Waves of destruction in the East Indies: the Wichmann catalogue of earthquakes and tsunami in the Indonesian region from 1538 to 1877

RON HARRIS[1]* & JONATHAN MAJOR[1,2]

[1]*Department of Geological Sciences, Brigham Young University, Provo, UT 84602–4606, USA*

[2]*Present address: Bureau of Economic Geology, The University of Texas at Austin, Austin, TX 78758, USA*

**Corresponding author (e-mail: rharris@byu.edu)*

Abstract: The two volumes of Arthur Wichmann's *Die Erdbeben Des Indischen Archipels* [*The Earthquakes of the Indian Archipelago*] (1918 and 1922) document 61 regional earthquakes and 36 tsunamis between 1538 and 1877 in the Indonesian region. The largest and best documented are the events of 1770 and 1859 in the Molucca Sea region, of 1629, 1774 and 1852 in the Banda Sea region, the 1820 event in Makassar, the 1857 event in Dili, Timor, the 1815 event in Bali and Lombok, the events of 1699, 1771, 1780, 1815, 1848 and 1852 in Java, and the events of 1797, 1818, 1833 and 1861 in Sumatra. Most of these events caused damage over a broad region, and are associated with years of temporal and spatial clustering of earthquakes. The earthquakes left many cities in 'rubble heaps'. Some events spawned tsunamis with run-up heights >15 m that swept many coastal villages away.

2004 marked the recurrence of some of these events in western Indonesia. However, there has not been a major shallow earthquake ($M \geq 8$) in Java and eastern Indonesia for the past 160 years. During this time of relative quiescence, enough tectonic strain energy has accumulated across several active faults to cause major earthquake and tsunami events, such as those documented in the historical records presented here. The disaster potential of these events is much greater now than in the past due to exponential growth in population and urbanization in areas destroyed by past events.

Supplementary material: Translation of the catalogues into English, scanned PDFs of the original catalogues and geographical locations of most place names found in the catalogue (as a KMZ file) are available at https://dx.doi.org/10.6084/m9.figshare.c.2860405.v1

Recent earthquake catastrophes in Japan (2011), Haiti (2010) and Chengdu, China (2008) all occurred in regions mapped as relatively 'low' seismic hazard (Stein *et al.* 2012). One factor contributing to this forecasting failure is the over-reliance on the relatively short (50 year) instrumental earthquake record. Although historical records of centuries of seismic events exist in these regions, they were rarely used in hazard assessments. Reliable data from historical accounts of earthquake and tsunami events can help constrain long-term seismic potential in areas with little to no earthquakes during the past 50 years (Musson & Jimenez 2008).

An example of earthquake and tsunami forecasting success using historical records is the reconstruction by Newcomb & McCann (1987) of mega-thrust events along the Sumatran subduction zone. They primarily used *Die Erdbeben Des Indischen Archipels* [*The Earthquakes of the Indian Archipelago*] by Arthur Wichmann (1918, 1922) to demonstrate that a series of megathrust earthquakes occurred during the nineteenth century along various segments of the subduction zone. Some of these events have now reoccurred, such as the 2005 northern Sumatra earthquake near Nias Island, which was nearly of the same magnitude and ruptured close to the same area as that estimated by Newcomb & McCann (1987) from descriptions in the Wichmann catalogue of an 1861 earthquake and tsunami (see Supplementary material).

Arthur Wichmann was a German geologist and professor in geology at Utrecht University in the Netherlands. Much of Wichmann's professional career was spent studying the geology of Indonesia, including several expeditions to eastern Indonesia. He wrote the catalogue in old German, but included passages in Dutch, English, French and Latin. It is evident that Wichmann tried to preserve and use the original accounts as much as possible. However, he was careful to note conflicting reports, errors in dates

From: Cummins, P. R. & Meilano, I. (eds) *Geohazards in Indonesia: Earth Science for Disaster Risk Reduction*. Geological Society, London, Special Publications, **441**, http://doi.org/10.1144/SP441.2

and other inconsistencies. The catalogue includes 350 years of observations of earthquakes and tsunamis, and some volcanic eruptions for the entire Indonesian region (see Supplementary material).

The observations were mostly compiled from Dutch records kept by the Dutch East India Company of Indonesia (Vereenigde Oost-Indische Compagnie: VOC). Seismic events are included that reach west to east from the Cocos Islands to New Guinea, and north to south from Bangladesh to Timor. Although the catalogue is cited in some tsunami and earthquake databases (i.e. Soloviev & Go 1974), it remains largely unknown to the scientific community (i.e. Hamzah *et al.* 2000; Rastogi & Jaiswal 2006). For this reason, we have translated the catalogue into English and supplied scanned PDFs of the original; these are included in the Supplementary material to this paper.

For ease of comparison and consistency, the English translation is formatted and paginated in the same way as the original document. Footnotes with abbreviations used and works commonly cited are included with the translation. The Index, containing mostly locations, was not translated and so readers should refer to the original catalogue. Volume II also contains a list of additions and corrections for the previous volume. We have also included geographical locations of nearly all the place names found in the catalogue as a KMZ file (see Supplementary material).

The number of entries in the catalogue increases towards the end (1877), which reflects, to some extent, the increasing number of observation posts. However, many of the events in the later part of the catalogue are also the result of temporal and spatial clustering from a few extreme events, such as megathrust earthquakes in Sumatra, Java and eastern Indonesia. Other clusters may be associated with eruptions of Tambora and precursor events to the eruption of Krakatoa, which happened shortly after the end date of the catalogue. Events associated with the collapse of buildings, tsunamis (flood waves) and fatalities are highlighted by bold text in the catalogue.

Most of the locations listed in the catalogue where major earthquakes or tsunamis occurred have experienced a dramatic increase in population and urbanization (see the maps of Padang in Natawidjaja *et al.* 2006). To make the catalogue accessible to those actually in harm's way, we have worked with Indonesian geoscientists to translate large parts of it into Indonesian. For example, the sections of the catalogue for the Maluku and Nusa Tenggara regions have already been translated into Indonesian, and updated to include earthquakes and tsunamis to 2010. In November 2013, the Indonesian version of the catalogue was distributed throughout some of the most vulnerable areas of eastern Indonesia by 'In Harm's Way', a non-profit organization for natural disaster prevention (inharmswayhelp.org).

During the time covered by the catalogue (1538–1877), the population of Indonesia doubled from 15 million to 30 million. Since 1877, the population has increased by nearly an order of magnitude and is projected to reach 300 million by 2030. At least 94% of the population of Indonesia lives in active seismic and volcanic regions, or in tsunami inundation zones. However, from our experience of conducting informal surveys throughout Java and eastern Indonesia over the past 25 years, for most Indonesians, their sense of history, especially regarding natural disasters, is limited to the living memory of the oldest residents of each area. One factor that is likely to contribute to the lack of awareness is a distinct lull in seismic and tsunami activity in the region between 1883, when Krakatoa erupted, and the recent past (Ghose & Oike 1988). Another problem is that historical records of past events in Indonesia are not available to those in harm's way (Harris *et al.* 1997; Harris & Prasetyadi 2002). These problems contributed to the disaster potential of recent earthquakes such as the Banda Aceh event and other earthquakes during the past 10 years.

Many of the events documented in the Wichmann catalogue have reoccurred in western Indonesia during the past decade and account for around 200 000 fatalities. However, in eastern Indonesia, seismic quiescence continues to mask the fact that significant amounts of elastic strain energy is accumulating on many active faults dangerously close to burgeoning urban centres. As in the past, the strain will eventually be unleashed and may result in a cluster of large events like those documented throughout eastern Indonesia in the Wichmann catalogue during 1629–99, 1754–80 and 1814–77, and like the cluster of events that initiated in 2004 in western Indonesia.

The recurrence of temporal and spatially clustered seismic events in Sumatra and Java also demonstrate a significant increase in the disaster potential of Indonesia. More death and destruction is occurring from events that caused few losses in the past. The reasons behind the greater losses to nature are multifaceted, but the one main contributing factor is non-resilient urbanization in hazardous regions. For example, some of the most seismically active regions of Indonesia, from a historical perspective, are transitioning from traditional woody building materials to unreinforced masonry structures built in hazardous areas. With limited resources to address these issues, it is imperative that mitigation efforts focus on the regions at highest risk, which are proximal to active faults. Our hope is that this paper can help better identify these regions by extending the earthquake records back far enough to reveal likely areas of high seismic potential and to better constrain the locations of active fault zones in Indonesia.

Summary of significant events and possible source regions

The purpose of this section is to augment what we know about earthquake source regions in Indonesia (Fig. 1) with data from the Wichmann catalogue. We first summarize as many characteristics as possible about each significant event in the catalogue in Tables 1–7. By 'significant event' we mean those that caused damage or a tsunami. A summary of all of the events felt regionally is provided in Table 1. Summaries of significant events for various regions of similar tectonic setting are listed in Tables 2–7. Besides the obvious characteristics of place and time, the catalogue also notes direction of ground motion and documents possible foreshocks or aftershocks. Other characteristics of note include fatalities (F), regional extent (R), tsunami (T) with the height in metres and volcanic activity (V). Distinguishing between volcanic and tectonic earthquakes can be problematic in the catalogue. Many times volcanic eruptions are noted in association with strong ground shaking, but it is not clear whether the eruption or its precursors caused the earthquakes or a tectonic earthquake caused the eruption.

One way of addressing this problem is to determine the regional extent of each earthquake. Columns in the tables to the right of 'Other' list several of the observation stations in each region and how many reported each event. We have divided Indonesia into six regions based mainly on tectonic setting (Table 1). In the tables for each region (Tables 2–7), the locations of individual reporting stations are listed. An upper case 'X' refers to strongly felt (>Mercalli scale 5), while a lower case 'x' refers to weakly felt (<Mercalli scale 5). 'Mercalli' always refers to the Modified Mercalli Intensity (MMI). In many cases, earthquakes were felt over several sub-regions, but records documenting the event in the sub-regions are lacking. Other locations where the earthquake was felt that are not listed in columns are provided in the last column on the right of each table.

The majority of the earthquakes listed in the catalogue are probably aftershocks from major events. For example, in Volume I, a detailed list of aftershocks from each of the Uliasser Islands is reported after the 1754 earthquake in Ambon. In Volume II, most of the events are low-intensity earthquakes following larger events in Sumatra (1861), Java (1865), northern Timor (1857) and in the eastern Banda Arc (1852). The number of reliable reporting stations increased dramatically during the late nineteenth century, which provides a better estimate of the location and parameters of earthquake sources.

Since more is now known about the structure and tectonics of earthquake and tsunami source regions in Indonesia than when Wichmann compiled the catalogue, we include here a summary of active faults for each region.

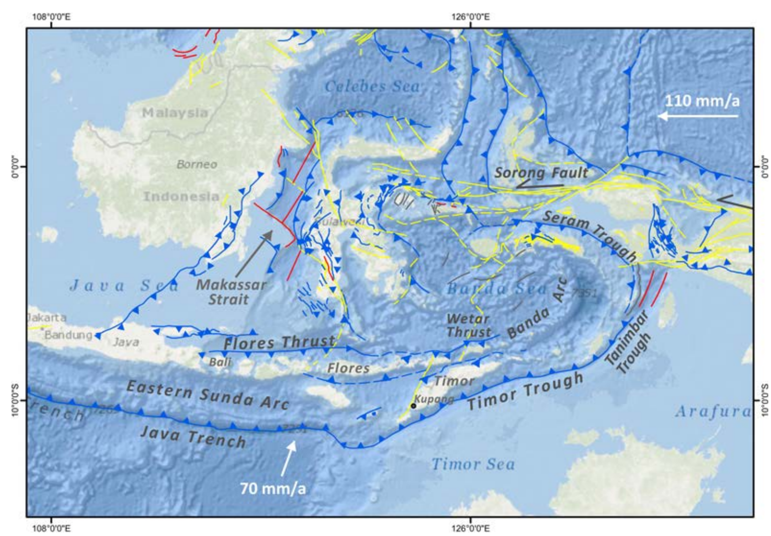

Fig. 1. Location map of active faults through Java and eastern Indonesia.

Table 1. *Significant earthquakes and tsunamis throughout Indonesia, 1584–1877*

Primary reporting location	Year	Date (month/day)	Time	Intensity (MMI)	Aftershocks reported	Other	Molucca Sea	Banda Arc	Lesser Sunda	Java	Sumatra	New Guinea	Other locations
Java	1584–86			VIII		T?				x			
Ternate	1608	7/18	Night	VIII		V	X						
Banda Islands	1629	8/1	9:30 p.m.	XI	9 years	T (15 m)		X					
Amboina (Ambon)	1644	5/12	Morning	VIII–IX	2 weeks			X					
Molukken (Makjan) Island	1646	7/19		VIII–IX		F, V, T (1.5 m)	X						
Fort Henricus, Solor	1648	2/2		IX–X	3.5 months	F			X				
Saparua (Ambon)	1671	10/17	Evening	X–XI	2 months			X					
Ambon	1672	?		X				X					
Ternate	1673	8/12	10:00 p.m.	IX	1 month	T	X						
Ambon	1675	2/17	7:30 p.m.	XI	3 months	F, T (2.5 m)		X					
Banda Islands	1683	10/16	8:00 a.m.	IX	1 year	V		X					
Batavia (Jakarta)	1699	1/5	1:30 a.m.	X	13 months	F				X	X		
Ambon	1705	10/?		IX	1 month			X					
Banda Islands	1710	3/6		IX	4 weeks	T		X					
Batavia (Jakarta)	1722	10/?	8:00 a.m.	IX		T				X			
Banda Islands	1743	?		X				X					
Ambon	1754	8/18	3:30 p.m.	X	1.5 months	F, T		X					
Bengkulen (west Sumatra)	1756	11/3		X	1 month						X		
Assam (India)	1762	4/3	5:00 a.m.										Burma, Bangladesh
Banda Islands	1763	9/12	5:00 p.m.	IX	4 years			X					
Ternate	1770	7/26		IX	5 years	V	X						
Bengkulen (west Sumatra)	1770	?		X		V, T					X		
Ambon	1777	3/30	9:00 a.m.	VIII	3 months			X					
Banda Islands	1778	4/2		IX		T?		X					
Batavia (Jakarta)	1780	1/22	2:39 p.m.	IX	12 months					X	X		
Kupang (Timor)	1793–95	?		IX					X				
Padang (west Sumatra)	1797	2/10	10:00 p.m.	IX	1 week	T					X		
Palembang (west Sumatra)	1799	?		IX		T (15 m)					X		
Ambon	1802	8/25		X		T		X					
Kupang (Timor)	1814	?		IX		T		X	X				

Sumbawa (Tambora)	1815	4/1	10:00 p.m.		1 year	T (4 m), V		X	X	x			1 year
Ambon	1815	4/11		VIII–IX		V, T		X					
Banda Islands	1816	10/8	7:00 a.m.	IX	3 months	F		X					
Bima (Sumbawa)	1818	?		X		T (4 m)			X				
Benkulen (SW Sumatra)	1818	3/18		IX	2 months	T					X		
Makassar (west Sulawesi)	1820	12/29	10:00 a.m.	X	3 months	F, T (29 m)			X				
Ambon	1830	3/28	10:00 a.m.	IX	4 months			X					
West Sumatra	1833	11/24	8:30 p.m.	X	1.5 years	T				x	X		Singapore
Batavia (Jakarta)	1834	10/10	5:30 a.m.	X						x	X		
Ambon	1835	11/1	3:00 a.m.	X	2–3 years	F		X					
Pajitan (central Java)	1840	1/4	1:15 p.m.	VIII	1 month	T				X			
Ternate	1840	2/14	10:00 a.m.	X	3 months	V	X						
Barus (NW Sumatra)	1843	1/5	11:30 p.m.	XI	3 months	T					X		
Menado, (north Sulawesi)	1845	2/8	3:30 p.m.	XIII	2 weeks	T	X						
Nicobar minor	1847	10/31	3:30 a.m.	X	3 weeks	T					X		
Cheribon (Java)	1847	11/16	12:55 p.m.	X	2 weeks					X	X		
Saparua (Ambon)	1849	5/30		VIII	1 week			X					
Banda Islands, Ambon	1852	11/26	7:50 a.m.	XI	3 + years	F, R, T (8 m)	x	X	x	x	x		
Solok (Sumatra)	1853	2/8	Night	VIII							X		
Ternate	1855	4/25	Morning	IX	1 year	F	X						
Ternate	1855	6/14	11:00 a.m.	IX			X						
Ternate	1855	7/14	4:00 p.m.	IX	1 year		X						
Gorontolo (north Sulawesi)	1856	8/6		VIII	16 months		X						
Astrolabe Bay (New Guinea)	1856	?	Night	IX		F, T						X	
Rook Island (New Guinea)	1857	4/17	Evening	VIII								X	
Dilli (Timor)	1857	5/13	10:30 a.m.	IX–X	1 month	F, T (3 m)		x	X				
Minahassa (north Sulawesi)	1858	11/13	4:00 p.m.	IX	Years	T	X		x				
Ternate	1859	7/29	3:15 p.m.	IX	Years	T (1 m)	X	x?					
Kau Territory (Halmahera)	1859	10/8	2:00 p.m.	VIII			X						

(*Continued*)

Table 1. *Significant earthquakes and tsunamis throughout Indonesia, 1584–1877* (*Continued*)

Primary reporting location	Year	Date (month/day)	Time	Intensity (MMI)	Aftershocks reported	Other	Molucca Sea	Banda Arc	Lesser Sunda	Java	Sumatra	New Guinea	Other locations
West Sumatra	1861	2/16	6:30 p.m.	X	4 + years	F, T (7 m)				x	X		Malaysia, Singapore
Geelvink Bayk (P.N.G.)	1864	5/23	12:30 a.m.	IX	1 week	F, T (3 m)						X	
Ambarawa (central Java)	1865	7/17	2:27 a.m.	VIII	15 months					X			
Djogjakarta (central Java)	1867	6/10	4:30 a.m.	IX	1 year	F				X			
Bengkulen (SW Sumatra)	1871	8/18	8:16 p.m.	VIII						x	X		
Astrolabe Bay (Papua New Guinea)	1873	?		IX		T						X	
Singkel (NW Sumatra)	1873	8/19	3:15 p.m.	IX	1 month						X		
Cheribon (West Java)	1875	10/25	5:50 a.m.	X	3 months	F					X		
	63 total significant events (MMI >VII)												

F, fatalities reported; V, during or followed by volcanism; T, tsunami (maximum run-up); X, strongly affected; x, weakly affected.

Table 2. *Molucca Sea (Maluku North) events*

Primary reporting location	Date			Intensity (MMI)	Aftershocks reported	Other	Affected locations						
	Year	Month/day	Time				Ternate	Halmahera	Menado	Makjan	Minahassa	Gorontalo	Other locations
Ternate	1538	4					X						
Ternate	1538	9					X						
Ternate	1546	9/29					X						
North Halmahera	1550	11 or 12				V	X	X					
NW Halmahera	1564					V	X	X					
Molukken (Makjan)	1608	7/1				T				X			
Molukken (Makjan)	1646	7/20		IX		F, T, V				X			
North Halmahera	1673	5/20		VI		T, V	x	X					
Ternate	1673	8/12	10:00 p.m.	IX	1 month	T	X						
Ternate	1686	10/26	11:00 a.m.	VI			X						
Ternate	1770	7/27		X	5 years	T, V	X						
Ternate	1770	8/2	9:00 a.m.	VIII									
Ternate	1773	2/21, 10/21		VIII		V	X						
Ternate	1775	7/4	8:00 a.m.	VI			X						
Ternate	1840	2/15	10:00 a.m.	X	3 months	V	X						
Menado, (north Sulawesi)	1845	2/9	3:30 p.m.	XIII	2 weeks	T			X		X		
Ternate	1854	11/24	1:30 p.m.	VIII									
Ternate (east–west)	1855	4/25	Morning	IX	1 year	F	X						
Ternate	1855	6/14	11:00 a.m.	IX	1 year	T							
Ternate	1855	7/14	4:00 p.m.	IX	1 year	F, T							
Gorontolo (north Sulawesi)	1856	8/7		VIII	16 months							X	
Ternate	1858	6/4	7:00 a.m.	VII			X						
Minahassa (north Sulawesi)	1858	12/13	4:00 p.m.	IX	Years	F, T	X		X		X	X	
Ternate (NW–SE)	1859	6/28	8:07 p.m.	IX		R, T (2 m)	X	T (9 m)	x		T, (east–west)		
Ternate	1859	7/29	3:15 p.m.	IX		R, T (>1 m)	X	X	X	x	T (2 m)	X	T, Banggai
NE Halmahera	1859	10/8	2:00 p.m.	VIII			X	X					
Minahassa (north Sulawesi)	1859	12/17	8:00 p.m.	VII	Aftershock?	T			x		X	X	
Menado (north Sulawesi)	1859	12/26	Early morning	?	Aftershock?	T			T (>2 m)				
Halmahera	1860	10/6	12:00 a.m.	VIII		T		X					

F, fatalities reported; V, during or followed by volcanism; T, tsunami (maximum run-up); X, strongly affected; x, weakly affected.

Table 3. *Banda Arc (Maluku South) events*

Primary reporting location	Date			Intensity (MMI)	Aftershocks reported	Other	Affected locations							
	Year	Month/day	Time				Ambon	Saparua	Haruku	Buru	Banda Islands	Kei Islands	Seram	Other locations
Ambon	1612			V			X							
Banda Islands	1618			VII							X			
Banda Islands	1629	8/2	9:30 p.m.	XI	9 years	F, T (15 m)	X				X			
Ambon	1644	5/12 5/13	Morning	IX	2 weeks		X						x	
Ambon	1644	5/17		IX	Aftershock		X							
Ambon	1648	2/29				T	X							
Kei Islands	1649			VIII		New island						X		
Teon Island	1659	11/9		VII	2 years	V								
Buru	1659	1/13		VII		T	x			X				
South Seram	1664	1/8		V									X	
Saparua	1671	10/17–10/18	Evening	XI	2 months		x	X	x				x	
Ambon	1672			X			X							
Ambon	1674	2/17	7:30 p.m.	XI	3 months	F, T (80 m)	X	X	X	X	X	X	x – west	
Banda Islands	1683	10/16–10/30	8:00 a.m.	IX	1 year	V					X			
Serua SW (Islands)	1683			IX		F								
Ambon	1687	2/19–4/4	6:30 a.m.	IV	3 months		X							
Banda Islands	1691			V		V					X			
Banda Islands	1699	5/11	2:00 p.m.	V							X			
Ambon	1705	10/?		IX	1 month	F	X	x	x				x – west	
Ambon	1708	11/28	10–11 p.m.			T	x	x	x					
Ambon	1710	2/15–2/17		IX		T	X				X			
Banda Islands	1710	3/6		IX	4 weeks									
Ambon	1711	9/5		VI		T	X	x	X		x			
Leti (SW Islands)	1714	1/12		VI	2 years									

Leti (SW Islands) (south–north)	1716	12/20		VII										
Banda Islands	1743			IX							X			
Banda Islands	1750			VI							X			
Amboina	1754	8/19	3:30 p.m.	X	1.5 months	F, T	X	X	X	X				Felt in Java?
Banda Islands	1763	9/13	5:00 p.m.	IX	4 years						X			
Ambon (SW–NE)	1775	4/19	1:00 a.m.	VII			X							
Ambon (NW–SE)	1777	3/31	9:00 a.m.	VIII	3 months		X							
Ambon	1777	4/28		VIII	Aftershock		X							
Ambon	1781			VIII			X							
Amboina (south–north)	1802	8/26		X		R, T	X	X	X	x	x	x	x	East Sunda
Banda Islands	1811			IX	6 years						X			
Sumbawa (Tambora)	1815	4/1	10:00 p.m.		1 year	T (4 m), V	x				x			Java, Ambon, Ternate
Amboina	1815	4/11–4/12		VIII–IX		T	X		X					SE Borneo
Banda Neira	1816	10/8–10/11	7:00 a.m.	IX	3 months	F					X			
Saparua, Ambon	1817	11/11	3:00 a.m.	VI				X	x					
Banda Neira (east–west)	1824	5/26		VII		T, V					X			
Ambon	1830	3/28	10:00 a.m.	IX	4 months		X							
Ambon	1835	11/2	3:00 a.m.	X	2–3 years	F	X	X	X		x			
Ambon	1836	9/16		VI			X							
Saparua, Ambon	1837	1/21	9:00 p.m.	VIII	1 month		x	X	X					
Ambon	1841	12/16	2:00 a.m.	VI	2 years	T (1.7 m)	x			T(>2m)				
Buru	1848	8/7		VI	12 days					X				
Saparua, Ambon	1849	5/30		VIII	1 week		x	X						
Ambon	1851	11/20	11:55 p.m.	VIII			X	x	x					
Banda Islands (NW–SE)	1852	11/26	7:50 a.m.	VII	10 years	F, R, T (8 m)	X	X	X	X	X	X	X	Java, Ternate
Ambon	1852	11/26	7:30 a.m.	VIII	10 years		T (1.8 m)	T (5 m)	T	T				
Haruku and Saparua	1854	1/2		VIII	Aftershock	T	x	X	X					
Banda Islands (SW–NE)	1857	4/6	1:30 a.m.	VII	Aftershock									
Banda Islands	1858	11/9	5:30 a.m.	VIII	Aftershock									
Banda Islands	1859	9/25	Evening	VII	Aftershock	T					X			

F, fatalities reported; V, during or followed by volcanism; T, tsunami (maximum run-up); X, strongly affected; x, weakly affected.

Table 4. *Lesser Sunda Island events*

Primary reprting location	Date			Intensity (MMI)	Aftershocks reported	Other	Affected locations						
	Year	Month/day	Time				Sumbawa	Flores	Makassar	Timor	Solor	Kisar	Other locations
Timor	1638?			IX		V?				X			
Solor Island	1648	2/3		X	4 months						X		
Makassar	1690	12/1		VI					X				
Kupang (West Timor)	1793–95			VIII						X			
Mampawa (west Borneo)	1803			VI									
Kupang (West Timor)	1814			IX		T, new island				X		X	
Tambora (Sumbawa)	1815	4/10	10:00 p.m.	VIII	4 days	V, T (4 m)	X	x	x	x			Java, Banda, Ternate?
Bima (Sumbawa)	1818			X		T (4 m)	X						
Makassar	1820	12/30	10:00 a.m.	X	3 months	F, R, V, T (29 m)	X	X	X				Java
Kisar	1823	6/1		V								X	
West Timor	1829	2		VIII			X			X			
Bima (Sumbawa)	1836	3/5		VIII		T	X						
Kisar	1836	10		VIII	3 months								
Bima (Sumbawa)	1836	11/28	10:30 a.m.	IX	1 month	T							
Timor	1854	8/21								X			
Flores	1855	5/14	09:00 p.m.			T		T					
Ocussi (NW Timor)	1857	4/26	05:30 p.m.	VII						X			
Dilli (Timor Leste) (south–north)	1857	5/14	10:30 a.m.	IX–X	1 month	F, T (3 m)				X			Ambon
Atapupu (NE–SW, north–south)	1858–69			VI	Nine aftershocks					X			
West Timor (east–west, north–south)	1866			VI	Two aftershocks					X			Savu
Roti Island (west–east)	1866			VI	Aftershock					X			
Sumba (NE–SW)	1869	8–9		VI	Three aftershocks								

F, fatalities reported; V, during or followed by volcanism; T, tsunami (maximum run-up); X, strongly affected; x, weakly affected.

Table 5. *Java and Bali events*

Primary reporting location	Date: Year	Date: Month/ day	Date: Time	Intensity (MMI)	Aftershocks reported	Other	Affected locations: Jakarta	Buitenzorg	Cheribon	West Java	Central Java	East Java	Other locations
Java	1500					V							
Java	1584			VII		R							
Java	1638			VIII						x	X	x	
Batavia (Jakarta)	1681	11/2		V			X						
Batavia	1699	1/6	1:30 a.m.	X	13 months	F	X	X		X			South Sumatra
Batavia	1722	10/?	8:00 a.m.	IX		T	X						
Batavia	1737			V			X						
Batavia	1739	7/22		VII			X						
Batavia	1757	8/24	2:00 a.m.	VII	9 months		X						
Batavia	1765	1/10		VIII			X						
Java	1771			X			x	x	x	x	x	x	
Batavia	1772	5/10		V?			X						
Semarang (central Java)	1773	4/21	12:00 a.m.	VII							X		
Batavia	1780	1/23	2:39 p.m.	IX	12 months		X	X		X	X	x	South Sumatra
Batavia	1807						X						
Bali	1808			VII								X	Bali
Batavia	1810	12/5	7:30 p.m.	VII			X						
Buitenzorg	1812	10/14	11:00 p.m.	VII			X	X					
Batavia	1814	3/24	12:00 a.m.	VIII			X	X					
Bali	1815	11/22	10:00 p.m.	IX		F, T						X	Lombok, Sumbawa
Surabaya (Java)	1815	11/22	11:00 p.m.	VII	Aftershock							X	
Jakarta	1818	3/29	2:30 p.m.	VII			X						NW–SE
Buitenzorg	1818	10/2	1:30 p.m.	VI			x	X					
Pasuaran, East Java	1818	11/8	11:15 p.m.	VIII			x	x		x	x	X	NNW–SSE
Galunggung, Java	1822	10/8	1:30 p.m.	VIII		F, V				X			
Buitenzorg	1823	9/9	8:00 a.m.	VIII	4 months	T		X	X				
Batavia (Jakarta)	1833	1/28	12:00 p.m.	VII			X						
Batavia (Jakarta)	1834	10/11	5:30 a.m.	X			X	X		X			South Sumatra
Jakarta	1836	3/22	3:30 a.m.	VIII			South–north	X		X	x		
Pajitan, (central Java)	1840	1/5	1:15 p.m.		1 month	T					X		
Cheribon (Java)	1847	11/16	10:18 a.m.	X	2 weeks	R	ESE–WNW	X	SE–NW	X	X		Sumatra

(*Continued*)

Table 5. *Java and Bali events (Continued)*

Primary reporting location	Date			Intensity (MMI)	Aftershocks reported	Other	Affected locations						
	Year	Month/day	Time				Jakarta	Buitenzorg	Cheribon	West Java	Central Java	East Java	Other locations
Java	1848	1/7	4:00 a.m.	X	1 month	R	x			North–south	North–south	North–south	
East Java, north Bali	1848	2/17	10:00 a.m.	VII	8 years	R, V						X	Bali
Sunda Strait	1848	6/4	11:00 a.m.	V	12 years	V	x	x	x	x			South Sumatra, Krakatoa?
Sunda Strait	1851	5/4	3:00 p.m.	VI		V?, T (1.2 m)	x						South Sumatra, Krakatoa?
Batavia and Sunda Strait	1852	1/9	6:00 p.m.	VI		T	North–south	SSW–NNE	East–west	X	x		South Sumatra
Central Java	1856	1/19	6:00 a.m.							x	N–S	x	
Patjitan (central Java)	1859	10/20	5:30 p.m.	VII		F, T							
Central and East Java	1865	5/17	7:00 p.m.	VIII	15 months		x	x	x		X	X	Madura, Bali
Ambarawa (central Java)	1865	7/18	2:27 a.m.	VII	Aftershock						X		
Ambarawa (C Java)	1866	4/22	6:30 p.m.	VII	Aftershock						X		
Central and East Java	1866	9/30	9:18 a.m.	VI	Aftershock						X	X	Madura, Borneo
Djogjakarta (central Java)	1867	6/11	4:30 a.m.	IX	1 year	F				x	X	x	
Cheribon (West Java)	1875	10/26	5:50 a.m.	X	3 months	F	x		X		X		

F, fatalities reported; V, during or followed by volcanism; T, tsunami (maximum run-up); X, strongly affected; x, weakly affected.

Table 6. *Sumatra events*

Primary reporting location	Date			Intensity (MMI)	Aftershocks	Other	Affected locations					
	Year	Month/day	Time				South Sumatra	Central Sumatra	North Sumatra	Andaman Islands	Nicobar Islands	Other locations
Ache (north Sumatra)	1621	3/7	1:00 a.m.		3 years	V?			X			Sumatra Fault?
West Sumatra	1681	12/11		VI			x	x	x			
Bengkulen, (west Sumatra)	1755	11/3		X	1 month	V	X	x?	x?			
Nias (west Sumatra)	1763			X		F		X				
Bengkulen (west Sumatra)	1770			X		F, T, V						
Padang (west Sumatra)	1795	2/11	10 p.m.	IX	1 week	T	x	X	x			1797?
Palembang (west Sumatra)	1799			IX		T (15 m)	New land	x				
Benkulen	1818	3/18		IX	2 months	T	X					
Bengkulen	1818	5		VII	Aftershock							
Padang (west Sumatra)	1824	4		VI								
Bengkulen, Padang	1833	11/25	8:30 p.m.	XI	24 years	F, R, T, V	X	X	x			SSW–NNE, Java, Singapore
Padang (west Sumatra)	1835	8/26	9:00 p.m.	VIII	Aftershock	R		North–south				Singapore, Java, Malaysia
Ache (north Sumatra)	1837	9/30		VIII		T, V						
Barus (NW Sumatra)	1843	1/5 to 1/6	11:30 p.m.	XI	3 months	T		x	West–east, north–south			Singapore, Malaysia
Nicobar Minor	1847	11/1	3:30 a.m.	X	3 weeks	T					X	
Padang Mountains	1852			V	1 year	F, V?		X				Sumatra Fault?
Solok, Sumatra	1853	2/9	Night	VIII		F				X		
Sumatra	1861	2/16	6:30 p.m.	X	4+ years	F, T (7 m)	SE–NW	North–south	X	X		Malaysia, Singapore, Java
NW Sumatra	1861	4/26	6:30 a.m.	VII	Aftershock	T (>2 m)			X			
Bengkulen	1871	8/19	8:16 p.m.	VIII			X					West Java
Singkel (NW Sumatra)	1873	8/19	3:15 p.m.	IX	1 month			x	X			

F, fatalities reported; V, during or followed by volcanism; T, tsunami (maximum run-up); X, strongly affected; x, weakly affected.

Table 7. *New Guinea events*

Primary reporting location	Date			Intensity (MMI)	Aftershocks reported	Other	Affected locations		
	Year	Month/day	Time				Geelvink Bay	Astrolabe Bay	Rook Island
Astrolabe Bay (New Guinea)	1856–58	No date	Night	IX		F, T		X	
Rook Island (New Guinea)	1857	4/18	Evening	VIII		F, T			North–south
Geelvink Bayk (New Guinea)	1864	5/24	12:30 a.m.	IX	1 week	F, T (2.6 m)	X		
Astrolabe Bay	1873	No date		IX		T		X	

F, fatalities reported; V, during or followed by volcanism; T, tsunami (maximum run-up); X, strongly affected; x, weakly affected.

The Molucca Sea region (north Maluku: Table 2), including Ternate, Makjan, Minahassa (north Sulawesi) and Halmahera

The first authenticated earthquake in the Wichmann catalogue is from 1538 in Ternate (Fig. 2, Supplementary material). At that time, the volcanic island of Ternate was one of the world's major producers of cloves. Ternate is part of the Halmahera intra-oceanic arc, which forms above the eastwards-subducting Molucca Sea oceanic slab (Hamilton 1979; Hall 2011). The same slab is also subducting westwards beneath the Sangihe Arc. The accretionary wedges of these opposing subduction zones are colliding near the middle of the Molucca Sea to form one of the youngest submarine collisional mountain belts in the world (Fig. 2).

Earthquakes and tsunamis in this region could have several different sources. In the northern part of the region, the major active faults include the southern Philippine Trench and the Cotabato Fault, which overlap with the Molucca collision complex (Fig. 1). Benioff zones beneath the Sangihe Arc to the west and the Halmahera Arc to the east dip in

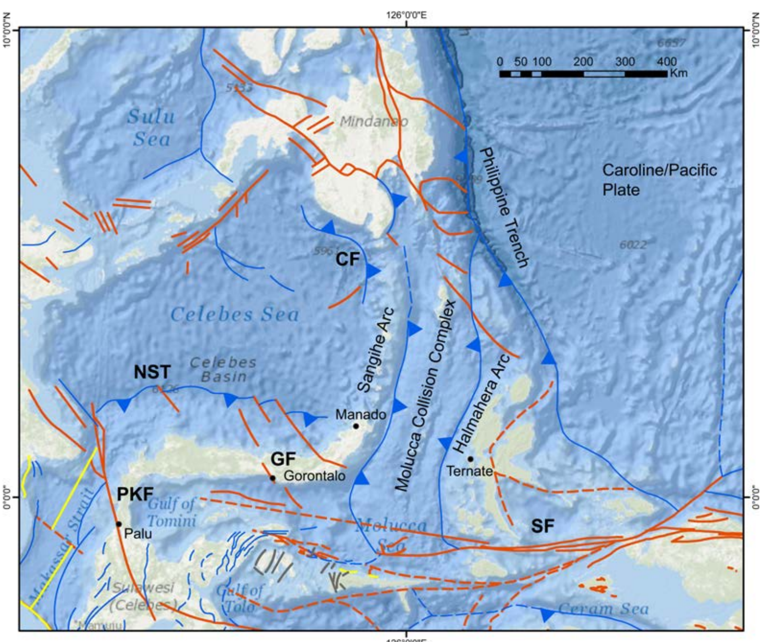

Fig. 2. Location map and active faults of the Molucca Sea region. Fault colours: blue, convergence; red, transvergence; yellow, divergence; grey, uncertain motion. Fault abbreviations: CF, Catabato Fault; GF, Gorontalo Fault; NST, North Sulawesi Trench; PKF, Palu-Koro Fault; SF, Sorong Fault. For the locations of earthquake events in the catalogue use the KMZ file in the Supplementary material.

opposite directions, which indicates that the Molucca Sea Plate in the middle is almost completely consumed by the opposing subduction zones. Most earthquakes occur along the subduction interfaces of these colliding arcs, from internal deformation within the opposing accretionary wedges, within the Molucca Sea Plate and from explosive volcanic eruptions. However, most of the active faults in the region, like nearly all of Indonesia, are submarine. Marine geophysical studies (Silver & Moore 1978; Bader & Pubellier 2000; Watkinson *et al.* 2011) document surface ruptures in several places throughout the Moluccas, but many areas where earthquakes are common remain unexplored. Local explosive volcanic events may also account for a few of the earthquakes included in the catalogue, such as those in 1646, 1673, 1770 and 1840.

Active thrust faults are found within the accretionary wedge collision complex near the Talaud Islands, rising up in the middle of the Molucca Sea (Silver & Moore 1978; Bader & Pubellier 2000). Other major thrust faults involve backthrusting of the accretionary wedges over associated forearc basins (Hamilton 1979). Along the East Sangihe Fault, the accretionary wedge collision complex is thrust westwards over the Sangihe Forearc (Fig. 2). A similar relationship is inferred on the east side of the accretionary wedge collision complex, with top-to-the-east thrusting over the Halmahera Forearc (Fig. 2). To the west of the Molucca collision complex, the Minahassa Trench forms from SSE subduction of the Celebes seafloor. The volcanic arc above this subduction complex forms the eastern part of the northern arm of Sulawesi. The Gorontalo Fault slices through the middle of the northern arm of Sulawesi (Fig. 2).

The southern part of the Molucca Sea region hosts many active faults associated with the westwards translation of the Caroline–Pacific Plate against continental crust of the northern Australian Plate (Silver *et al.* 1983*a*, *b*; Garrard *et al.* 1988; Smith & Silver 1991). The Sorong fault system forms the southern boundary of the Molucca Sea Plate, which may reach as far west as the Gorontalo Basin (Watkinson *et al.* 2011). The Sula and Matano faults form the southern-most strike-slip faults of the Sorong fault system, with associated pop-up and pull-apart structures (Watkinson *et al.* 2011).

Relative to the Sunda Craton, GPS measurements indicate 89 mm a^{-1} of westwards convergence across the Sangihe arc–arc collision, 22–46 mm a^{-1} of NNW convergence across the Minahassa Trench and as much as 53 mm a^{-1} of left-lateral oblique WNW convergence along the Sula–Sorong fault system (Rangin *et al.* 1999). Models combining these GPS data with patterns of seismicity over the past 50 years yield very high shear and dilatational strain rates in the Molucca Sea region (Kreemer *et al.* 2000). Yet, several earthquakes documented in the Wichmann catalogue are larger than anything recorded instrumentally. For example, between 1855 and 1860, there were several significant earthquakes and at least six tsunami that caused damage on both sides of the Molucca Sea, including Ternate, Tidore, Makjan and Halmahera on the west, and Minahassa, Gorontolo and Kema (north Sulawesi) on the east (Supplementary material). One tsunami, 9 m high, crashed into the west coast of Halmahera and was also noted on other islands (Table 2). The largest earthquake in the Harvard catalogue for the region (post-1976) is a M_w 7.9 subduction interface event in 1996. However, this event caused few casualties and only a local tsunami (Pelinovsky *et al.* 1997).

The regional nature of the events documented in the Wichmann catalogue, and the years of aftershocks that followed, indicate they were probably megathrust earthquakes. In a recent paper on possible megathrust earthquake sources (Heuret *et al.* 2011), the Moluccas and the Banda Arc (see below) are not included. This omission highlights the importance of examining historical records to validate models based on the relatively short instrumental catalogue and other geophysical criteria.

The Banda Sea region (south Maluku: Table 3), including Seram Island, Ambon, Buru, Amblau, Saparua, Haruku, Nusalaut (the Uliassers), Banda Neira, Lonthor and Ai (Banda Islands)

The majority of earthquakes and tsunami documented in the Wichmann catalogue are from the southern Maluku region (Fig. 3). However, just the opposite is true for the earthquake and tsunami rate during the past 100 years. Even though the post-1970 seismic rate in Maluku is the second highest in the Indonesia (United States Geological Survey: USGS), it is much lower than the rate of major earthquake and tsunami events between 1629 and 1876 (Tables 3). For example, from 1612 to 1859, the earthquake rate was one major event (>MMI 6) every 3 years (this catalogue) compared with a rate of one major event every 7 years since 1859 (Hamzah *et al.* 2000).

The abundance of observations in the region is partly attributed to the many Dutch settlements in the ‘Spice Islands’ found there (Hanna 1978; Milton 1999). Most of the observations in the catalogue from the Maluku region are from Ambon (Figs 4 & 5), the neighbouring islands to the Uliassers, and the Banda Islands 200 km to the SW (Fig. 3, Supplementary material). These island groups are part of the northern section of the Banda Arc. The

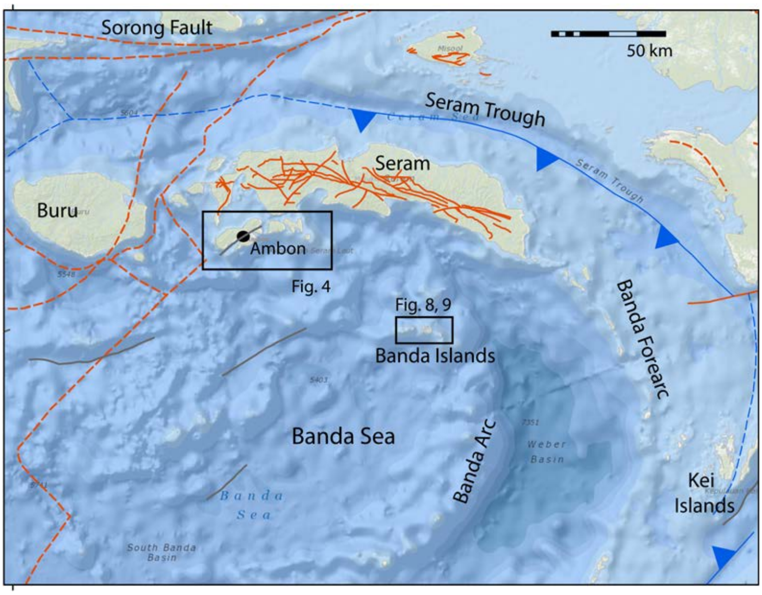

Fig. 3. Location map and active faults of the southern Maluku region. Fault colours: blue, convergence; red, transvergence; grey, uncertain motion.

Banda Arc formed in the Late Miocene above an intra-oceanic subduction system. At around 16 Ma, the arc began to collide with the NW continental margin of Australia in the Seram region (Berry & McDougall 1986; Linthout *et al.* 1996; Pownall *et al.* 2014). The current arc–continent collision zone makes a 180° bend from the Southwest Islands east of Timor to Ambon (Fig. 1). The collision is more advanced in the Uliasser Islands, where the volcanic arc is extinct and forearc basement is exposed.

Volcanism still persists in the Banda Islands and other volcanoes of the Banda Arc, although they are contaminated by subducted continental crust. Notwithstanding the active volcanism, only one of the earthquakes cited in the Wichmann catalogue, the disputed eruption of Banda Api in 1824, is likely to have been associated with a local volcanic eruption.

On multiple occasions, earthquakes and tsunami destroyed most of the buildings in Ambon or Banda Neira, including the regional earthquakes of 1648, 1754 and 1802. The colonial-era Fort Victoria, built in the early seventeenth century, is the only structure from this time that remains standing in Ambon. The Wichmann catalogue documents that

Fig. 4. Map of Ambon and the Lease Islands showing locations of many of the events mentioned in the text.

Fig. 5. Ambon City was destroyed by earthquakes in 1644, 1675, 1754, 1781, 1835 and 1841. Multiple tsunamis are also documented, inundating what is now the major urban centre of the Maluku region.

the walls of the fort were damaged by earthquakes in 1644, 1673 and 1705, and inundated by a tsunami in 1648 (Fig. 6).

Around 1.5 million people now live in the southern Maluku region, with more than a third of a million crowded into the low-lying coastal plain that has been inundated with past tsunamis. The city has now burgeoned up onto landslide-prone hills (Fig. 4). There are several accounts of major landslides in and around Ambon City throughout the Wichmann catalogue that are similar to the fatal slides that occurred in 2012 and 2013. Development is also increasing in coastal areas throughout the region that were probably inundated by the 15 regional tsunamis that occurred between 1629 and 1877.

The active fault sources for the earthquakes and tsunami in the Maluku region are poorly constrained

Fig. 6. Conjugate fractures in the walls of Fort Victoria from earthquake damage. The fort was damaged four different times by earthquakes and inundated by a tsunami. Surrounding the fort now is the urban centre of Ambon City.

(a)

Fig. 7. (**a**) Fort Amsterdam on the north coast of Ambon., which was built in the fifteenth century and is described in the catalogue as completely inundated by the 1675 tsunami. The central part of the fort has been reconstructed. (**b**) The 1675 tsunami poured over this wall and killed most of the inhabitants who went to the fort for shelter.

owing to a lack of marine geophysical surveys. One of the most dangerous aspects of this active arc–continent collision is the distribution of strain away from the deformation front in the Tanimbar and Seram troughs into other parts of the upper plate, such as the populated backarc region of Ambon and the surrounding islands (Harris 1991, 2011). It is likely that there are active faults near Ambon, such as in Ambon Bay, (Hamilton 1979) and offshore to the north and south associated with accretion of the Banda Arc onto Australian continental margin. Earthquakes felt in Ambon may also be sourced from the Sorong strike-slip fault system to the north (Fig. 3).

Intermediate to deep earthquakes in the Benioff zones surrounding this region on three sides are broadly felt, but have weak intensities and cause little to no damage. The largest instrumentally recorded event (M_w 8.5) occurred in 1938. The epicentre was located at the rear of the accretionary wedge south of the Watubela Island of Tioor (Okal & Reymond 2003). The depth is estimated at 60 km, which is consistent with the lack of damage reported (MMI 6) and the small tsunami run-up (1.5 m). This event was felt as far south as Darwin, Australia and in eastern New Guinea. The focal mechanism is an east–west-striking thrust with some left-lateral oblique slip. A similar focal mechanism is also found for the M_w 8.3 earthquake in 1963 in a similar tectonic position north of Babar Island (Welc & Lay 1987). These events are the largest along a NNE–SSW line of mostly intermediate-depth earthquakes of M_s 6.5–7.1 beneath the southern Weber Basin. They are interpreted as deformation of the subducting slab, with slip in the NNE–SSW direction of plate convergence (Okal & Reymond 2003).

One of the most damaging historical earthquakes occurred in 1675. It flattened the entire Chinese district and many other stone buildings in Ambon. Landslides also caused at least 2500 fatalities. A coastal landslide on the north shore of Ambon generated a tsunami with a run-up height of up to 100 m, based on the coastal vegetation trim line that it left (Soloviev & Go 1974). The wave flowed over the walls of Fort Amsterdam (Fig. 7) and destroyed most of the homes inside the fort, causing many fatalities.

The most damaging instrumentally recorded earthquake was in 1899, a M_s 7.8 event in Seram. It generated a 10 m tsunami that was probaby assisted by a landslide. The tsunami killed around 3500 people (Brune *et al.* 2010). No earthquake of this magnitude has occurred since this event. With elastic strain energy accumulating across the Seram Trough at rates of up to 7 m/century (Bock *et al.* 2003), it is likely that earthquake recurrence intervals are relatively short (*c.* 100 years).

Banda Neira, which is nestled in the Banda Islands (Fig. 8), has been destroyed several times by earthquakes and inundated by some of the most massive waves recorded in Indonesia. Two earthquakes in particular, one in 1629 and the other in 1852, showed clear characteristics of megathrust seismic activity. Both of these events were felt over a large region, generated large tsunamis of at least 15 and 8 m, respectively, at Banda Neira (Fig. 9), and are associated with at least a decade of aftershock-like seismic activity. The accounts of both events provide key details, such as the duration of shaking and the travel time of the tsunami after the shaking stopped:

> 1629, August 1 9:30 p.m. Banda-Islands. A half hour after the termination of a violent seismic shock there formed in the sound … a high mountain of water. The…wave rolled westward … against Fort Nassau … where it achieved a height of 9 fathoms [15.3 m] above the springtide stand … Houses lying on the beach were swept away, while others were laid to rubble … Eastwards the tidal wave crashed on the west beach of the island Lonthor, where … it achieved … a height of 13 feet [4 m].

(b)

Fig. 7. *Continued.*

These particulars make it possible to inversely model the tsunami, and to test likely source areas and earthquake magnitudes. Models of the 1629 tsunami by Liu & Harris (2013) required a megathrust earthquake (M_w 8.2–8.8) along the Seram Trough. The Seram Trough accumulates strain from NNW convergence relative to the Sunda Craton at a rate of around 40 mm a^{-1} (Socquet *et al.* 2006). At these strain rates, enough elastic strain energy has already accumulated along the Seram Trough to cause an earthquake of similar magnitude to what occurred in 1629.

Archaeological excavations in Banda Neira (Lape 2000) found evidence of several destructive events throughout the colonial era. We excavated a trench adjacent to site BN4 of Lape (2000) and found three likely tsunami deposits, which we are currently analysing. The stratigraphic ages of the two largest deposits, based on the archaeological ages, correspond to the 1629 and 1852 tsunamis (Fig. 10).

The 1852 event was recorded at 20 different locations from Sumatra to Ternate. From these accounts and from modelling of the tsunami that was recorded in several locations, the source region is most likely to have been in the Tanimbar Trough (Fisher & Harris, in press). This collisional plate boundary accumulates strain from highly oblique NNE convergence of the Australian continental margin beneath the Banda Arc at a rate of around 70 mm a^{-1}. The event, like another one previously noted in the catalogue in 1649, caused the rise of new mud volcano islands in the Kei archipelago (Fig. 3).

We are concerned about the hazard potential of this very active tectonic region. During the past century, population and urbanization in the region has increased 10-fold, particularly in coastal area susceptible to tsunami inundation. The tsunami

Fig. 8. Panorama of Banda Islands. Photograph looking NE from Gunung Api. Banda Neira is the island in the middle. Lonthor is the crescent-shaped island behind it. The Lonthor Strait, to the left of Lonthor Island (near the rainbow), is where the tsunamis of 1629 and 1852 approached Banda Neira.

Fig. 9. Detail of Figure 8 showing the city of Banda Neira. The Wichmann catalogue documents four tsunamis that inundated Fort Nassau. The dashed lines are the approximate run-up heights of the 1629, 1841 and 1852 tsunamis.

potential also threatens large cities outside the region. For example, modelling of the 1629 earthquake and tsunami on the southern Seram Trough (Liu & Harris 2013) predicts run-up heights of 5.3 m along the north coast of Tanimbar, >3 m in Dili and >1 m in Darwin, Australia.

The Nusa Tenggara and South Sulawesi region (Table 4), including Lombok, Sumbawa, Flores, Sumba, Timor and Wetar

Nusa Tenggara and Sulawesi form a transition zone between the Greater Sunda Islands of Java and Bali,

Fig. 10. Trench near Fort Nassau of Banda Neira exposing tsunami deposits from earthquakes most likely in 1629 (lower white layer) and 1852 (upper white layer). The darkest black layers are volcanic ash. The trench site corresponds to archeological site BN4 of Lape (2000). See Figure 9 for the location of trench site.

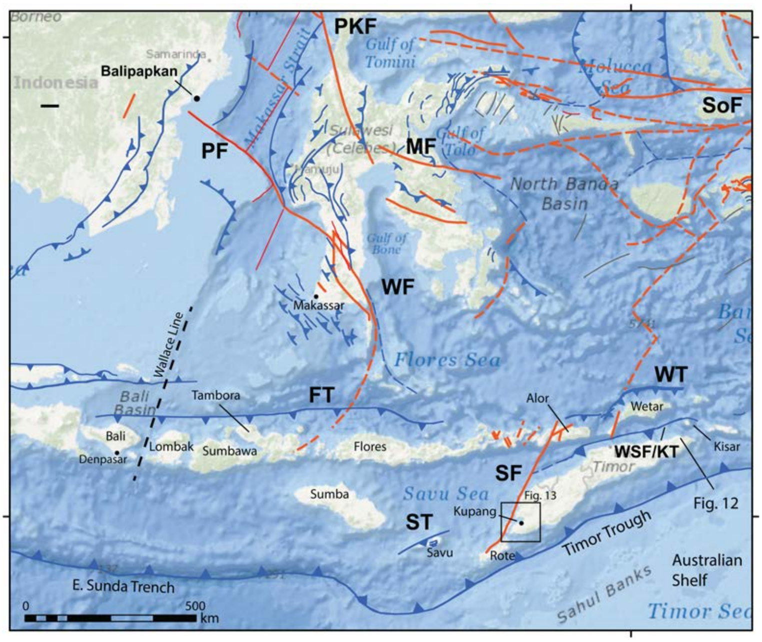

Fig. 11. Location map and active faults of the Nusa Tenggara and south Sulawesi region. FT, Flores Thrust; MF, Matano Fault; PKF, Palu-Koro Fault; PF, Pasternoster Fault; SF, Semau Fault; SoF, Sorong Fault; ST, Savu Thrust, WF, Walanae Fault; WST/KS, Wetar Strait Fault/Kisar Thrust; WT, Wetar Thrust. The locations of Figures 12 and 13 are shown.

which are part of the Sunda Craton, and the Banda Sea marginal basin. Sulawesi and various continental fragments in the Banda Sea basin were rifted from the Sunda Craton by intra-arc extension (Harris 2006). The intra-oceanic Banda Arc forms along the outer edge of the young oceanic crust of the Banda Sea basin.

The western boundary of Nusa Tenggara is the famous Wallace Line through the deep straight between Bali and the Lombok Islands (Fig. 11). The eastern boundary is disputed, but here is defined as the eastern edges of Wetar and the Timor Islands. The Timor region, which is similar to the Seram and the Ambon portion of the Banda Arc to the east, represents an evolving arc–continent collision that propagates westwards from central Timor at around 110 km myr^{-1} (Harris 1991). The collision initiation point is south of the island of Sumba, with progressively more mature parts of the collision represented to the east on the island of Timor (Harris 2011).

Also included in the Nusa Tenggara region is the Makassar Strait, which has one of the highest rates of tsunami in Indonesia since 1900 (Prasetya *et al.* 2001). However, only a few events are recorded in the Wichmann catalogue during the previous three centuries. How much of this relative quiescence is from a lack of reporting or a lack of seismic events is unknown. Between 1600 and 1900, only three earthquakes are recorded and one tsunami. Since 1820, there have been at least 18 tsunamis (Baeda 2011).

The most active faults in the Makassar Strait (Fig. 11) are found by geophysical investigation (e.g. Guntoro 1999; Hall *et al.* 2009), which includes: (1) thrust faults along the east and west edges of the northern Makassar Basin, with the eastern edge forming the Makassar Trench and Majene fold–thrust belt (Bergman *et al.* 1996); (2) the Palu Koro Fault (Katili 1978) that forms the northern boundary of the northern Makassar Basin; (3) the Mentano Fault of central Sulawesi; (4) the Paternoster Fault (Guntoro 1999) that forms the southern boundary of the northern Makassar Basin; and (5) the Walanae Fault (van Leeuwen 1981), forming the Salajar Trough offshore and the western edge of the Bone Mountains onshore, which is 85 km west of Makassar City. Makassar City is one of the largest urban areas in eastern Indonesia, with a population of 1.4 million (Fig. 11). The region surrounding the city is identified as a seismic gap (Baeda 2011) owing to the fact that it has a history of earthquakes, but very little seismicity, over the past 50 years.

The GPS velocity field in Sulawesi (Socquet *et al.* 2006) shows between 8 and 21 mm a^{-1} of strain accumulation across the Makassar Thrust.

Earthquakes near the convergent boundary have fault-plane solutions consistent with low-angle, east-dipping thrust faults beneath the western coast of Sulawesi, where most of the population is concentrated.

Five significant tsunamigenic earthquakes caused major damage in Nusa Tenggara in 1814, 1818, 1820, 1836 and 1856. A tsunami was also generated in 1815 from the colossal eruption of Tambora (Fig. 11).

The Tambora eruption (Volcanic Explosivity Index (VEI) 7) is the largest of recorded history. It is also one of the most notable extreme global geohazards of the Holocene (Wood 2014). The colossal eruption caused at least 100 000 deaths locally and years of global climate upheaval that accounted for, perhaps, as many as 6 million deaths worldwide (Oppenheimer 2011). Months prior to the eruption, there was an earthquake near Kupang, West Timor that created a new island and caused a tsunami. Shortly after the Tambora eruption, there were significant regional earthquakes in Maluku in 1815, 1816 and 1817, and a major event in the southern Makassar Basin in 1820. The spatial and temporal clustering of these events is a common feature throughout the Indonesian region and many other plate boundaries (Jagla & Kolton 2010).

Accounts of the 1820 Makassar (Belekomba) earthquake in the Wichmann catalogue are consistent with a Walanae Fault source. For example, the strongest ground motion ($>1g$, cannons hopping) and the longest time of shaking (4–5 min) are recorded from Bulukomba, which is only 20 km from the fault. The Dutch Fort there was also inundated by an 18–26 m-high tsunami. It is possible, from the account, that the tsunami was from an earthquake-induced submarine landslide near, but west of, Bulukomba:

> Fort Bulekomba fluctuated to and fro. The six-pounders … hopped from their mountings. After the 4–5 minute long quake, shots were believed to be heard in the west, coming from the sea. Barely had the sent envoy returned with the news that ships were nowhere to be seen, than did the sea, under both a whistling and thunder-like rumble, come in, formed as a 60–80 foot high wall, and flooded everything. The barracks in the fort were destroyed, likewise, as a result of the flood wave that penetrated 400–500 feet inland … 400–500 persons drown.

The earthquake ‘violently’ shook Flores and Sumbawa for 2 min, and was felt as far west as Madura (800 km from Belekomba). Each of these locations also experienced tsunamis. In Sumbawa, the tsunami, ‘flung anchored ships far inland’.

Investigations of the GPS velocity field in Nusa Tenggara reveals a pattern of increased coupling with the NNE-subducting Australian Plate towards the eastern edge of the province (Genrich *et al.* 1996; Nugroho *et al.* 2009). It is likely that this pattern of strain is associated with increased amounts of subducted continental crust towards East Timor (Harris 1991). Between Sumba Island, where the arc–continent collision initiates, and the island of Rote (Fig. 11), 70–80% of the convergence is taken up at the deformation front (Timor Trough), with the bulk of the remainder occurring along the Flores backarc thrust (Nugroho *et al.* 2009). This changes to only 35% east of the 121° shear zone off the coast of West Timor (Harris *et al.* 2009). East of the shear zone, an additional 30% of the NNE motion of the Australian Plate is transferred to the Wetar backarc thrust system (Nugroho *et al.* 2009).

Recent earthquakes along the Flores and Wetar thrust systems demonstrate just how vulnerable this rapidly growing region is to even moderate-sized seismic hazards (McCaffrey & Nabelek 1984). In 1992, a M_w 7.8 earthquake on the Flores Thrust struck the area around Maumere and generated a tsunami with submarine landslide-assisted wave heights of up to 26 m (Budiono *et al.* 1995). The earthquake destroyed 90% of the buildings in the region, including around 800 schools. Half of the deaths were caused by the tsunami.

The Wetar thrust system, which is further to the east and along strike of the Flores Thrust, is also very seismically active and caused a M_w 7.5 earthquake and tsunami in November 2004. Around 800 homes were destroyed on Alor Island (USGS). Damage from the earthquake and tsunami also reached Dili, the capital of East Timor (with a population of *c.* 200 000).

Little onshore historical seismicity is recorded for Timor Leste. However, several thrust events have occurred offshore, with hypocentres on or close to the décollement at depths of 18–30 km below the northern flank of the Timor Trough. Immediately north of the Timor Leste capital city of Dili, a thrust event was recorded at approximately 30 km, along with extensional earthquakes at 16–20 km.

The Wichmann catalogue documents that, between 1793 and 1836, several tsunamigenic earthquakes struck the Nusa Tenggara region and were felt more widely than both the 1992 and 2004 events. One of the most notable earthquakes occurred along the north coast of East Timor in 1857. The earthquake caused a tsunami consisting of four waves, the highest of which was >3 m. The tsunami inundated the north coast around Dili, and completely flooded the villages of Liquica and Hera.

It is likely that the source of this earthquake/tsunami event was the Wetar Strait Thrust first inferred by Carter *et al.* (1976), and later documented as an active fault by Breen *et al.* (1989). This south-dipping thrust system accommodates the northwards motion of the Timor orogenic wedge over the forearc basin of the Banda Arc (Fig. 11). The thrust system can be traced just offshore the north coast of Timor eastwards to the islands of Kisar and Leti, where it was imaged breaching the seafloor by the BIRPS seismic reflection profile (Snyder *et al.* 1996). Mapping and age analysis of uplifted and warped coral terraces on the north coast of Timor (Fig. 12) and Kisar document co-seismic uplift, tsunami deposits and continued shortening along the Wetar Strait and the Kisar Thrust (Cox 2009; Major *et al.* 2013).

Tsunamigenic earthquakes have also struck the area around Kupang, West Timor (Fig. 13). Kupang is one of the main commercial centres of Nusa Tenggara, with a population of around 0.5 million. There are four known active faults in the region that may have sourced these events. The most significant is the Timor Trough to the south. Recent GPS measurements determined a strain rate across the Timor Trough of 22 mm a^{-1} (Nugroho *et al.* 2009). As noted earlier, there are several earthquakes with low-angle thrust fault-plane solutions along the projection of the Timor Trough beneath Timor. It is possible that there may have been a major earthquake along the Timor Trough some time between 1793 and 1814, which immediately preceeded the 1815 eruption of Tambora.

Another possible source of major earthquakes much closer to Kupang is the Semau Fault (Fig. 13) or 121° discontinuity shear zone (Harris *et al.* 2009). This left-lateral transpressional fault system is mapped on Rote Island (Roosmawati & Harris 2009) and expressed along the west coast of Timor as a linear zone of mud volcano islands (Barber *et al.* 1986). The fault is identified in seismic reflection profiles just offshore of Kupang (Karig *et al.* 1987) and is associated with uplift of several flights of coral terraces (Merritts *et al.* 1998). GPS measurements show 11 mm a^{-1} of strain accumulation across the fault (Nugroho *et al.* 2009).

Known active faults onshore in West Timor are indicated by earthquakes with generally transtensional fault-plane solutions, and include strike-slip and normal earthquakes with T-axes orientated east–west (McCaffrey 1988, 1989). A surface-rupturing M_w 5.7 strike-slip earthquake in westernmost Timor in 1975 (Fig. 13) showed both dextral and sinistral slip along vertical faults striking mostly NW–SE (Tjia 1983; Duffy *et al*. 2013).

The other active fault found in the Savu Sea is the Savu thrust system (Fig. 11). This north-verging thrust forms the rear of the Sumba–Savu accretionary wedge (Harris *et al.* 2009), much like the Wetar Strait Fault north of Timor. Thrust faults are imaged breaking the seafloor on seismic reflection profiles (Harris *et al.* 2009). It is likely that the March 1866 earthquake felt in Kupang, but strongly felt in Savu, was along the Savu Thrust. GPS measurements indicate 6–8 mm a^{-1} of strain across this plate boundary segment (Nugroho *et al.* 2009). At this rate of strain, at least 1 m of strain may have accumulated along the Savu Thrust since 1866. Uplifted coral terraces along the north coast of Savu attest to the long-term activity of the thrust fault.

Fig. 12. Photograph looking south from the Wetar Strait at flights of uplifted coral terraces along the north coast of Timor Leste. The uplift is mostly attributed to movement along the Wetar Strait Thrust (Cox 2009).

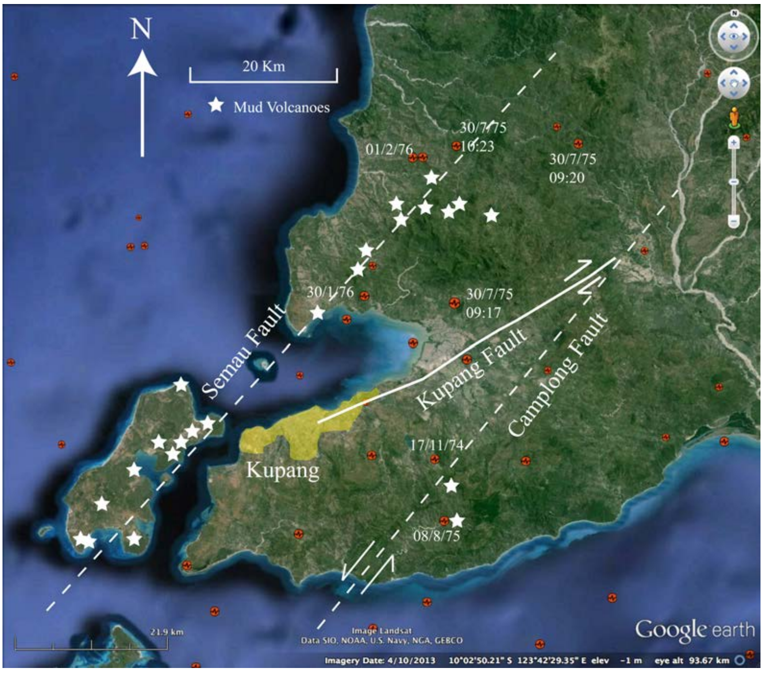

Fig. 13. Active faults of the Kupang region of West Timor. The Semau Fault is inferred from lines of mud volcanoes (white stars). The mud volcanoes and Kupang Fault are taken from Rosidi *et al.* (1979). The Camplong Fault ruptured on 30 July 1975 at 09:17 GMT. The dates and times of the associated earthquake cluster are shown. The urban centre of Kupang is shaded.

The earthquake and tsunami disaster risk of the Nusa Tenggara region has increased almost exponentially since the events documented in the Wichmann catalogue occurred. The only major event along the subduction zone to the south of the region is the 1977 M_w 8.0 Sumba earthquake, which generated a 15 m-high tsunami. However, this event was caused by normal faulting on the downgoing oceanic slab. There is no evidence of major earthquakes along the subduction interface from Java to Timor in over 400 years, notwithstanding the 70 mm a^{-1} of convergence along this section of the eastern Sunda subduction zone. It is possible that up to 28 m of strain has accumulated along the subduction interface.

The population of Nusa Tenggara region (Nusa Tenggara) is currently around 10 million. Another 2 million people live along the coast of the Makassar Strait. Most of the people now live in cities, most of the buildings in the cities are of unreinforced masonry construction and many of the cities are within historical tsunami inundation zones. The western shores of the Makassar Strait are near active faults and coastal cities, such as Balikpapan and Bontang, are vulnerable to tsunami hazards from events such as the one in 1820. Other parts of Kalimantan, which account for <6% of Indonesia's population, are considered highly unlikely to experience earthquakes. No entries of significant damage due to earthquakes in Kalimantan are found in the Wichmann catalogue.

Java and Bali (Table 5)

The islands of Java and Bali mostly consist of products of the Sunda Arc, which is mounted on the southern edge of the relatively young Sunda Craton (Hamilton 1979). Jurassic-age seafloor with >1 km of sediment cover is subducting beneath the edge of the craton at the Java Trench. Between the trench and the southern coast of Java and Bali is a well-developed accretionary ridge and forearc basin. Orthogonal convergence is estimated at a rate of around 75 mm a^{-1} (Nugroho *et al.* 2009). GPS measurements indicate little or no internal shortening across Java (Bock *et al.* 2003), which is interpreted as evidence for loose coupling across the subduction interface. However, there is a broad seismic zone across Java that is mostly the result of intermediate-depth events in the Benioff zone and more localized events associated with deformation of the volcanic arc (Ghose & Oike 1988). The Benioff zone continues to a depth of 650 km and produces deep earthquakes that are felt over long distances, but cause little or no damage.

Some of the most widely felt and damaging events in this region were in 1586, 1699, 1722, 1757, 1780, 1815, 1834, 1840, 1847, 1859, 1862, 1865, 1867 and 1875. It is difficult from the historical records to constrain which of these events are from inter- v. intra-plate earthquakes or large intermediate to deep Benioff zone earthquakes. Most of the known deep events are characterized by broad zones of small intensity, such as the 2007 M_w 7.5 event at a depth of 290 km that was felt throughout Java and as far away as Malaysia, but did little or no damage. Descriptions in the Wichmann catalogue of the event of 2 January 1780 fit the characteristics of a strong, but deep event.

It is also possible that some earthquakes, where little damage is observed (MMI <5) but a tsunami was generated, may have been slow-rupture events, such as the M_w 7.8 and 7.7 inter-plate earthquakes on the Java Trench in 1994 and 2006, respectively. These earthquakes were hardly felt on shore, but produced larger than expected tsunamis that claimed hundreds of lives (Kerr 2006; Kato *et al.* 2007).

The most damaging events in the historical catalogue, and therefore the ones that are likely not to be slow slip or deep earthquakes, were those in 1699, 1780, 1834, 1840, 1847, 1865, 1867 and 1875. Some of these events were likely to have been sourced from onshore faults accommodating deformation in and around the Sunda Arc (Fig. 14). However, inferring source regions is hampered by a lack of data for active faults in Java.

Active faults in Java have been described by Van Bemmelen (1949) and Tjia (1977). These include: (1) the left-lateral Lembang Fault, north of the densely populated urban centre of Bandung; (2) the Cimandiri normal fault that has sourced several destructive earthquakes within the NE-striking Cimandiri River Valley; (3) the Bency normal fault, which sourced the surface-rupturing Sukabumi earthquake, 1982 (Kertapati & Koesoemadinata

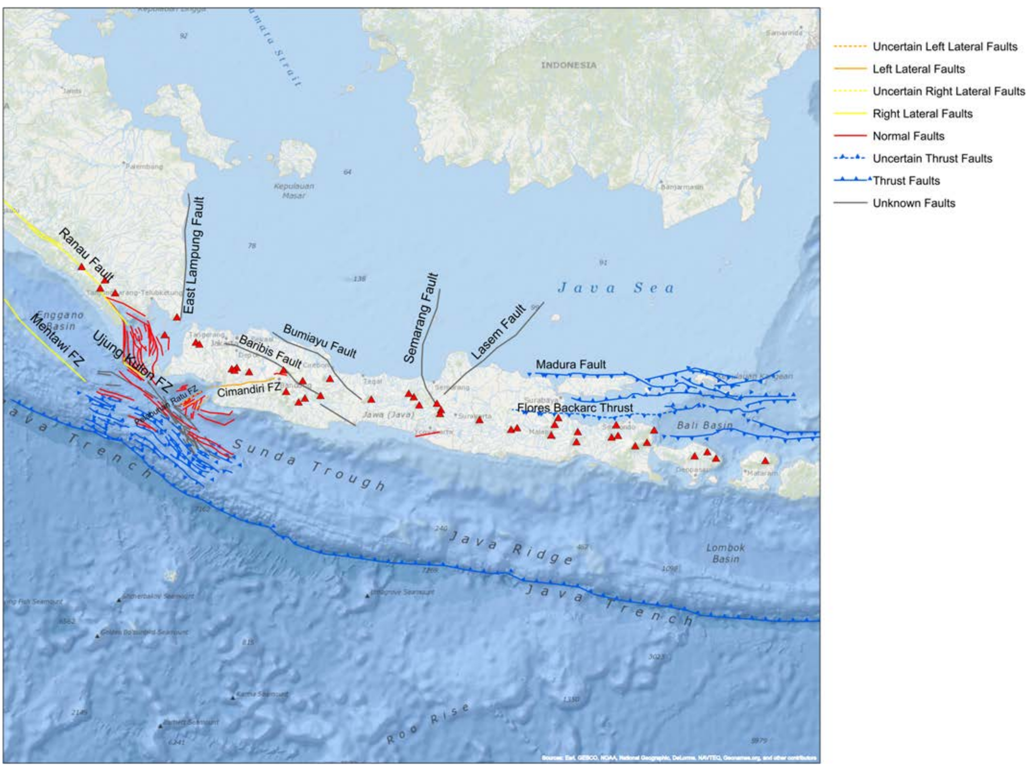

Fig. 14. Active faults and volcanoes of the Java and Bali region. Blue, thrust; red, normal; yellow, strike slip; grey, oblique slip; red triangles, volcanoes. The Lembang Fault is the small red line south of the Bandis Fault. The Opak Fault is the red line near the south central coast. Marine geophysical mapping off the SW coast of Java (Kopp *et al.* 2001) provides a glimpse of the structural complexity in the forearc ridge south of Java. Map modified from Irsyam *et al.* (2008).

1983); (4) the left-lateral Opak Fault, south of densely populated Yogyakarta; and (5) fault zones in the Citanduy Valley near Banjarsari, which has sourced many destructive earthquakes (Simandjuntak 1993).

The general trend for Indonesia of increasing casualties per event is clearly demonstrated in the Wichmann catalogue as well as in more recent events in Java. In 2006, a shallow M_w 5.9 earthquake on a previously unknown fault near Yogyakarta caused around 6000 casualties and damaged around 451 000 homes (Tsuji *et al.* 2009). Much of the damage from the earthquake resulted from the poor soil conditions upon which much of the built environment rests. The relatively small extent over which this event was felt and caused damage was not significant enough to have made the above list of most damaging earthquakes. Five million people now live within 100 km of this fault and the nearby Opak Fault, which is expressed geomorphically (Fig. 15).

The question of whether a megathrust earthquake event can occur on the Java Trench is still debated (McCaffrey 2007; Stein & Okal 2007). The well-developed forearc basin and accretionary wedge, and subduction of a relatively thick (>1 km) package of sediment, are characteristic of subduction zones that produce megathrust earthquakes $>M_w$ 8.5 (Ruff & Kanamori 1980).

There is circumstantial evidence from multiple sources that a megathrust event may have happened during the period of 1584–87, when the whole island shook and several volcanoes erupted that were previously, and have since been, dormant. During this time, the two largest temple complexes in central Java (Prambanan and Borobudur) were also severely damaged by an earthquake (Fig. 15). A tsunami deposit along the south coast of Java (Fig. 16) also dates to around this time (Eko Yulianto pers. comm.). If the Java Trench is capable of causing a megathrust earthquake and the last one was 428 years ago, then up to 30 m of potential slip could have accumulated along the trench since the last megathrust event. The densely populated areas that would be affected by the strong ground motions of this event are mostly constructed of unreinforced masonry buildings that would most probably experience a high rate of structural failure. Tsunami hazards are also high along much of the southern Java coast, where higher than expected run-up heights (Fig. 17) were observed from the July 2006 Tsunami (Fritz *et al*. 2007).

Sumatra (Table 6)

Much attention has been currently focused on the Sumatra region since the megathrust event occurred on 26 December 2004, and the spatial and temporal clustering of events in the region since 2004. Publications describing the history and potential of megathrust earthquakes along the Sunda Trench offshore Sumatra relied heavily on the Wichmann

Fig. 15. The Opak Fault scarp (ridge on the horizon) as seen from the Prambanan Temple site. The Prambanan Temple was severely damaged in the ?1584–86 regional earthquake and again in 2006 by a local M_w 5.9 earthquake on a previously unknown fault associated with the Opak Fault.

Fig. 16. Tsunami deposit near Pangandaran. It is most likely from a 1584–86? earthquake that damaged the Prambanan and Borobudur temples of central Java. The tsunami deposit is the 10 cm-thick dark layer of coarse sand, near the top of the shovel handle. The tsunami deposit (light grey layer by shovel handle) overlies a palaeosol, which overlies peat (dark grey). A tsunami deposit from the 2006 M_w 7.7 event overlies the surface.

catalogue (e.g. Newcomb & McCann 1987). Some of the earthquakes reconstructed from the catalogue have reoccurred. For example, the 2005 northern Sumatra earthquake near Nias Island was nearly of the same magnitude and ruptured close to the same area as that which was proposed by Newcomb & McCann (1987) from descriptions in the Wichmann catalogue of an earthquake in 1861.

The catalogue documents tsunamis that may have been generated by megathrust earthquakes in 1797, 1799, 1818, 1833 and 1861. Investigations of microatolls of the forearc islands offshore of Sumatra extend the record of abrupt land-level changes that are likely from co-seismic events back to over 1 kyr (Natawidjaja *et al.* 2004; Meltzner *et al.* 2010).

Besides the inter-plate seismic events along the Sunda Trench, there are three other sources of intra-plate earthquakes in Sumatra. These include thrusting within the accretionary wedge, and strike-slip faulting within the arc and forearc. The strike-slip faults are known as the Sumatran and Mentawai faults, respectively.

The Sumatran Fault is a dextral-slip shear zone that accommodates the oblique convergence of the subducting Australian Plate. The fault is marked by a linear topographical depression filled with offset river valley segments that extend over the entire

Fig. 17. Damage in Pangandaran from the 2006 earthquake and tsunami. The wave destroyed most of the buildings along the beach and reached the second floor of the lone surviving home in the distance.

length of the island (Sieh & Natawidjaja 2000). At least 25 km of offset of granitic intrusions has been documented since the Late Miocene. Some Jurassic units may be offset by as much as 180 km (Tjia 1977). At least 18 different fault segments have been identified that have caused more than 20 destructive earthquakes over the past century. Some of the earthquakes in the Wichmann catalogue share characteristics with these events.

The Papua region (Table 7)

Several large earthquake events were recorded in the 1800s in the Papua region, which included two destructive tsunamis. However, the rate of seismicity in this region has been much higher over the past 50 years than in the sparse accounts found in the Wichmann catalogue. This discrepancy is likely to be due to a lack of reporting. The source of most large earthquakes in this region is thrusting along the New Guinea Trench and oblique-slip deformation associated with the Sorong fault system, and other strike-slip structures accommodating the mostly westwards motion of the Pacific Plate relative to the Australian Plate (Fig. 1).

Significant earthquake and Tsunami events in Indonesia from 1600 to 1877

The following summaries are taken from the Wichmann catalogue. We have speculated on the likely source of each event from known active faults. The complete account of each event and many others is found in the translation of the catalogue (Supplementary material). Summaries of the events for each region are provided in Tables 2–7.

1584–86, Java: An earthquake spread over the entire island and caused damage to both the Prambanan and Borobudur Temple complexes [Fig. 15]. Tsunami deposit in Pangandaran may document that this event was a megathrust earthquake along the Java Trench [Fig. 16].

1608, 1 July, Makjan (Makian): A large wave wrecked ships. No earthquake was felt, suggesting a different source, but there was also no storm at the time.
Likely source: Volcanic eruption or distant earthquake.

1608, 18 July, Ternate: Earthquake at night during 'the first watch' 1 year after the Dutch took control of the island. The earthquake shook 9 or 10 cannons loose from their mountings and was accompanied by a volcanic eruption that emitted smoke and steam. No tsunami was noted.
Likely source: Nearby volcanic eruption possibly triggered by a seismic event that generated the tsunami on 1 July.

1629, 1 August, Banda Islands: At 9:30 p.m., a violent shock struck the Banda Islands, followed in half an hour by a large tsunami. The earthquake was also felt in Ambon, but no tsunami is mentioned. In the Banda Islands, the tsunami entered the sound between Lonthor and Banda Niera from the NE. It swept the village of Banda Neira away and damaged many stone structures. The tsunami inundated Fort Nassau and reached a height of 15.3 m above springtide [Fig. 9]. The quake was also felt on Ambon, but no tsunami is mentioned. At least 9 years of aftershocks followed the event.

Likely source: Megathrust earthquake $>M_w$ 8.2–8.8 on the Seram Trough (Liu & Harris 2013).

1644, 12–13 May, Ambon Island: The Portuguese had first arrived on the island in 1513, and the Dutch had occupied it for over 50 years when ‘a terrible earthquake never before seen in this province’ struck. Fort Victoria’s walls were heavily cracked [Fig. 6] and some collapsed. Many buildings were damaged such that their collapse was feared. Fissures formed in the ground in Leitimor (peninsula), but no loss of life was mentioned. The ground remained in motion for many days. A strong aftershock struck on 17 May, causing the near-total collapse of the governor’s residence, and was especially damaging on the island of Haruku.

Likely source: Unknown active fault near Haruku.

1646, 19–21 July, Makjan (Makian): A very violent earthquake accompanied a powerful eruption of the volcano. The earthquake was so terrible that residents thought the area would have to be abandoned. Several locals were killed by fire (or lava?).

Likely source: Nearby volcanic eruption.

1648, 2 February, Solor (Lesser Sunda): Earthquake caused wall collapse in Fort Henricus on the north side of Solor. Gaping fissures formed in the mountains and in Larantuka on the east coast of Flores. A probable aftershock cracked walls again in May of the same year.

Likely source: Flores Thrust.

1648, 29 February, Ambon Island: A flood wave formed and crashed against Fort Victoria [Fig. 6], but not causing notable damage.

Likely source: Distant earthquake or volcanic eruption.

1659, 11 November, Ambon Island: Earthquakes followed by a volcanic eruption of Teon in the southwest Banda Arc sent locals to neighbouring islands. The eruption was heard on Ambon and the Banda Islands a few hundred kilometres away. A 1–1.5 m-high tsunami was observed in the Bay of Ambon.

Likely source: Eruption on Teon Island.

1671, 17–18 October, Saparua Island: Earthquake causing destruction of the entrenchment Velsen and heavy damage of Fort Hollandia. The beach at Hatuwana sank by 0.3 m and the reef before Paparu village even more. Ground fissures were so deep that coco palms sank to the crown. The earthquake was also felt on Haruku, Ambon and the south coast of Seram. Aftershocks kept the ground in motion for a month and isolated shocks were felt for a year.

Likely source: Haruka–Saparua Fault

1672, date unknown, Ambon Island: Very strong earthquake that triggered landslides. Villages were buried under the rubble, and fissures 35–55 m deep formed.

Likely source: Ambon Fault Zone.

1673, 20 May, Halmahera: An eruption of Gamkanora on the NW coast of Halmahera was accompanied by an earthquake that was felt in Ternate 60 km away. A tsunami followed that flooded villages.

Likely source: Unknown.

1673, 12 August, Ternate: A violent earthquake that caused Mount Gamalama to split open on the south side from bottom to top, but no eruption was reported. Rocks sank away and houses collapsed. A tsunami crashed against the beach with such force that shipwrecks were feared.

Likely source: Unknown, but perhaps related to the event on 20 May of the same year.

1675, 17 February, Ambon and the Uliasser Islands; Buru; Ceram; Banda Islands; Nusa Tello Islands: The most violent earthquake experienced in living memory in the Ambon region. The quake was felt, and a tsunami was observed on Ambon, Haruku, Buru, Amblau, Manipa, Keland, Buano, the Banda Islands and the western peninsula of Ceram.

Many buildings collapsed and claimed victims. Fissures opened belching bluish sludge 6–7 m upwards. Landslides buried villages and dammed streams.

On the north coast of Ambon, whole villages slid into the sea causing a major tsunami that engulfed the entire region. The smallest of the three Nusa Tello islands off the NW coast of Ambon was fully flooded over by the wave. Trees were washed away as high as 90–100 m on some slopes near Cyst. At least 2243 persons perished from the tsunami. At Fort Amsterdam, it spilled over the walls and killed most of those who fled to the fort for shelter [Fig. 7].

Likely source: Ambon Bay Fault.

1681, 11 and 17 December, west coast, Sumatra: Sky-high mountains were shaken and shifted. Seaquakes reported by several ships.
Likely source: Subduction interface near Mentawai Islands (perhaps the same event as the *c.* 1685 one documented by Sieh *et al.* 2008).

1683, 16–30 October, Banda Islands: A violent earthquake with 2 weeks of strong aftershocks. Cracks and fissures appeared on the mountains. Most of the houses became heaps of rubble and the walls of Fort Revengie were damaged.
Likely source: Banda Api or intermediate-depth event on Banda Trench.

1699, 5 January, Jakarta: Powerful earthquake in West Java and southern Sumatra. Several homes collapsed and landslides dammed rivers. An increase in earthquake frequency, including two strong events in the next 10 years, likely to represent aftershocks or stress contagion onto other faults.
Likely source: Source unknown.

1705, October, Ambon Island: Earthquakes were felt over the entire month, especially on Hitu peninsula and west Ceram. A particular 2 day quake opened fissures, some which damaged houses. Fort Victoria's walls were rent asunder in several places and many were surprised that all the houses did not collapse.
Likely source: Aftershock from the likely stress contagion from the 1674 event.

1708, 28 November, Ambon Island: A tsunami penetrated the Bay of Ambon up to Batu Merah, three waves struck in total, and they were also observed on other coasts.
Likely source: Unknown.

1711, 5 September, Ambon and Uliasser Islands: A similar event to the 1708 tsunami, but three waves went up the Bay of Ambon within an hour. A violent earthquake was felt in Haruku and a weak shock was felt on Nusalaut and Saparua, 13 or 14 flood waves were observed on the beaches of these islands. The earthquake also felt in Banda Islands.
Likely source: Haruka–Saparua Fault.

1754, 18 August, Ambon and the Uliasser Islands: Earthquake caused the market hall sitting on 60 stone piers to collapse, several other buildings were destroyed, and houses were cracked. Fissures a few centimetres wide formed with one of them in Batu Merah ejecting bluish sludge with water and sand like a fountain. A tsunami struck the south coast of Ambon at Hutumuri.
Likely source: South of Ambon.

1755, 3 November, Mana, Bengkulu, SW Sumatra: Powerful shock with 12 aftershocks felt until 3 December. The walls of the Cumberland House, the administration building in Fort Marlborough in Bengkulen, and other buildings, suffered heavy damage. The same was the case with houses in Lais, Mana, as well as on a sugar plantation located 5–6 miles away from Bengkulu. In the area of Mana several villages were also destroyed. On the Bengkulu River [Ajer Bangkulu] or, more precisely, at the delta and also further upriver, the ground opened and a great amount of water gushed forth with 'sulphureous earth that spread an unbearable stench'. At the same time on Pablo Point [Cape of Si Abung], numerous cracks and fissures formed.
Likely source: Sumatra Fault.

1763, (no date), Nias Island, west Sumatra: Earthquake, by which a village was buried.
Likely source: Sunda Trench or accretionary wedge fault.

1763, 12 November, Banda Islands: Violent earthquake was followed by 16 shocks in the evening and night. 75% of the houses on Banda Neira were reduced to rubble. Great boulders crashed down from the mountains.
Likely source: Volcanic quake (Banda Api) or nearby fault zone.

1770, no date, District of Mana, Bengkulu, west Sumatra: Very violent earthquake that destroyed a village as the ground rose up and a fissure 400 m in length, 4 m wide and 8 m deep formed. Bituminous material gushed from the fissure. At the same time, near the delta of the Padang Gutji, likewise located in Mana, a piece of land was laid dry. Finally, a flood wave occurred simultaneously with this quake.
Likely source: Forearc thrust fault.

1793–95, date unknown, Kupang, Timor: The church and several buildings were destroyed in a violent earthquake.
Likely source: Timor Trough or Semau Fault.

1797 *(1795 in Wichmann catalogue)***, 10 February, west coast of Sumatra**: The first vibration lasted a minute, following which a flood wave immediately arose, which penetrated into the River of Padang with great force, such that the city was flooded. Afterwards, the water ran back out so far that even the riverbed was left dry. The process repeated itself three times. The village on the beach, Ajer Manis, was flooded and at the same time many huts were washed away. In Padang, proper fissures of 7–8 cm in breadth formed and closed again. Most buildings were damaged. During the entire night, and the next day the ground was in movement. Every 15–20 minutes a powerful vibration occurred, which persisted for a week, with the pauses between events gradually became longer.

The earthquake spread over two degrees north and south of the equator. Moreover, the flood wave it produced had also struck the Batu Islands. [See Natawidjaja *et al.* 2006 for more details.]

Likely source: Sunda megathrust.

1799, (no date), Sumatra: Earthquake and seaquake associated with a flood wave that achieved a height of 15 m above the usual water level. A reef was uplifted, such that it became a danger for sea navigation. The shock caused significant damage at Palembang.

Likely source: Aftershock or stress contagion to another segment of the Sunda Trench after 1795 event.

1818, 18 March, Bengkulu, SW Sumatra: Earthquake observed at Fort Marlborough where people were thrown out of bed and walls collapsed. The sea withdrew before a tsunami drove everything with great force back on shore. On the ships *Northumberland* and *Sunbury*, the shock was so strong that the sailors were thrown from their berths. The water flooded up over the bridge inland. Aftershocks were noted until at least 8 April.

Likely source: Sunda megathrust or accretionary wedge fault.

1833, 24 November, Bengkulu, Sumatra: Violent earthquake that was felt as far away as Singapore and Java. The shaking in Singapore was felt for 1 minute, 5 minutes after it was noted in Bengkulu. The report also notes that it was the first earthquake since Singapore has been in English possession [1819]. Ships also felt a seaquake.

In Bengkulu, the earthquake lasted for 5 minutes and caused building collapse. A tsunami stormed the coast destroying the port dams and houses in the vicinity, two schooners and several smaller vessels were thrown onto land.

In Padang the earthquake lasted for 3 minutes with several days of aftershocks. Direction SSW–NNE. Buildings were damaged, and water and sulphurous steam rose from cracks. A tsunami caused considerable damage.

In Indrapura and Pulu Tjingko, the tsunami caused considerable damage and killed many people. Two local volcanoes in this area were also affected. Gunung Singalang cracked and Gunung Merapi erupted.

In Pariaman, an extremely powerful shock caused ground fissures up to 1 m in width. The sea retreated and then returned in the form of a massive flood wave that tore all of the ships from their anchors. The vibrations continued for multiple days on end.

On the volcano Bukit Kaba, Ajer Lang a landslide dammed a river that was subsequently destroyed by an aftershock. The flooding destroyed many villages downstream. [See Natawidjaja *et al.* 2006 for more details.]

Likely source: Sunda megathrust.

1840, 14 February, Ternate: A violent eruption of Gamalama started on 2 February, followed by powerful earthquakes several days later that ‘nearly transformed the city into a rubble heap’. The strongest quake on 14 February caused 500 houses to collapse along with heavy damage to Fort Oranje. Shocks continued through March.

1841, 16 November, Banda Islands: A weak shock was felt, followed by a wave 15 minutes later that struck the south coast at a height of 2.5–3 m. Water reached the door of Fort Nassau, even though it was low tide at the time [Fig. 9].

Likely source: Active fault zone south of Banda Islands.

1841, 16 December, Ambon, Amblau and Buru Islands: A not particularly strong earthquake was felt on Ambon, which was followed 15 minutes later by a wave *c.* 1.5 m above the highest water level that crashed against the beach in Ambon Bay. Several huts were washed away west of Ambon City [Figs 4 & 5]. The quake was much stronger on Buru and Amblau Islands. On Amblau, the wave washed away huts and mosques of beach villages.

Likely source: Sula or Matano strike-slip faults.

1843, 5 January, Nias Island and Baros, NW Sumatra: Violent quake causing damage to buildings and numerous cracks to form in Sumatra.

On the Island of Nias, shocks came from the west then continued to the north. The shaking was initially weak, but increased in intensity gradually for 9 minutes. Part of Mount Horifa fell into the chasm, and part of the ramparts of the fort at Gunungsitoli sank. With the exception of the barracks and the apartment of the commandant, all the houses collapsed. After the passage of 9 minutes, a ‘sky-high’ flood wave coming from the SE crashed against the NE beach and flooded away Kampong Mego, an hour south of Gunungsitoli. The flood phenomena lasted for 5 hours, after which a yet more violent earthquake occurred that lasted about 6 minutes. The shock waves came ‘from the west and roamed towards the north’. Many days later, the vibrations were still perceptible, though to a weaker degree.

In Barus a flood wave stormed against the coast at 12.30 am and cast boats 600 m on land.

The earthquake was felt in Penang and Singapore.

Likely source: Sunda megathrust or accretionary wedge fault.

1845, 8 February, Menado, north Sulawesi: A violent earthquake spread over all of Minahassa peninsula, north Celebes. At Menado, it was barely possible to stand upright and objects were thrown about in houses. The walls of Fort Amsterdam formed gaping cracks. Many houses collapsed resulting in 56 fatalities and more injured. Many of the walls of the fort in Amurang collapsed. Many fissures formed in the ground and landslides occurred. The water in the roadstead (harbour) emptied, leaving fish to gather from the seafloor.

Likely source: Northern Sulawesi Trench

1846, 15 January, Ternate and neighbouring coasts; Menado, north Sulawesi: A non-violent, but long-duration earthquake was followed by a 1 m flood wave at Ternate. The water level rose in wells. The wave was also observed on the coasts of neighbouring islands and as far away as Menado, north Celebes.

Likely source: Molucca Sea subduction zones.

1847, 31 October, Nicobar Minor: A series of earthquakes and tsunami waves are documented for 19 days. On the small islands located in the St George Channel, the shocks were most powerful and caused large boulders to fall, collapse of houses and formation of fissures that spewed cold and salty water, and flooding of coastal areas tsunami waves.

Likely source: Sunda Megatrench.

1852, 26 November, Banda Islands; Ambon and Uliasser Islands: At 7:50 a.m., perhaps the largest earthquake ever documented in the Banda Sea region, similar to the 1629 event. It was felt from S. Sumatra to Australia to Ternate. New islands fitting the description of mud volcanoes appeared in the Kei Islands region [Fig. 3]. In Banda Neira 'the majority of the residences … were transformed to a rubble heap … and those that remained standing were uninhabitable'. 15 minutes after the shaking stopped the bay emptied to a narrow river. Three waves followed that came through Lonthor Sound and 'reached the hill on which Fort Belgica is built' [Fig. 9] and the foot of the mountains on Lonthor. The difference between the high and low of the waves was 8.2 m. The tsunami was not observed on the north coast of Bandaneira or on the south coast of Lonthor. The islands of Rosengain and Ai were also affected by the earthquake and the tsunami, which reached around 1 m above the usual sea level on Ai. Gunung Api did not show volcanic activity.

Violent shaking was experienced in and around Ambon where a wave >1 m was observed. Aftershocks were noted for at least a decade.

Likely source: Megathrust on the eastern Seram and northern Tanimbar troughs (Fisher & Harris, in press).

1854, 2 January, Haruku and Saparua Islands (Uliassers): Powerful shocks were followed by a 'not particularly strong flood wave' also noticed on Ambon.

Likely source: Haruka–Saparua Fault.

1855, 25 April, Ternate; Halmahera: Shocks were felt from the morning until 2 p.m.. Multiple buildings were damaged and the shocks were felt aboard ships. The quake was also felt on Halmahera and the fort on Dodingga 'was damaged so badly that it had to be abandoned'.

Likely source: Volcano or Molucca collision.

1855, 4 May, Nanga Rama, south Flores: A series of waves struck the south coast. The first penetrated into a schooner, the second broke the anchor chain and set it on the beach, and the following wave turned it into wreckage.

Likely source: Java Trench, Timor Trough, Savu Thrust or thrust in Savu Sea.

1855, 14 July, Ternate and Tidore Islands; Halmahera: A very violent quake struck at 4 p.m. and lasted 2 minutes, badly damaging all buildings. The earthquake was stronger on Tidore Island and caused 25 houses to collapse, killing 24. 32 more died from rockfalls from Mt Dojado. The quake was felt with equal force at Dodingga, Halmahera. Mount Gamalama on Ternate showed no activity at the time.

Likely source: Halmahera Trench.

1856, 2 March, Sangihe Island (north of Sulawesi): An eruption of Mount Awa, north of Celebes on Sangihe Island, was accompanied by a powerful shock. A tsunami penetrated far inland.

1856, 25 July, Ampenan, Lombok: A quake was felt and a 'heavy surge' noticed on the beach at Ampenan.

Likely source: Fault between Lombok and Bali, West Flores Thrust or Java Trench.

1856, 6–7 August, Gorontolo, Minahassa peninsula, north Sulawesi: Powerful shocks heavily damaged the walls of the fort.

Likely source: Gorontolo Fault or North Sulawesi Subduction Zone.

1857, 13 May, northern East Timor: A violent earthquake threw people to the ground. Part of the walls of the fort collapsed and ground subsidence was observed. A tsunami with four waves struck the bay and reached 3.1 m high. Fissures were created on the beach. The quake was also 'very strong' in Hera, Laclo, Lautem, Lale and Batugade. A mud volcano erupted near Viqueque. At Liquica village, a tsunami flooded almost the entire village. A hill sank on Palau Kambing (north of Dili) killing more than 36 persons. The quake was felt in Kupang (285 km SW of Dili) and Ambon (600 km to NE). Aftershocks were felt through June when the record stops.

Likely source: Wetar Strait Thrust or Wetar Thrust.

1857, 17 October, Kema and Manado, Minahassa peninsula, north Sulawesi; Ternate: At 4:30 a.m., a shock was felt in Kema and Menado followed by a tsunami that washed away multiple huts and trees near Kema. Other shocks occurred at 6 and 9 a.m., and another tsunami accompanied the second shock at Kema. Shocks were still felt in Menado in March and later.

At Ternate, on the other side of the Molucca Sea, a weak shock was also felt at around 4:30 a.m. and the following groundswell (tsunami?) reached a height that was unknown even to the oldest residents and caused devastations.

Likely source: Sangihe megathrust.

1858, 13 November, Minahassa, north Sulawesi; Ternate: 'An extraordinarily strong and long lasting earthquake' in all of Celebes. Effects in Tondano were strongest with 15 huts collapsing and landslides. According to ships in the area, a tsunami appeared along the entire east coast of Celebes to the Banggai Islands, destroying villages and causing other damage.

A powerful quake was also felt in Ternate at 'noon', but no volcanic eruption occurred. It was also strongly felt on Batjan Island (Bacan) to the south. A tsunami also may have appeared.

Likely source: Sangihe megathrust.

1859, 28 May, Sidangola Bay, Ternate; east Sulawesi: At around 8:30 p.m. and midnight shocks were accompanied by waves that threw a government schooner onto the beach at Kema, north Celebes.

In Ternate also, a strong quake was felt and ships began to roll in the roadstead. Two small boats were thrown on the beach. At the Bay of Sidangoli on the west coast of Halmahera the tsunami reached over 10 m.

Likely source: Sangihe megathrust.

1859, 29 July, Minahassa, Kema, Gorontalo, Sulawesi; Banggai Islands; Ternate, Tidore and Makjan Islands: At Minhassa at 1:30 p.m. powerful shocks lasted 5 minutes 'which threatened to knock everything down'. Shocks repeated at 4:30, and through the evening and night. A tsunami stuck Kema and washed away a shed. The quake was also felt in Gorontalo, Mondono and Banggai Island. A tsunami also occurred on Banggai Island.

At 3:15 p.m. on Ternate, a quake struck creating fissures that opened and closed. Directly after, a flood wave came in 1 m above flood level, even though it was at low tide. The earthquake was also observed on Tidore, Makjan and other islands.

Likely source: Sangihe megathrust.

1859, 25 September, Banda Islands: A powerful shock occurred in the evening accompanied by a flood wave 'with great force' that struck the southern coast.

Likely source: Banda Sea Fault like the 1975 event.

1859, 17 December, Belang, Minahassa peninsula, north Sulawesi: A shock was felt accompanied by a tsunami.

Likely source: Sangihe megathrust (aftershock of earlier events)

1859, 25 December, Kema, north Sulawesi: A tsunami reached the roof of a coal shed and partly beat away palisades (protective fence) along the gangway.

Likely source: Sangihe megathrust (perhaps aftershock of earlier events).

1860, 6 October, south Halmahera: A tsunami was observed not far from the south tip of the island but cause no damage. 10–12 more waves came in before 'the sea became again smooth as glass'.

Likely source: Sangihe megathrust (aftershock of earlier events).

1861, 16 February, 6.30 pm, Nias Island and west Sumatra: Thought at the time to be the most widespread quake that ever struck Sumatra, which was also felt on the Malay peninsula and in Java. The earthquake was most strongly manifest in Nias Island, and the area between the Batu Islands to the north and Bengkulu to the south. The shaking lasted for 4 minutes around Nias Island and the immediately adjacent parts of the Sumatran coastline, as noted in Sibolga, Natal and Tapanuli where numerous buildings collapsed. The duration of shaking and damage from shaking was less to the north and south of this region. Shaking lasted for 1 minute in Bengkulu. The shaking in Singapore lasted for about 2 minutes and was in a SW–NE direction. On the west coast of Nias, coral reefs were uplifted that changed the coastline. Within 15 minutes of the earthquake, a 7 m tsunami arrived at Langundi on the south coast of Nias where it destroyed most of the buildings and claimed 50 lives. In Gunungsitoli on the NE coast of Nias, the sea retreated 32 m, then inundated multiple beach villages bringing ships onto the beach destroying nearly everything. On Simuk Island, which is south of Nias, most of the villages were destroyed by the tsunami, which claimed 675 lives. Tsunami waves also struck the west coast of Sumatra where the sea withdrew for some time then flooded shorelines from Singkil to the north to Bengkulu to the south, a distance of around 5 degrees of latitude. Even on the north coast of Java, 1.5 hours after the earthquake, a 1.6 m tsunami was noted in the Tji River, which tossed watercraft around and tore them from their anchors. Several ships also reported a seaquake.

Likely source: Sunda megathrust similar to the M_w 8.6 Nias earthquake in 2005.

1864, 23 May, Cenderawasih Bay, Papua: A strong earthquake struck in Dore territory, which collapsed buildings and generated a 2.5–3 m tsunami. The tsunami washed away the huts and claimed 250 lives.

Likely source: New Guinea Trench or Yapen Fault Zone.

1871, 2 March, Tagulandang Island (north of Sulawesi): An eruption of Ruang volcano caused a landslide that triggered a large tsunami. The wave hit the west beach, penetrating 188 m inland with a run-up height of 26 m in the village of Buhias. The village was entirely destroyed and 277 people perished. Other villages on the west and SW sides of the island also sustained similar damage.

1873, date unknown, Astrolabe Bay, New Guinea: An earthquake caused the collapse of many huts, especially in the mountain villages. Around sunrise, a tsunami struck that destroyed forests and threw debris onland, blocking the mouths of river estuaries. Rivers changed their courses, fissures were observed, and sinkholes and lagoons were formed.

Likely source: New Britain Trench.

1873, 19 August, Tapanuli Province, west Sumatra: Strong earthquake that lasted for 2 minutes in Padang, Sidimpuan and throughout the Tapanuli Province. In Natal, the fort, other buildings and most bridges were destroyed. Landslides were widespread.

Likely source: Sumatran Fault or downgoing plate similar to the 2009 Padang earthquake.

1875, date unknown, Luf Island, New Guinea: A tsunami struck the small islands north of New Guinea. Several of the low islands were inundated, causing ‘great sickness and mortality on the Island Lub (or Hermit Island)’.

Likely source: Orphan tsunami (New Caledonia, 28 March 1875, Monterey Bay 18 March 1875) or Manus Trench.

1876, 28 May, Kajeli Bay, Buru Island: Strong shocks damaged buildings on the SW part of the island and caused a 0.3 m tsunami in the Bay of Kajeli.

Likely source: Sorong Fault system.

Reconstructing the earthquakes

Many of the events described in the Wichmann catalogue provide key observations that can be used to locate more accurately possible source regions for the events and the magnitudes of the earthquakes in these regions. The power of this approach is demonstrated in the reconstruction of the 1629 earthquake and tsunami in the southern Maluku region (Liu & Harris 2013). The earthquake was felt over a broad area and lasted for 5 min, which are characteristics of a major tectonic event. The tsunami was observed in the Banda Islands 30 min after shaking stopped. It came from the east. Acknowledging that there is the possibility that tsunamis are generated by earthquake-induced slides, the possibilities of large earthquakes should also be investigated.

If the ground shaking felt in the Banda Islands did, indeed, cause the tsunami that arrived 30 min later, then the distance of the epicentre from the Banda Islands can be reconstructed by modelling wave propagation across the Banda Sea. The bathymetry around the Banda Islands is the determining factor in how fast a tsunami can reach there. Numerical modelling of the wave propagation demonstrates that the only known fault zone of sufficient size to cause a 15 m tsunami that arrives in the Banda Islands from the east 30 min after the earthquake is the Seram Trough (Liu & Harris 2013).

In order to determine the size of the event, Liu & Harris (2013) had to estimate the geometry of the Seram Trough subduction interface that produced it. The strike and dip of the fault was estimated from the existing database of fault-plane solutions, which includes several small earthquakes along the subduction interface over the past 30 years. The size of the earthquake scales with fault-plane dimensions and the amount of slip, which can be constrained by the size of the tsunami. The length and width of the rupture zone and amounts of slip on the fault are scaled to produce a tsunami that matches what was observed.

In the case of the 1629 event, the earthquake would have to be M_w 8.2–8.8, depending on which parameters are favoured (Liu & Harris 2013). A sensitivity analysis of the reconstruction shows that changes in the dip angle of the fault influence tsunami height most, by a factor of 2 between 10° and 45°. Variations in hypocentral depth from 5 to 30 km have very little influence (10%) on tsunami height.

Reconstruction of the 1852 earthquake and tsunami, which was more widely felt than the 2011 M_w 9.0 Sendai earthquake, and the tsunami observed at many sites, points to a megathrust earthquake along the Tanimbar Trough (Fisher & Harris, in press). Many other events in the Wichmann catalogue have enough details to constrain likely source areas and magnitudes with much more accuracy than we speculated for each event.

We are in the process of translating the catalogue into Indonesian so it can be made available to those who are actually in harm's way. In November 2013, we completed and distributed the Indonesian version of earthquakes and tsunamis from 1600 to 2010 in the southern Maluku region.

Communicating the hazard

One of the most difficult, but important, lessons learned from the 2004 Banda Aceh earthquake and tsunami is the vital need for earthquake and tsunami hazard education. Although several papers were published warning of the likelihood of the recurrence of megathrust earthquakes in Sumatra, most of the people in harm's way did not know there was a threat or that they should evacuate low-lying coastal regions after prolonged ground shaking.

Since the 2004 event, a tsunami warning system has been installed for the Indian Ocean region. Four tsunamis have occurred since the warning system was installed, but the warnings are still not reaching the beaches before the waves. One of the problems with having a tsunami warning system is that people in harm's way wait until they receive word from official channels before responding to the ground shaking. Efforts to educate communities at the local level about earthquake and tsunami hazards, and to conduct evacuation drills, is proving much more effective in raising awareness at a fraction of the cost of high-tech solutions.

Key factors in persuading local communities to take the threat of earthquakes and tsunami seriously, and actively prepare for it, is to provide historical accounts of what has happened in these areas in the past. The sections of this paper on Maluku and Nusa Tengarra have already been translated into Indonesian and distributed throughout these regions by the non-profit organization 'In Harm's Way' (inharmswayhelp.org).

Conclusion

It is our hope that the English translation of the Wichmann catalogue, which we provide here, will assist in seismic and tsunami disaster prevention, reversing the mounting losses to nature in the Indonesian region. The catalogue significantly extends the temporal range of earthquake and tsunami events in Indonesia back in time by more than 400 years.

With strain rates as high as 70–110 mm a^{-1}, it is likely that some active faults have reoccurring earthquakes during the time covered by the catalogue. Although, it is more likely that the catalogue has only captured single events along active faults with recurrence intervals longer than the time since the last event. However, these data provide a way in which to predict where many active faults in the region are in their earthquake cycle. With new GPS constraints on loading rates for most of these faults, the amount of elastic strain energy that has accumulated since the last major earthquake can be determined, which provides a way to estimate expected earthquake magnitudes in various regions across Indonesia. With these estimates, it is possible to construct numerical models of tsunamis that may be generated by future earthquake events. However, these records are of limited worth if the information does not result in education and implementation of disaster mitigation strategies for those who are actually in harm's way.

This research was partially funded by NSF EAR 0337221, grants from the BYU College of Physical and Mathematical Sciences, and the BYU Office of Research and Creative Activities. We thank those who helped with the translation of the Wichmann catalogue: Aden Williamsen, Tanner Duncan, Marti Major, Carolyn Dedari, Sarah Reed, Douwe van Hinsbergen and Tobias Weisenberger. Jamie Robinson, Bradley Bishop and Stina Nyhus helped with compiling active fault data. Universitas Pembangunan Nasional (UPN) Yogyakarta sponsored our research in Indonesia. We thank Carolus Prasetyadi and Arif Rianto, and others at UPN for field support and cultural insights. Others members of the research team who helped immensely are Nova Roosmawati, Hendro Nugroho, Hanif Ibadurrahman and Stenley Loupatty. We also thank Eko Yulianto of LIPI and Juilian Fretha of the Badan Nasional Penanggulangan Bencana (BNPB) for invaluable support in the field.

References

Bader, A.G. & Pubellier, M. 2000. Forearc deformation and tectonic significance of the ultramafic Molucca central ridge, Talaud islands (Indonesia). *The Island Arc*, **9**, 653–663.

Baeda, A.Y. 2011. Seismic and tsunami hazard potential in Sulawesi, Indonesia. *Journal of International Development and Cooperation*, **17**, 17–30.

Barber, A.J., Tjokrosapoetro, S. & Charlton, T.R. 1986. Mud volcanoes, shale diapirs, wrench faults and mélanges in accretionary complexes, Eastern Indonesia. *American Association of Petroleum Geologists Bulletin*, **70**, 1729–1741.

Bergman, S.C., Coffield, D.Q., Talbot, J.P. & Garrard, R.A. 1996. Tertiary tectonic and magmatic evolution of western Sulawesi and the Makassar Strait, Indonesia; evidence for a Miocene continent–continent collision. *In*: Hall, R. & Blundell, D. (eds) *Tectonic Evolution of Southeast Asia*. Geological Society, London, Special Publications, **106**, 391–429, http://doi.org/10.1144/GSL.SP.1996.106.01.25

Berry, R.F. & McDougall, I. 1986. Interpretation of $^{40}Ar/^{39}Ar$ and K/Ar dating evidence from the Aileu Formation, East Timor, Indonesia. *Chemical Geology and Isotope Geoscience*, **59**, 43–58.

Bock, Y., Prawirodirdjo, L. *et al.* 2003. Crustal motion in Indonesia from Global Positioning System measurements. *Journal of Geophysical Research*, **108**, 2367, http://doi.org/10.1029/2001JB000324

Breen, N.A., Silver, E.A. & Roof, S. 1989. The Wetar backthrust belt, eastern Indonesia: the effects of accretion against an irregularly shaped arc. *Tectonics*, **8**, 85–98.

Brune, S., Ladage, S., Babeyko, A.Y., Mueller, C., Kopp, H. & Sobolev, S. 2010. Submarine slope failures at the eastern Sunda Arc; bathymetry analysis and tsunami modeling. *Deutsche Geophysikalische Gesellschaft*, **2**, 15–18.

Budiono, K., Astjario, P., Kusnida, D. & Lubis, S. 1995. Coastal and marine geological survey after the earthquake of 12 December 1992 at Maumere Bay, Flores. *Bulletin of the Marine Geological Institute of Indonesia*, **10**, (1), 13–31.

Carter, D.J., Audley-Charles, M.G. & Barber, A.J. 1976. Stratigraphical analysis of island arc–continental margin collision in eastern Indonesia. *Journal of the Geological Society, London*, **132**, 179–198, http://doi.org/10.1144/gsjgs.132.2.0179

Cox, N.L. 2009. *Variable uplift from Quaternary folding along the northern coast of East Timor, based on U-series age determinations of coral terraces*. Unpublished MSc, Brigham Young University.

Duffy, B., Quigley, M., Harris, R.A. & Ring, U. 2013. Arc-parallel extrusion of the Timor sector of the Banda arc-continent collision. *Tectonics*, **32**, 641–660, http://doi.org/10.1002/tect.20048

Fisher, T.M. & Harris, R.A. In press. Reconstruction of the 1852 Banda Arc megathrust earthquake and tsunami. *Natural Hazards*, https://doi.org/10.1007/s11069-016-2345-6

Fritz, H., Widjo, K. *et al.* 2007. Extreme runup from the 17 July 2006 Java tsunami. *Geophysical Research Letters*, **34**, L12602, http://doi.org/10.1029/2007GL029404

Garrard, R., Supandjono, J. & Surono. 1988. The geology of the Banggai-Sula microcontinent, eastern Indonesia. *Proceedings of the Indonesian Petroleum Association 17th Annual Convention*, 23–52.

Genrich, J.F., Beck, Y., McCaffrey, R., Calais, E., Stevens, C.W. & Subarya, C. 1996. Accretion of the southern Banda arc to the Australian plate margin determined by Global Positioning System measurements. *Tectonics*, **15**, 288–295.

Ghose, R. & Oike, K. 1988. Characteristics of seismicity distribution along the Sunda Arc: some new observations. *Bulletin of Disaster Prevention Research Institute*, **38**, 29–48.

Guntoro, A. 1999. The formation of the Makassar Strait and the separation between SE Kalimantan and SW Sulawesi. *Journal of Asian Earth Sciences*, **17**, 79–98.

Hall, R. 2011. Australia–SE Asia collision: plate tectonics and crustal flow. *In*: Hall, R., Cottam, M.A. & Wilson, M.E.J. (eds) *The SE Asian Gateway: History and Tectonics of the Australia–Asia Collision*. Geological Society, London, Special Publications, **355**, 75–109, http://doi.org/10.1144/SP355.5

Hall, R., Cloke, I.R., Nur'aini, S., Puspita, S.D.&, Calvert, S.J. 2009. The North Makassar Straits; what lies beneath? *Petroleum Geoscience*, **15**, 47–158, http://doi.org/10.1144/1354-079309-829

Hamilton, W. 1979. *Tectonics of the Indonesian Region*. United States Geological Survey, Professional Papers, **1078**.

Hamzah, L., Puspito, N.T. & Imamura, F. 2000. Tsunami catalogue and zones in Indonesia. *Journal of Natural Disaster Science*, **2**, 25–43.

Harris, R.A. 1991. Temporal distribution of strain in the active Banda orogen: a reconciliation of rival hypotheses. *Journal of Asian Earth Sciences*, **6**, 373–386.

Harris, R.A. 2006. Rise and fall of the eastern Great Indonesian Arc recorded by the assembly, dispersion and accretion of the Banda Terrane, Timor. *Gondwana Research*, **10**, 207–231.

Harris, R.A. 2011. The nature of the Banda Arc–continent collision in the Timor region. *In*: D.Brown, & P.D. Ryan (eds) *Arc–Continent Collision*. Frontiers in Earth Sciences. Springer, Berlin, 163–211, http://doi.org/10.1007/978-3-540-88558-0_7

Harris, R.A. & Prasetyadi, C. 2002. Who's Next? Assessing vulnerability to geophysical hazards in densely populated region of Indonesia. *Bridges*, **2002**, 14–17.

Harris, R.A., Donaldson, K. & Prasetyadi, C. 1997. Geophysical disaster mitigation in Indonesia using GIS. *Bulletin Teknologi Mineral*, **5**, 2–10.

Harris, R.A., Vorkink, M.W., Prasetyadi, C., Roosmawati, N., Zobell, E. & Apthorpe, M. 2009. Transition from subduction to arc–continent collision: geological and neotectonic evolution of Savu, Indonesia. *Geosphere*, **5**, 152–171, http://doi.org/10.1130/GES00209.1

Hanna, W.A. 1978. *Indonesian Banda: Colonialism and its Aftermath in the Nutmeg Islands, Philadelphia*. Institute for the Study of Human Issues, Philadelphia, PA.

Heuret, A., Lallemand, S., Funiciello, F., Piromallo, C. & Faccenna, C. 2011. Physical characteristics of subduction interface type seismogenic zones revisited. *Geochemistry, Geophysics, Geosystems*, **12**, Q01004, http://doi.org/10.1029/2010GC003230

Irsyam, M., Dangkua, D. *et al.* 2008. Proposed seismic hazard maps of Sumatra and Java islands and microzonation study of Jakarta city, Indonesia. *Earth System Science*, **117**, 865–878.

JAGLA, E.A. & KOLTON, A. 2010. A mechanism for spatial and temporal earthquake clustering. *Journal of Geophysical Research*, **115**, B05312.

KARIG, D.E., BARBER, A.J., CHARLTON, T.R., KLEMPERER, S. & HUSSONG, D.M. 1987. Nature and distribution of deformation across the Banda Arc Australian collision zone at Timor. *Geological Society of America Bulletin*, **98**, 18–32.

KATILI, J.A. 1978. Past and present geotectonic position of Sulawesi, Indonesia. *Tectonophysics*, **45**, 289–322.

KATO, T., ITO, T., ABIDIN, H.Z. & AGUSTAN, 2007. Preliminary report on crustal deformation surveys and tsunami measurements caused by the July 17, 2006 South off Java Island Earthquake and Tsunami, Indonesia. *Earth, Planets and Space*, **59**, 1055–1059.

KERR, R. 2006. Stealth tsunami surprises Indonesian coastal residents. *Science*, **313**, 742–743.

KERTAPATI, E. & KOESOEMADINATA, R.P. 1983. Aftershock studies of the February 10, 1982, Sukabumi earthquake, West Java, Indonesia. *Bulletin of the International Institute of Seismology and Earthquake Engineering*, **20**, 91–101.

KOPP, H., FLUEH, E.R., KLAESCHEN, D., BIALAS, J. & REICHERT, C. 2001. Crustal structure of the central Sunda margin at the onset of oblique subduction. *Geophysical Journal International*, **147**, 449–474.

KREEMER, C., HOLT, W.E., GOES, S. & GOVERS, R. 2000. Active deformation in eastern Indonesia and the Philippines from GPS and seismicity data. *Journal of Geophysical Research*, **105**, 663–680.

LAPE, P.V. 2000. Political dynamics and religious change in the late pre-Colonial Banda islands, eastern Indonesia. *World Archaeology*, **32**, 138–155.

LINTHOUT, K., HELMERS, H., WIJBRANS, J.R. & VAN WEES, J.D.A.M. 1996. $^{40}Ar/^{39}Ar$ constraints on obduction of the Seram ultramafic complex: consequences for the evolution of the southern Banda Sea. *In*: HALL, R. & BLUNDELL, D. (eds) *Tectonic Evolution of Southeast Asia*. Geological Society, London, Special Publications, **106**, 455–464, http://doi.org/10.1144/GSL.SP.1996.106.01.28

LIU, Y.C. & HARRIS, R.A. 2013. Discovery of possible mega-thrust earthquake along the Seram Trough from numerical modeling of 1629 tsunami in the eastern Indonesian region. *Natural Hazards*, **72**, 1311–1328, http://doi.org/10.1007/s11069-013-0597-y

MAJOR, J., HARRIS, R.A. *ET AL.* 2013. Pleistocene hinterland evolution of the active Banda Arc: surface uplift and neotectonic deformation recorded by coral terraces at Kisar, Indonesia. *Journal of Asian Earth Sciences*, **73**, 149–161.

MCCAFFREY, R. 1988. Active tectonics of the eastern Sunda and Banda arcs. *Journal of Geophysical Research*, **93**, 15163–15182.

MCCAFFREY, R. 1989. Seismological constraints and speculations on Banda arc tectonics. *Netherlands Journal of Sea Research*, **24**, 141–152, http://doi.org/10.1016/0077-7579(89)90145-2

MCCAFFREY, R. 2007. The next great earthquake. *Science*, **315**, 1675–1676.

MCCAFFREY, R. & NABELEK, J. 1984. The geometry of back arc thrusting along the Eastern Sunda Arc, Indonesia – constraints from earthquake and gravity-data. *Journal of Geophysical Research*, **89**, 6171–6179.

MELTZNER, A.J., SIEH, K. *ET AL.* 2010. Coral evidence for earthquake recurrence and an A.D. 1390–1455 cluster at the south end of the 2004 Aceh–Andaman rupture. *Journal of Geophysical Research*, **115**, B10402, http://doi.org/10.1029/2010JB007499

MERRITTS, D., EBY, R., HARRIS, R., EDWARDS, R.L. & CHENG, H. 1998. Variable rates of Late Quaternary surface uplift along the Banda Arc–Australian plate collision zone, eastern Indonesia, *In*: STEWART, I.S. & VITA-FINZI, C. (eds) *Coastal Tectonics*. Geological Society, London, Special Publications, **146**, 213–224, http://doi.org/10.1144/GSL.SP.1999.146.01.12

MILTON, G. 1999. *Nathaniel's Nutmeg: How One Man's Courage Changed the Course of History*. Hodder & Stoughton, London.

MUSSON, R.M.W. & JIMENEZ, M.J. 2008. *Procedures for Macroseismic Estimation of Earthquake Parameters. Deliverable D3*. Network of Research Infrastructure for European Seismology (NERIES), Sixth Framework Programme, EC Project number 026130.

NATAWIDJAJA, D.H., SIEH, K., WARD, S.N., CHENG, H., EDWARDS, R.L., GALETZKA, J. & SUWARGADI, B.W. 2004. Paleogeodetic records of seismic and aseismic subduction from central Sumatran microatolls, Indonesia. *Journal of Geophysical Research*, **109**, B04306, http://doi.org/10.1029/2003JB002398

NATAWIDJAJA, D.H., SIEH, K. *ET AL.* 2006. Source parameters of the great Sumatran mega-thrust earthquakes of 1797 and 1833 inferred from coral microatolls. *Journal of Geophysical Research*, **111**, B06403, http://doi.org/10.1029/2005JB004025

NEWCOMB, K.R. & MCCANN, W.R. 1987. Seismic history and seismotectonics of the Sunda Arc. *Journal of Geophysical Research*, **92B**, 421–439.

NUGROHO, H., HARRIS, R.A., AMIN, W.L. & BILAL, M. 2009. Active plate boundary reorganization in the Banda arc–continent collision: insights from new GPS measurements. *Tectonophysics*, **479**, 52–65, http://doi.org/10.1016/j.tecto.2009.01.026

OKAL, E.A. & REYMOND, D. 2003. The mechanism of great Banda Sea earthquake of 1 February 1938: applying the method of preliminary determination of focal mechanism to a historical event. *Earth and Planetary Science Letters*, **216**, 1–15.

OPPENHEIMER, C. 2011. *Eruptions that Shook the World*. Oxford University Press, New York.

PELINOVSKY, E., YULIADI, D., PRASETYA, G. & HIDAYAT, R. 1997. The 1996 Sulawesi Tsuanmi. *Natural Hazards*, **16**, 29–38.

POWNALL, J., HALL, R., ARMSTRONG, R.A. & FORSTER, M.A. 2014. Earth's youngest known ultrahigh-temperature granulites discovered on Seram, eastern Indonesia. *Geology*, **42**, 279–282.

PRASETYA, G.S., DE LANGE, W.P. & HEALY, T.R. 2001. The Makassar Strait tsunamigenic region, Indonesia. *Natural Hazards*, **24**, 295–307.

RANGIN, C., LE PICHON, X. *ET AL.* 1999. Plate convergence measured by GPS across the Sundaland/Philippine Sea Plate deformed boundary: the Philippines and eastern Indonesia. *Geophysical Journal International*, **139**, 296–316.

RASTOGI, B.K. & JAISWAL, R.K. 2006. A catalogue of tsunamis in the Indian Ocean. *Science of Tsunami Hazards*, **25**, 128–143.

Roosmawati, N. & Harris, R.A. 2009. Surface uplift history of the incipient Banda arc–continent collision: geology and synorogenic foraminifera of Rote and Savu Islands, Indonesia. *Tectonophysics*, **479**, 95–110, http://doi.org/10.1016/j.tecto.2009.04.009

Rosidi, H.M.D., Tjokosapoetro, S., Gafoer, S. & Suwitodirdjo, K. 1979. *Geologic Map of the Kupang–Atambua Quadrangles, Timor, 1: 250,000*. Geological Research Development Centre, Bandung, Indonesia.

Ruff, L. & Kanamori, H. 1980. Seismicity and the subduction process. *Physics of the Earth and Planetary Interiors*, **23**, 240–252.

Sieh, K. & Natawidjaja, D. 2000. Neotectonics of the Sumatran fault, Indonesia. *Journal of Geophysical Research*, **105**, 28,295–28,326, http://doi.org/10.1029/2000JB900120

Sieh, K., Natawidjaja, D.H., Meltzner, A.J. & Shen, C.-C. 2008. Earthquake supercycles inferred from sea-level changes recorded in the corals of west Sumatra, *Science*, **322**, 1674–1678.

Silver, E.A. & Moore, J.C. 1978. The Molucca Sea collision zone, Indonesia. *Journal of Geophysical Research*, **83**, 1681–1691.

Silver, E.A., McCaffrey, R., Joyodiwiryo, Y. & Stevens, S. 1983*a*. Ophiolite emplacement and collision between the Sula Platform and the Sulawesi island arc, Indonesia. *Journal of Geophysical Research*, **88**, 9419–9435.

Silver, E.A., Reed, R., McCaffrey, R. & Joyodiwiryo, Y. 1983*b*. Back arc thrusting in the eastern Sunda arc, Indonesia: a consequence of arc continent collision. *Journal of Geophysical Research*, **88**, 7429–7448, http://doi.org/10.1029/JB088iB09p07429

Simandjuntak, T.O. 1993. Neogene tectonics and orogenesis of Indonesia. *In*: Teh, G.H. (ed.) *Proceedings of the Symposium on Tectonic Framework and Energy Resources of the Western Margin of the Pacific Basin*. Geological Society of Malaysia Bulletin, Geological Society of Malaysia, Kuala Lumpar, **33**, 43–64.

Smith, R.B. & Silver, E.A. 1991. Geology of a Miocene collision complex, Buton, eastern Indonesia. *Geological Society of America Bulletin*, **103**, 660–678, http://doi.org/10.1130/0016-7606(1991)103<0660:goamcc>2.3.co;2

Snyder, D.B., Prasetyo, H., Blundell, D.J., Pigram, C.J., Barber, A.J., Richardson, A. & Tjokrosapoetro, S. 1996. A dual doubly vergent orogen in the Banda arc continent collision zone as observed on deep seismic reflection profiles. *Tectonics*, **15**, 34–53.

Socquet, A., Simons, W. *et al.* 2006. Microblock rotations and fault coupling in SE Asia triple junction (Sulawesi, Indonesia) from GPS and earthquake slip vector data. *Journal of Geophysical Research*, **111**, B08409, http://doi.org/10.1029/2005JB003963

Soloviev, S.L. & Go, Ch.N. 1974. *A Catalogue of Tsunamis on the Western Shore of the Pacific Ocean (173-1968)*. Nauka Publishing House, Moscow (Canada Institute for Scientific and Technical Information. 1984. Canadian Translation of Fish and Aquatic Sciences, 5077).

Stein, S. & Okal, E.A. 2007. Ultra-long period seismic study of the December 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process. *Bulletin of the Seismological Society of America*, **97**, S279–S295.

Stein, S., Geller, R.J. & Liu, M. 2012. Why earthquake hazard maps often fail and what to do about it. *Tectonophysics*, **562–563**, 1–25.

Tjia, H.D. 1977. Tectonic depressions along the transcurrent Sumatra fault zone. *Geology of Indonesia*, **4**, 13–27.

Tjia, H.D. 1983. Earthquake stress directions in the Indonesian Archipelago. *In*: Hilde, T.W.C. & Uyeda, S., (eds) *Geodynamics of the Western Pacific–Indonesian Region*. American Geophysical Union, Geodynamics Series, **11**, 413–422.

Tsuji, T., Yamamoto, K. *et al.* 2009. Earthquake fault of the 26 May 2006 Yogyakarta earthquake observed by SAR interferometry. *Earth, Planets and Space*, **61**, 29–32.

Van Bemmelen, R.W. 1949. *The geology of Indonesia; vol. IA, General geology of Indonesia and adjacent archipelagos*. Martinus Nijnhoff, Government Printing Office sole Agent, The Hague.

Van Leeuwen, T.M. 1981. The geology of southwest Sulawesi with special reference to the Biru area. *In*: Barber, A. & Wiryosujono, S. (eds) *The Geology and Tectonics of Eastern Indonesia*. Geological Research and Development Centre, Special Publications, **2**, 277–304.

Watkinson, I., Hall, R. & Ferdian, F. 2011. Tectonic re-interpretation of the Banggai-Sula–Molucca Sea margin, Indonesia. *In*: Hall, R., Cottam, M.A. & Wilson, M.E.J. (eds) *The SE Asian Gateway: History and Tectonics of the Australia–Asia Collision*. Geological Society, London, Special Publications, **355**, 197–218 http://doi.org/10.1144/SP355.10

Welc, J.L. & Lay, T. 1987. The source rupture process of the Great Banda Sea earthquake of November 4, 1963. *Physics of the Earth and Planetary Interiors*, **45**, 242–254.

Wichmann, C.E.A. 1918. *Die Erdbeben des indischen Archipels bis zum Jahre 1857*. Muller, Amsterdam.

Wichmann, C.E.A. 1922. *Die Erdbeben des Indischen Archipels von 1858 bis 1877*. Koninklijke Akademie van Wetenschappen, Amsterdam.

Wood, G.D. 2014. *Tambora*. University Press, Princeton, NJ.