion' in the early morning, felt in Batavia (Jakarta), Bantam (Banten), Krawang (Karawang), Buitenzorg (Bogor), and Preanger (Priangan) Residencies. The ground shaking was felt as far as Tagal (Tegal) (Central Java) in the east to Lampongs (Lampung) in Sumatra in the west (*Javasche Courant* 22 November 1834, No. 94) (Figure 2.16). Musson (2012) stated that the minimum likely magnitude was M_w 7.0. Damage by regency is described below.

Batavia (Jakarta) Residency:

- Several houses and stone buildings including the palace in Weltevreden (Paleis van Daendels/Het Groot Huis, Governor General Palace, recently it has become the Ministry of Finance Building) was damaged. A country warehouse and a number of townhouses were also damaged.
- Stone houses in Tjilangkap (Cilangkap, East Jakarta) were partially or greatly damaged.
- Shaking was considered as worst earthquake ever to strike the region, dismay was widespread in Batavia, however no injuries were reported.

Buitenzorg (Bogor) Residency:

- Almost all stone buildings were rendered uninhabitable or were very badly battered and partially collapsed.
- A major portion of Buitenzorg Palace (Istana Bogor, Bogor City) collapsed, including the northern part of the central building, the exterior wall of the eastern wing and the northernmost remittances.
- A large stone house in Tjitrap (Citeureup) collapsed
- The postal station in Tjiandjavar (Cihanjavar) was completely buried under the earth, which killed 5 people and 10 horses.
- As a consequence of the earthquake, debris had jammed the river Tjiandjavar. When the jam was dislodged, a violent inundation occurred which carried the postal station along with masses of earth, stones and trees downstream.
- Stone houses were damaged at Kedung Allang (Kedung Halang), Tjitrap, Tjimangis (Cimanggis, Depok) and Pondok Tjina (Pondok Cina, Depok).
- Smaller shaking was felt in Tjileboet (Cilebut) and Koripan (Kuripan, Ciseeng) in present-day Bogor Regency, and in Pondok Terong, Sawangan, and Cineri (Cinere) in present-day Depok.

Parahyangan (Preanger) Residency

- Many buildings in Tjanjor (Cianjur), the capital city, collapsed or were rendered uninhabitable. The Regent's house partially collapsed and the prison was torn apart.
- Ground cracks were found on the rear slope of Mt. Gede and on the road between Buitenzorg and Tjanjor.
- Closer to the mountain, many wooden and bamboo houses were overturned.

Krawang (Karawang) Residency

- Stone houses in Pondok Gede, Krangan (Kranggan, Bekasi City) were greatly or partially damaged.

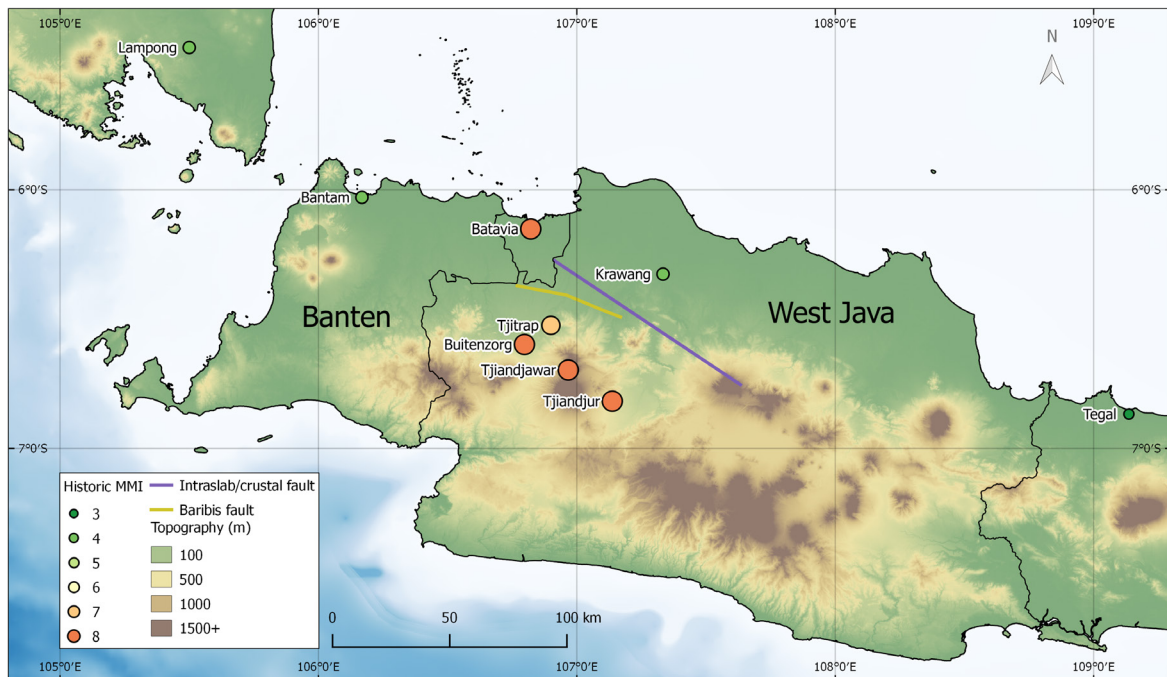


Figure 2.16 Distribution of observed MMI based on historical evidence, and fault traces used to model ground motion shaking for October 10, 1834.

2.2.5.2 Scenarios

Batavia (Jakarta) and Buitenzorg (Bogor) were highly affected (MMI 8) by this event as had been experienced 35 years earlier. In addition, Tjanjor (Cianjur) was reported to have experienced strong shaking (MMI 8). On the other hand, there was no damage reported from Lampongs (Lampung), and lower intensity was felt in Bantam (MMI 5). The similarity of the distribution and intensity of the area affected indicates the epicentre of this earthquake may be close to or similar with 1699 but with a smaller magnitude. With this in mind, three scenarios were modelled for this earthquake event. These are Scenario A: Baribis thrust (Table 2.11), Scenario B: crustal fault (Table 2.12), and Scenario C: intraslab (Table 2.13).

Table 2.11 Model parameters for Scenario A: Baribis thrust.

Ground Motion Prediction Equation	BooreAtkinson2008
Moment Magnitude	7.0
Fault type	Reverse
Earthquake rupture co-ordinates	107.169° -6.492° 106.769° -6.371°
Earthquake rupture length	45 km
Hypocentre/ Depth	106.958° -6.470°/ 12 km
Rake	90°
Dip	45°

Table 2.12 Model Parameters for Scenario B: crustal fault

Ground Motion Prediction Equation	BooreAtkinson2008
Moment Magnitude	7.0
Fault type	Strike-slip
Earthquake rupture co-ordinates	106.430° -6.314° 106.814° -6.361°
Earthquake rupture length	45 km
Hypocentre/ Depth	107.203° -6.543°/ 70 km
Rake	0°
Dip	90°

Table 2.13 Model parameters for Scenario C: intraslab

Ground Motion Prediction Equation	AtkinsonBoore2003SSlab
Moment Magnitude	7.7
Earthquake rupture co-ordinates	106.914° -6.275° 107.633° -6.753°
Earthquake rupture length	97 km
Hypocentre/ Depth	106.914° -6.275°/ 180 km
Rake	-90°
Dip	45°

2.2.5.3 Results and Discussion

Results from Scenario A, a M_w 7.0 on the Baribis thrust (Figure 2.17) gave a good fit with observed MMIs of the 1834 earthquake event, especially for areas that were most affected. Based on the reports, areas most affected were Batavia, Buitenzorg, Tjanjor and Tjiandjavar, where the landmarks, such as palaces and the Regent's house were partially collapsed and mega-landslides occurred. Strong shaking would have been needed to ruin well-constructed buildings such as the palace and to trigger a huge landslide. A minimum intensity of MMI 8 is required to cause such damage. Simulated MMI based on the Baribis thrust predicted intensity between 8 and 9 in those areas which fit well with reported intensity. However, Scenario A produced high intensity in Bantam, Krawang and Tegal where there were no reports of significant damage. This may be due to historical bias. Since the source depth is set at 12 km, ground motion shaking concentrated mostly near the fault. As the distance increases from the source, intensity decreases, except for certain areas where site amplification caused high intensity.

However, simulated intensity was over predicted for all of Bantam, Krawang and Tegal in the crustal model in Scenario B (Figure 2.18).

In Scenario B, by changing the movement sense and depth into a strike-slip fault (Figure 2.18), the simulation gives similar results for Batavia, Buitenzorg and Tjanjor; where those cities experienced intensity of MMI 8. At Tjiandjavar the modelled intensity was MMI 7, lower than results from Scenario A. On the other hand, Scenario B gives a better prediction for Tegal; the simulation gave intensity of MMI 5 while the reported intensity was MMI 4. The area that experienced the maximum intensity of MMI 9 decreased as the source depth increased because energy radiated further compared to Scenario A in which the source was shallower.

In Scenario C (Figure 2.19), a M_w 7.7 intraslab earthquake at 180 km depth was simulated. The ground shaking intensity resulting from this scenario is MMI 7-8 on the north coast of West Java, including Batavia and Bantam. The intensity in Batavia is slightly underpredicted compared to the intensity inferred from historical data as at that in Buitenzorg, Tjiandjavar and Tjanjor. Conversely, the intensity in Bantam and Krawang is over predicted. In Tegal and Mt. Gede, simulated intensity was MMI 6, which is over predicted in comparison with the historical data. When the magnitude increases, intensity increases by one level for the whole area except Buitenzorg and Tjanjor, which are situated on mountainous areas. The RMSE for Scenarios A, B and C are 1.8, 1.9, 1.7 respectively.

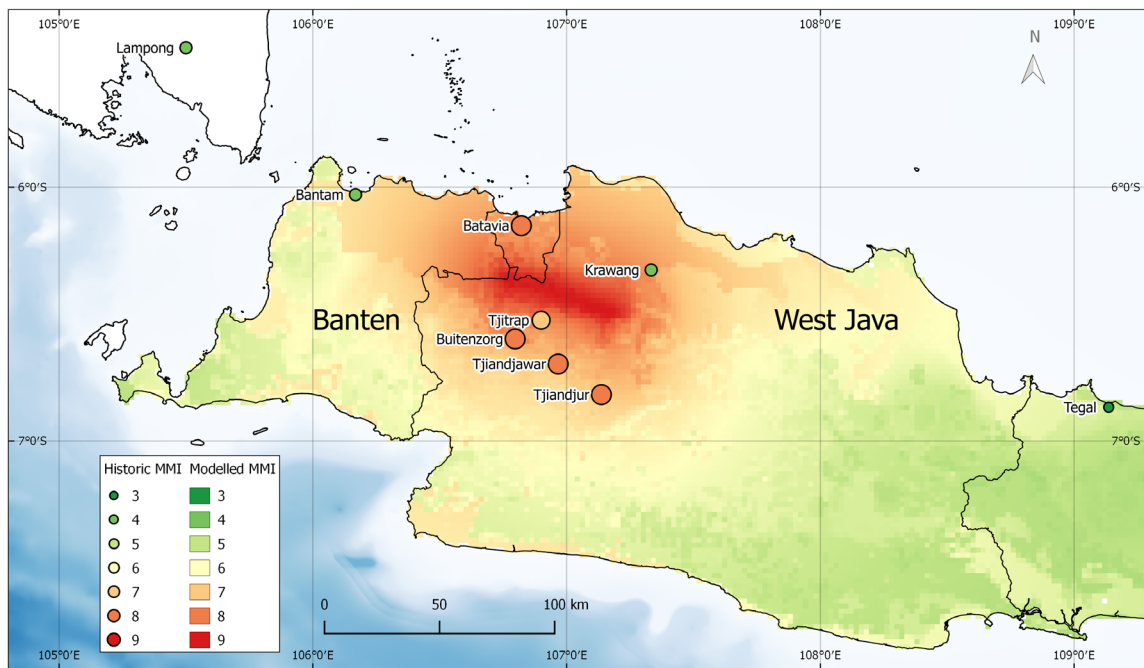


Figure 2.17 Modelled MMI result for Scenario A: Baribis thrust for October 10, 1834.

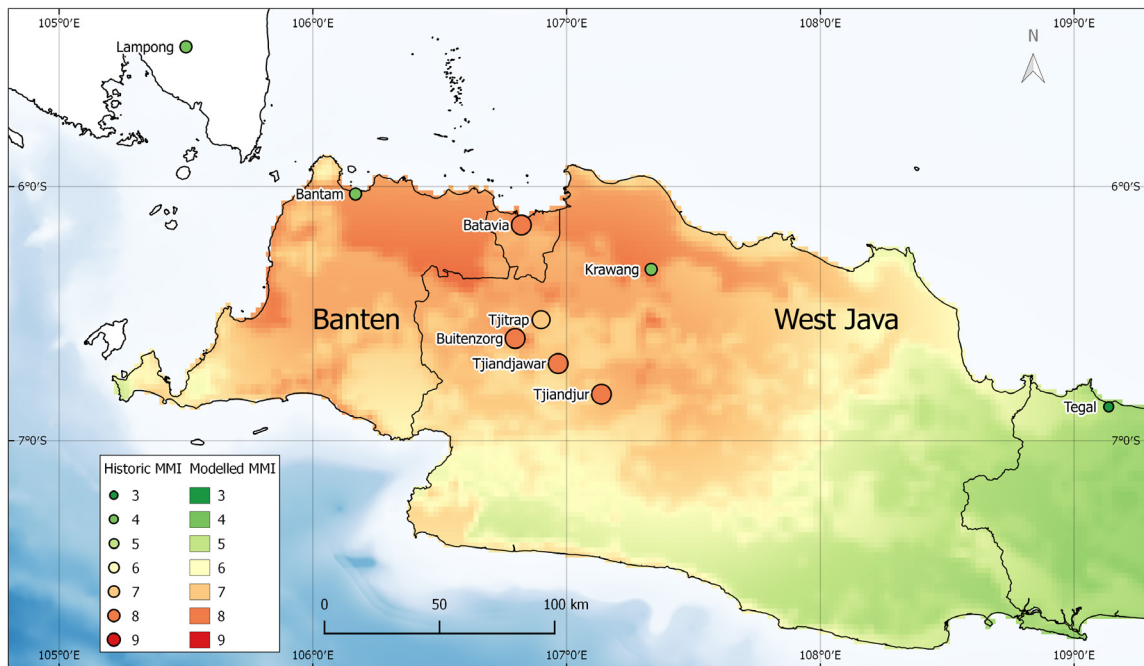


Figure 2.18 Modelled MMI results for Scenario B: crustal fault for October 10, 1834.

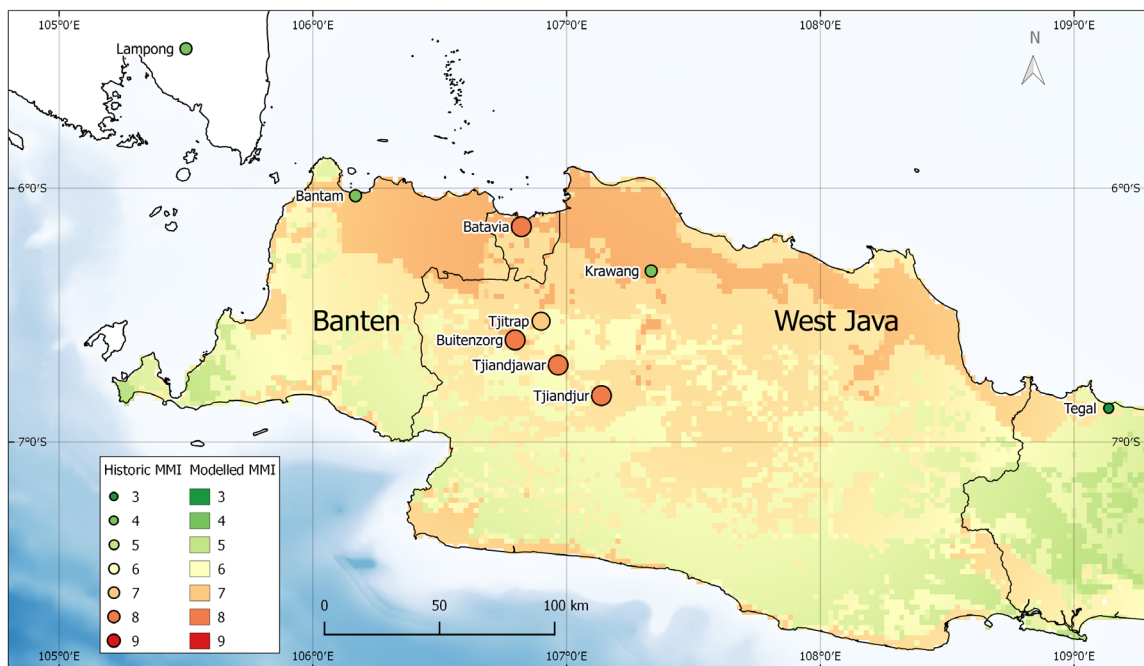


Figure 2.19 Modelled MMI results for Scenario C: intraslab for October 10, 1834.

Although results from the three scenarios (Baribis Thrust (Scenario A), crustal fault (Scenario B) and intraslab (Scenario C)) produced similar intensities to that historically observed, and have similar root mean squared errors, Scenario A fits better with historical data in cites that suffered less damage such as Bantam and Krawang. At the same time, the M_w 7.0 thrust earthquake in this scenario produced large ground shaking that concentrated around Jakarta, Bogor and Cianjur, therefore the spatial distribution of ground shaking for this scenario best matches the observed data because modelled intensities cannot match localities. Intensities at individual localities may match.

2.2.6 January 4, 1840

2.2.6.1 Historical Account

On January 4, 1840 a large earthquake was felt over most of Central Java (Figure 2.20). At 1:15 p.m. local time in Semarang, Demak and Salatiga the earthquake was felt for about two minutes (*Javasche Courant* 15 January 1840, p.1). At Semarang, the walls of the bastions had collapsed, and significant cracks formed in the walls of the Catholic church and the Citadel (Reiche, 1859). A small portion of the main road near Kendal had collapsed (Reiche, 1859). Further north, in Japara and Pati the earthquake was felt for about 15 seconds. In the Residency of Pekalongan, two powerful shocks were reported. In Central Java, at Ambarawa and Fort Willem I, the earthquake caused 113 significant cracks and 640 small cracks to buildings (van Musschenbroek, 1867).

Further south, in Saporan (Sapuran) several buildings collapsed causing injury, and those that did not collapse suffered badly (Algemeene Konst-en Letterbode, 1840). In the Residency of Bagalen, two shocks were felt for almost a minute (Reiche, 1859). In Poeworedjo (Purworejo) two buildings collapsed injuring several people, and many other stone buildings were damaged. Also in Purworejo, cracks formed in the bridge over the Bogowonto River (Reiche, 1859). In Wonosobo, buildings were heavily damaged. It was also felt in Banjoemaas (Banyumas) for over 30 seconds (Algemeene Konst-en Letterbode, 1840). In Djocjakarta (Yogyakarta) three shocks were felt for over one minute and caused people to prostrate. The earthquake was felt as far as Kediri (Reiche, 1859).

In Patjitan (Pacitan), an earthquake was felt on the 4th of January between 1 p.m. and 2 p.m., which lasted almost two minutes, accompanied by a subterranean rumbling. Shocks repeated on the night of the 5/6th, and one at 6 a.m. on the 6th was reported to have been violent (*Javasche Courant* 22 January 1840, No. 7). The event was followed by smaller vibrations until the end of the month (Reiche, 1859). Some cracks in the buildings were reported (Reiche, 1859), but it is unclear if these cracks were a result of the main event or the aftershocks. According to Harris and Major (in press), a flood wave followed the earthquake in Patjitan, however this was not in any of Wichmann's (1918) original references.

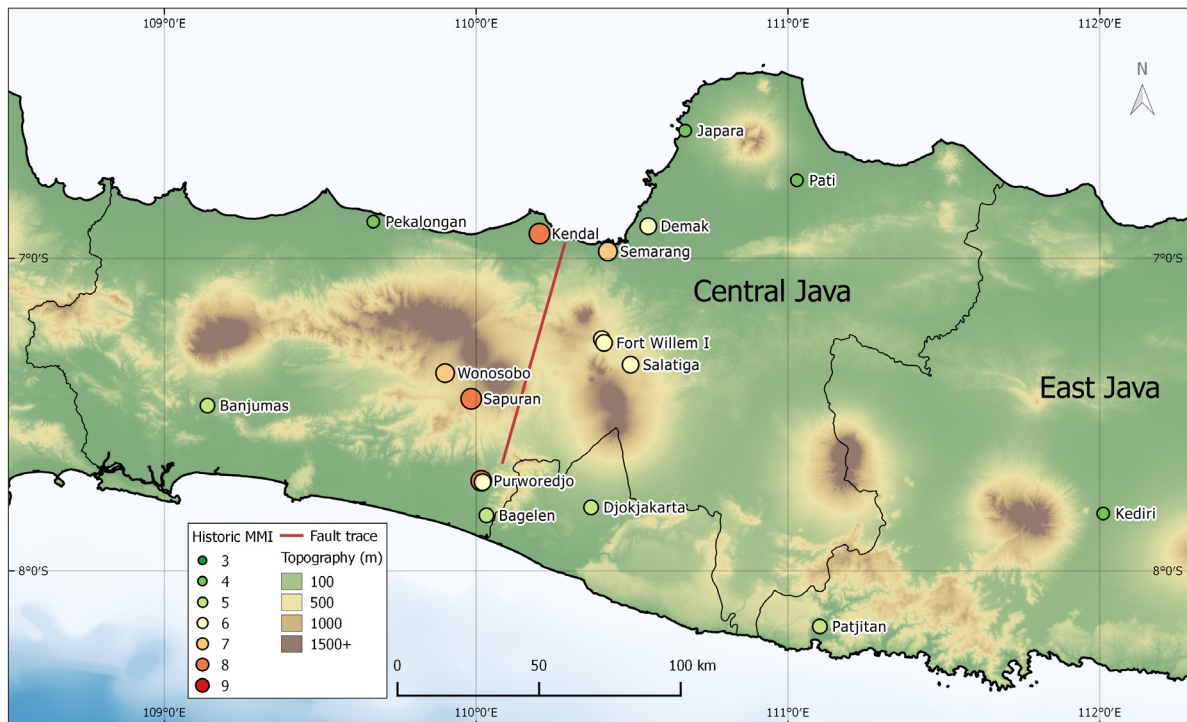


Figure 2.20 Distribution of observed MMI based on historical evidence, and fault trace used to model ground motion shaking for January 4, 1840.

2.2.6.2 Scenario

Using current geological interpretations of Java, the Luk-Ulo suture or Muria-Progo lineament is the best fitting feature for this event based on the distribution of historical MMI. Smyth et al. (2005) defined the Progo-Muria fault as a significant NE-SW trending structure that marks sudden changes in gravity anomalies of the Kendeng Depocentre and Rembang High. Hall et al. (2007) re-named it the Muria-Progo lineament and considered it the most fundamental structural division that separates Central and East Java. To the east of this inferred fault, the basement of the Southern Mountains is Archean continental crust whereas to the west it is Cretaceous ophiolitic rocks (Hall et al., 2007). Satyana (2007) also suggested a NE-SW fault in a similar position, the Muria-Kebumen fault. Hall et al. (2007) suggest they are a conjugate pair of strike-slip faults that bound Central Java.

There is no surface evidence of strike-slip movement on either of the faults, but they have similar orientation to other faults in East Java (e.g. Opak fault, Lasem fault). Supporting evidence for the presence of the lineament can be found from recent GPS plate motion measurements (Koulali, unpub. data). Based on GPS measurements of plate motion movements (Koulali, unpub. data), we place the structural division further west (in Central Java) (Figure 2.20). Using this approximate location for the inferred fault, a number of scenarios were modelled, and the parameters resulting with the best fit to the observed MMI are outlined in Table 2.14.

Table 2.14 Model parameters for January 4, 1840.

Ground Motion Prediction Equation	ChiouYoungs2008
Moment Magnitude	6.5
Fault type	Strike-slip
Earthquake rupture co-ordinates	110.284° -6.953° 110.084° -7.653°
Earthquake rupture length	80 km
Hypocentre/ Depth	110.162° -7.381° / 10 km
Rake	0°
Dip	90°

2.2.6.3 Results and Discussion

If a M_w 6.5 had occurred on a strike-slip fault along the proposed locality of the Muria-Progo lineament then Kendal, Semarang, Purworejo and Sapuran would have experienced intensities around MMI 7 and 8 (Figure 2.21). Modelled MMI (6.5) is lower than observed MMI (7) for Wonosobo. One of the reasons for this discrepancy may be due to the site amplification (V_{S30}) applied. Wonosobo and the surrounding mountainside may have experienced higher damage as a result of topographic amplification (Murphy, 2006; Lee et al., 2010). The RMSE calculation for this event is 1.6.

The modelled MMI matches historical MMI for Banyumas, Pacitan and Ambarawa, but is higher for Yogyakarta and Demak. This is probably because Yogyakarta and Demak are classified as sedimentary basins with high site amplification. However, the V_{S30} applied may be over estimating the site amplification. According to the Smithsonian global volcano program (Smithsonian Institute, 2013) there was a confirmed volcanic eruption from Gunung Merapi at the time of this event, however the historical records merely mentions that it smoked (Anon 1840, p.383).

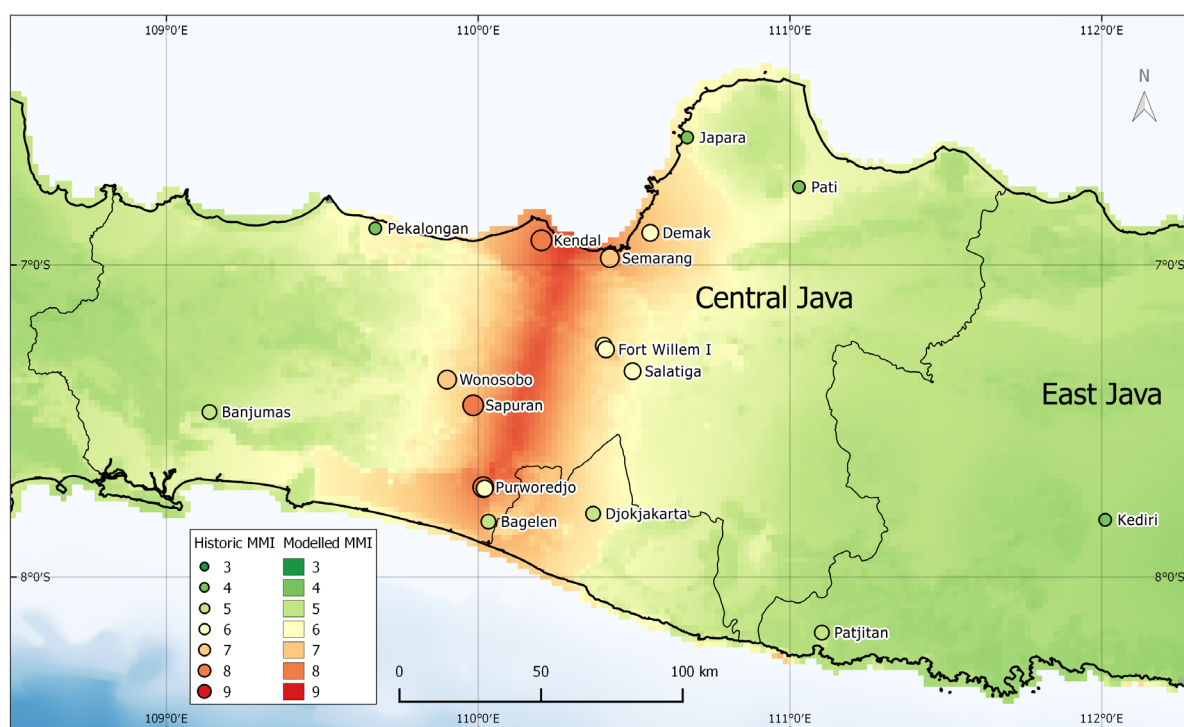


Figure 2.21 Modelled MMI results using parameters outlined in Table 2.14 for January 4, 1840.

2.2.7 November 16, 1847

2.2.7.1 Historical Account

The historical earthquake event that occurred on November 16, 1847, was felt intensely over most of West Java (Figure 2.22). It was also felt in Central Java and in the Province of Lampung, Sumatra. The total distance over which the earthquake was felt was approximately 700 km. Based on historical reports the most impacted region was in the Regencies of Indramajoe (Indramayu) and Cheribon (Cirebon) (Junghuhn, 1954). Other Regencies that were also affected include Madjalengka (Majalengka), Koeningan (Kuningan), Sumedang, Bandong (Bandung), Batavia (Jakarta), Buitenzorg (Bogor), and Bantam (Banten) (Junghuhn, 1954).

In Batavia, two violent shocks were felt. The first shock at 10:18 a.m. lasted approximately 8 seconds, and the second at 10:25 a.m. lasted 12 seconds. With the exception of October 1834, the earthquake was said to have been the largest in the last 30 years (*Javasche Courant* 20 November 1847, p.1).

Three shocks at intervals of 5 to 10 minutes were felt from about 10:30 a.m. in Buitenzorg (Junghuhn, 1954). In Preanger Residency, the earthquake was felt at various localities; in Bandjaran (Banjaran) three shocks caused the swaying motion of wooden buildings, and in Sumedang the stone house of the Assistant-Resident was damaged to an uninhabitable degree (Versteeg, 1859).

The earthquake caused extensive damage to government buildings and the fort, along with the collapse of over 40 houses belonging to the Chinese in the District of Indramajoe (*Javasche Courant* 24 November 1847, No. 94). In addition, fissures 1 - 2 feet (30 - 60 cm) wide formed in the ground in other areas of the Regency of Indramajoe (*Javasche Courant* 24 November 1847, No. 94). At Boentamatii, 24 km south of Indramajoe, all residences collapsed (*Javasche Courant* 20 November 1847, No. 93).

According to the *Javasche Courant* (24 November 1847, No. 94), the earthquake was most severe in the northern and western Residency of Cheribon. Ground shaking began at around 10:45 a.m. and lasted for almost 30 seconds. Moments later a similar one followed and by 11:05 a.m. the most intense shaking, lasting 61 seconds, was observed. The earthquake was so fierce that few buildings could withstand it. From then until midnight another 13 shocks were observed. A quiescent period followed but by 6 a.m. on the 17th the earthquakes began again with renewed vigour. Nine earthquakes were felt between 6 a.m. and 10 a.m., one of which lasted about 31 seconds. As a consequence of the violent shaking, the capital of Cheribon was in ruins. All government buildings, with the exception of wooden structures such as storehouses, were heavily damaged. Over 200 private stone dwellings were heavily damaged and uninhabitable. Numerous aftershocks continued to be felt up to the 20th of November at Cheribon (*Javasche Courant* 24 November 1847, No. 94).

Elsewhere in the Residency of Cheribon, extensive damage was also reported. Residential and government buildings collapsed in Tomo, Palimanang (Palimanan), Ardjowinangon (Arjawinangun), Glagamidang, Radjagaluh (Rajagaluh), and Pamankiran. Building collapse and ground ruptures occurred in Tjiboeloe (Cibuluh), Dana Radja (Darmaraja?), Genting and Persana (*Javasche Courant* 27 November 1847, No. 95).

The earthquake was also felt in Lampung (Lampung, Sumatra). In Natar, a village located at the foothills of Gunung Rate (Mt Ratai), an earthquake was felt at 10:38 a.m. and then another two at intervals of 4 or 5 minutes. The same earthquakes were also felt in the villages at the foothills of Guenoeng Radja-Bassa (Mt. Rajabasa) (*Javasche Courant* 22 December 1847, No. 105).

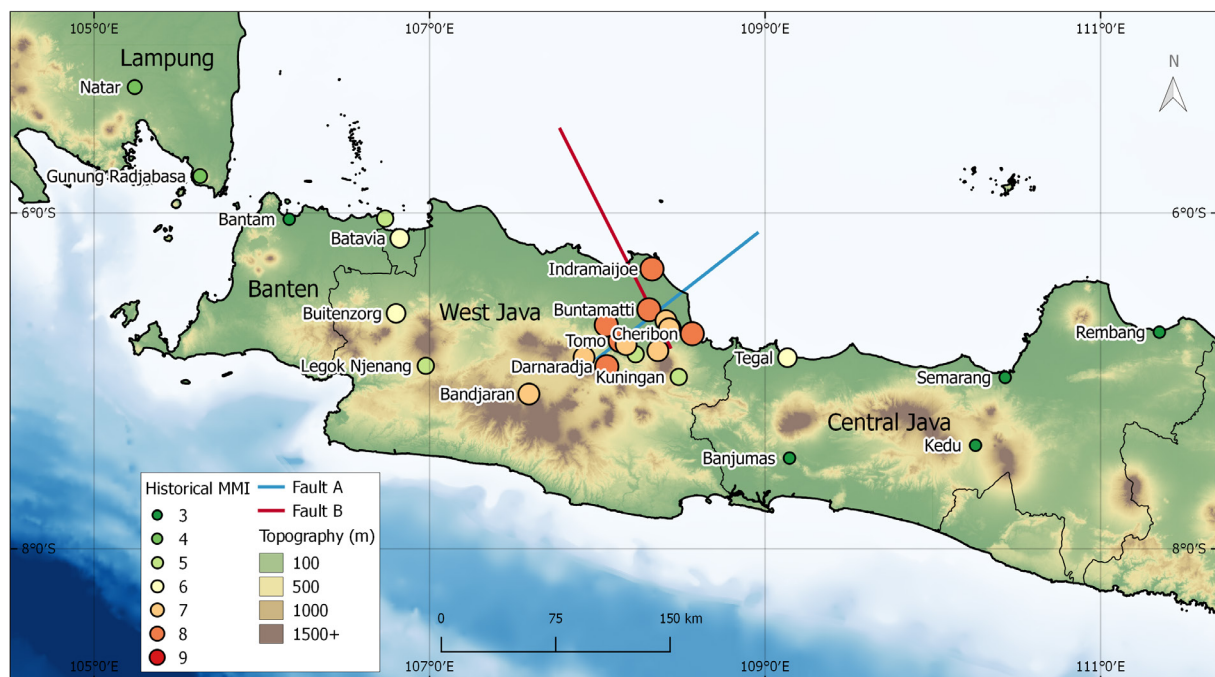


Figure 2.22 Distribution of observed MMI based on historical evidence, and fault traces used to model ground motion shaking for November 16, 1847.

2.2.7.2 Scenarios

Several small faults have been identified in Indonesia's current geological surveys of present Indramayu, Cirebon and Majalengka regencies. However, current mapped faults are between 5-10 km long and do not have the capacity to generate a large earthquake with a magnitude that would be large enough to cause destruction matching that seen in the historical record. Likewise, modelled results on the Baribis thrust fault do not produce MMI distributions that are similar to historical MMI. If there was a large earthquake event on the Baribis thrust fault, there should have been greater damage reported in the historic regencies of Sumedang, Bandung, and Majalengka. However, the greatest intensities were seen in the historic regencies of Indramayu and Cirebon. Consequently, two faults are proposed; Fault A (Table 2.15) and Fault B (Table 2.16). Fault A begins to the east of the Baribis thrust; both Fault A and the Baribis thrust fault can be clearly seen in aerial photography and geological sedimentology maps. Fault A follows the river Cimanuk downstream and continues off the coast of Java near Karangampel into the Java Sea. Both proposed faults produced similar intensity to the historical earthquake event when certain parameters were used. In Scenario A, a M_w 7.5 at 10 km depth along a NW to SE direction was needed to closely match the historically assigned MMI. However, in Scenario B, a M_w 7.6 at 15 km depth along a NE to SW orientation was used to achieve MMI patterns similar to the historical record.

Table 2.15 Model parameters for Scenario A: Fault A

Ground Motion Prediction Equation	ChiouYoungs2008
Moment Magnitude	7.5
Fault type	Strike-slip
Earthquake rupture co-ordinates	108.000° -6.865° 108.955° -6.120°
Earthquake rupture length	130 km
Hypocentre/ Depth	108.335° -6.600°/ 10 km
Rake	0°
Dip	90°

Table 2.16 Model parameters for Scenario B: Fault B

Ground Motion Prediction Equation	ChiouYoungs2008
Moment Magnitude	7.6
Fault type	Strike-slip
Earthquake rupture co-ordinates	107.778° -5.501° 108.435° -6.799°
Earthquake rupture length	160 km
Hypocentre/ Depth	108.335° -6.600°/ 15 km
Rake	0°
Dip	90°

2.2.7.3 Results and Discussion

In Scenario A, modelled results are between MMI 8-9 at Sumedang, Pamankiran, Darmaraja, Boentamatii, Ardjowinangon, Palimanang and Pamankiran (Figure 2.23). Similarly, modelled results are between MMI 7-8 at Cheribon and Indramajoe. However, modelled MMI (5) is lower than observed MMI (7) at Bandjaran. A possible reason for this inconsistency is that the current GMPE and site amplification do not factor in topographic amplification. Topographic amplification occurs at ridge crests and the reverse is seen in canyons and hill valleys (Murphy, 2006). It may also have higher historical MMI because the soil on top of the topography, such as colluvium, is unconsolidated and therefore structures built on there are more prone to collapse (Havenith et al., 2003). At Batavia and Buitenzorg the model matches perfectly. However, modelled MMI (6) is higher than historic MMI (4) at Semarang. Similarly, modelled MMI is overestimated at Banyumas, Kedu, Rembang, Bantam, and Natar. This discrepancy may be caused by both site amplification and a lack of historical damage report. The RMSE for Scenario A is 1.6.

Results in Scenario B give Indramajoe and Cheribon higher MMI than in Scenario A. Modelled intensity is high with MMI between 7 and 9 in the outer divisions of Cheribon Residency (Figure 2.24). Historically, the concentration of ground rupture is located north of Sumedang and in Indramayu. Although significant structural damage has been reported in Cheribon, no ground rupture was reported. Additionally, there is less damage reported to the south of Mt. Cereme, but the historical record may bias these factors. Results of modelled MMI for Fault B suggests Indramayu (8.4) may have experienced stronger intensity than Cheribon (8.2), matching historical data. But, Fault B overestimates intensity in Kunungan Regency and at Tegal, and underestimating at Bandjaran. The RMSE for Scenario B is 1.7.

The fault lengths were calculated using Wells and Coppersmith's (1994) empirically derived equations. Accordingly, a M_w 7.6 on a strike slip fault needs to be 30 km longer in surface rupture length than a M_w 7.5. Situmorang et al. (1976) proposed a complimentary first order right-lateral wrench fault running from south of Cilacap to north of Indramayu, which is very similar to where Fault B is proposed. However, Satyana (2007) proposed that the Pamanukan-Cilacap Fault is the complimentary wrench fault. Both the Pamanukan-Cilacap Fault and Situmorang et al.'s (1976) proposed wrench fault can be seen on Bouguer anomaly maps (Fauzi et al., 2015). Although there is more evidence to support the existence of Fault B, we argue that the earthquake event which occurred on November 16, 1847, was more likely to have been on Fault A. This is because the modelled distribution of intensity of Fault A closely matches that of historic intensity better than Fault B.

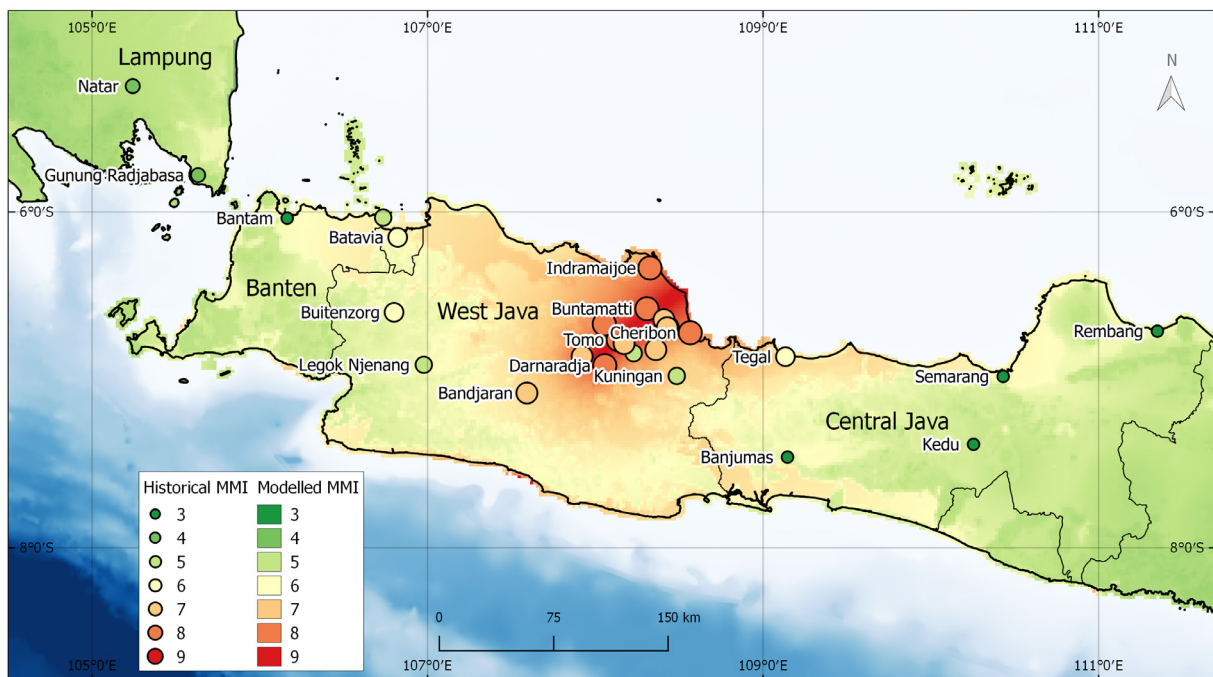


Figure 2.23 Modelled MMI results using parameters outlined in Table 2.15 for Scenario A: Fault A.

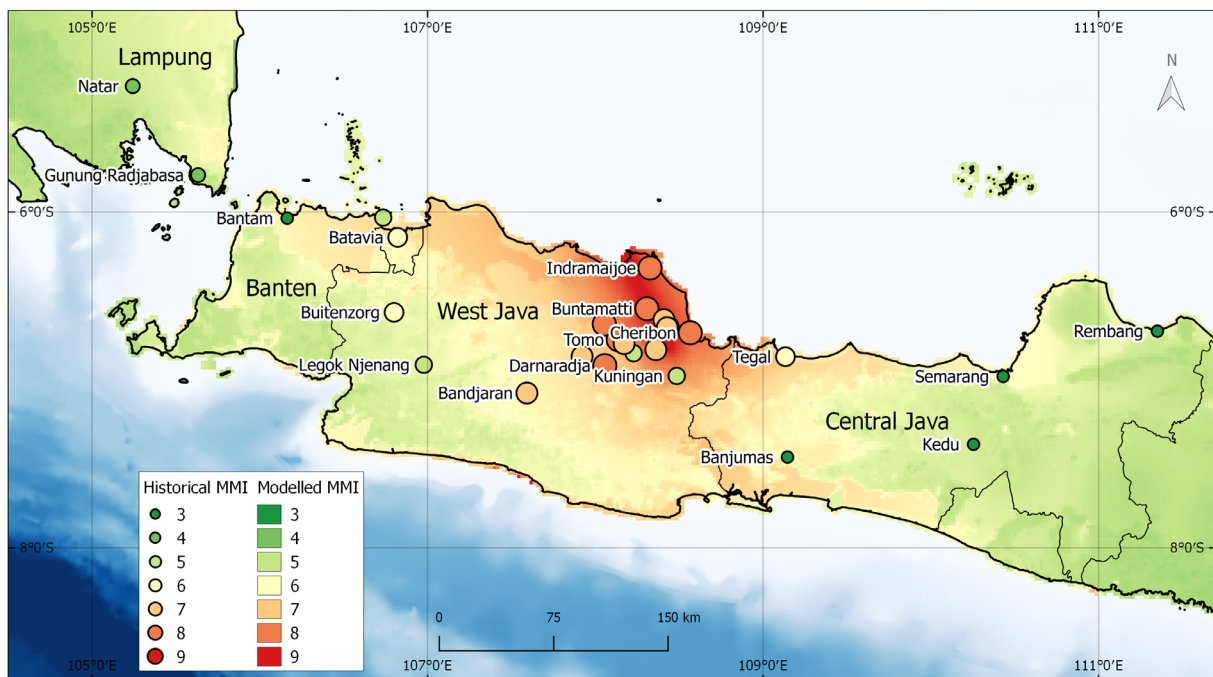


Figure 2.24 Modelled MMI results using parameters outlined in Table 2.16 for Scenario B: Fault B.

2.2.8 June 10, 1867

2.2.8.1 Historical Account

A large and widespread earthquake was felt from Bantam in the west of Java to Negara in Bali on the 10th of June 1867 (van Laar, 1867) (Figure 2.25). Ground shaking caused by this earthquake event was felt over a total distance of approximately 900 km. In most places, the earthquake was felt for over 2 minutes. Ground ruptures appears to be concentrated in Central and East Java, in the historic regencies of Klaten (Wonosari, Prambanan), Boyolali (Kurang Gede), Grobogan, Ampel, Sragen, Wonogiri, Kediri, Toeloeng-Agung (Talungagung) and Trenggalik (van Laar, 1867; Bergsma, 1868).

In the capital and surrounding areas of Djokjakarta (Yogyakarta) approximately 500 people, including 12 Europeans, died (Bergsma, 1868; Fuchs, 1868). Of the 305 European and Chinese stone houses, 136 had collapsed or were damaged to an uninhabitable degree, whilst another 119 houses needed to be repaired (van Laar, 1867). In Pasar-Gedeh, another 236 deaths were reported (Bergsma, 1868), and 1169 buildings had collapsed (van Laar, 1867). The Kraton (royal palace) of Djokjakarta suffered greatly as almost all buildings were either damaged or collapsed (van Laar, 1867; Bergsma, 1868). Similarly, the Kraton of Surakarta had also experienced great damage, and two thirds of the ring wall had collapsed (van Laar, 1867). Almost all sugar or indigo factories on the main road from Surakarta to Djokjakarta were reported to have been heavily damaged or collapsed (van Laar, 1867; Bergsma, 1868).

Along the north coast, the earthquake caused more damage in Central than West Java. In Batavia (Jakarta) over 20 cm of liquid from a gas tank was spilled (Bergsma, 1868). Similarly, liquids were also spilt in a sugar factory in Bandjardjawa, and slight damage had occurred elsewhere in Tegal Regency (Bergsma, 1868). Pekalongan Regency was notably more damaged. The Regent's house was significantly damaged, whilst stone houses in the Chinese camp collapsed killing 4 people (van Laar, 1867). The post-stations in Semboong (Sembung), Pedawettan (Pedawetan), Poetjoonkrep (Pucungkerep) and Toelies (Tulis) were damaged (van Laar, 1867). Some houses collapsed in Semarang Regency. In Grobogan Regency salty water emerged from small cracks in the ground. In Japara the inner walls of the Regent's home collapsed.

Further along the east coast, cracks formed in a church and two sugar factory chimneys were damaged in Soerabaia (Surabaya) (van Laar, 1867). On Madoera (Madura), the earthquake was felt for about 30 seconds in the divisions of Pamakasan (Pamekasan), Soemanap (Sumenep) and Sampang (Bergsma, 1868).

In central and southern Java, the damage was more intense. Regencies in Preanger Residency were heavily struck. In Manondjaja (Manonjaya) the house of the Assistant Resident suffered wall collapses and the walls of the prison crumbled (van Laar, 1867). In Central Java, in the Regencies Kedoe (Kedu), Kepoemen (Kebumen), Wonosobo, Banjoemas (Banyumas), Sapoeran (Sapuran), Ledok, and Bagalen the earthquake caused substantial damage (van Laar, 1867). In Tjilatjap (Cilacap) almost all government and private estates suffered some form of damage including total collapse.

The widespread destruction causing various degrees of damage to total house collapse continues further east in the Regencies Surakarta, Klatten (Klaten), Madiun, Ponorogo, Kediri, Toeloeng-Agung (Talungagung), Trenggalek, and Passoeroean (Pasuruan) (van Laar, 1867; Fuchs, 1868).

The earthquake was so strong that it was also observed on the Dutch ships *Batavia* docked in Semarang, and *Europea* which was anchored 100 geographical miles offshore from Batavia (van Laar, 1867). Strong aftershocks were felt for over a week in several places throughout Java (Fuchs, 1868).

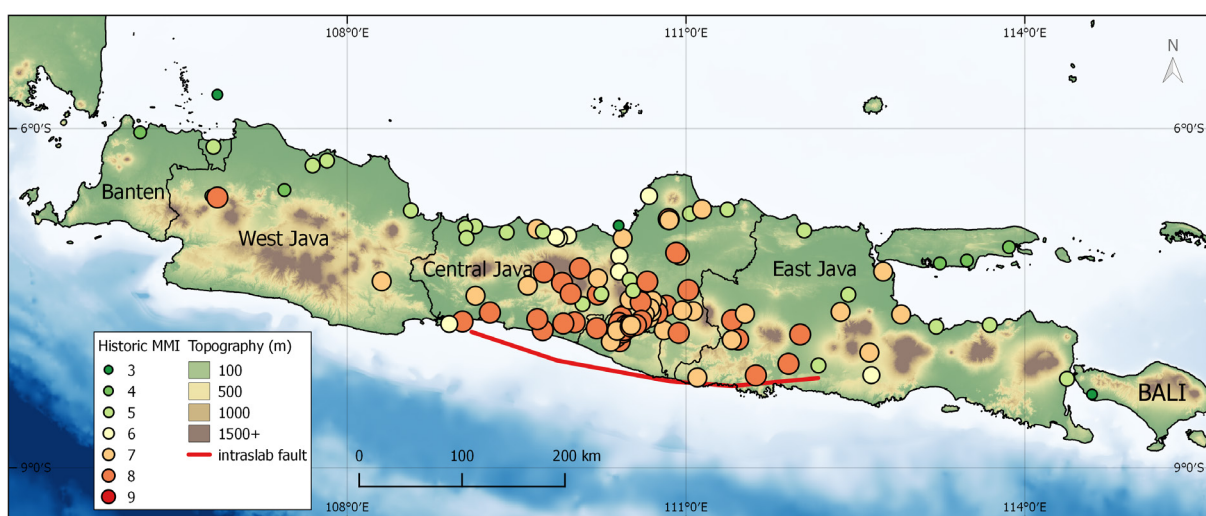


Figure 2.25 Distribution of observed MMI based on historical evidence, and fault trace used to model ground motion shaking for June 10, 1867.

2.2.8.2 Scenario

The widespread distribution of damage and ground rupture over 150 km suggests the earthquake was likely to have been an intraslab event, and unlikely to have been a megathrust event because no tsunamis were reported along the southern coast. If there had been any destructive tsunamis, they probably would have been reported along with other damage reported at Tjilatjap (Cilacap) and/or Patjitan (Pacitan). Hence, it is assumed the event was an intraslab earthquake in order to cause widespread damage centring on the southern half of Central and East Java. Generally, intraplate earthquakes occurring at less than 100 km depth are tsunamigenic (Satake and Tanioka, 1999). Accordingly, scenarios were modelled with epicentres below 100 km depth. Slab 1.0 by Hayes et al. (2012) was used to model this. The model with the best fit to historical MMI indicated that if fault rupture had occurred in the slab, the earthquake would need to be at least M_w 7.7 at 105 km depth with site amplification to produce similar MMI as the historical earthquake event (Table 2.17).

Table 2.17 Model parameters for June 10, 1867

Ground Motion Prediction Equation	ZhaoEtAl2006SSlab
Moment Magnitude	7.7
Fault Type	Intra-slab
Earthquake rupture co-ordinates	109.101° -7.797° 112.169° -8.206°
Earthquake rupture length	350 km
Hypocentre/ Depth	110.860° -8.425 /105 km
Rake	90°
Dip	90°

2.2.8.3 Results and Discussion

In Djokjakarta Regency and its capital, where the earthquake damage was most severe, modelled MMI results are between MMI 7-9 (Figure 2.26). In the southwest corner of East Java, modelled results are above MMI 8 in Ponorogo, Kediri, Talungagung, and Trenggalek, where ground rupture had occurred. In the north and northeastern side of East Java, modelled results range between MMI 6-8. In Surabaya and Pasuruan, modelled MMI and observed MMI are matching. However, in Tuban, modelled result is MMI 7 whereas historic MMI was only 5. The north coast of Java is classified as a sedimentary basin with low shear wave velocity based on the current V_{S30} . As a consequence, the modelled MMI is higher than historic MMI. Similarly, on Madura Island, modelled results reach up to 7.5 on the western side and decreases to MMI 6 eastwards, which is higher than observed MMI (4). The RMSE calculations for this event is 1.5.

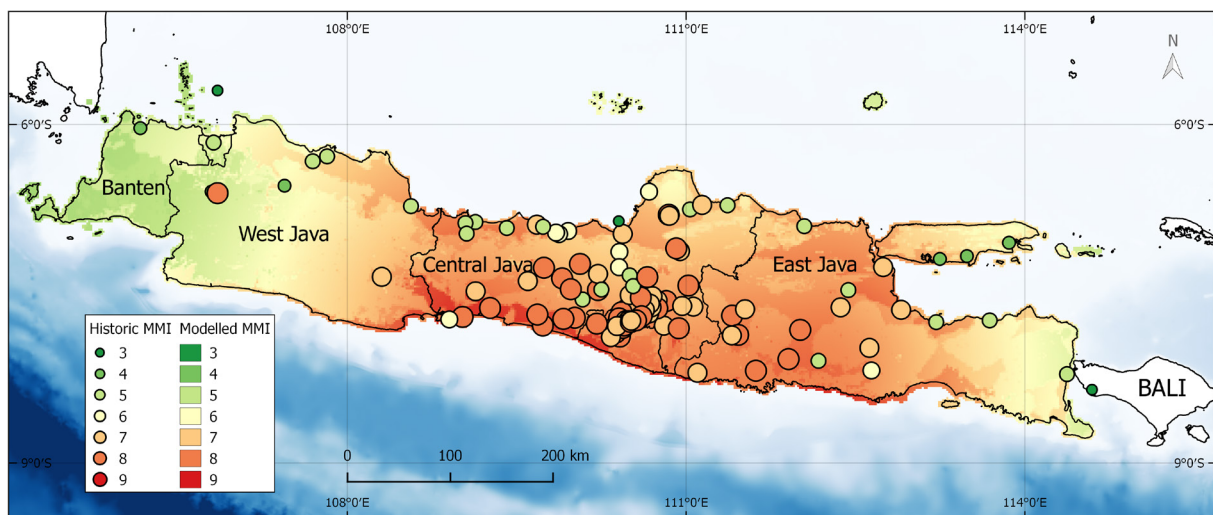


Figure 2.26 Modelled MMI results using parameters outlined in Table 2.17 for June 10, 1867.

In the same year, Mt. Merapi was reported to have flowed with lava (Bergsma, 1868), which may have been active from 1865 to 1871 (Smithsonian Institute, 2013). This is relevant because on May 19, 1865 an earthquake that appears to be slightly less intense was reported in almost all the same locations as 1867, and although Djokjakarta was not heavily damaged, the extent of the event was equally widespread from Jakarta to Jembrana District on Bali (see Table 5.11).

The modelled scenario for June 10, 1867 is based on observed MMI from historical reports; however, as mentioned previously, the Dutch record is incomplete. Preanger Regency (West Java) and eastern East Java's lack of observed MMI may be a reflection of little economic interest. Therefore, it is likely that the event was larger than modelled.

3. Validating the Hazard Map

3.1 Assessing the Probabilistic Seismic Hazard Assessment of Indonesia

In 2010 Irsyam et al. (2010) developed the seismic hazard map (Figure 3.1) that currently informs building codes in Indonesia. This hazard map was a substantial advancement on the previous 2002 map, in particular through the inclusion of crustal fault models. For most of the southern half of Java, Bali and parts of Sumbawa and Flores this hazard map predicts a 10% probability of exceeding Peak Ground Acceleration (PGA) values of 0.25 – 0.30 g in 50 years. Northern Java has slightly lower PGA values of 0.1 – 0.2 g. In order to test the validity of this hazard map, we compare the predicted probability of exceeding certain ground shaking levels with the observations from the historical window we examine here.

There are significant limitations in using historical MMI records to compare with calculated hazard maps, in particular as there are large uncertainties associated with the historical MMI records. This includes assumptions made about the response of buildings to ground shaking, biases in reporting due to a tendency to focus on the regions of greatest damage and/or commercial interest, and the incompleteness of the record, particularly for lower intensities. Nevertheless, Stirling and Petersen (2006) argue that such comparisons have value as historical MMI records are generally either not included, or only indirectly included, in the creation of the PSHA model, and therefore represent an independent dataset to test the PSHA model with.

Due to construction of the Great Post Road along the north coast of Java and the greater penetration of Dutch control, we consider the Wichmann record of large damaging earthquakes in Java to be complete from 1808 until the end of the catalogue in 1877. We therefore constrain our analysis to events within this 69-year period. We make an exception for Jakarta (Batavia) due to the long and continuous occupation of this city by the Dutch. Although the VOC moved their headquarters to Batavia in 1619 (Figure 1.4), earthquakes felt there in the early and mid-17th century noted from other sources (Reid, in press) are not recorded in the Wichmann catalogue. The first well-documented earthquake reported by Wichmann for Batavia is a small event in 1681, followed by the damaging 1699 event. We therefore consider the period of completeness for Jakarta from 1681 until the end of the catalogue, that is, 196 years.

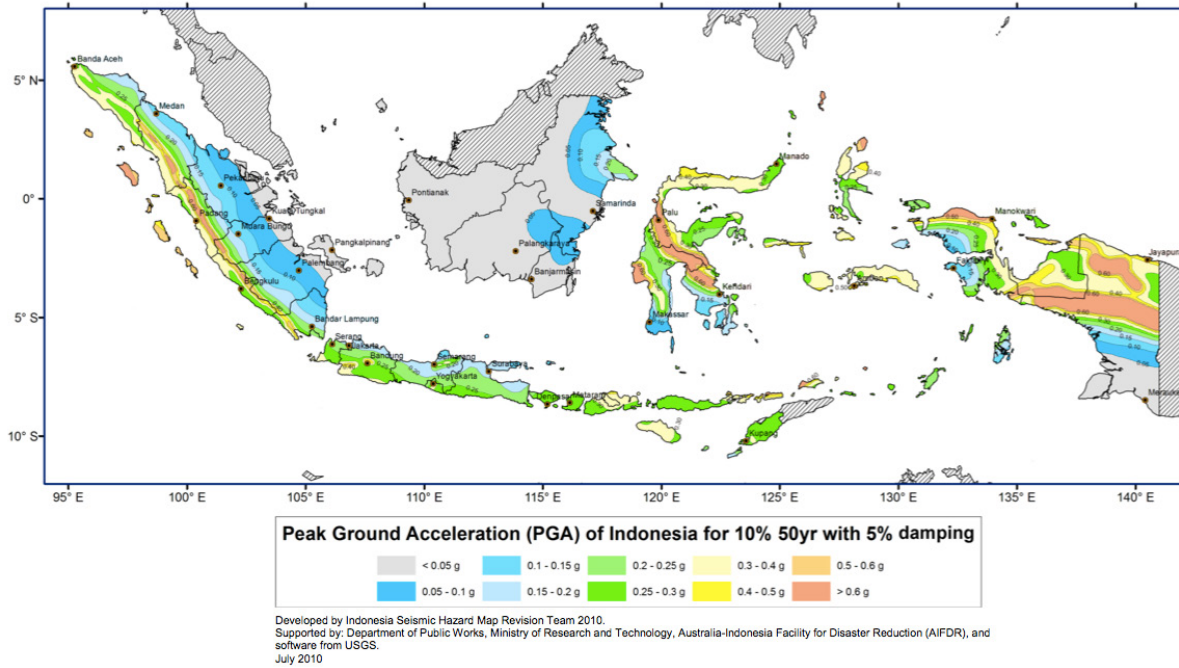


Figure 3.1 Seismic hazard map from Irsyam et al. (2010) showing peak ground acceleration (PGA) with a 10% probability of being exceeded in 50 years.

3.2 Methods

Following Stirling and Petersen (2006) and Stirling and Gerstenberger (2010), we calculate the annual rate of exceedance for MMI values greater than 5 based on the events considered in this study. These are plotted against the PSHA hazard curves for Jakarta, Bandung, Semarang, Yogyakarta and Surabaya. Historical MMI values are converted to PGA and RSA1.0 using the relationships of Atkinson and Kaka (2007). These values, which are observed on sites classified as NEHRP site classes C (Bandung and Yogyakarta) and D (Jakarta, Semarang and Surabaya), are then converted to bedrock shaking estimates using amplification factors from Borchardt (1994).

PSHA methodology assumes that the temporal occurrence of earthquakes, and hence earthquake ground shaking, is described by a Poisson process. This means that the probability of ground shaking exceeding a given level y^* within a period of time t is:

$$P[Y_t > y^*] = 1 - e^{-\lambda_{y^*} t} \quad (6)$$

where λ_{y^*} is the annual average rate of exceedance of ground shaking y^* (Kramer, 1996)

Following Stirling and Gerstenberger (2010) we can statistically test the national PSHA by considering the 95% Poisson confidence intervals for the predicted number of exceedances and compare this with the observed number of exceedances at each site. Exact 95% Poisson confidence intervals can be calculated as:

$$Y_l = \frac{\chi^2(\frac{95}{2}, 2x)}{2} \quad (7)$$

$$Y_u = \frac{\chi^2(1-\frac{95}{2}, 2(x+1))}{2} \quad (8)$$

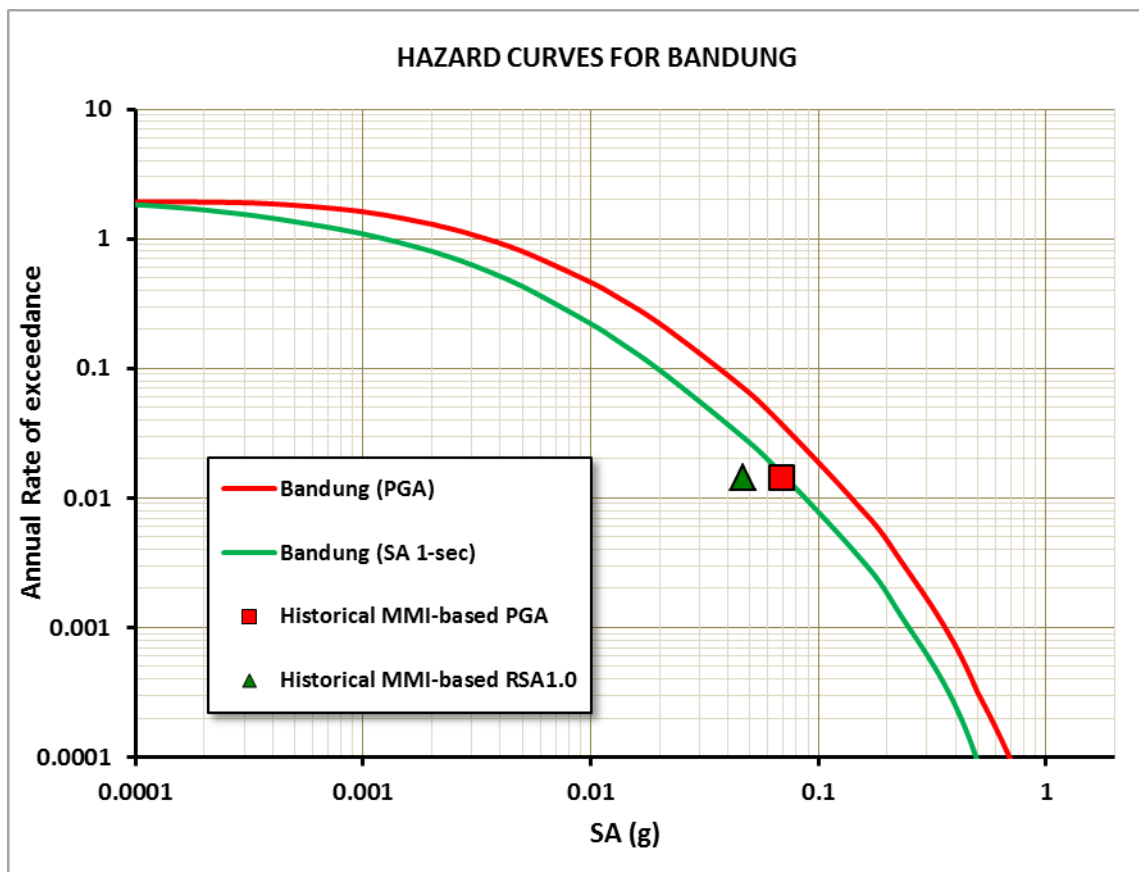
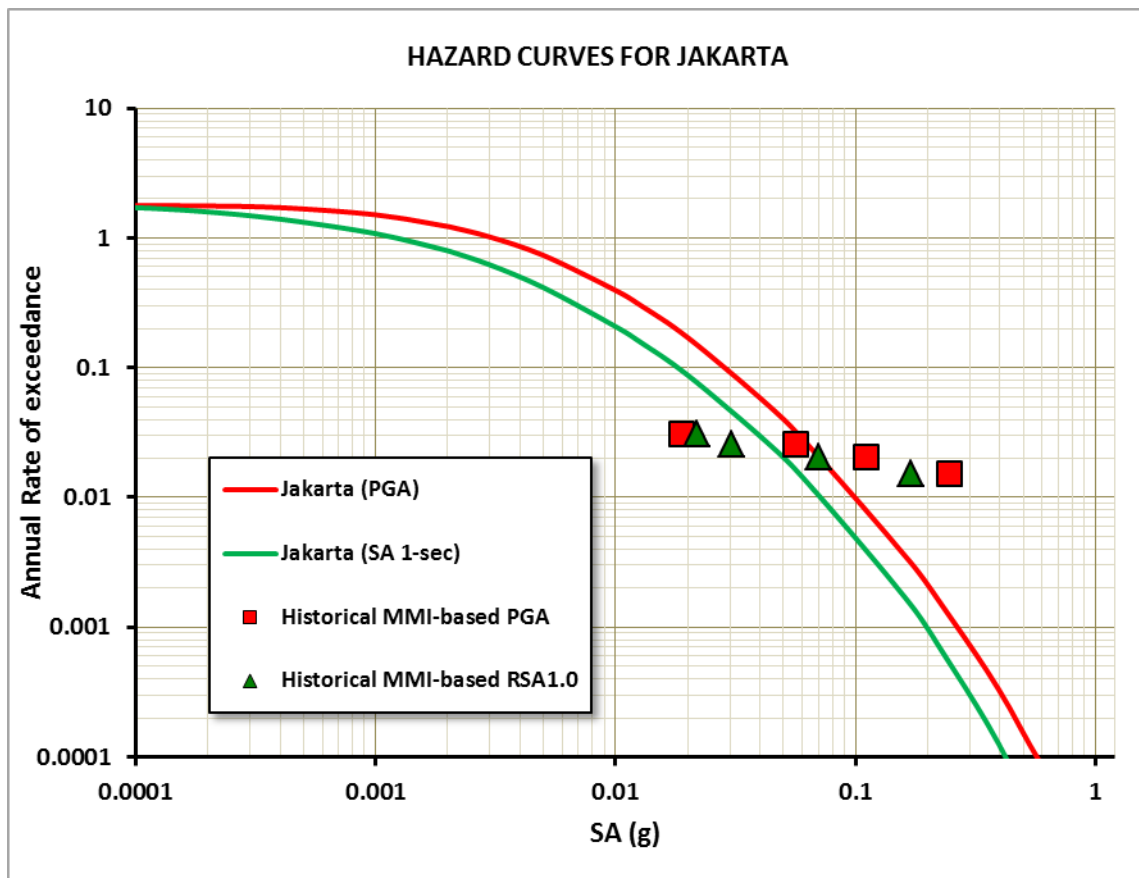
where Y_l and Y_u are the lower and upper bounds respectively, χ^2 is the chi-squared distribution, and x is the predicted number of exceedances in the time interval. We do this for MMI 6, 7 and 8.

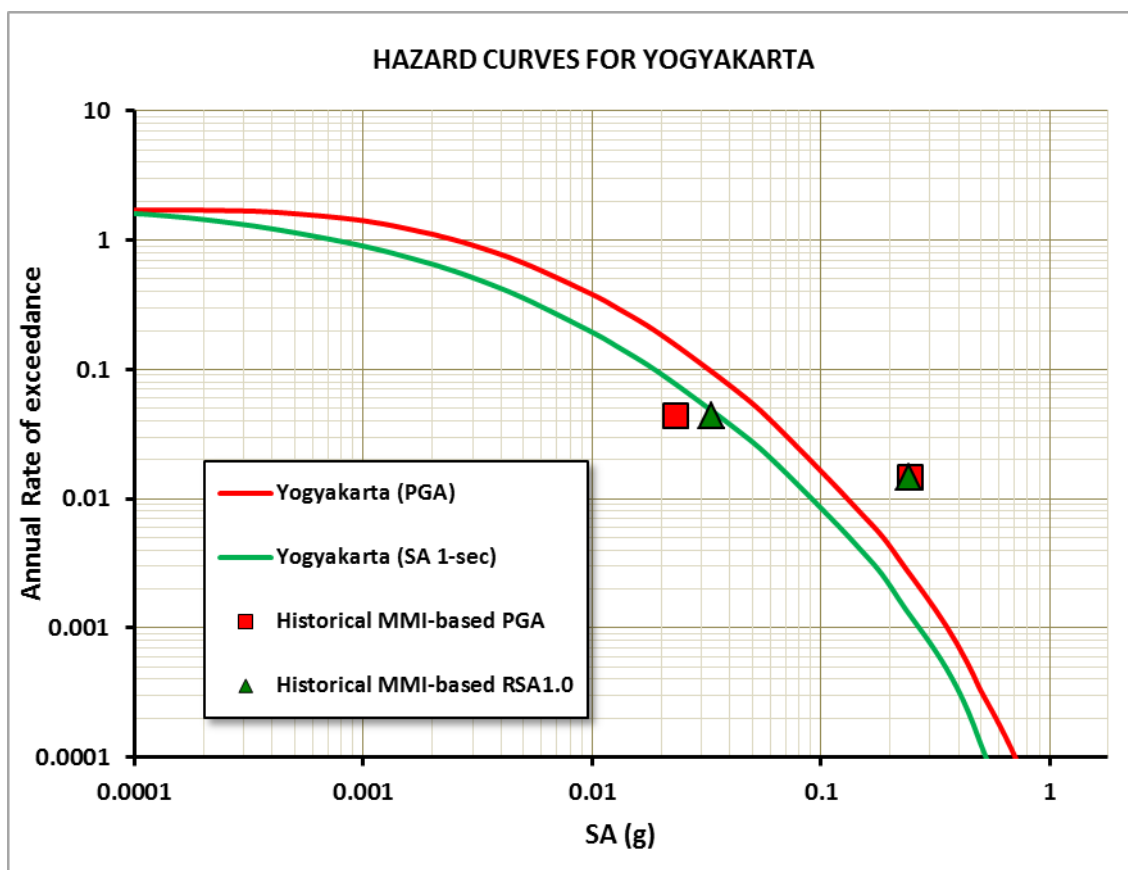
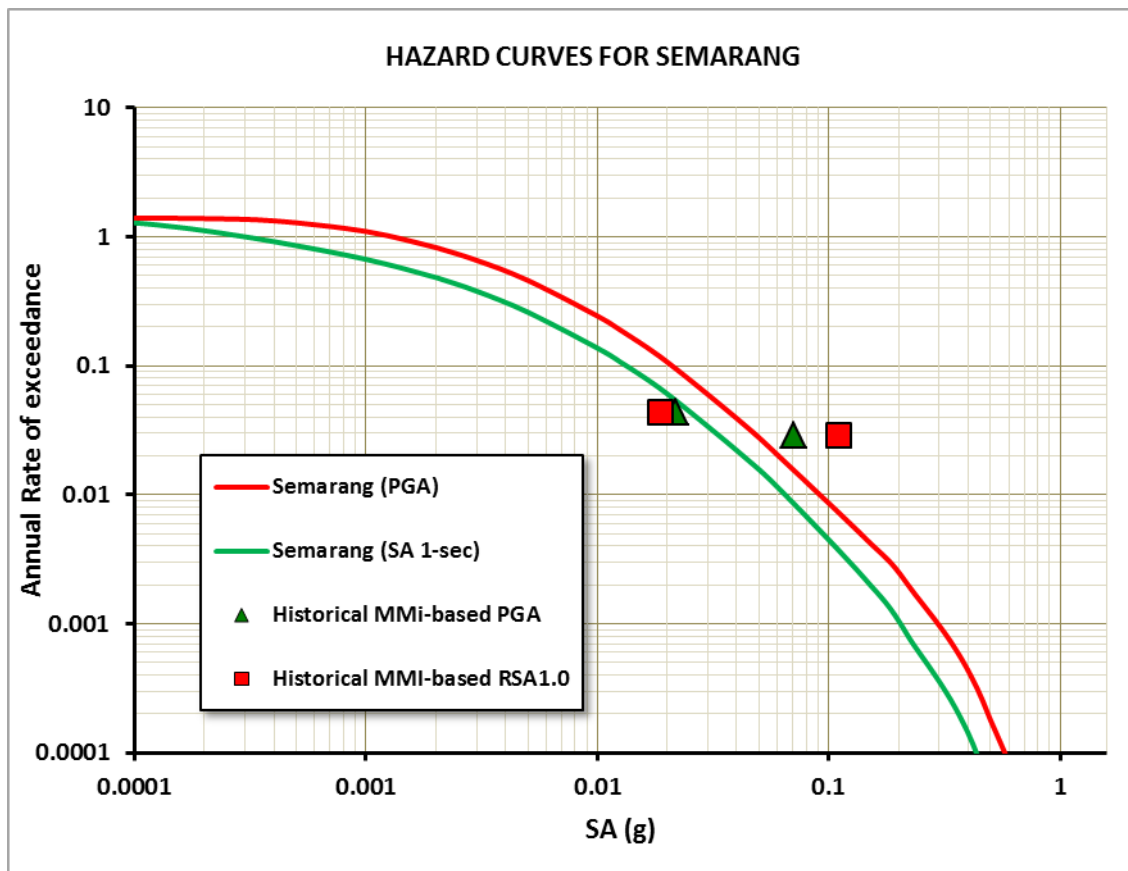
Furthermore, if we make the assumption that each of the cities considered is far enough away from the other cities for ground shaking probabilities at each city to be independent, we can consider whether the total number of exceedances is consistent with the total number of exceedances predicted by the hazard map. Under this assumption, the expected number of exceedances across all sites is the sum of the expected number of exceedances at each site. The expected number of exceedances is based on the time windows of 196 years (Jakarta) and 69 years (other cities), with the Jakarta results normalised to the 69 year time period.

3.3 Results and Discussion

Figure 3.2 plots the observed annual exceedance rate of historical observations against the PSHA hazard curves for Jakarta, Bandung, Semarang, Yogyakarta and Surabaya. For low levels of ground shaking, the PSHA curves tend to match or over-estimate the frequency of ground shaking. This is likely due to an incomplete record, particularly for MMI 5 and 6, as our study has focused on large damaging earthquakes. For high ground shaking values (MMI 8) the hazard curves tend to underestimate the frequency of ground shaking. The statistical significance of these results is limited (Table 3.1), as in most cases there is only one observation of MMI 8 within the 69 year time period. For Jakarta, which has a longer window of completeness, the results are more robust, with 3 observations of MMI 8 within a 196 year time period, a result that is significantly different from the national PSHA at the 95% confidence interval (Table 3.1). These results suggest that the current seismic hazard map may underestimate the frequency of high ground motion levels occurring in Jakarta. Results for Bandung suggest the hazard map over-predicts the hazard compared to the observations, however this result must be treated with caution as Bandung was not a major centre for early Dutch interests, and therefore damaging earthquakes may not always have been reported. For example, for the 1834 event where MMI 8 is observed for nearby Cianjur there are no reports from Bandung despite being only 50 km away.

Considering the performance of the hazard map as a whole, we can look at the total number of exceedances at all sites in Table 3.1. This shows that for MMI 6, we observe about half as many occurrences as predicted by the hazard map. This is likely due to incompleteness of observations at this level of shaking in the events considered here. For MMI 7, the number of observations is similar to that predicted by the hazard map while for MMI 8 we observe about three times as many occurrences as the hazard map predicts. Calculating Poisson rate confidence intervals, differences between the observed and predicted number of occurrences are not statistically significant as a whole, with the exception being for MMI 8 in Jakarta and MMI 7 in Bandung. Following Stirling and Gertenberger (2010) this means that we cannot reject the national PSHA for Java as a whole. However, the limited number of observed events and sites considered limits our ability to statistically test the hazard map. Despite this, the overall greater number of exceedances for MMI 8 compared with predictions suggests that future revisions of the national PSHA should consider whether high intensity hazard levels are being accurately predicted, particularly for Jakarta.





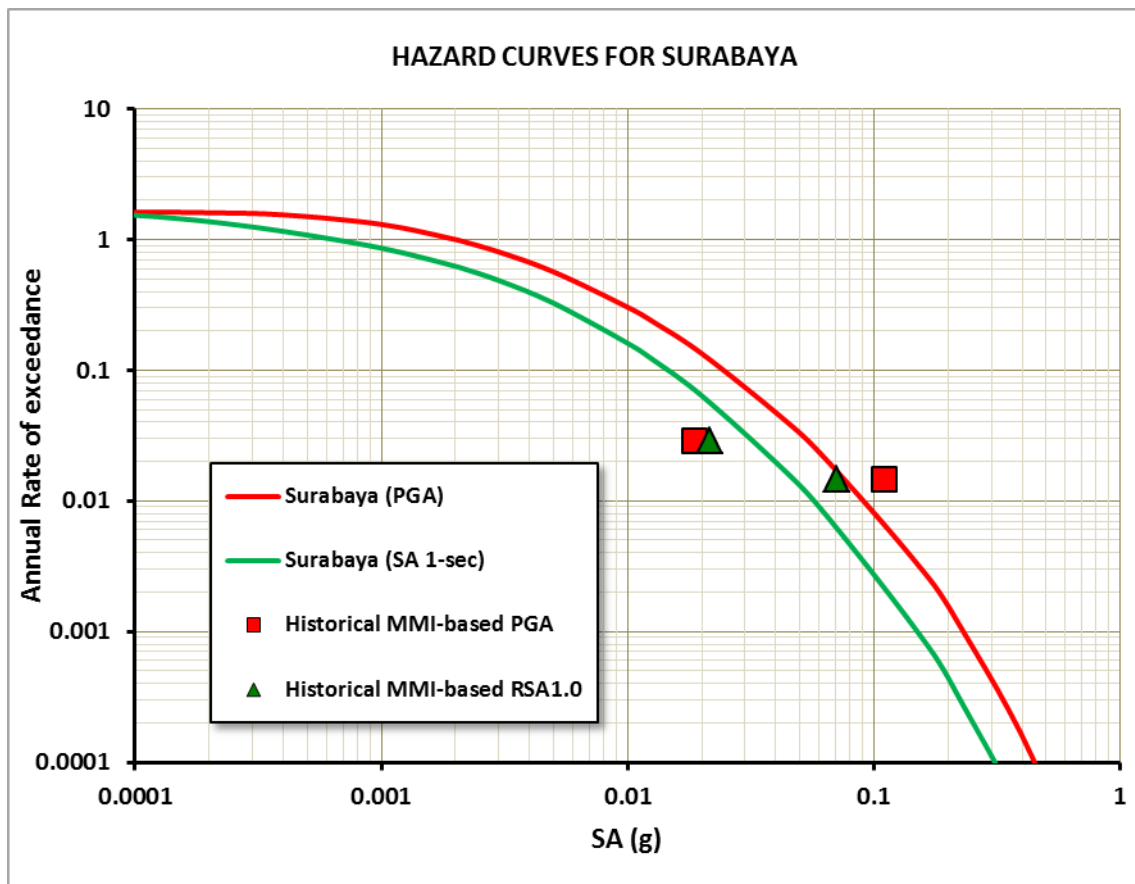


Figure 3.2: Comparison of hazard curves from the national seismic hazard map (Irsyam et al. 2010) and historical observations of ground shaking frequency. Historical MMI observations are converted to PGA and RSA1.0s using Atkinson and Kaka (2007) and then normalised to hard-rock site class (site class B) using amplification factors in Borchardt (1994).

Table 3.1 Number of exceedances for MMI 6, 7 and 8 for the selected cities. Equivalent PGA values are calculated from MMI as outlined in section 3.2, and the predicted annual rate from the national PSHA (Irsyam et al. 2010) compared with the observed annual rate. Total across all cities given at the bottom of the table. * Number of exceedances for Jakarta normalised to same 69-year window as other sites.

City	MMI	PGA	Number of exceedances	Predicted annual rate (Y_p , Y_u)	Observed Annual rate	Reject (lower)	Reject (upper)
Jakarta	6	0.0563	1.76*	0.0300 (0.0038, 0.0825)	0.0255	N	N
Jakarta	7	0.1107	1.41*	0.0070 (0, 0.0357)	0.0204	N	N
Jakarta	8	0.2455	1.06*	0.0015 (0, 0.0145)	0.0153	N	Y
Bandung	6	0.0692	1	0.0350 (0.0056, 0.0910)	0.0145	N	N
Bandung	7	0.1292	0	0.0180 (0.0008, 0.0606)	0.0000	Y	N
Bandung	8	0.2455	0	0.0027 (0, 0.0210)	0.0000	N	N

City	MMI	PGA	Number of exceedances	Predicted annual rate (Y_p , Y_u)	Observed Annual rate	Reject (lower)	Reject (upper)
Semarang	6	0.0563	2	0.0250 (0.0024, 0.737)	0.0290	N	N
Semarang	7	0.1107	2	0.0080 (0, 0.0384)	0.0290	N	N
Semarang	8	0.2455	0	0.0015 (0, 0.0145)	0.0000	N	N
Yogyakarta	6	0.0692	1	0.0300 (0.0038, 0.0825)	0.0145	N	N
Yogyakarta	7	0.1292	1	0.0130 (0.0002, 0.0503)	0.0145	N	N
Yogyakarta	8	0.2455	1	0.0025 (0, 0.0201)	0.0145	N	N
Surabaya	6	0.0563	1	0.0350 (0.0056, 0.0910)	0.0145	N	N
Surabaya	7	0.1107	1	0.0075 (0, 0.0371)	0.0145	N	N
Surabaya	8	0.2455	0	0.0008 (0, 0.0090)	0.0000	N	N
Total	6		6.76	0.1550 (0.0765, 0.2608)	0.0980	N	N
Total	7		5.41	0.0535 (0.0136, 0.1203)	0.0784	N	N
Total	8		2.06	0.0090 (0.0000, 0.0410)	0.0298	N	N

4. Fatality Estimates with InaSAFE

4.1 InaSAFE Methodology

The InaSAFE impact assessment software (InaSAFE.org, 2015) has been developed to estimate the affected population, buildings and infrastructure from a given hazard scenario. It is multi-hazard and the user can define thresholds for different levels of damage.

In this study we use InaSAFE v3.1 to estimate fatalities using the ground shaking modelled with OpenQuake for each of the historical scenarios analysed here for a modern day population. We combine the hazard layer with the WorldPop population layer for Indonesia using the fatality model developed by the Bandung Institute of Technology (Sengara et al., 2012). This calculates fatality rates as:

$$F = 10^{(0.62275231MMI - 8.03314466)} \quad (9)$$

where F is the fatality rate (i.e. expected proportion of the population that will be killed) for a given level of MMI shaking intensity.

Following the standard implementation of InaSAFE in Indonesia by Indonesia's National Disaster Management Agency (BNPB), the potential for people to be displaced is estimated by identifying the total population experiencing MMI of 6 or greater. The actual number of people displaced may vary greatly from this number.

4.2 Analysis of InaSAFE Results

Table 4.1 show fatality estimates for each of the scenarios presented in this study. Note that there is a considerable uncertainty in these results that we do not attempt to quantify, including uncertainty around the estimate of the source (magnitude, location and geometry), GMPE selection, site amplification and the fatality model. Despite these uncertainties, the results do indicate the potential for high impact (10 000s of fatalities) events to occur in Java were one of the historical earthquake events to re-occur today. The dense population of Java means that the number of people affected (e.g. to be evacuated and/or suffer damage to their dwelling) by a large earthquake could easily be 10s of millions. This can pose significant challenges for disaster managers, both in terms of how they would respond to significant numbers of displaced people during an event, and how effective policies can be implemented to build community resilience before such an event occurs.

Table 4.1. Impact estimates for modelled scenarios calculated using InaSAFE. *Rounded to nearest thousand people. ^Rounded to nearest million people.

Event	Scenario	Estimated fatalities*	Potentially displaced people^
1699	Intraslab M_W 8.0	100 000	76 million
1699	Megathrust M_W 8.0	7000	79 million
1780	Baribis Thrust M_W 7.0	34 000	50 million
1780	Crustal M_W 7.0	33 000	60 million
1780	Intraslab M_W 7.0	60 000	53 million
1815	Flores Thrust M_W 7.3	5 000	11 million
1820	Flores Thrust M_W 8.4 A	5 000	15 million
1820	Flores Thrust M_W 8.4 B	3 000	9 million
1834	Baribis M_W 7.0	40 000	62 million
1834	Crustal M_W 7.0	23 000	64 million
1834	Intraslab M_W 7.7	12 000	73 million
1840	Crustal M_W 6.5	5 000	24 million
1847	Crustal M_W 7.5	17 000	85 million
1847	Crustal M_W 7.6	18 000	87 million
1867	Intraslab M_W 7.7	60 000	125 million

5. General Conclusions

5.1 Summary of Research Findings

In-depth investigations of eight historical earthquake events were used to better understand the seismicity of Java, Bali and Nusa Tenggara. The results from this analysis were used to assess the validity of Indonesia's current probabilistic seismic hazard map (Irsyam et al., 2010). Ground shaking scenarios were modelled for each event using the OpenQuake software and the resulting ground motion estimates used in the InaSAFE software to estimate potential fatalities and displaced people were similar events to occur today.

In the process of developing scenarios to explain the observations, a better understanding of earthquake sources in Java is developed. The results suggest that between 1699 and 1867 there may have been four $M_w \geq 7$ intraslab events, demonstrating the importance of considering intraslab events in hazard assessment. This research has also identified five possible faults that are currently unrecognised in West and Central Java. The historical record demonstrated that Java was very active in the past, and will continue to be a seismically active island that has potentially damaging fault sources that are presently unrecognised and are yet to be characterised. The following is a summary of the eight historical events modelled.

One of the most historically significant earthquakes to have struck Java occurred on 5 January 1699. The event was felt over the whole of Java but was particularly intense in the Province of Banten and West Java with building collapse and fatalities in Batavia (Jakarta). Modelled intensity results suggest that the event could have been generated by a $\sim M_w$ 8.0 earthquake in the subducting slab at around 160 km depth.

Three scenarios were proposed for the 22 January 1780 earthquake. The event was felt across all of Java but was particularly intense over West Java. Results from an intraslab M_w 8.0 earthquake at 160 km depth produced higher modelled ground shaking intensity than observed. Modelled intensity for two alternative crustal fault scenarios, each with a M_w 7.0 earthquake, produced results that closely matched the observations. Hence, it is proposed that the Baribis fault or an active but currently unknown fault is the fault source.

Modelled earthquake simulations on the Flores back-arc thrust north of Bali suggests a M_w 7.3 or similar was likely the source of the 22 November 1815 event. Within several months of the infamous Toba eruption on Sumbawa, a volcanic eruption may have also occurred on Bali, which in turn, may have caused a flank collapse and triggering a tsunami. The death toll for this earthquake event reached over 10 000 people. The event indicates that convergence in the Bali basin north of Bali was active 200 years ago and is supportive evidence for Silver et al.'s (1983; 1986) interpretation of the Flores back-arc thrust extending from north of the Flores Basin to the Bali Basin.

The event with the largest earthquake modelled for this research was that of December 29, 1820. This earthquake event was felt most intensely at Bima, Sumbawa. It was felt as far east as Sumenep (Java), as far north as Makassar (Sulawesi) and as far east as Palu Island (Flores). The earthquake ($\sim M_w$ 8.4) was likely to have sourced from the Flores back-arc thrust as opposed to the Walanae fault proposed by Harris and Major (in press). Tsunami modelling suggests that a M_w 8.4 earthquake at 10 km depth in the Flores Basin would result in tsunami heights reaching over 15 m for Bima and over 10 m on the southern coast of Sulawesi.

On October 10, 1834, a large (possibly M_w 7.0) earthquake was felt from Lampung (Sumatra) to Tegal (Central Java); however the concentration of heavy damaged was centred in West Java. Three scenarios were modelled for this event. Results from two proposed scenarios, the Baribis thrust fault and a proposed crustal fault produced very similar results in Bogor, Cianjur and Jakarta. However, modelled intensity on the Baribis fault produced better matching intensities to the observed data.

Earthquake simulations of a strike slip crustal fault that is approximately M_w 6.5 and oriented NNE – SSW from Semarang to Purworejo in Central Java was required to match the distribution of observed MMI reported for 4 January 1840. The outcome from the modelled intensity indicates the current location of Central Java's structural divide, that is, the Luk-Ulo suture/ Muria-Progo lineament (Smyth et al. 2005; Hall et al. 2007) or Muria-Kebumen fault (Satyana, 2007), may be further west than proposed by some of these authors. Alternatively, other structures which may be associated with and/or have the same orientation as this structure may be present and possibly active.

Modelled intensities on currently identified faults in West Java do not produce, and do not have the required fault properties to produce, a large earthquake that was necessary for widespread ground rupture and damage reported on November 16, 1847. It is probable that not all active faults in West Java have been identified yet. Accordingly, this research proposes two possible faults that closely match historically observed data; these are termed Fault A and Fault B. A M_w 7.5 at 10 km depth along a NW to SE direction (Fault A) was needed to closely match historically reported intensity. Likewise, a M_w 7.6 at 15 km depth along a NE to SW orientation (Fault B) would also generate MMI patterns similar to the historical record.

Java's most well documented earthquake event, of those investigated, occurred on June 10, 1867. The distance over which the earthquake was felt covers over 900 kilometres, from westernmost Java to Bali. Surface ground rupture occurred over most of Central Java and destroyed entire villages, including extensive damage to the Kratons' of Yogyakarta and Surakarta. Modelled scenarios indicate that a strong ($\sim M_w$ 7.7) intraslab earthquake at depths of 105 km would produce intensities closely matching that observed.

A comparison of the historical frequency of intense ground motions with that predicted from the national PSHA is used to test the validity of the PSHA model. The limited number of observations restricts the statistical confidence of the analysis; nevertheless the historical frequency of high intensity ground motion (MMI 8) exceeds that predicted by the PSHA model for Jakarta, Bandung, Semarang, Yogyakarta and Surabaya. For Jakarta, where the historical record is more complete over a longer period, this result is statistically significant. Therefore, future revisions of the national PSHA should consider closely whether earthquake source models for Java fully consider the range of possible earthquake sources, maximum magnitudes and probabilities.

Due to the massive population of Jakarta and surrounding regions, fatality estimates from the modelled 1699 M_w 8.0 intraslab scenario are approximately 100 000. Modelled fatality results for other historic events also produced high (tens of thousands) fatality estimates. Considering the potential for people to be otherwise impacted and displaced, tens of millions of people would likely be impacted in some way in the scenarios proposed here.

5.2 Future Recommendations

This work has produced a limited set of earthquake shaking scenarios derived from historical events between 1699 and 1867 for Java, Bali and Nusa Tenggara. Although this does not consider all earthquakes that occurred within this time period, it does provide evidence to assist with the identification and characterisation of active faults in this region.

Revision of Indonesia's national earthquake hazard map should consider the implications of the comparisons of the historical events with the current hazard map. In particular, and of great importance to risk assessment and infrastructure planning, it appears likely that the current hazard map underestimates the hazard for Jakarta, and more broadly may underestimate the frequency of high intensity events across Java. A more complete consideration of active faults in Java and a better understanding of the contribution of intraslab earthquakes should improve the accuracy of the hazard map.

The database of shaking scenarios produced here can also be used with the InaSAFE software and modern exposure data to estimate the impacts to life and infrastructure if these events were to occur today. This in turn can inform disaster management and preparedness activities. There can be great value in using historical events for such planning, as the knowledge that such an event has occurred previously can assist with communicating the relevance of being prepared for such an event to occur again. It must however be cautioned that there can exist the potential for larger, more damaging events to occur than have been observed in the historical record.

Additional large events that we could not model due to time constraints and which may be of special interest in future research are listed in Appendix B.

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Appendix A Historical MMI: Events Modelled

Table 5.1 Evidence used to obtain observed MMI for January 5, 1699.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-6.6260	106.667	Minjan	Gunung Menyan	2	no damage	Nata and Witsen, 1700
-6.7020	16.996	Talaga Warna	Talaga Warna	2	No damage	Nata and Witsen, 1700
-6.6530	106.930	Silember	Cilember	6	Many damages	Nata and Witsen, 1700
106.567	-6.6150	Dauw	Dahu	2	No damage	Nata and Witsen, 1700
-6.7088	107.127	Tjissalak	Cisalak	6	Many damages	Nata and Witsen, 1700
-6.7100	106.953	Oedjoeng Toeboe	Ujung Tebu	2	No damage	Nata and Witsen, 1700
-6.6125	106.791	Tjipinang-gading	Cipinang-gading	6	Many damages	Nata and Witsen, 1700
-6.0382	106.156	Bantam	Banten	5	King's store house was damage	Nata and Witsen, 1700
-6.5971	106.780	Buitenzorg	Bogor	2	No damage	Nata and Witsen, 1700
-6.7909	106.982	Mt. Gede	Mt. Gede	8	Landslide	Nata and Witsen, 1700

Table 5.2 Evidence used to obtain observed MMI for January 22, 1780.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-6.59743	106.7993	Buitenzorg	Bogor	6	Buildings damaged	Wichmann, 1918
-6.73725	108.5507	Cheribon	Cirebon	3	Weak vibrations felt	Wichmann, 1918
-6.16604	106.8342	Zandsee & Gracht, Batavia	Jakarta	8	27 sheds and houses collapsed	Wichmann, 1918
-6.02934	106.1682	Bantam		4	Strong vibrations	Wichmann, 1918
-6.24767	105.1337	Willem Frederik Ship		2	Seaquake observed in Sunda Strait	Wichmann, 1918
-6.70757	106.7328	Gunung Salak	Mount Salak	1	Thundering sound heard	Wichmann, 1918
-6.78707	106.9825	Gunung Gede	Mount Gede	1	Smoked	Wichmann, 1918

Table 5.3 Evidence used to obtain observed MMI for November 22, 1815.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-7.26748	112.7507	Soerabaja	Surabaya	5	Powerful shock, 30 second duration	Java Government Gazette No. 199, 16 December 1815
-8.11545	115.1055	Boeileleng	Buleleng	8	Violent quake for almost an hour, Tsunami flooded land, killing 1200 people	Java Government Gazette No. 199, 16 December 1815
-8.25701	115.0966	Danau Tamblingen	Lake Tamblingan	8	Rent in the basin causing flooding	Zollinger 1847
-8.12416	115.0951	Singaradja		8	Mudslide which buried the town (10 253 people died)	Vriesman 1883
-8.61894	116.3198	Lombok		5	Very strong earthquake felt	Zollinger 1847

Table 5.4 Evidence used to obtain observed MMI for December 29, 1820.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-5.13086	119.4165	Makassar		5	10 a.m., violent quake, 2.5 minutes duration	Bataviasche Courant, No. 17, 28 April 1821
-5.54314	119.9397	Banthain	Bantaeng	6	Villages destroyed, many hundreds died	Bataviasche Courant, No. 17, 28 April 1821
-5.53207	120.2459	Boelekombas	Bulukumba	6	4-5 minute duration, fort Boelekombas fluctuated to and fro, tsunami 60-80 ft flooded 400-500 yards inland, 400-500 lives lost, village destroyed	Roorda van Eysinga, 1830
-5.53972	120.0261	Nipa-Nipa		6	Entire village washed away	Roorda van Eysinga, 1830
-5.55486	120.1979	Terang-Terang		6	Entire village washed away	Roorda van Eysinga, 1830
-8.45491	118.7278	Bima		8	More than 2 minutes duration, stone houses badly damaged or collapsed, ground ruptures formed, tsunami wave followed which flung anchored ships far inland and uprooted trees and houses	Reinwardt, 1858
-8.33504	121.7103	Island of Paloweh	Palu Island	3	Earthquake felt	Wichmann, 1918
-7.05944	113.8735	Soemanap	Sumenep	4	10 a.m. earthquake felt for more than a minute, 3 p.m. river flooded, several small coastal vessels broken/damaged	Bataviasche Courant, No. 3, 20 January 1821

Table 5.5 Evidence used to obtain observed MMI for October 10, 1834.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-6.15151	106.8219	Batavia	Jakarta	7	Extremely violent earthquake, stone buildings significantly damaged	Reiche 1859
-6.362782	106.83258	Pondok-Tjina	Pondok Cina	8	Stone houses greatly damaged or partially collapsed	(Algemeene Konst-en Letterbode, 1840)
-6.364437	106.85928	Tjimangis	Cimangis	8	Stone houses greatly damaged or partially collapsed	(Algemeene Konst-en Letterbode, 1840)
-6.59803	106.7973	Buitenzorg	Bogor	8	Major portion of Governor Generals Palace collapsed, wide cracks formed on the main road from Buitenzorg to Tjanjor	(Algemeene Konst-en Letterbode, 1840)
-6.52414	106.8997	Tjitrap		8	Stone house collapsed on Augustijn Michiels' estate, killing one person	Reiche, 1859
-6.69662	106.9669	Tjiandjavar		8	Post station buried and carried away by mass of earth killing 5 men and 10 horses	Javasche Courant, No. 83, 15 October 1831
-6.79668	107.0026	Eastern Gunung Gede	Eastern Mt. Gede	6	More damage	(Algemeene Konst-en Letterbode, 1840)
-6.77866	106.9129	Western Gunung Gede	Western Mt. Gede	4	Less damage	(Algemeene Konst-en Letterbode, 1840)
-6.8174	107.1373	Tjiandjur	Cianjur	8	Regents house partially collapsed, all stone buildings partially or completely collapsed	Reiche, 1859 Javasche Courant, No. 83, 15 October 1831
-6.32594	107.3335	Krawang	Karawang	4	Violent shaking	Reiche 1859
-6.86713	109.1365	Tegal		3	Earthquake felt	Reiche 1859
-6.02934	106.1682	Bantam	Banten	4	Violent shaking	Reiche 1859
-5.45	105.5	Lampong	Lampung	3	Earthquake felt	Reiche 1859

Table 5.6 Evidence used to obtain observed MMI for January 4, 1840.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-6.9782	110.4224	Semarang		7	A rupture formed in the church and barracks, walls of the bastions collapsed	Reiche, 1859
-6.9211	110.2030	Kendal		8	A small section of the road collapsed	Reiche, 1859
-6.8971	110.5522	Demak		6	2 minutes in duration	Javasche Courant, No. 5, 15 January 1840

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-7.3407	110.4954	Salatiga		6	2 minutes in duration	Javasche Courant, No. 5, 15 January 1840
-7.2590	110.4031	Ambarawa		6	Reports of over 100 significant cracks and over 600 small cracks in buildings	Musschenbroek, 1867
-7.2709	110.4101	Fort Willem I		6	2 minutes in duration, cracks formed in the fortress	Musschenbroek, 1867
-6.5914	110.6705	Japara	Jepara	4	15 seconds duration	Javasche Courant, No. 5, 15 January 1840
-6.7504	111.0290	Patti	Pati	4	15 seconds duration	Javasche Courant, No. 5, 15 January 1840
-7.4715	109.1381	Banjoemaas	Banyumas	5	Two shocks, the first was 30 seconds in duration	Javasche Courant, No. 5, 15 January 1840
-7.7329	109.0071	Tjilatjap	Cilacap	0	"the weather at the time of the quake was stormy"	Javasche Courant, No. 5, 15 January 1840
-7.7972	110.3688	Djakakarta	Yogyakarta	5	Three shocks accompanied by subterranean rumbling, duration one minute, persons flung to the ground	Javasche Courant, No. 5, 15 January 1840
-7.5410	110.4479	Gunung Merapi	Mt. Merapi	0	"smoked more heavily than previous"	Javasche Courant, No. 5, 15 January 1840
-7.8228	110.0331	Baglen	Bagelen	5	Two shocks, almost a minute in duration	Javasche Courant, No. 5, 15 January 1840
-7.7124	110.0163	Poerworedjo	Purworejo	8	Several houses collapsed, persons injured as a result of house collapse	Javasche Courant, No. 5, 15 January 1840
-7.7166	110.0207	Bogowonto River		6	Cracks formed in the stone bridge	Javasche Courant, No. 5, 15 January 1840
-7.8942	110.0322	Soetjen	Sutji	8	Indigo heavily damaged, roof ripped from foundation, chimney and walls collapsed	Javasche Courant, No. 5, 15 January 1840
-7.3676	109.9004	Wonosobo		7	Buildings suffered badly	Javasche Courant, No. 5, 15 January 1840
-7.4498	109.9841	Sapoeran	Sapuran	8	Buildings suffered badly warehouse collapsed	Javasche Courant, No. 5, 15 January 1840

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-8.1785	111.1025	Patjitan	Pacitan	5	Over a minute in duration, walls of the houses received cracks, shocks repeated during the night, one at 6 a.m. on the 6th was rather powerful followed by insignificant vibrations until the end of the month	Javasche Courant, No. 7, 22 January 1840
-6.8829	109.6700	Pekalongan		4	Two powerful shocks	Javasche Courant, No. 6, 18 January 1840
-7.8169	112.0114	Kediri		4	Two powerful shocks	Javasche Courant, No. 6, 18 January 1840
-7.3842	110.2528	Kedu		3	Quake observed	Javasche Courant, No. 5, 15 January 1840
-7.7318	113.6879	Bezoeki	Besuki	0	Stormy weather observed	Javasche Courant, No. 13, 12 February 1840

Table 5.7 Evidence used to obtain observed MMI for November 16, 1847.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-6.9156	108.0565	Dana Radja	Darmaraja?	8	All stone buildings had collapsed, over 50 fissures formed in the ground, from which water sprouted	Javasche Courant, No. 95, 27 November 1847
-6.7605	108.1362	Tomo		8	Roof of warehouse collapsed	Javasche Courant, No. 94, 24 November 1847
-6.6677	108.0533	Tjiboeloe	Cibuluh	8	Ground rupture	Javasche Courant, No. 94, 24 November 1847
-6.5765	108.3077	Boentamatti		8	All that could fall laid on the ground, fissures formed, fine bluish sand sprouted	Javasche Courant, No. 95, 27 November 1847
-6.9771	108.4854	Kuningan		5	Regent's house suffered little	Junghuhn, 1854
-6.8419	108.2284	Madjalenska		5	Sugar factory suffered insignificant damage	Versteeg, 1859
-6.0372	106.1631	Bantam		3	Weak vibrations felt	Wichmann, 1918
-6.8624	109.1333	Tagal	Tegal	6	Tearing of the walls	Java Courant No. 93 20 November 1847
-7.4606	109.1456	Banjoemas	Banyumus	3	Weak vibrations felt	Junghuhn, 1854
-7.3843	110.2546	Kedu		3	Weak vibrations felt	Junghuhn, 1854
-6.9798	110.4314	Semarang		3	Weak vibrations felt	Junghuhn, 1854
-6.7101	111.3507	Rembang		3	Weak vibrations felt	Junghuhn, 1854

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-5.2503	105.2422	Natar		4	Several weak vibrations at intervals of 5-10 minutes	Javasche Courant, No. 105, 22 December 1847
-5.7806	105.6319	Gunung Radjabasa	Mt. Rajabasa	4	Vibrations felt	Javasche Courant, No. 105, 22 December 1847
-6.1515	106.8219	Batavia	Jakarta	6	Two shocks of 8 and 12 seconds duration, cracks formed in the walls, tower tilted	Junghuhn, 1854
-6.0338	106.7351	Onrust Island		5	Two shocks, second one more intense	Versteeg, 1859
-6.5982	106.8	Buitenzorg	Bogor	6	Three shocks, pillars cracked	Java Courant No. 93 20 November 1847
-6.9107	106.9773	Legok Njenang		5	Three severe shocks	Java Courant No. 93 20 November 1847
-6.8607	107.921	Soemedang	Sumedang	7	Assistant residents house became uninhabitable	Javasche Courant, No. 94, 24 November 1847
-7.0788	107.5921	Bandjaran	Banjaran	7	Buildings swayed to and fro	Junghuhn, 1854
-6.7197	108.5658	Cheribon	Cirebon	8	Over 200 stone buildings heavily damaged or collapsed	Versteeg, 1859
-6.6898	108.4285	Palimanan		8	All the stone buildings in the fort were severely damaged and uninhabitable	Versteeg, 1859
-6.6421	108.4091	Ardjowinangun	Arjawinangun	7	Everything in ruins	Versteeg, 1859
-6.6898	108.4285	Glagamidan		7	Nothing left standing	Javasche Courant, No. 94, 24 November 1847
-6.8206	108.3607	Radjagaluh		7	Nothing left standing	Javasche Courant, No. 94, 24 November 1847
-6.7843	108.1716	Pamankiran		7	Buildings collapsed	Versteeg, 1859
-6.3336	108.3259	Indramajoe	Indramayu	8	Over 40 houses in the chinese camp collapsed, lives lost, fissures 1-2 feet wide formed in the ground	Versteeg, 1859

Table 5.8 Evidence used to obtain observed MMI for June 10, 1867.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-6.0334	106.1663	Bantam		4	Some shocks, no damage	Laar, 1867 Bergsma, 1868

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-6.1611	106.8152	Batavia	Jakarta	5	Weak shock, liquids from gas tanked spilled	Bergsma, 1868; Laar, 1867
-6.5957	106.7973	Buitenzorg	Bogor	4	Weak shock	Bergsma, 1868; Laar, 1867
-6.5433	107.4436	Purwakarta		4	Weak shock	Laar, 1867
-6.3267	107.6932	Tjiassem	Chiasem	5	Violent shock	Laar, 1867
-6.2833	107.8208	Pamanukan		5	Violent shock	Laar, 1867
-7.3507	108.3049	Manondjaja	Manonjaya	7	Some walls collapsed, many cracked	Laar, 1867
-6.7244	108.5633	Cheribon		5	Strong shock	Laar, 1867; Bergsma, 1868
-6.8649	109.1339	Tegal		5	Violent shock	Laar, 1867; Bergsma, 1868
-6.9180	109.4121	Bandja Djawa		5	2 minute duration	Bergsma, 1868
-6.8749	109.0461	Brebes		5	Violent shock	Laar, 1867
-6.9677	109.0564	Djatibarang		5	Violent shock	Laar, 1867
-6.8883	109.6781	Pekalongan		7	Stone building collapsed killing 5 people, others sustained cracks	Laar, 1867
-6.9449	109.9555	Sembung		6	Coaching inns suffered damage	Laar, 1867
-6.9718	109.8750	Pedawetan		6	Coaching inns suffered damage	Laar, 1867
-6.9589	109.8482	Poetjungkerep		6	Coaching inns suffered damage	Laar, 1867
-7.3762	109.8944	Toelies	Tulis	6	Coaching inns suffered damage	Laar, 1867
-6.9071	109.7333	Batang		5	Walls sustained cracks	Laar, 1867
-6.9706	110.4386	Semarang		7	Walls sustained cracks, houses collapsed	Laar, 1867; Bergsma, 1868
-7.1227	110.9459	Grobogan Regency		7	Cracks formed in the ground	Laar, 1867
-7.0984	110.9130	Purwodadi		8	A gaping crevice formed, well no longer supplied oil	Laar, 1867
-7.1290	110.4097	Oenarang	Ungaran	6	Slight damage	Laar, 1867
-7.2650	110.4064	Ambawara		6	Some buildings suffered damage	Laar, 1867
-7.3378	110.5009	Salatiga		5	Little damage	Laar, 1867
-7.4674	110.2191	Magelang		8	All government buildings heavily damaged, walls and houses collapsed	Laar, 1867
-7.3249	110.2199	Kranggan		7	Post office partially destroyed, several homes uninhabitable	Laar, 1867
-7.4632	110.2496	Tegalredjo	Tegalrejo	5	Violent shock	

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-7.7128	110.0146	Poerworedjo	Purworejo	8	Many houses collapsed, entire Chinese neighbourhood destroyed	Laar, 1867
-7.7824	109.7312	Ambal		8	Many houses collapsed, forts and barracks suffered heavy damage	Laar, 1867
-7.6848	109.6831	Kebumen		8	Many houses collapsed, forts and barracks suffered heavy damage	Laar, 1867
-7.3640	109.9021	Wonosobo		8	Many houses collapsed, forts and barracks suffered heavy damage	Laar, 1867
-7.7234	109.9134	Kutuardjo	Katuarjo	8	Many houses collapsed, forts and barracks suffered heavy damage	Laar, 1867
-7.4604	109.9787	Sapoeran	Sapuran	8	Many houses collapsed, forts and barracks suffered heavy damage	Laar, 1867
-7.2702	109.7409	Ledok		8	Many houses collapsed, forts and barracks suffered heavy damage	Laar, 1867
-7.6944	111.4078	Kawodanan	Kawedanan	8	Many houses collapsed, forts and barracks suffered heavy damage	Laar, 1867
-7.2363	110.0606	Ngadiredjo	Ngadirejo	8	Deep crevices formed in the ground	Laar, 1867
-7.6089	109.7044	Krakal		0	Springs exhibit high temperatures for several days	Laar, 1867
-7.4786	109.1360	Banjoemas	Banyumas	7	A house and telegraph office collapsed, many homes suffered heavy damage	Bergsma, 1868; Laar, 1867
-6.6093	106.8503	Sukaradja	Sukaraja	8	Most houses collapsed or heavily damaged, lives lost	Laar, 1867
-7.7060	109.0208	Tjilatjap	Cilacap	8	Houses in the Chinese camp collapsed, many others heavily damaged	Laar, 1867
-7.7280	108.9032	Nusa Kambangan		6	Fort suffered damages	Laar, 1867
-7.7971	110.3705	Djokjakarta	Yogyakarta	8	Kraton heavily damaged 136 houses collapsed, over 500 deaths	Laar, 1867; Fuchs, 1868; Bergsma, 1868
-7.8189	110.3979	Pasar Gede	Kota Gede	8	1169 residences destroyed, over 190 people were killed and 135 wounded	Laar, 1867
-7.7653	110.2093	Nangoelan	Nanggulen	8	Sugar factory completely destroyed	Bergsma, 1868
-7.6650	110.4286	Paduan	Padukan	8	Sugar factory completely destroyed	Bergsma, 1868

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-6.8008	110.8468	Barongan		8	Sugar factory completely destroyed	Bergsma, 1868
-7.8801	110.4130	Pleret		8	Sugar factory completely destroyed	Bergsma, 1868
-7.8438	110.3773	Ngoto		8	Sugar factory completely destroyed	Bergsma, 1868
-7.8034	110.4388	Tandjong Tirto		8	Sugar factory completely destroyed	Bergsma, 1868
-7.7343	110.4653	Kandjang		7	Sugar or indigo factory partly destroyed	Bergsma, 1868
-7.8846	110.3341	Bantul		7	Sugar or indigo factory partly destroyed	Bergsma, 1868
-7.7439	110.4929	Tjandi-Sewu	Candi Sewu	8	Temple collapsed	Bergsma, 1868
-7.7818	110.4504	Postal road between Tjandi-Sewu and Djokjakarta		8	Ground uplifted in several places where sulphuric water spilled, 66 buildings damaged	Bergsma, 1868
-7.7868	110.3884	Dumanga	?Dumandan	7	Sugar or indigo factory partly destroyed	Bergsma, 1868
-7.7830	110.8030	Rewulu		7	Sugar or indigo factory partly destroyed	Bergsma, 1868
-7.6267	109.2636	Badjing	Bajing	8	Deep creviced formed, ground level shifted up to 5 feet, mud welled up	Bergsma, 1868
-7.5653	110.8244	Solo	Surakarta	8	Kraton/ palace damaged, roofs torn, walls and houses collapsed	Laar, 1867; Bergsma, 1868
-7.5123	110.5002	Soekaboemi	Sukabumi	7	Bridge and houses collapsed	Bergsma, 1868
-7.5585	110.7463	Kartasura	Kartosuro	8	Cracks formed in the ground, black sand welled, sugar factory partly destroyed	Bergsma, 1868
-7.6298	110.7453	Wonosari		8	Crevices formed, mud welled up, sugar factory partly destroyed	Bergsma, 1868
-7.6753	110.6723	Tjeper	Ceper	7	Sugar factory and houses suffered damage	Bergsma, 1868
-7.6090	110.6422	Pongak	Ponggok	7	Sugar factory and houses suffered damage	Bergsma, 1868
-7.6002	110.6372	Tjokro	Cokro	7	Sugar factory and houses suffered damage	Bergsma, 1868
-7.5217	110.7018	Bangak		7	Sugar factory and houses suffered damage	Bergsma, 1868
-7.6205	110.6944	Delangu	Delanggu	7	Sugar factory and houses suffered damage	Bergsma, 1868
-7.5885	110.6802	Mandjung	Manjung	7	Sugar factory and houses suffered damage	Bergsma, 1868
-7.6440	110.6348	Karang-Anom		7	Houses suffered damage	Bergsma, 1868

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-7.5345	110.5988	Bojolali	Boyolali	8	Houses collapsed	Bergsma, 1868
-7.5412	110.4459	Gunung Merapi		0	Rock fall, landslide occurred	
-7.4332	110.5311	Ampel		5	Houses sustained cracks	Bergsma, 1868
-7.3531	110.6570	Kurang gede		8	Land elevated some feet and salt water bubbled	Bergsma, 1868
-7.6997	110.6054	Klatten	Klaten	8	Over 372 houses collapsed, lives lost	Laar, 1867; Bergsma, 1868
-7.7503	110.5104	Brambanan	Prambanan	8	Land subsidence and mud welling occurred	Laar, 1867
-7.4279	111.0206	Sragen Regency		8	Several mosques collapsed, cracks formed in the ground	Bergsma, 1868
-7.6149	111.0641	Kurang Pandan		7	Heavily damaged	Bergsma, 1868
-7.7363	110.5567	Djo Gonalen	Jogonalen	8	Indigo factory completely destroyed	Bergsma, 1868
-7.7398	110.5133	kemoedo	Kemudo	7	Sugar or indigo factory partly destroyed	Bergsma, 1868
-7.6088	110.9655	Pasanggrahan (Karang-Anjar regency)	~ Karanganyar	7	Heavily damaged	Bergsma, 1868
-7.8063	110.9353	Wonogiri		8	Cracks formed in the ground, mud welling occurred	Bergsma, 1868
-6.5962	110.6722	Japara		6	Suffered damage	Bergsma, 1868
-6.7535	111.0347	Pati		5	Violent shocks	Laar, 1867
-6.7132	111.1418	Djuana/ Joanna	Juwana	7	Walls collapsed	Laar, 1867
-6.8097	110.8509	Kudus		7	Prison walls and houses suffered heavy damage	Laar, 1867
-6.7167	111.3668	Rembang		5	Violent shock	Bergsma, 1868; Laar, 1867
-6.9019	112.0467	Tuban		5	Violent shock	Laar, 1867
-7.6375	111.5219	Madiun		7	Walls collapsed, houses heavily damaged	Bergsma, 1868; Laar, 1867
-7.8649	111.4611	Ponorogo		8	Buildings collapsed	Laar, 1867
-7.8691	111.4047	Sumo-rotto	Sumoroto	7	Extensive damage to many buildings	Laar, 1867
-8.2006	111.1002	Patjitan	Pacitan	7	Extensive damage to many buildings	Laar, 1867
-7.8207	112.0108	Kediri		8	Crevice formed, mud welling occurred, all government buildings and private estates suffered heavy damage	Bergsma, 1868; Laar, 1867
-7.6211	112.3685	Modjopagoong	Mojoagung	7	Factories with wall and chimney collapse, lives lost	Laar, 1867
-8.1825	111.6184	Trengalek	Trenggalek	8	Crevice formed, mud welling occurred, prison destroyed, houses collapsed	Laar, 1867

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage	Reference
-8.0795	111.9073	Tulungagung		8	Ground torn open, houses collapsed	Fuchs, 1868; Laar, 1867
-8.0948	112.1728	Blitar		5	Several violent shocks	Fuchs, 1868
-7.2642	112.7456	Surabaya	Surabaya	7	Walls collapsed while many others sustained cracks	Bergsma, 1868; Laar, 1867
-7.4681	112.4371	Modjokerto		5	Violent shock	Laar, 1867
-7.6431	112.9050	Pasuruan		7	Buildings suffered heavy damage	Bergsma, 1868
-7.9803	112.6237	Malang		7	Stone buildings suffered heavy damage	Laar, 1867
-8.1803	112.6412	Gondang Legie		8	Stone buildings collapsed	Laar, 1867
-7.7520	113.2156	Probolingo	Probolinggo	5	Heavy shocks, 2 minutes	Bergsma, 1868
-7.7368	113.6889	Bezoeki	Besuki	5	Some shocks, little damage	Laar, 1867
-8.2130	114.3735	Banjoewangi	Banyuwangi	5	Violent shocks	Laar, 1867
-8.3505	114.5950	Negara		3	A shock was felt	Wichmann, 1922
-7.1668	113.4872	Pamekasan		4	Weak vibrations, 30 seconds	Bergsma, 1868
-7.0486	113.8600	Sumanep		4	Weak vibrations, 30 seconds	Bergsma, 1868
-7.1923	113.2474	Sampang		4	Weak vibrations, 30 seconds	Bergsma, 1868
-2.9919	104.7570	Palembang		7	A house collapsed killing 4, injuring 3, may not be related	Laar, 1867
-6.8576	110.4034	Batavia Steamship		3	Sequake observed	Laar, 1867
-5.7000	106.8500	Dutch ship Europa		3	Sequake observed	Laar, 1867

Appendix B Historical MMI: Events Not Modelled

All damage descriptions in the following tables are summarised from Wichmann (1918; 1922) translated by Harris and Major (in press).

Table 5.9 Evidence used to obtain observed MMI for August 24, 1757.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage
-6.1623	106.79101	Batavia	Jakarta	7	2 a.m. violent quake, duration 5 minutes, Tji Liwun (Ciliwung) River shifted up and down by up to 2 metres

Table 5.10 Evidence used to obtain observed MMI for November 22, 1818.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage
-8.214721	114.372848	Banjuwangi		5	Violently felt
-7.636357	112.909547	Pasuruan		6	Violently felt, 4 minute duration, followed by 6-7 weaker aftershocks
-8.104473	114.423742	Bali Strait		1	Seauquake observed
-7.968614	112.628865	Malang		4	A weak shock was felt
-7.980401	113.340818	Gunung Lamongan	Mount Lamongan	1	Erupted
-8.45342	118.726234	Bima		8	Violent earthquake, 3 minutes in duration, people could not stand upright, all stone buildings collapsed, sea rose by 2 fathoms (3.6 m) in the bay and a flood wave penetrated the city. No Date. Assumed to be related.

Table 5.11 Evidence used to obtain observed MMI for May 19, 1865.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage
-6.1643	106.8359	Batavia	Jakarta	3	Weak shock
-6.8173	107.1372	Tjiandjur	Cianjur	5	Several violent shocks
-6.8530	107.9227	Sumedang		5	Several violent shocks
-7.3527	108.3083	Manondjaja	Manonjaya	5	Violent shocks, 20 seconds duration
-6.7214	108.5689	Cheribon	Cirebon	3	4 second shock
-6.8644	109.1367	Tegal		5	Violent shock
-7.1175	109.2467	Moga		5	Violent shaking, 2 minutes duration
-7.1701	109.1314	Pasanggrahan		5	Violent shaking, 2 minutes duration
-6.9756	110.4277	Semarang		5	Strong shock, 30 seconds duration

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage
-7.0651	110.4207	Srondel	Srondol	4	A short shock
-7.2709	110.4102	Fort Willem I	Ambarawa	5	Several violent shocks
-7.3354	110.4151	Banjubiru	Banyubiru	5	Several violent shocks
-7.3306	110.4929	Salatiga		5	Several violent shocks
-7.4428	109.1488	Banjumas	Banyumas	5	Strong shock, one minute duration
-7.7228	109.0123	Tjilatjap	Cilacap	5	Violent shock, walls sustained cracks
-7.3881	109.3600	Purbalingga		5	Violent shock
-7.4007	109.6185	Bandjarnegara		5	Violent shock
-7.2075	109.8851	Dieng Plateau		5	Strong shock, one minute duration
-7.3838	110.2561	Kedu		5	Several violent shocks
-7.7973	110.3759	Djokjakarta	Yogyakarta	5	Several violent shocks
-7.5617	110.8233	Surakarta		4	Horizontal shock
-6.5947	110.6697	Japara	Jepara	5	Strong shock
-6.7537	111.0401	Pati		5	Strong shock
-6.7364	111.3706	Rembang		5	Strong shock, one minute duration
-7.0575	111.3771	Blora		5	Several violent shocks
-7.6294	111.5340	Madiun		5	Violent shock, 20 second duration
-8.1997	111.0951	Patjitan	Pacitan	5	Several violent shocks
-7.8210	112.0155	Kediri		5	Violent shock
-8.0731	111.9073	Tulungagung		5	Several violent shocks
-7.2998	112.7373	Surabaja	Surabaya	4	Weak shock of 2 minutes duration
-7.6222	112.3260	Modjowarno		5	Several strong shocks
-7.6474	112.9032	Pasuruan		3	Weak shock
-7.7535	113.2150	Probolinggo		5	Violent shock
-7.1611	113.4837	Pamekasan		3	Weak shock
-7.0067	113.8614	Sumanep		4	Several weak shocks followed by a violent one
-8.3533	114.6264	Djembrana	Jembrana	3	Weak shock

Table 5.12 Evidence used to obtain observed MMI for October 25, 1875.

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage
-7.714374	110.008629	Purworedjo	Purworejo	3	Weak shock
-7.462319	109.141044	Banjumas		3	Weak shock
-6.752547	111.035551	Pati		3	Two weak shocks
-6.887879	109.672962	Pekalongan		3	Several seconds duration
-6.917342	107.61106	Bandong	Bandung	5	Violent shaking
-6.830885	107.952103	Soemedang	Sumedang	5	Violent shaking

Latitude	Longitude	Historic Name	Modern Name	MMI	Description of Damage
-7.351523	108.306736	Manondjaja	Manonjaya	6	Buildings were damaged, longer than a minute in duration
-6.723854	108.561488	Cheribon	Cirebon	5	Extremely intense, longer than 10 seconds in duration
-6.979947	108.487041	Kuningan		9	Several violent shocks felt throughout the day, 628 houses collapsed and 428 severely damaged (excluding stables and sheds), lives lost
-6.996319	108.459144	Windudjanten	Windujanten	8	Fissures formed in the ground from which sulphuric water gushed
-6.980217	108.451965	Tjilelei	Cileuleuy	8	Black sand wells up in many places
-6.895791	108.407622	Gunung Tjerimai	Mt. Cereme	8	Large landslides formed on the slopes, killing 51 and burying 26 people
-6.162415	106.80207	Batavia	Jakarta	4	Strong shock, several seconds in duration