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Timing, magnitude and geochemistry of major Southeast Asian volcanic eruptions: identifying tephrochronologic markers

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ABSTRACT: We review the current knowledge about Southeast Asian volcanoes and their eruption histories, and focus on identifying tephrochronologic markers representing major explosive eruptions in order to further future palaeoclimate and volcanological studies. Forty-one volcanic edifices in Southeast Asia have been classified as large calderas by Whelley *et al.* (2015) and thus have, or are likely to have, produced large explosive eruptions with a Volcanic Explosivity Index (VEI) of 6–8. Unfortunately, only 20 such eruptions have known ages, spanning from 1.2 Ma to 1991 AD, and fewer have geochemical data that can be used for tephrostratigraphic correlations. Volcanic products from different geodynamic regions and different sources can generally be distinguished on major element plots (e.g. K_2O versus CaO) of matrix glass composition. However, the distinction of multiple eruptions from the same source often requires additional data such as trace element compositions of matrix glass and/or mineral compositions. Biotite, but also magnetite compositions (MgO and TiO_2 content in particular) appear to be very discriminating. Up to nine tuffs in addition to the three to four Toba tuffs can be utilised as widespread tephrochronologic markers and span a range from 1.2 to 1.6 Ma to recent. As only a few Holocene major eruptions have been well characterised and dated, many large calderas are still unstudied, and many distal tephra layers are still lacking a source, more tephrochronologic markers can certainly be defined in the future.
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KEYWORDS: calderas; Southeast Asia; tephra; tephrochronologic markers; volcanoes

Introduction

Improving our knowledge of volcanic eruption histories in Southeast Asia is important for a number of reasons, the most obvious of which is regional hazards. Southeast Asia is home to a population of ~600 million. Indonesia and the Philippines, for example, have the world's greatest number of people living within 100 km of an active volcano (Brown *et al.*, 2015). Another important factor is that Southeast Asian volcanoes are predominantly located close to the equator. Large volcanic eruptions that send ash into the stratosphere have particularly global impacts on climate when they occur in equatorial to tropical regions because the ash and aerosols released propagate into both hemispheres (Sigl *et al.*, 2014).

Southeast Asia hosts one of the densest distributions of volcanoes on Earth, with more than 750 active or potentially active volcanoes (Fig. 1; Whelley *et al.*, 2015). Despite this wealth of opportunities, tephrochronology is an underutilised tool due to insufficient geological investigations, a lack of knowledge about eruption sources, magnitudes, ages and geochemical compositions. Volcanoes that frequently erupted during historical time have generally been more studied, e.g. Merapi (Andreastuti *et al.*, 2000; Gertisser and Keller, 2003; Jousset *et al.*, 2013 and references therein), Krakatau (Self and Rampino, 1981; Rampino and Self, 1982; Camus *et al.*, 1987; Dahren *et al.*, 2012), Kelut (Zen and Hadikusumo, 1965; Bourdier *et al.*, 2002; Jeffery *et al.*, 2013; Kristiansen *et al.*, 2015; Maeno *et al.*, 2017), Agung (Rampino and Self, 1982; Self and Rampino, 2012; Fontijn *et al.*, 2015), Taal (Delos Reyes *et al.*, 2018 and references therein), or Mayon (Moore and Melson, 1969; Newhall, 1979; Castillo and Newhall, 2004). People remember large eruptions well for decades to centuries, e.g. Tambora in 1815 (Oppenheimer, 2003), Krakatau in 1883 (Self, 2006) and Pinatubo in 1991 (Tayag *et al.*, 1996). Most of the research on these volcanoes has focused on the eruption dynamics, the distribution and characteristics of deposits, pre-eruptive dynamics in the magma plumbing system, or the eruption consequences for the atmosphere, human lives and the environment (e.g. Devine *et al.*, 1984; Foden, 1986; Wheller *et al.*, 1987; Mandeville *et al.*, 1996; Rutherford and Devine, 1996; Chesner, 1998; Turner and Foden, 2001; Reubi and Nicholls, 2005). Unfortunately, there are few publications relating to local or regional tephrostratigraphy due to the often difficult access to samples: limitations of proximal stratigraphical studies to the past 3000–5000 years, older deposits being buried (Andreastuti *et al.*, 2000; Fontijn *et al.*, 2015), continual changes in land use in this very densely populated region, and poorer ash preservation potential given the equatorial climate with high mean annual precipitation, frequent lahars and landslides (Kirschbaum *et al.*, 2010; Petley, 2010). Nevertheless, some tephrochronologic markers have been identified and used, such as the tuffs from the Toba caldera (e.g. Shane *et al.*, 1995; Pattan *et al.*, 1999; Smith *et al.*, 2011; Lane *et al.*, 2013; Westgate *et al.*, 2013; Mark *et al.*, 2017). Whelley *et al.* (2015) identified 41 large, >5 km diameter calderas in Southeast Asia, suggesting that more such markers could be defined (Fig. 1).

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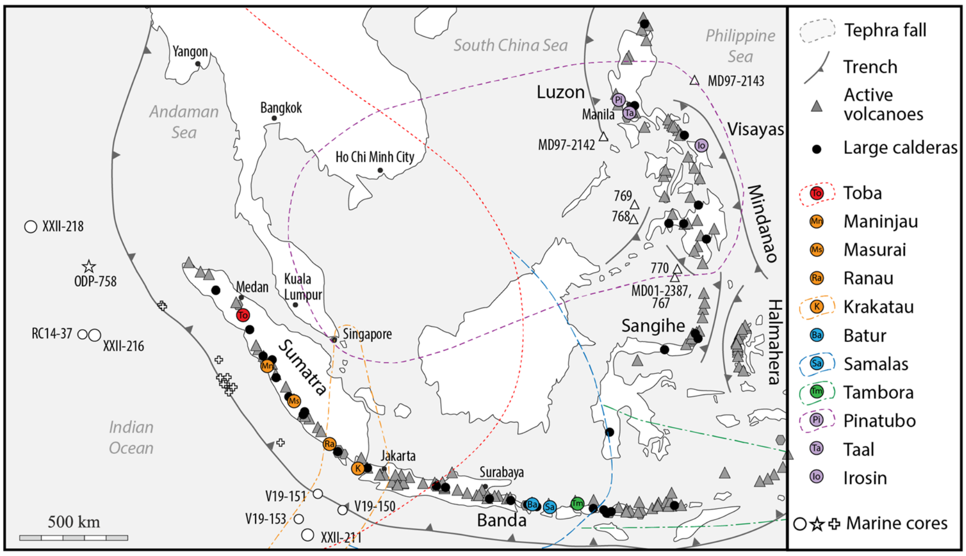

Figure 1. Map of Southeast Asia showing the location of Holocene active volcanoes (grey triangles; GVP), large, >5 km diameter calderas (black dots; Whelley *at al.*, 2015), the sources of VEI 6–8 eruptions for which geochemical data are available (coloured symbols), and marine cores discussed in the text (circles refer to those studied by Ninkovich (1979), the star is ODP-758, pluses are those studied by Salisbury *et al.* (2012), and triangles are cores around the Philippines). Arc segments are labelled and coloured ellipses indicate the spatial extent of ash fall for the Young Toba Tuff (red), 1257 Samalas (blue), 1815 Tambora (green), 1883 Krakatau (orange), and 1991 Pinatubo (grey) eruptions (modified from from Takarada *et al.*, 2016). [Color figure can be viewed at wileyonlinelibrary.com]

A good tephrochronologic marker is an ash layer with a large spatial distribution (i.e. produced from a large explosive eruption), relatively good age constraints, and that has been well characterised in terms of its (glass) chemical and/or mineralogical composition (Lowe, 2011). To robustly characterise a tephrochronologic marker, it is also useful to report regional information, such as the major stratigraphic units it is commonly found in and other tephra layers it may be confused with (in terms of age or geochemistry).

In this paper we collated all published and available information about large volcanic eruptions in Southeast Asia, their timing, magnitude, geochemistry and mineralogical characteristics, in order to define new tephrochronologic markers. We provide a comprehensive geochemical database for comparison with any new data, hoping that this will promote and facilitate tephrochronological and tephrostratigraphic studies in the region.

Data and sources

We concentrated on Quaternary volcanoes, i.e. volcanoes that have erupted in the past 2.5 Ma, in Indonesia and the Philippines, as they represent the largest number and the most active volcanoes in Southeast Asia. We focused mainly on eruptions with a Volcanic Explosivity Index (VEI; Newhall and Self, 1982) of 6–8, which erupt 10 to a few thousand km^3 of volcanic ejecta into the stratosphere and thus spread ash over great distances (hundreds to thousands of kilometres from the source). For each eruption, we report the source volcano, the age and magnitude of the eruption, the dominant transport direction of tephra (where known), and the geochemical and/or mineralogical characteristics. We also collected information about the source volcano and the dominant transport direction of tephra (when available) for all the smaller eruptions (VEI < 6) in order to investigate general tendencies at the scale of the arc. Background information about the likely direction(s) of ash dispersal may be useful in refining tephrochronologic markers or identifying source volcanoes.

Our review investigated all eruptive activity until November 2018. Information about the source volcano, the number of eruptions, their date or age, the erupted volume and/or VEI, the elevation of the ash column, and direction of ash propagation were taken from publicly available databases: the Smithsonian Institution's Global Volcanism Program (GVP; https://volcano.si.edu/), and the Large Magnitude Explosive Volcanic Eruptions (LaMEVE) database of the Volcanic Global Risk Identification and Analysis Project (VOGRIPA) (Crosweller *et al.*, 2012). For each eruption, the source references were checked, and the source reference for the age is reported in Table 1. Some eruption ages were discarded, such as that of an old Maninjau ignimbrite (because Ar-Ar dating on plagioclase (Leo *et al.*, 1980) is not very robust and Alloway *et al.* (2004) describe only one ignimbrite) or that of the Dieng caldera (which must be older than the oldest post-caldera lava flow, as reported in Newhall and Dzurisin (1988) and not of the age of this lava flow, as reported in LaMEVE).

Meteorological observations of the strongest eruptions were used to describe the elevation of ash clouds, the transport directions, and the possible areas of ash fall. Since 2003, several meteorological and geological surveys have provided valuable satellite data for weak eruptions and/or gas emissions in addition to eruptions with VEI > 3. More comprehensive datasets are those from the Center for Volcanology and Geological Hazard Mitigation (CVGHM, Indonesia) and the Darwin Volcanic Ash Advisory Centre (VAAC, Australia), which were posted in GVP.

For large VEI 6–8 eruptions we report the matrix glass composition (when available) in addition to the whole-rock composition, as glass compositions are more useful for comparison with distal tephra (glass shards). We also include mineralogical data, as these can help discriminate between or correlate tephra units (e.g. Fierstein, 2007; Smith *et al.*, 2011; Rawson *et al.*, 2015). Geochemical information was taken from journal articles and their supplementary material, as the publicly available databases generally did not contain enough contextual information to evaluate the relevance and reliability of the data. All data were renormalised to 100% anhydrous in order to ensure inter-comparability. Descriptions of analytical methods vary widely, from the simple mention of the instrument used to the extensive description of each setting and analytical condition. Sometimes the data provided is normalised, other times not, and when it is normalised,

Table 1. List of dated Quaternary VEI 6-8 eruptions in Indonesia and the Philippines. Volcanic Explosivity Index (VEI) are reported and are identical for GVP and VOGRIPA. * indicates that we report the radiocarbon corrected age from VOGRIPA. When no reference [Ref] is mentioned for the age, it is from VOGRIPA. The availability of any type of geochemical (Geochem) data is reported in the form of a reference [Ref]. [2] (Mandeville *et al.*, 1996), [3] (Foden, 1986), [4] (Reubi and Nicholls, 2005), [5] (Vidal *et al.*, 2015), [6] (Alloway *et al.*, 2017), [7] (Natawidjaja *et al.*, 2017), [8] (Alloway *et al.*, 2004), [9] (Chesner, 1998), [10] (Chesner and Luhr, 2010), [11] (Sutawidjaja, 2009), [12] (Wheller and Varne, 1986), [13] (Turner and Foden, 2001), [14] (Devine *et al.*, 1984), [15] (Gertisser *et al.*, 2012), [16] (Métrich *et al.*, 2017), [17] (Camus *et al.*, 1987), [18] (Smith *et al.*, 2011), [19] (Vidal *et al.*, 2016), [20] (Pallister *et al.*, 1996), [21] (Rutherford and Devine, 1996), [22] (Luhr and Melson, 1996), [23] (Bernard *et al.*, 1996), [24] (Castillo and Punongbayan, 1996), [25] (Fournelle *et al.*, 1996), [26] (Imai *et al.*, 1993), [27] (Hammer *et al.*, 1999), [28] (Borisova *et al.*, 2005), [29] (Ku *et al.*, 2008), [30] (Mirabueno *et al.*, 2007), [31] (Mirabueno *et al.*, 2011), [32] (Delfin *et al.*, 1993), [33] (Martinez and Williams, 1999), [34] (Newhall *et al.*, 1996), [35] (Dam *et al.*, 1996), [37] (Rohiman *et al.*, 2019), [38] (Mark *et al.*, 2017), [39] (Nishimura *et al.*, 1977).

	Source	Region	Eruption name	VEI	Eruption age [Ref]	Geochem data
					AD	
1	Pinatubo	Luzon		6	1991	[20–28]
2	Krakatau	Sumatra – Java		6	1883	[2,13,14,17]
3	Tambora	Banda		7	1815	[3,13,14,15]
4	Rinjani	Banda	Samalas	7	1257	[5,6,16,19]
					BP	
5	Pinatubo	Luzon	Maraunot	6	3000 ± 500 cal BP [34*]	[34]
6	Pinatubo	Luzon	Crow Valley	6	5500 ± 500 cal BP [34*]	[34]
7	Taal	Luzon	Taal scoria pyroclastic flow	6	6875 ± 859 [33*]	[33]
8	Pinatubo	Luzon	Pasbul	6	9410 ± 150 cal BP [34*]	[34]
9	Batur Caldera	Banda	Gunungkawi ignimbrite	6	24 380 ± 3072 cal BP [11*]	[4,12]
10	Masurai	Sumatra		?	32 768 ^{14}C BP [37]	[37]
11	Ranau	Sumatra	Ranau tuff	7	33 640 ± 190 cal BP [7]	[7]
12	Batur Caldera	Banda	Bali (or Ubud) ignimbrite	7	34 565 ± 3683 cal BP [11*]	[4]
13	Irosin Caldera – Bulusan	Luzon	Irosin ignimbrites	6	41 329 ± 169 cal BP [30]	[31,32]
14	Maninjau	Sumatra		7	52 ± 3 ka [8]	[8]
15	Toba	Sumatra	Young Toba tuff	8	73.7 ± 0.3 ka [38]	[9,10,13,18]
16	Pinatubo	Luzon	Inararo tuff/Tayawan caldera	6	81 ± 2 ka [29]	[29,34]
17	Tangkubanparahu	Java	Sunda caldera	6	105 ka [41]	no
18	Toba	Sumatra	Middle Toba tuff	7	502 ± 0.7 ka [38]	[9,10,18]
19	Toba	Sumatra	Old Toba tuff	8	792.4 ± 0.5 ka [38]	[9,10,18]
20	Toba	Sumatra	Haranggoal dacite tuff	6	1.2 ± 0.16 Ma [40]	[9]

original totals may or may not be mentioned. Sometimes individual matrix glass analyses are provided, often averages are reported instead, and in some cases matrix glass separates were analysed in bulk. Supplementary material is rare and the data for secondary standards is almost never provided. Given the limited number of studies (<30 publications for 19 eruptions), all data were incorporated in the database except when it was clearly flawed (e.g. severely affected by Na-loss, quartz instead of plagioclase analysis, etc.). No more than five data points were discarded and results from different studies generally overlap closely, which lends support to the reliability of the data. The compiled data are available in the Supplementary Material or from (https://doi.org/10.21979/N9/ZB2NY5).

Volcanic activity in Indonesia and the Philippines

The database contains information for 143 volcanoes in Indonesia, 45 of which have had eruptions with a VEI ≥ 3 and at least 10 have had large eruptions with a VEI of 6–8 (Table 1, Fig. 2). The database also contains information for 45 Quaternary volcanoes in the Philippines, 11 of which have had eruptions with a VEI ≥ 3 and at least three have had large eruptions of VEI 6–8 (Table 1, Fig. 3). The eruption record of small to moderate (VEI 1–4) eruptions greatly improves from ~1600 AD onwards, with fewer than 10 volcanoes in Indonesia and the Philippines having reported eruptions prior to then.

The Sumatran arc segment, including Krakatau volcano, is characterised by relatively rare volcanic activity but common violent eruptions with a VEI > 5 (e.g. from Krakatau, Maninjau and Ranau calderas), and the only VEI 8 eruptions from Southeast Asia (from the Toba caldera). Although these VEI 6–8 eruptions occurred only every few tens to hundreds of thousand years, their magnitude is such that their impact was surely global (e.g. Oppenheimer, 2003; Self, 2006; Costa *et al.*, 2014). Ash clouds spread over thousands of kilometres as far as India (e.g. Westgate *et al.*, 1998) and eastern Africa (Lane *et al.*, 2013) for the most violent, the young Toba tuff (YTT) eruption (Fig. 2, Table 2). Conversely, the Java arc segment is characterised by frequent VEI 3–5 eruptions (from Raung, Kelut, Galunggung and Merapi volcanoes) and rare eruptions with a VEI > 5. The Banda arc segment (from Bali to Timor Leste) is characterised by frequent VEI 1–3 eruptions and occasional VEI 5–7 eruptions, particularly during historic times (e.g. the 1257 Samalas eruption from Rinjani, the 1815 Tambora eruption and the 1963 Agung eruption). The dominant directions of ash cloud distribution are to the west and southwest (Figs 1 and 2). The Sulawesi (Sangihe) and Halmahera arc segments have been the locus of VEI 1–4 eruptions and host a couple of undated calderas. Meteorological observations suggest multiple directions of ash cloud distribution but most of the ash is transferred to the southwest and southeast, over more than 130 km (Fig. 2).

The geodynamic setting of the Philippines is complex with multiple arc segments and subduction zones rimming both the eastern and western sides of the country. For the sake of simplicity, volcanic activity can be divided geographically into three main subregions: Luzon in the north, Visayas in the central part, and Mindanao in the south. In Luzon, the most active and hazardous volcano is Mount Pinatubo, because it has erupted three or four times in the last 10 000 years with a VEI of 6 (Fig. 3). All other volcanoes in Luzon have occasionally erupted with a VEI of 4 (e.g. Laguna Caldera, Natib, Taal). In Visayas,

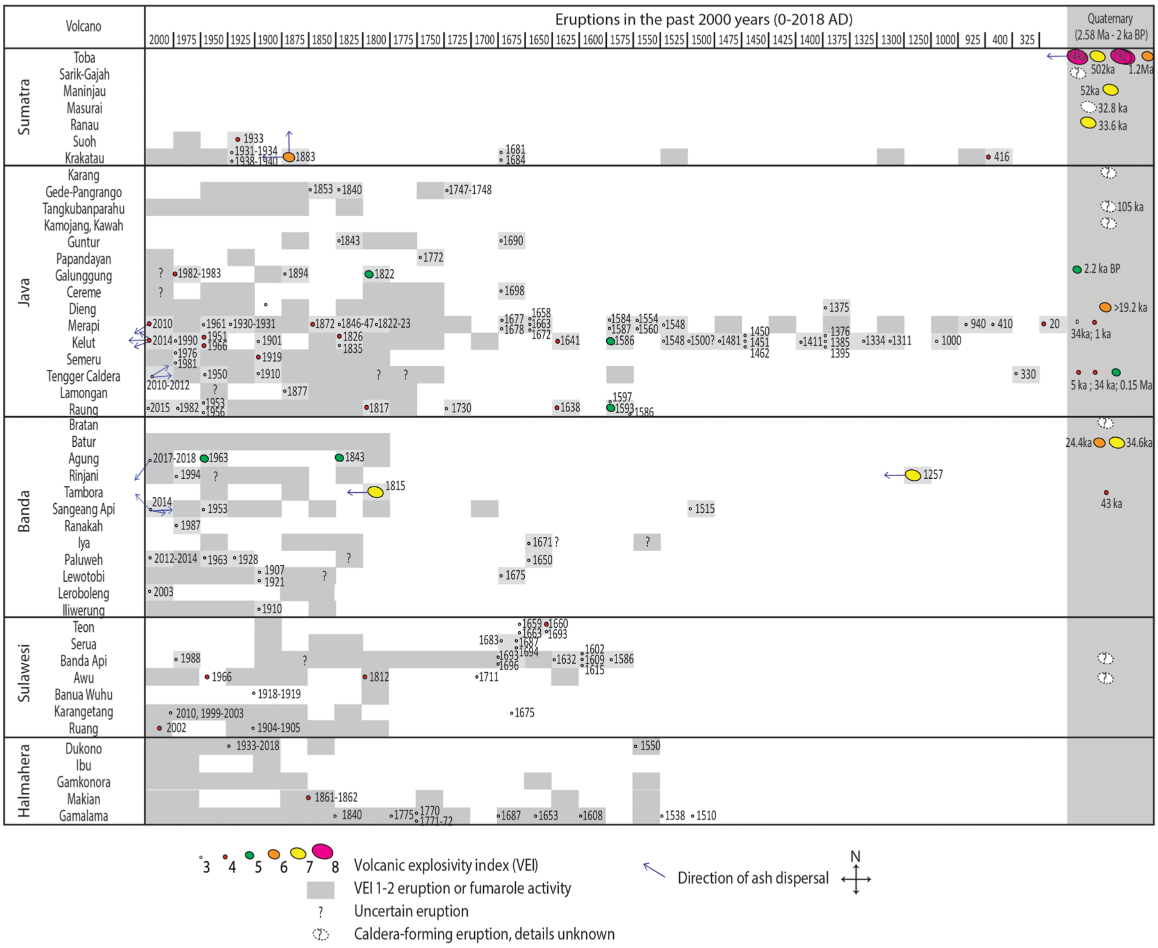

Figure 2. Summary of volcanic activity in Indonesia through time, with present day on the left. Grey shaded areas indicate periods of volcanic activity with a VEI<3. Black numbers refer to the eruption year of all eruptions with VEI≥3. Blue arrows indicate the direction of ash dispersal. A question mark symbol denotes a major eruption of unknown age, and a white dashed ellipse signifies a major eruption of unknown VEI. [Color figure can be viewed at wileyonlinelibrary.com]

there is only one record of a large caldera-forming eruption. It is from Bulusan volcano and produced the Irosin caldera during a VEI 7 eruption (41 cal ka BP; Mirabueno *et al.*, 2007). In Mindanao, Parker volcano erupted twice with a VEI 4 and once with a VEI 5, the Camiguin complex was active in 1948 with VEI 3 eruptions, and the Leonard Range has a caldera rim, but eruption details are unknown (Fig. 3). The dominant direction of ash cloud distribution is to the southwest, and tephra can be dispersed over distances greater than 2500 km (e.g. the Pinatubo eruption in 1991; Fig. 1), implying that tephra from volcanic sources in the Philippines can be found adjacent to Indonesian volcanoes.

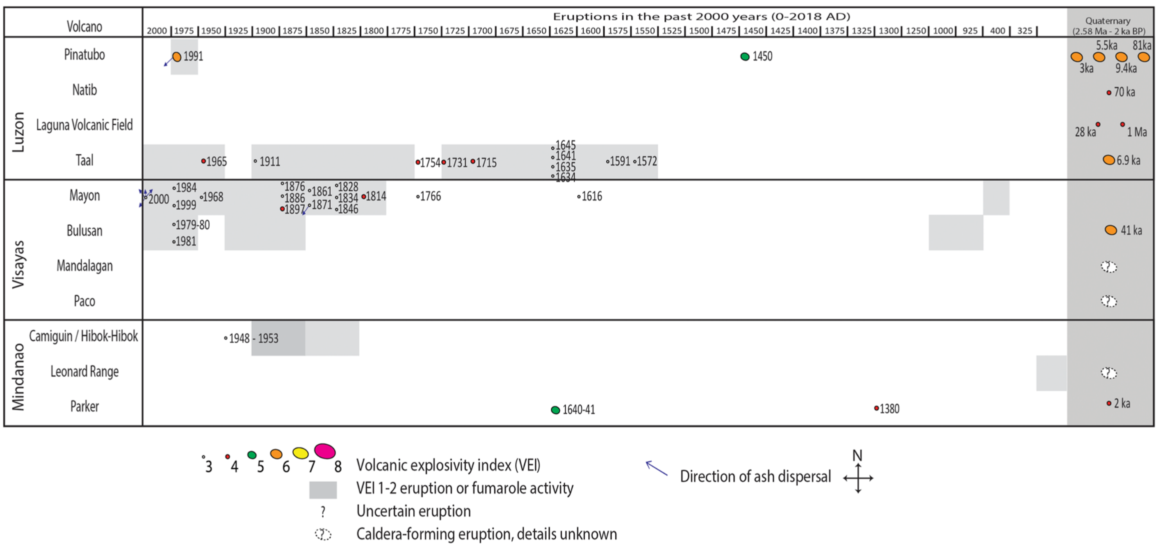

Figure 3. Summary of volcanic activity in the Philippines through time, with present day on the left. Grey shaded areas indicate periods of volcanic activity with a VEI<3. Black numbers refer to the eruption year of all eruptions with VEI≥3. Blue arrows indicate the direction of ash dispersal. A question mark symbol denotes a major eruption of unknown age, and a white dashed ellipse signifies a major eruption of unknown VEI. [Color figure can be viewed at wileyonlinelibrary.com]

Table 2. Mineralogical assemblage of VEI 6–8 eruptions in Indonesia and the Philippines. m = microlites (as defined by the source publication), i = inclusions, al = allanite, an = anhydrite, c = cummingtonite rims, unk = unknown. Same reference numbers as in Table 1.

Eruption	Plagioclase	Clinopyroxene	Orthopyroxene	Amphibole	Biotite	Sanidine	Quartz	Magnetite	Ilmenite	Olivine	Apatite	Zircon	Others	Ave Crystallinity	Ref.
Indonesia															
Krakatau 1883	x	x	x					x	x					5–15%	[2,17]
Tambora 1815	x	x			±	m		x		±	x			15–20%	[3,15]
Samalas 1257	x	±	x	x				x			x			5–15%	[16,19]
Batur – Gunungkawi	x	x						x	x	x	i			6–12 & 30–35%	[4]
Batur – Ubud	x	x	x	±				x	x	x	i			8–11%	[4,12]
Ranau	x				±			±	±					5%	[7,36]
Maninjau	x				x			x	x					unk	[6]
Young Toba tuff	x		±	x	x	x	x	x	x	±		x	al	≤40%	[9]
Middle Toba tuff	x		x	x	x	x	x	x	x	±		x	al	≤40%	[9]
Old Toba tuff	x		±	x	x	x	x	x	x			x	al	≤40%	[9]
Haranggoal dacite tuff	x	x	x					x	x					≤40%	[9]
Philippines															
Pinatubo 1991	x		±	xc	±		x	x	x		x		an	15–47%	[20]
Pinatubo – Maraunot	x			xc	±		±	?						unk	[35]
Pinatubo – Crow Valley	x			xc	±		±	?						unk	[35]
Bulusan – Irosin	x	±	±	xc	x		±	x			x			6–10%	[31]
Pinatubo – Inararo	x			xc	x		x	?						unk	[35]

Large, VEI 6–8, eruptions from Indonesia and the Philippines

Although Whelley *et al.* (2015) identified 41 large, >5 km diameter calderas in Southeast Asia, only a total of 20 VEI 6–8 eruptions have been dated to between 1.2 Ma and 1991 AD (Table 1). Thirteen of these were sourced from nine volcanoes in Indonesia; another seven from three volcanoes in the Philippines (seven eruptions). Nineteen eruptions have whole-rock compositions but only 14 have glass geochemical data that can be used for tephrostratigraphic correlations, and these are presented by source region (arc segment; Fig. 1). The Sumatran arc segment hosts: (1) Toba caldera in the north, which produced the 1.2 ± 0.16 Ma Haranggoal dacite tuff (HDT; Nishimura *et al.*, 1977; Chesner *et al.*, 1991), the 792.4 ± 0.5 ka old Toba tuff (OTT), the 502 ± 0.7 ka middle Toba tuff (MTT), and the 73.7 ± 0.3 ka YTT (Mark *et al.*, 2017); (2) Maninjau caldera in West Sumatra, which formed at 52 ± 3 ka (Alloway *et al.*, 2004); (3) Masurai caldera in Jambi, which formed at 32.768 ^{14}C ka BP (Rohiman *et al.*, 2019); (4) Ranau caldera in the south, which formed at 33.64 ± 0.19 cal ka BP (Natawidjaja *et al.*, 2017); and (5) Krakatau caldera in the straits between Sumatra and Java, which is the source of the famous 1883 AD caldera-forming eruption (Self, 2006). The Banda arc segment hosts: (1) Batur caldera on the island of Bali, which produced the 29.3 ^{14}C ka BP (34.56 ± 3.68 cal ka BP; VOGRIPA) Ubud ignimbrite and the 20.15 ± 0.71 ^{14}C ka BP (24.38 ± 3.07 cal ka BP; VOGRIPA) Gunungkawi ignimbrite (Reubi and Nicholls, 2005; Sutawidjaja, 2009); (2) Samalas caldera on Lombok island, which formed in 1257 AD on the flank of Rinjani volcano (Lavigne *et al.*, 2013); and (3) Tambora caldera on West Nusa Tenggara island, which is the source of the famous 1815 AD eruption followed by the year without a summer (Oppenheimer, 2003). The only three calderas in the Philippines with some published geochemical data are: (1) the Irosin caldera, which formed 41.329 ± 0.169 cal ka BP and in which Bulusan volcano has grown since (Mirabueno *et al.*, 2011); (2) the Taal caldera, which is thought to have produced four caldera-forming eruptions (the silicic Alitagtag and Caloocan Pumice Flow deposits, the dacitic Sambong Ignimbrite, and the 6.875 ± 0.859 ^{14}C ka BP basaltic-andesitic Taal Scoria Pyroclastic Flow; Delos Reyes *et al.*, 2018); and (3) the Pinatubo caldera, which is the source of the 81 ± 2 ka Inararo tuff (Ku *et al.*, 2008), the 9.41 ± 0.15 cal ka BP Pasbul, the 5.5 ± 0.5 cal ka BP Crow Valley and the 3 ± 0.5 cal ka BP Maraunot eruptions, and the recent 1991 AD eruption (Newhall *et al.*, 1996; VOGRIPA).

Glass trace element data are rare; only available for the young, middle, and old Toba tuffs, the 1257 Samalas, and the 1883 Krakatau eruptions. Whole-rock trace element data is reported instead, as a possible proxy for the glass. Below we review the geochemical and mineralogical characteristics of the ignimbrites produced during these VEI 6–8 eruptions, with the goal of defining distinguishing features that can enable their successful fingerprinting and thus their use as tephrochronologic markers.

Geochemical characteristics of VEI 6–8 eruptions

Volcanic products from different arc segments have different geochemical characteristics in terms of whole-rock (Fig. 4) and matrix glass (Fig. 5) major element compositions. Sumatran ignimbrites are relatively K_2O-rich and Na_2O-poor, calc-alkaline dacites to rhyolites, with mostly high-silica

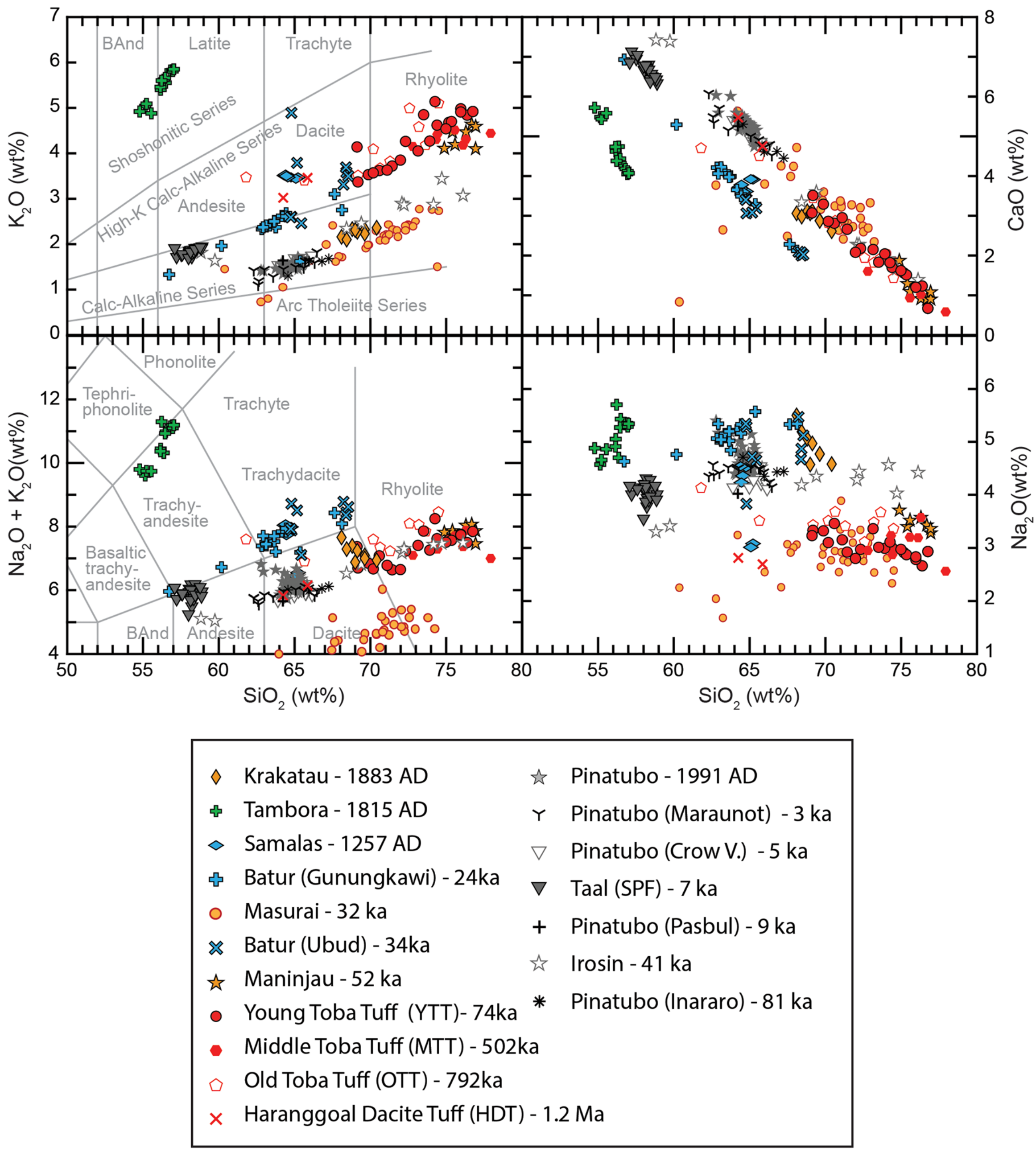

Figure 4. Whole-rock major element variation diagrams for VEI 6–8 eruptions in Indonesia and the Philippines. 'BAnd' stands for Basaltic-Andesite. Data from [2] (Mandeville *et al.*, 1996), [3] (Foden, 1986), [4] (Reubi and Nicholls, 2005), [5] (Vidal *et al.*, 2015), [9] (Chesner, 1998), [10] (Chesner and Luhr, 2010), [12] (Wheller and Varne, 1986), [13] (Turner and Foden, 2001), [15] (Gertisser *et al.*, 2012), [19] (Vidal *et al.*, 2016), [20] (Pallister *et al.*, 1996), [22] (Luhr and Melson, 1996), [23] (Bernard *et al.*, 1996), [24] (Castillo and Punongbayan, 1996), [25] (Fournelle *et al.*, 1996), [32] (Delfin *et al.*, 1993), [33] (Martinez and Williams, 1999), [37] (Rohiman *et al.*, 2019). [Color figure can be viewed at wileyonlinelibrary.com]

rhyolitic matrix glass. The ignimbrite from the 1883 eruption of Krakatau has lower K_2O and higher Na_2O than Sumatran ignimbrites in addition to being slightly less evolved (rhyodacitic). The Masurai ignimbrite also appears to be less evolved and has particularly low K_2O (Fig. 4). However, these data need to be treated with care as the methods or errors are not reported by Rohiman *et al.* (2019), and it is not a peer-reviewed article. Ignimbrites from the Banda arc are generally less evolved, having dacitic whole-rock and matrix glass compositions, high K_2O content, and higher Na_2O content than Sumatran products. The ignimbrite from the 1815 Tambora eruption is very distinct from all other ignimbrites, due to very high K_2O content and high Na_2O content inherited from the volcano's back-arc setting (Foden, 1986). Ignimbrites in the Philippines show a range from andesite to rhyolite, with rhyolitic to high-silica rhyolitic matrix glass. They generally have higher Na_2O and lower K_2O than Sumatran ignimbrites, except for the Taal Scoria Pyroclastic Flow.

Within arc segments it is more challenging yet still feasible to differentiate the products from different source volcanoes using major elements only. In Sumatra, the K_2O content of ignimbrites increases northwards, reflecting gradual changes in subduction parameters (e.g. depth to slab, crustal thickness, incoming crust and sediments; Whitford, 1975; Gasparon and Varne, 1998; Syracuse and Abers, 2006) and enabling the products to be distinguished from Ranau, Maninjau and Toba (Fig. 5). In the Banda arc, products from Batur and Rinjani (Samalas) are very similar but can be distinguished on a plot of K_2O versus CaO, with a steeper trend of decreasing K_2O with increasing CaO for Samalas than for the Batur ignimbrites. In the Philippines, the Irosin ignimbrite from Bulusan volcano has higher K_2O and slightly lower CaO content than the

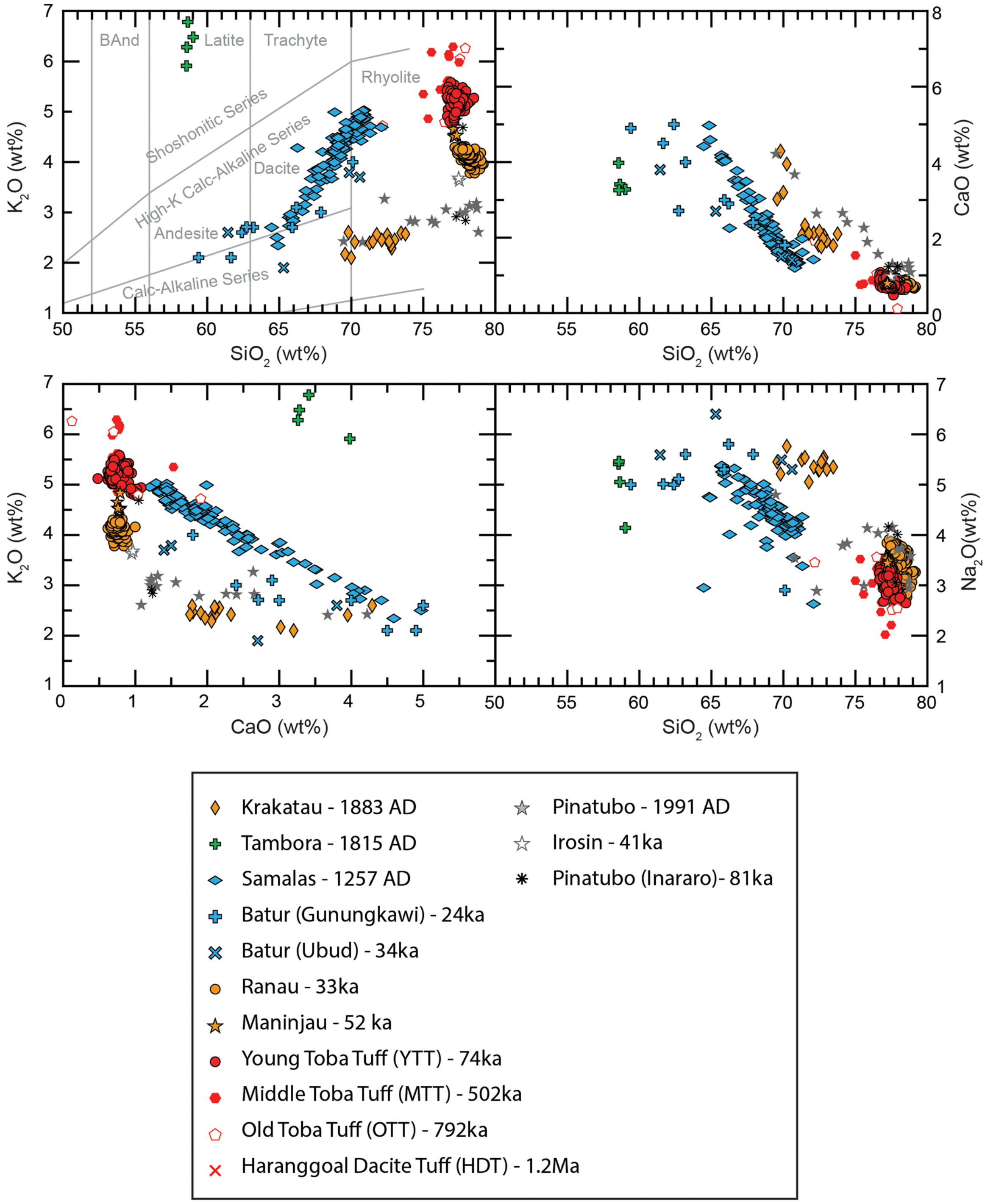

Figure 5. Matrix glass major element variation diagrams for VEI 6–8 eruptions in Indonesia and the Philippines. 'BAnd' stands for Basaltic-Andesite. Data from [2] (Mandeville *et al.*, 1996), [3] (Foden, 1986), [4] (Reubi and Nicholls, 2005), [5] (Vidal *et al.*, 2015), [6] (Alloway *et al.*, 2017), [7] (Natawidjaja *et al.*, 2017), [8] (Alloway *et al.*, 2004), [9] (Chesner, 1998), [10] (Chesner and Luhr, 2010), [14] (Devine *et al.*, 1984), [15] (Gertisser *et al.*, 2012), [17] (Camus *et al.*, 1987), [18] (Smith *et al.*, 2011), [19] (Vidal *et al.*, 2016), [20] (Pallister *et al.*, 1996), [21] (Rutherford and Devine, 1996), [22] (Luhr and Melson, 1996), [25] (Fournelle *et al.*, 1996), [27] (Hammer *et al.*, 1999), [29] (Ku *et al.*, 2008), [31] (Mirabueno *et al.*, 2011). [Color figure can be viewed at wileyonlinelibrary.com]

ignimbrites from Pinatubo, but more data would be needed to ascertain the trend.

Trace elements may be more effective to differentiate between eruption sources. However, matrix glass trace element data are less routinely acquired and thus data are currently only available for the ignimbrites of Krakatau, Samalas and Toba (YTT, MTT and OTT). Whole-rock trace element compositions may serve as proxies for matrix glass trace element compositions, if the crystallinity of the ignimbrite is low. Fig. 6 shows relatively similar overlapping trace element compositions and ratios for matrix glass and whole-rocks, and thus provides a preliminary means of assessing the trace element characteristics of ignimbrites from Indonesia and the Philippines. The Irosin, Pinatubo and Tambora ignimbrites have an adakitic signature with much higher Sr/Y ratios and Al_2O_3 contents than all other ignimbrites. Salisbury *et al.* (2012) found that tephra layers from Indian Ocean cores were best discriminated and correlated using a plot of Zr/Y versus La/Th. The same plot also appears efficient at discriminating the various Indonesian and Philippine ignimbrites of this compilation. A plot of Pb versus Nb/Ta seems equally efficient. Nb and Ta behave in a very similar way in magmas, with

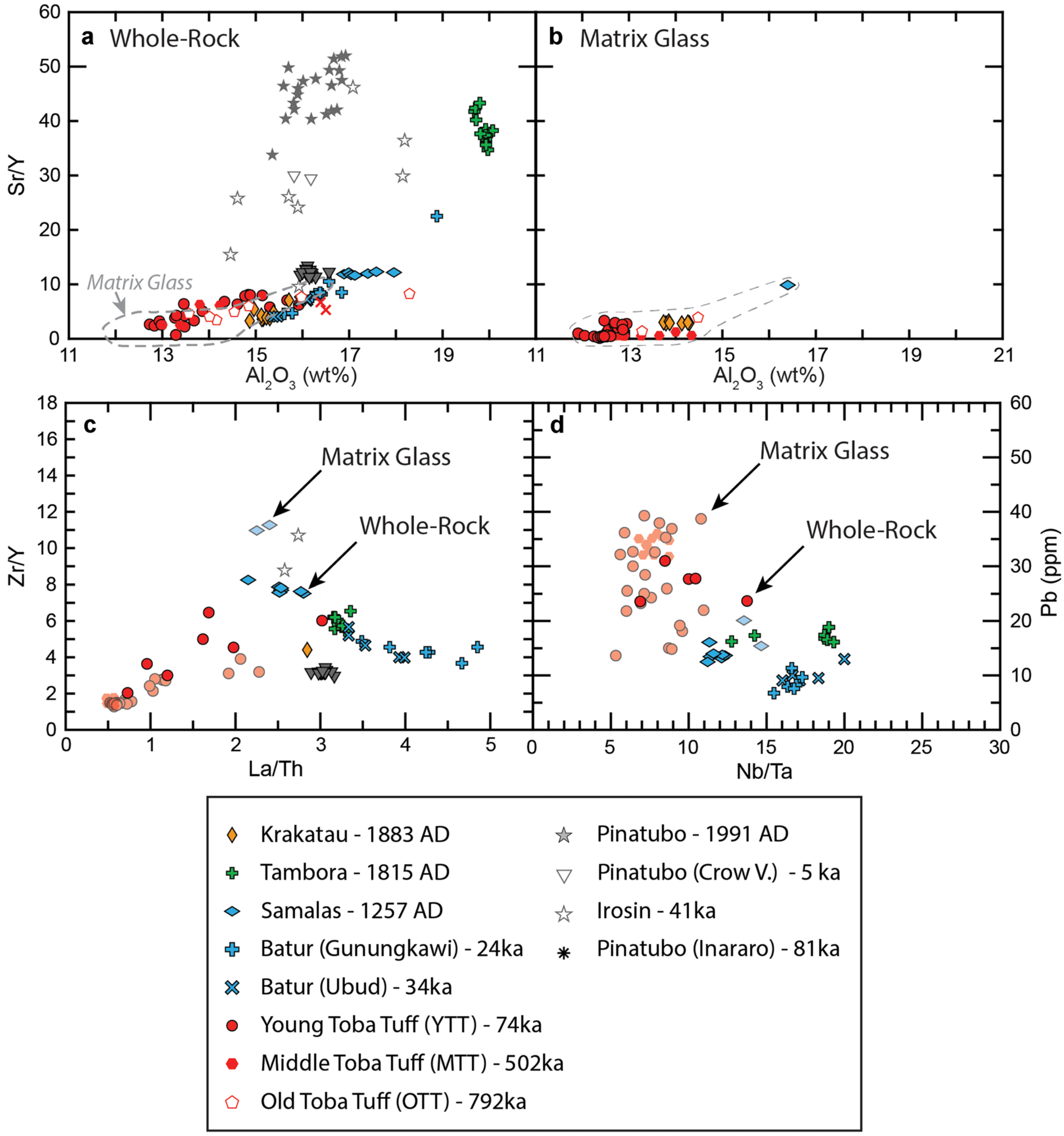

Figure 6. Whole-rock and matrix glass trace element variation diagrams for VEI 6-8 eruptions in Indonesia and the Philippines. The dashed outline in (a) refers to the range in matrix glass compositions as seen in (b). In (c) and (d) matrix glass compositions are shown in pale colours for comparison with whole-rock compositions in bright colours. Data from [2] (Mandeville *et al.*, 1996), [3] (Foden, 1986), [4] (Reubi and Nicholls, 2005), [5] (Vidal *et al.*, 2015), [9] (Chesner, 1998), [10] (Chesner and Luhr, 2010), [12] (Wheller and Varne, 1986), [13] (Turner and Foden, 2001), [15] (Gertisser *et al.*, 2012), [16] (Métrich *et al.*, 2017), [18] (Smith *et al.*, 2011), [19] (Vidal *et al.*, 2016), [23] (Bernard *et al.*, 1996), [32] (Delfin *et al.*, 1993), [33] (Martinez and Williams, 1999). [Color figure can be viewed at wileyonlinelibrary.com]

partition coefficients that are of the same order of magnitude (GERM; https://earthref.org/KDD/). This implies that a ratio of Nb/Ta is unlikely to vary by one or more orders of magnitude between the whole-rock and the matrix glass. Pb has partition coefficients of 0.2–1 for most minerals, including accessory minerals like zircons (GERM database), which suggests that it is also unlikely to fractionate much between the minerals and the glass. Such a plot of Nb/Ta versus Pb might therefore provide a bridge between whole-rock and matrix glass compositions. The absence of trace element data for most VEI 6–8 eruptions in Southeast Asia is obviously a major shortcoming for robust correlations with distal tephra layers.

The main challenge, whether trace element geochemistry is available or not, resides in discriminating between ignimbrites from the same source when no external age constraint is available. The Gunugkawi and Ubud ignimbrites from Batur, the YTT, OTT, and MTT from Toba, and the 1991 and Inararo ignimbrites from Pinatubo are consistently overlapping on all whole-rock and matrix glass major and trace element plots. In light of this, Smith *et al.* (2011) showed the potential of biotite compositions to discriminate between YTT and MTT or OTT (Fig. 7(g), (h)). In fact, mineralogy and mineral compositions in general may be very efficient at fingerprinting ignimbrites (e.g. Fierstein, 2007; Rawson *et al.*, 2015).

Mineralogical characteristics of VEI 6–8 eruptions

The mineralogy and crystallinity of ignimbrites from Indonesia and the Philippines is summarised in Table 2. All units contain plagioclase but in addition, the Toba tuffs contain sanidine, the Tambora ignimbrite contains microlites of alkali feldspar (Foden, 1986), and the Samalas ignimbrite contains anortho-

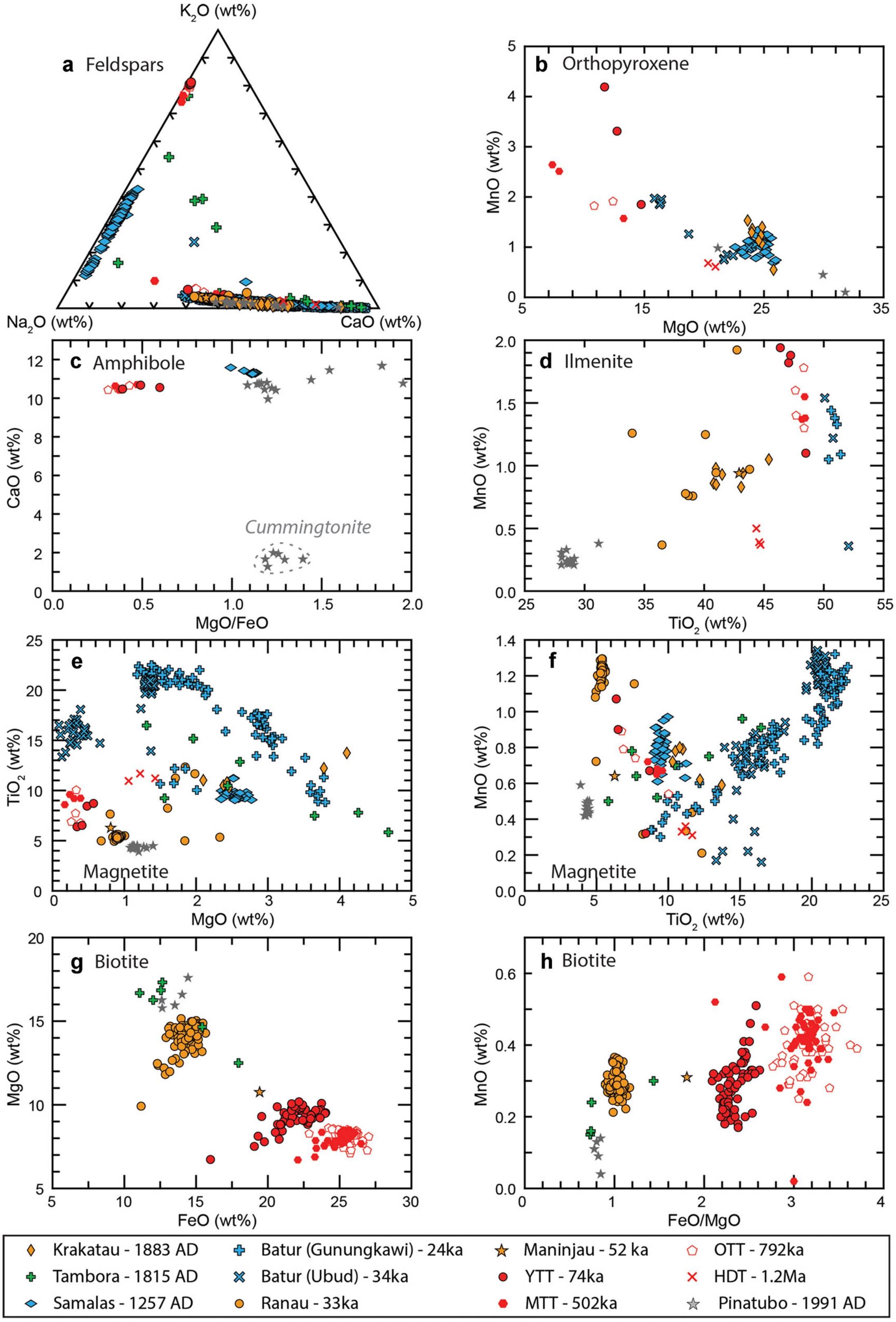

Figure 7. Mineral compositions of VEI 6–8 eruptions in Indonesia and the Philippines. Data from [2] (Mandeville *et al.*, 1996), [3] (Foden, 1986), [4] (Reubi and Nicholls, 2005), [7] (Natawidjaja *et al.*, 2017), [8] (Alloway *et al.*, 2004), [9] (Westgate *et al.*, 1998), [12] (Wheller and Varne, 1986), [15] (Gertisser *et al.*, 2012), [16] (Métrich *et al.*, 2017), [17] (Camus *et al.*, 1987), [18] (Smith *et al.*, 2011), [19] (Vidal *et al.*, 2016), [20] (Pallister *et al.*, 1996), [21] (Rutherford and Devine, 1996), [22] (Luhr and Melson, 1996), [23] (Bernard *et al.*, 1996), [25] (Fournelle *et al.*, 1996), [26] (Imai *et al.*, 1993), [28] (Borisova *et al.*, 2005), [29] (Ku *et al.*, 2008). [Color figure can be viewed at wileyonlinelibrary.com]

clase (Fig. 7a). Amphibole and biotite are found in all rhyolites, while amphibole with cummingtonite rims is characteristic of ignimbrites in the Philippines. Clinopyroxene is more typical of the dacites, and orthopyroxene is occasionally present in rhyolites or dacites. Ilmenite is found in all products except the Tambora and Samalas ignimbrites, while magnetite is ubiquitous.

In addition to biotite, orthopyroxene, amphibole and ilmenite compositions appear useful for discriminating eruption sources (Fig. 7(c), (d), (e), (f)) and sometimes individual deposits from a same source (e.g. YTT versus MTT or OTT are distinguishable from MnO content in orthopyroxene; Fig. 7(b)). Interestingly, MgO and TiO_2 content in magnetite appears efficient at differentiating between the Gunungkawi and Ubud ignimbrites, which are otherwise extremely similar. YTT and MTT or OTT are also distinguishable with slightly higher MgO and lower TiO_2 content for YTT magnetites, although a larger dataset would be required to confirm this. MTT and OTT appear to be distinguishable only based on the Fluorine content of biotites (Fig. 4b of Smith *et al.*, 2011). The main drawback of using mineralogy or mineral compositions to identify the source of distal tephra layers could be the lack of phenocrysts, as they sediment earlier or closer to the source given their greater density compared with glass shards (Bitschene and Schmincke, 1990; Ku *et al.*, 2009a). However, magnetites and ilmenites are often small and present in the groundmass making them highly valuable, in association with matrix glass major and trace element geochemistry, for identifying the source volcano and eruption. Fierstein (2007) and Rawson *et al.* (2015) have successfully used Fe-Ti oxides to fingerprint tephra deposits in Alaska and Chile, respectively, confirming their usefulness.

Correlating known VEI 6–8 eruptions with distal tephra layers

Salisbury *et al.* (2012) identified six visible tephra layers in marine cores collected from the trench off the coast of West Sumatra (Fig. 8). Layer V2 was attributed to the YTT and indeed overlaps in both major and trace element compositions with all the proximal data available for the YTT (Fig. 9(a), (b)). Layer V6 was attributed to the 33.640 ± 0.19 cal ka BP Ranau caldera by Natawidjaja *et al.* (2017) based on proximity, similar ages, and matching matrix glass major element geochemistry (Fig. 9(a)). Layers V4 and V5 seem to overlap with the Batur ignimbrites (24 ka and 34 ka), and layer V1 with the Samalas ignimbrite (1257 AD) on a plot of K_2O vs CaO, but not on trace element plots (Fig. 9(a)–(b)). The ages for these layers (1930 ± 190 y BP, 5470 ± 140 y BP, and $30\,940 \pm 280$ y BP for V4, V5 and V1, respectively, obtained from sedimentation rates and radiocarbon dating of sediments) also do not coincide. Layer V1 could correlate in time with the eruption from the Masurai caldera (32 768 ^{14}C BP; Rohiman *et al.*, 2019), but the whole-rock composition of this ignimbrite has very low K_2O (Fig. 4) unlike the glass of V1. Lastly, layer V3 (60–65% SiO_2, 13 610 y BP) has no temporal or geochemical correlative in the present database of proximal deposits. This implies that the sources of the young but distal layers V1 and V3–V5 are still unknown despite having produced relatively substantial eruptions (VEI $\geq$ 5; Salisbury *et al.*, 2012). It also implies that four caldera-forming eruptions occurred within a time span of ~4 ky between 31 and 35 ka BP, from the Batur, Ranau and Masurai calderas and the source of V1 (Fig. 8).

Deep sea drilling projects (DSDP) and ocean drilling projects (ODP) have obtained long cores from the Indian Ocean, mainly at the northern and southern ends of Sumatra (Fig. 8) that were studied for their tephra record (Ninkovich, 1979; Dehn *et al.*, 1991). Geochemical and geochronological data were obtained for 20 tephra layers across seven cores (Ninkovich, 1979) and 13 tephra layers in the ODP core from site 758 (Dehn *et al.*, 1991) (Fig. 8). Ages were constrained from a combination of direct K/Ar dating of the tephra and chronostratigraphy provided by the palaeomagnetic reversal record and the $\delta^{18}O$ record of the cores. Comparison of these ages with recent age determinations for proximal Toba deposits suggests an accuracy of approximately 5%. Layers A and B were attributed to the YTT (B being a reworked version of A), layer C was attributed to the MTT, layers D and d were attributed to two distinct OTT eruptions 6000 years apart (Mark *et al.*, 2017), and layer F was attributed to the HDT (Dehn *et al.*, 1991). The geochemistry of all these layers closely overlaps with that of proximal Toba tuffs (Fig. 9(e)–(f)), with slight deviations for layers F and C. Layer F has slightly higher FeO* (total iron as FeO) than most Toba tuffs (Fig. 9(f)), but no proximal HDT matrix glass data are available for comparison. Layer C has overlapping but slightly lower CaO and higher FeO* than that which has been reported for MTT and most Toba tuffs (Fig. 9(e)–(f)). The ~75 ka tephra layer in RC14-37 was attributed to YTT by Ninkovich (1979), and is similar in age to the second layer in V19-153, which is even more similar in composition to YTT (Figs 8 and 9(e)–(f); labelled "YTT"). It must be noted that all the data by Ninkovich (1979) seem to be biased toward lower SiO_2 content. The first and second tephra layers in DSDP (XXII) core 216 correlate in age and composition with MTT and OTT (Figs 8 and 9(e)–(f); labelled "MTT" and "OTT"). Interestingly, layer G (~1.6 Ma) in core ODP-758 is very similar in composition to all other Toba products (Fig. 9(e)–(f)) and to two layers of similar age in the DSDP cores from site 218 in the north (~1.7 Ma, analysis 11; Ninkovich, 1979) and 211 in the south (~1.5 Ma, analysis 16; Ninkovich, 1979) (Figs 8 and 9(e)–(f); labelled "G"). Layer h (~3.6 Ma) is also very similar in composition to the Toba products and to the third tephra layer in DSDP-216 (Figs 8 and 9(e)–(f), labelled "h"). If these correlations are true, it would imply that a fifth major Toba eruption would have occurred approximately 400 000 years before the HDT, expanding the 400 ka cyclic activity that had been previously recognised (Dehn *et al.*, 1991), and that this caldera has been the source of large caldera-forming eruptions for a very long time (at least 3.6 Ma).

All remaining tephra layers from ODP core 758 – except for layer E – have a distinct geochemical composition from the studied proximal deposits (Fig. 9(c)–(d)), and are significantly older (>2.2 Ma). Layer E (~800 ka) was previously attributed to the OTT (Dehn *et al.*, 1991) but has lower K_2O, slightly lower SiO_2, and higher FeO* (Fig. 9(c)–(f)). It overlaps geochemically with most of the tephra layers described in the V19-153 core collected south of Sumatra (Ninkovich, 1979), and is similar in composition to the Ranau tuff although with lower SiO_2. In particular, it correlates in time (and composition) with layers 7 or 8 in core V19-153 (Figs 8 and 9(e)–(f); labelled "E"). Such similarities suggest that the source of layer E is most likely from the southern end of Sumatra, and could be the same as the widespread Lampong or Pasomah tuffs discussed by Ninkovich (1979). Layer E is only 34 cm beneath layer d, making it ~14 ky older than layer d and ~20 ky older than layer D (Dehn *et al.*, 1991). This implies that over a short period of ~20–25 ky, three major caldera-forming eruptions occurred in Sumatra, centred around the time of the Australasian impact (e.g. Lee *et al.*, 2004) and slightly preceding the Matuyama–Brunhes magnetic reversal (e.g. Mark *et al.*, 2017); a period of intense geological activity.

Very few to no tephra layers younger than the YTT (75 ka) were retrieved from deep-sea cores in the Indian Ocean. As such, there is no distal correlative of the Maninjau or Ranau ignimbrites (other than layer V6 of Salisbury *et al.*, 2012). Only the V19-150 and V19-151 cores collected south of Sumatra contain "Krakatau-like" tephra layers (Figs 8 and 9(a)) dated at 60 ka and "recent", respectively (Ninkovich 1979).

Tephra in marine cores around the Philippines were studied to reconstruct the long-term volcanic and geodynamic activity of various arc segments (Desprairies *et al.*, 1991; Pouclet *et al.*, 1991; Ku *et al.*, 2009a, b). In the Celebes Sea, 49 tephra layers

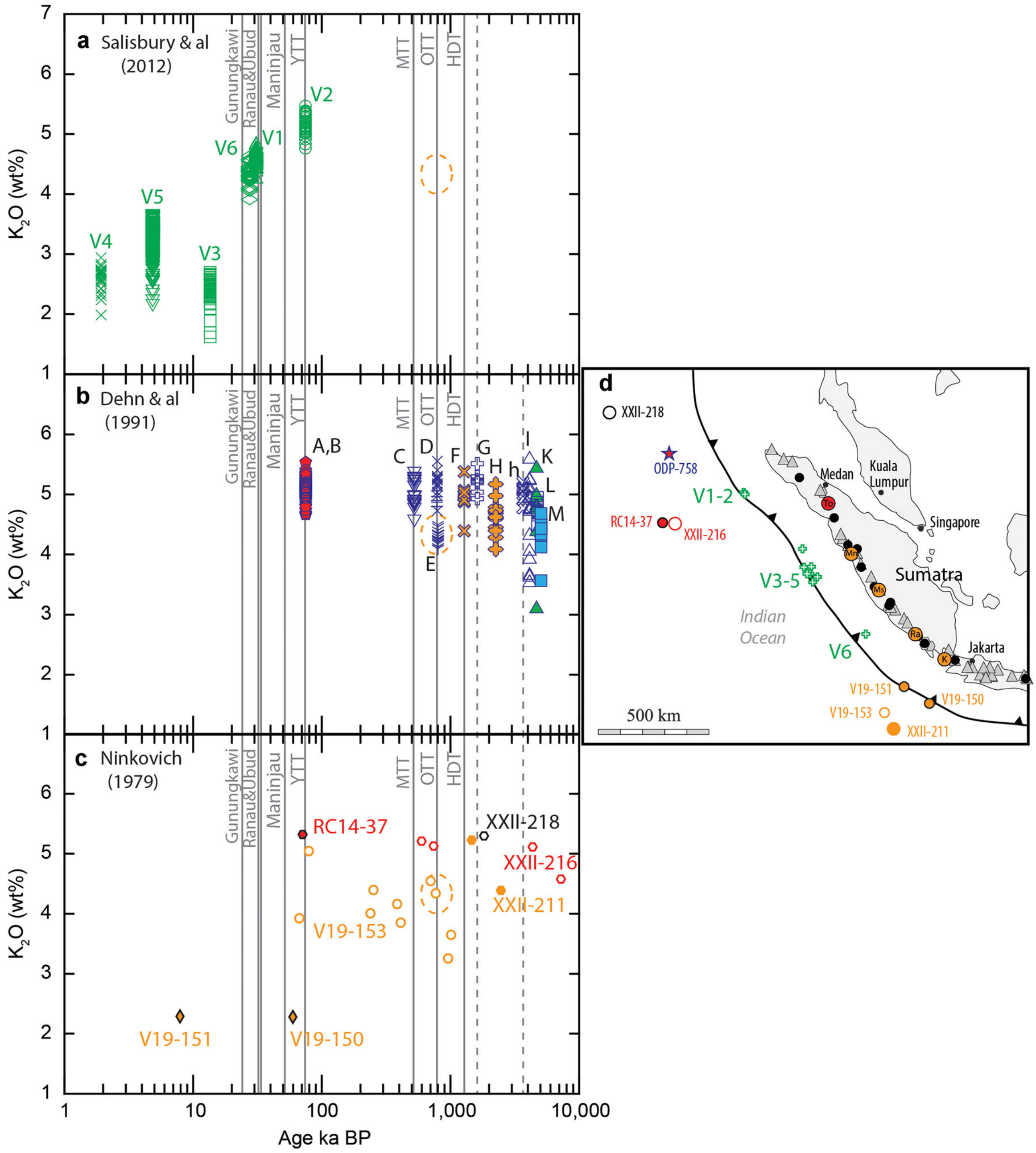

Figure 8. Temporal distribution of tephra layers in marine cores (symbols) versus known ages of Sumatran calderas (vertical lines). Approx. 800 ka there likely was a large eruption from South Sumatra (dashed orange ellipse) shortly prior to the possible double eruption of Toba caldera (OTTA and OTTB; Mark *et al.*, 2017). At ca. 1.6 Ma and 3.6 Ma (vertical dashed lines) there may have been previously unidentified eruptions from Toba caldera, given the coincidence of tephra layers with a Toba-like geochemical signature in cores ODP-758, XXII-218, 216, and 211. Most marine tephra layers, however, are still lacking knowledge of a source. [Color figure can be viewed at wileyonlinelibrary.com]

younger than 338 ka were found in core MD01-2387 (Fig. 1), and they are believed to have sources in Mindanao, Sangihe and Halmahera principally (Ku *et al.*, 2009a). In the Celebes and Sulu seas, 32 tephra layers of age Pleistocene to present in cores ODP- 767, 768, 769 and 770 were studied by Pouclet *et al.* (1991) and another 44 tephra layers were studied by Desprairies *et al.* (1991) and their sources are believed to be in Mindanao and Visayas (Negros) mainly. Around Luzon, 22 tephra layers younger than 870 ka (19 younger than 478 ka) were found in core MD97-2142 and 10 tephra layers younger than 2.14 Ma were found in core MD97-2143 (Ku *et al.*, 2009b). They are thought to originate from the Macolod corridor, which hosts the Taal and Laguna de Bay calderas, as well as from arc segments to the northwest and southeast (Bataan segment and Bicol arc; Ku *et al.*, 2009b). For all these layers, glass compositions range from andesitic to rhyolitic, along the calc-alkaline to shoshonitic series (Fig. 9(g)–(h)). Only the Inararo tuff from Mount Pinatubo was reliably correlated with a marine tephra layer (layer D in core MD97-2142, Fig. 9(g)–(h) labelled "D"; Ku *et al.*, 2008). No other layer was assigned to a specific eruption or source, nor correlated with other marine tephra layers. Layer A in core MD97-2142 is dated at 6 ± 2 ka and has a similar composition to the Taal Scoria Pyroclastic Flow (SPF) (Fig. 9(g)–(h), labelled "A"; Ku *et al.*, 2009b), but as there are no matrix glass compositional data for the Taal SPF this correlation needs to be verified. Two tephra layers dated at 301 ± 2 ka in MD97-2143 and 305 ± 2 ka in MD97-2142 (Ku *et al.*, 2009b) are quite thick (9 and 6 cm, respectively) and share rather similar average glass compositions (Fig. 9(g)–(h), labelled "M,4"). If they are indeed from the same eruption, the Laguna de Bay could be a potential source given its large size, central position

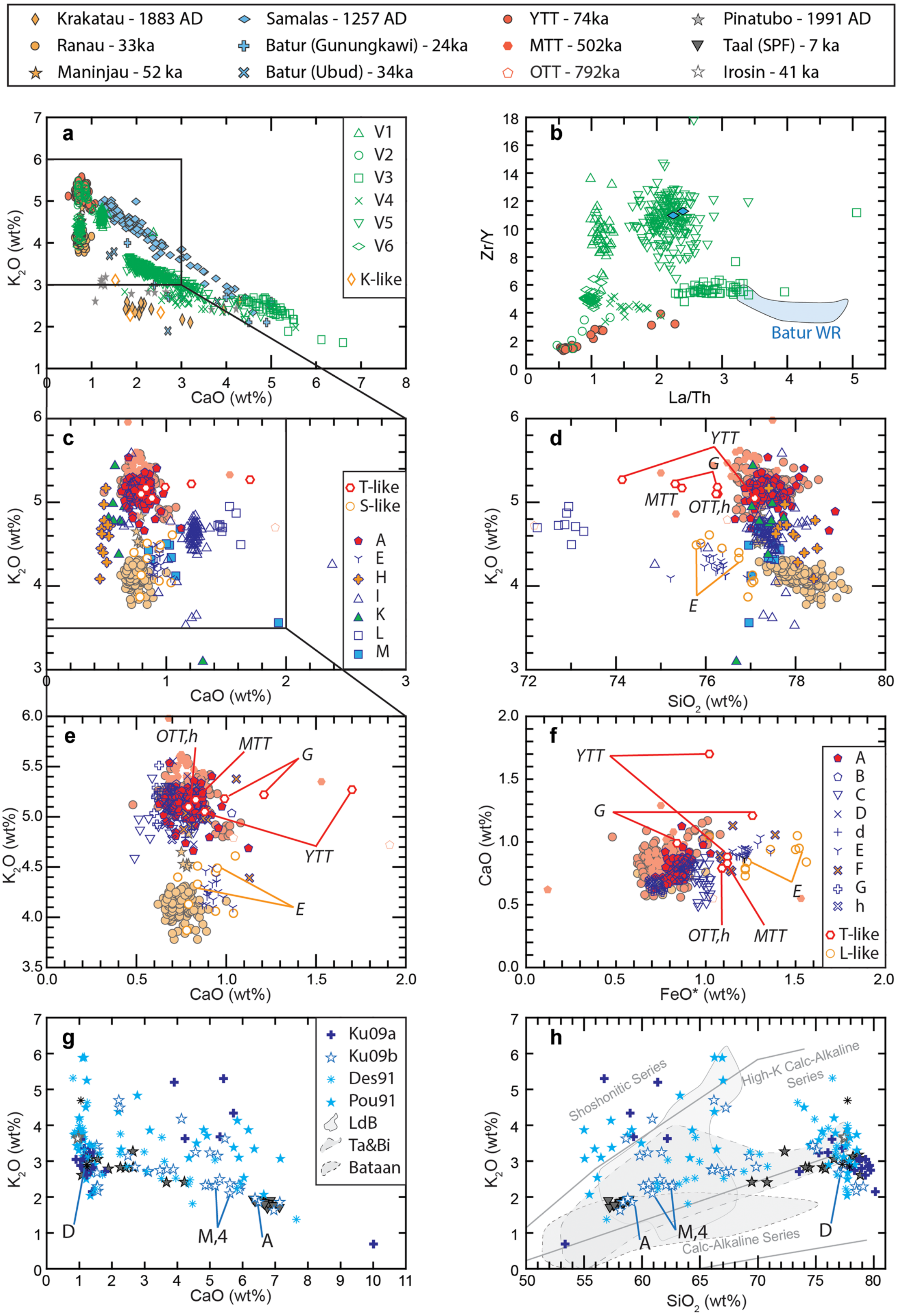

Figure 9. Comparison of distal tephra layers from marine cores collected in the Indian Ocean and around the Philippines (location shown in Fig. 1) with proximal data available for VEI 6–8 eruptions in Indonesia and the Philippines. (a–b) Green open symbols are V1–6 tephra layers studied by Salisbury *et al.* (2012), orange-outlined diamonds are Krakatau-like ("K-like") layers studied by Ninkovich (1979), and other symbols are matrix glass compositions of proximal deposits as in Figs 5 and 6. The whole-rock trace element compositions of Batur ignimbrites is shown with the blue shaded area for comparison. (c–d) Comparison of selected marine tephra layers (Ninkovich, 1979; Dehn *et al.*, 1991) with proximal glass compositions for Toba, Maninjau and Ranau. "T-like" and "S-like" stand for Toba-like and South Sumatra-like tephra layers studied by Ninkovich (1979). (e–f) Comparison of Toba-like marine tephra layers with ODP-758 layer E and South Sumatra-like tephra layers. Lines labelled "YTT", "MTT", "OTT,h", "E", and "G" are potential correlations between tephra layers in core ODP-758 and the cores studied by Ninkovich (1979). (g–h) Blue symbols are average compositions of individual marine tephra layers in cores from around the Philippines, studied by Ku *et al.* (2009a, 2009b), Desprairies *et al.* (1991) and Pouclet *et al.* (1991) abbreviated in the legend as "Ku09a", "Ku09b", "Des91" and "Pou91" respectively. Grey symbols are proximal matrix glass compositions, and the whole-rock compositions of Taal for comparison (symbols as in Figs 4 and 5). Grey shaded areas are proximal deposit compositions for Laguna de Bay ("LdB"), Taal and the Bicol arc ("Ta&Bi"), and the Bataan segment ("Bataan"), as compiled by Ku *et al.* (2009b). Lines labelled "A", "D", and "M,4" indicate a potential correlation of the Taal SPF with layer MD97-2142-A, the confirmed correlation of layer MD97-2142-D with the Inararo tuff from Pinatubo (Ku *et al.*, 2008), and the potential correlation of layers MD97-2142-M and MD97-2143-4 with each other. [Color figure can be viewed at wileyonlinelibrary.com]

between these two cores, and similar deposit compositions as compiled by Ku *et al.* (2009b). Given the large number of marine tephra layers described and the paucity of on-land correlatives, knowledge of the explosive volcanic history of the Philippines could be greatly improved.

Defining tephrochronologic markers for Southeast Asia

The Toba tuffs are numerous (four or maybe even five over the past 1.6 Ma) and have a narrow compositional range that has been well characterised. If they can be distinguished from each other geochemically or through external age constraints, they obviously provide excellent tephrochronologic markers. They are extremely widespread (the YTT has been identified in Lake Malawi, East Africa (Lane *et al.*, 2013) and in the South China Sea (Lee *et al.*, 2004; Liu *et al.*, 2006)) and thus offer the possibility of synchronising various sedimentary records over a large spatial scale.

The Maninjau and Ranau tuffs are also relatively voluminous and have a narrow compositional range that can be distinguished amongst the Sumatran ignimbrites. They have not been recognised in the distal record but this may be due to their only recent geochemical and geochronological characterisation (Alloway *et al.*, 2004; Natawidjaja *et al.*, 2017). We thus expect these tephra layers to become valuable tephrochronologic markers in future studies.

The eruptions from the Banda arc are slightly less voluminous and generally have a wide range in matrix glass composition. Except for the Tambora eruption with an atypical shoshonitic composition, we expect the Banda ignimbrites to be more challenging large-scale tephrochronologic markers, unless magnetites are used in conjunction with matrix glass compositions for more reliable correlations.

The Pinatubo and Irosin ignimbrites have a range in composition but distinguishable geochemical characteristics (particularly in their K_2O content), giving them the potential to become valuable tephrostratigraphic markers. The Inararo tuff from Mt Pinatubo was successfully recognised in a distal marine archive (Ku *et al.*, 2008), which enabled its more accurate dating. However, the current lack of geochronological and glass geochemical information for ignimbrites in the Philippines does not enable us to define multiple large-scale tephrochronologic markers.

Conclusion

We collated all published and accessible geochemical and mineralogical data for VEI 6–8 eruptions that occurred in Indonesia and the Philippines during the Quaternary, with the goal of determining and characterising tephrochronologic markers for future studies. We show that volcanic products from different geodynamic regions and different sources can generally be distinguished on major element plots (particularly K_2O versus CaO) of matrix glass composition, while the distinction of multiple eruptions from the same source requires additional data such as trace element compositions of matrix glass and/or mineral compositions. Biotite, but also magnetite compositions (MgO and TiO_2 content in particular) appear to be discriminating.

Through comparisons with the marine tephra record, we highlight: (1) a period of intense volcanic activity in Indonesia between ~31–35 ka BP with the occurrence of four rather substantial eruptions (from the Batur, Ranau, Masurai calderas and the source of tephra layer V1); (2) a period of intense geological activity between ~780 and 800 ka with the occurrence of a large caldera-forming eruption in South Sumatra, two large caldera-forming eruptions from Toba (OTT A and B; Mark *et al.*, 2017), the Australasian impact (e.g. Lee *et al.*, 2004) and the Matuyama-Brunhes magnetic reversal; and (3) the presence of earlier caldera-forming eruptions from Toba, in particular a YTT-like event at 1.6 Ma. Future studies of on-land deposits and marine correlatives would be needed to corroborate these findings and fully assess their implications.

Lastly, this review showed that a majority of large, >5 km diameter calderas still remain undated and un-characterised geochemically. Determining the age and geochemical characteristics of these calderas will greatly enhance our understanding of the frequencies of such events and enable solid correlations with tephra layers found in distal locations.

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Supporting information

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Electronic Supplementary Table 1. Compilation of whole-rock and matrix glass major and trace element compositions and mineral major and minor element compositions for VEI 6–8 eruptions in Indonesia and the Philippines. Jcode, Kcode, and Lcode refer to the codes used for plotting with IgPet, whereby Jcode refers to the analysis type (whole-rock, matrix glass, mineral type), Kcode refers to the eruptive unit, and Lcode refers to the data source (references as listed in the caption of Table 1).

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