The Orange Tuff: a Late Pleistocene tephra-fall deposit emplaced by a VEI 5 silicic Plinian eruption in West Java, Indonesia

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Abstract

A VEI 5 dacite eruption emplaced the Orange Tuff about between 34.3 cal kBP and 17.2 cal kBP. Gunung Salak is the unit's source and the Orange Tuff represents the most recent such eruption from any of the volcanoes southwest of Bogor, Indonesia. The Orange Tuff is the region's first such documented tephra-fall deposit whose characteristics and phenocryst geochemistry make it readily identifiable over at least 1250 km². Magnetite compositions and temperature and fO_2 estimates inferred from Fe-Ti oxide compositions are particularly useful for identifying the unit. Deposit characteristics suggest that the eruption lasted 1–11 h with mass eruption rates of $1.0\text{--}8.3 \times 10^8$ kg/s and a column height of 31–40 km. The eruption's column height and the deposit's 2.5–11 km³ volume suggest that the unit was dispersed over a much wider area than mapped. The unit is a marker bed throughout its mapped distribution and has potential to be applied over a much broader area as a regional marker bed. The large population and infrastructure proximal to Salak suggest that the unit should be considered in hazards assessments despite its age and the lack of subsequent similar eruptions.

Keywords Salak · West Java · Indonesia · Tephrostratigraphy · Eruption history · Plinian eruption

Introduction

Voluminous explosive eruptions occur infrequently but have dramatic consequences for people near the volcano and in downwind areas (e.g., Schuster 1981; Zen and Hadikusumo 1964; Naranjo et al. 1993). Java is one of the most densely populated islands in the world, with many people living close to potentially active volcanoes. A significant portion of the island's population is concentrated in West Java in the cities

of Jakarta, Bogor, and their suburbs. Large populations necessitate significant infrastructure, such as transportation networks, airports, ports, and power facilities to support them (Fig. 1b, c). The proximity of such populations and infrastructure to West Java's volcanoes exacerbates the volcanic hazards (e.g., Hadisantono et al. 2005, 2006; Haerani et al. 2006; Brown et al. 2015). The informally named Orange Tuff (Stimac and Sugiaman 2000; Stimac et al. 2008), distributed within Bogor, its suburbs, and the highlands and adjoining valleys south of the city exemplifies such a situation. Additionally, the unit crops out in the Mt. Halimun-Salak National Park, which is in the highlands southwest of Bogor and of significant conservation importance (e.g., Kool 1992; Whitten et al. 1996; Tan et al. 2006; Wiharto and Mochtar 2012; Collar and van Balen 2013; Mittelmeier et al. 2014; Peggie and Harmonis 2014). The Orange Tuff, however, has never been comprehensively investigated and scant published details exist.

Very few pre-historic Volcanic Explosivity Index (VEI; Newhall and Self 1982) 5 or larger eruptions are documented in the last 50 ky in Java (Newhall and Dzurisin 1988; Decker 1990; Bronto 1989). Such events are rare, occurring on average once a decade or more globally (Siebert et al. 2010) and

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Fig. 1 **a** Map of the region, showing the location of Java and other major landmasses. The black rectangle indicates the area shown in **b**. The base image is from Esri compiled from data provided by sources listed in the bottom right corner of the image. **b** Image showing the western tip of the island of Java and the overall setting of Salak. The area of **c** is within the white rectangle. Major cities are labeled, with those in *italics* having populations over 1 million people and those in **bold italics** having a population over 10 million (according to the 2010 Indonesia Census: <http://sp2010.bps.go.id/>). The locations of the cores, some of the volcanoes, and important infrastructure are shown. The border between West Java and Banten provinces is the gray line. The base image is from Esri compiled from data provided by sources listed in the bottom right corner. **c** A close-up of the volcanic highlands southwest of Bogor. The volcanoes forming the cluster and some other pertinent features are labeled. The Awibengkok Geothermal Development Area is an actively producing geothermal power plant. The digital elevation model (DEM) for the base hill shade map was made from 25-m contours scanned from the Indonesian 1:50,000 series topographic maps

preservation of their resulting deposits is complicated by Java's aggressive weathering and erosion conditions and long history of landscape modification for agriculture (Mohr 1944; Diemont et al. 1991; Tan 2008). Yet, three historical VEI 5 eruptions have occurred in Java (Siebert et al. 2010; Badan Geologi 2011) suggesting that many more pre-historic eruptions of similar magnitude have occurred in the last 50 ky than are recognized. Such under reporting of voluminous explosive eruptions is common even in regions with some of the most comprehensive eruption records in the world (Kiyosugi et al. 2015). Documenting these eruptions, delineating their deposits, characterizing their dynamics, constraining their age, and identifying their source volcano helps quantify the potential hazard from such future eruptions (e.g., Andronico and Cioni 2002; Macías et al. 2008; Harpel et al. 2011).

Such a previously undescribed eruption distributed the Orange Tuff over an area that contains a concentration of closely spaced Holocene and Pleistocene volcanic centers, including composite cones, dome complexes, and a caldera (Fig. 1c) that have been a focus of volcanism for at least the last 1.6 My (Stimac et al. 2008). Geothermal activity continues at several locations with hydrothermal explosions and small-volume phreatic or phreatomagmatic eruptions occurring into the early twentieth century (Hartmann 1938; Neumann van Padang 1951). Except for Gunung Salak (hereafter just Salak), only fragments of these volcanic centers' eruption histories are known, and in some cases, no published information exists (Hartmann 1938; Stimac et al. 2008; Siebert et al. 2010; Harpel and Kushendratno 2012). More broadly, detailed pre-historic eruption histories of only a few of West Java's Holocene volcanoes are currently documented on more than a preliminary level (Kartidinata et al. 2002; Belousov et al. 2015; Prambada et al. 2016). By characterizing and mapping the Orange Tuff, we document one of West Java's few known voluminous explosive eruptions and infer its age, dynamics, composition, and likely vent location.

Numerous explosive eruptions punctuate Java's history since the late Pleistocene. Many of these eruptions were small volume events of local effect, but some were voluminous paroxysms distributing ash over wide areas. Deposits from such eruptions can be useful as marker beds throughout their distributions. Detailed tephrostratigraphic frameworks exist for few of Indonesia's volcanoes (Andreastuti et al. 2000; Fontijn et al. 2015), none of which are in West Java. Additionally, scant individual regional tephra-fall deposits are mapped and described (e.g., Self et al. 1984; Rose and Chesner 1987; Sigurdsson and Carey 1989; Shane et al. 1995; Lavigne et al. 2013; Alloway et al. 2017). Characterizing the Orange Tuff provides an opportunity to use it as West Java's first tephrostratigraphic marker bed.

Antecedent descriptions

Only short descriptions of the Orange Tuff exist, though each provides some relevant details about the unit's physical characteristics. Verbeek and Fennema (1896) first noted the unit around the Awibengkok geothermal area (Fig. 1c). Subsequently, Mohr (1933, 1944) and Mohr and Van Baren (1954) provided information on its mineralogy and distribution. The Orange Tuff was incorporated within the broad Quaternary Pyroclastic Deposits unit and Salak Volcano Pyroclastic Fall (*Piroklastika Jatuhan Gunung Salak*) unit, a composite of multiple tephra-fall deposits during initial geologic and hazards mapping by the Volcanological Survey of Indonesia (now Center for Volcanology and Geological Hazards Mitigation; CVGHM) (Aswin et al. 1982a, b; Zaennudin 1988; Zaennudin et al. 1993). Subsequent mapping in the Awibengkok geothermal field and surrounding area established a local stratigraphy, resulting in the Orange Tuff being informally named and segregated as a discrete unit (Stimac and Sugiaman 2000; Stimac et al. 2008, 2010).

Using a combination of published photos, descriptions, and distributions, we correlate such antecedent descriptions to the Orange Tuff. The same deposit, however, has multiple names and is incorporated within several composite units. We use Orange Tuff (Stimac and Sugiaman 2000; Stimac et al. 2008) rather than Aswin et al.'s (1982a, b), Zaennudin's (1988), and Zaennudin et al.'s (1993) antecedent Quaternary pyroclastic deposits and Salak Volcano Pyroclastic Fall (*Piroklastika Jatuhan Gunung Salak*).

Methodology

We sampled and documented the Orange Tuff at 170 sites throughout its reported range. At outcrops where the deposit was not reworked, its thickness was measured. Rarely, the unit's thickness was estimated from photos of outcrops in which a scale of known dimensions was present. At 43 sites, the largest five to six lithics present were measured and averaged to obtain the site's reported maximum lithic diameter. Additionally, lithics were noted at six sites that were generally < 1 cm diameter, but not measured. Complete thickness and lithic size data are present in the effective online data supplement to this paper at <https://doi.org/10.5066/F7SJ1JJF> (Harpel et al. 2018). The deposit's pumice are usually too poorly preserved and fragile to successfully remove from the outcrop and measure. Two pumice, nonetheless, were successfully collected from the deposit and later vacuum impregnated with epoxy to preserve them. Phenocrysts were separated from the clay fraction in bulk samples through repeated steps of soaking in an ultrasonic bath and washing. Crystals were then handpicked, mounted, and polished for electron microprobe analysis (EPMA). Phenocryst identification was

accomplished through a combination of optical petrography, scanning electron microscopy, and EPMA. Scanning electron microscopy was carried out at the USGS Cascades Volcano Observatory petrology laboratory using an Aspek PSEM eXpress equipped with an integrated X-ray analyzer for energy dispersive spectroscopy. Phenocryst proportions were determined on five samples by optical estimations using a petrographic microscope. Proportions were estimated on and averaged from five aliquots of each sample.

Major element concentrations were determined for the unit's phenocrysts by EPMA at the Nanyang Technological University's electron microprobe laboratory using a JEOL JXA 8530-F Field Emission Electron Microprobe with five tunable wavelength-dispersive spectrometers. Analyses on plagioclases and pyroxenes were carried out using a 10- μ m beam diameter, a 15-keV accelerating voltage, and a 20-nA beam current. Analyses on magnetite and ilmenite were carried out using a concentrated point beam, a 15-keV accelerating voltage, and a 20-nA beam current. Repeated analyses of standard reference materials yielded analytical uncertainties at the 99% confidence level of less than 1% of reported values. Plagioclase and pyroxene analyses with totals below 98.5% and above 101% were discarded to maintain data quality. Similarly, magnetite and ilmenite analyses with totals outside of the range of 98–101% after adjustment for allowable stoichiometric substitution of ferric and ferrous iron were also excluded. The geochemical data and additional analytical details are present in the effective data supplement for this paper.

Radiocarbon dating was carried out by Beta Analytic Inc. on four samples. Subfossil wood contained within volcanoclastic deposits at a single location was collected, stored in a plastic bag, dried in a drying oven at 80 °C, and dated using standard radiocarbon analysis techniques. Three dark brown to black paleosols developed below and on top of the Orange Tuff were also sampled at two locations. The samples were stored in plastic bags and air dried. Organic sediment from the paleosols was dated using the accelerator mass spectrometry (AMS) method.

Deposit characteristics

The Orange Tuff is in many locations an orange to yellow color (10YR 7/8 to 10YR 8/8), but often has a white base (10YR 8/1) (Fig. 2c), which is sometimes present only at the top of small paleotopographic highs. Locally, the entire unit is white (10YR 8/2 to 10 YR 8/3; Fig. 2b), especially in the eastern part of its distribution. The unit is moderately sorted (Fig. 2d) with abundant loose crystals within the matrix (Fig. 3a), which give the deposit a gritty texture, congruent with antecedent descriptions (Mohr 1933; Mohr and Van Baren 1954). The unit is structureless except in the thickest sections where some crude bedding defined by several millimeter-thick zones enriched in ash and crystals and

depleted in pumice are present. The deposit drapes the paleotopography and typically crops out within 1–3 m below the modern surface (Fig. 2a), though it is locally exposed at the surface by erosion. Such a position in the soil profile is consistent with Mohr's (1933, 1944) and Mohr and Van Baren's (1954) descriptions. Aswin et al.'s (1982a, b), Zaennudin's (1988), and Zaennudin et al.'s (1993) composite units contain pervasive bedding and or zones of accretionary lapilli at the top and coarse lapilli at the bottom. The lack of such features suggests that the Orange Tuff is only one of the deposits included within their antecedent composite units.

Since emplacement, the Orange Tuff was intensely weathered, producing some of the unit's most identifiable features. Mohr (1944) mentions outcrops of non-weathered Orange Tuff present on Salak's upper slopes, but he likely conflates other less-weathered units present near the volcano, such as those described by Harpel and Kushendratno (2012) into his description. In all locations, the glass is completely altered to clay. Conversion of the unit's glass to clay and particularly degradation of its pyroxenes would facilitate formation of the iron-oxide and iron-hydroxide minerals likely responsible for the unit's orange color (Tan 2011) and Mohr's (1944) report of the presence of limonite dust.

Black Fe/Mn concretions are commonly present, decrease in frequency upward from the base, and are generally absent from the upper third of the unit. When concretions are present in the orange portion of the deposit, white aureoles generally surround them (Fig. 2e). Such aureoles represent the leached source zones for the manganese- and iron-oxides and manganese- and iron-hydroxides that form the concretions. The same mechanism is also responsible for forming the leached white layer often present at the base of the deposit. Although not always present, the Fe/Mn concretions are pervasive and distinct enough that they generally facilitate the unit's identification in the field.

Component characteristics and petrology

Crystals

Sufficient loose crystals are present in the deposit to be evident in the field and in bulk samples (Fig. 3a). Crystal separates from bulk samples average 85% plagioclase, 11% orthopyroxene, 4% Fe-Ti oxide, and trace amounts of clinopyroxene (Table 1). Such proportions represent the combined loose crystals in the matrix and those in relict pumice, which disaggregate during the separation process.

The plagioclases are generally bright and non-corroded, though can be slightly frosted at some locations. They are all andesine with compositions ranging from $An_{47}Or_4$ – $An_{31}Or_2$, (Tables 2 and 3, Fig. 4a), roughly consistent with the Na-rich alkali and “andesitic” feldspars that Mohr (1933, 1944)

Fig. 2 Photos showing features of the Orange Tuff. **a** The Orange Tuff 14 km west-northwest of Salak, showing its typical position with respect to the modern surface. Note that adjacent portions of the unit vary from the typical Orange color to the less common cream color. The unit at this location is 40–50 cm thick. **b** The Orange Tuff where it is completely white, to the southeast of Salak at the foot of Pangrango. The shovel's handle is 50 cm long. **c** A typical outcrop of the Orange Tuff, showing its orange color and white base. The black spots with white halos in the lower portion of the unit are Fe/Mg concretions. The shovel's handle is 50 cm long. **d** A close-up of the Orange Tuff where abundant relict pumice are preserved. Note the relatively large pumice at the person's fingertip and the unit's sorting. The part of the pencil shown in the photo is 7.5 cm long. **e** The Fe/Mg concretions in the lower portion of the Orange Tuff. Note the leached zones forming white halos that surround them. The pencil is 15 cm long. **f** The Orange Tuff, outlined in black, cropping out above the Loji sequence. The intervening erosional unconformity is subtle, but its approximate location is marked with the dashed line at the top of the uppermost Loji deposits. The handle of the shovel at the base of the photo is 50 cm

describes. The plagioclases are anhedral and can have subtle, small-scale oscillatory zoning (Fig. 3b). Rare, $< 5 \mu\text{m}$ euhedral apatite inclusions are present in a small proportion of the crystals and a single $< 5 \mu\text{m}$ euhedral orthopyroxene inclusion is also present in the analyzed samples.

The orthopyroxenes are partially weathered euhedral enstatites (nomenclature of Morimoto et al. 1988) up to 2.8 mm in length (Fig. 3c). Compositions of the enstatites

average En_{52} , with a range from En_{50-59} (Tables 2 and 3, Fig. 4b). Such compositions are consistent with the weathered hypersthene reported by Mohr (1933) and Mohr and Van Baren (1954). Sparse clinopyroxenes are present (Fig. 3a) and similar in size, morphology, and degree of weathering to the orthopyroxenes, which is congruent with antecedent observations (Aswin et al. 1982a; Zaennudin 1988). Rarely, clinopyroxenes and orthopyroxenes are intergrown.

Fig. 3 **a** Photo of typical phenocrysts. The abundant white crystals are plagioclase. Examples of orthopyroxene (Opx), oxides (Ox), and one of the scant clinopyroxenes (Cpx) are circled. The scale on the side is 5 mm. **b** Scanning electron backscatter image of a plagioclase with oscillatory zoning. **c** Scanning electron backscatter image of a typical weathered orthopyroxene containing abundant inclusions of ilmenite (I), magnetite (M), zircon (Z), and apatite (A). **d** Close-up of inclusions in a weathered orthopyroxene. The inclusions are marked as in image c

Titanomagnetite, apatite, ilmenite, and zircon, in order of their abundance, are common accessory phases. The apatites and zircons are intergrown with or included within the pyroxenes and oxides (Fig. 3c, d). Apatite inclusions are sub-rounded to euhedral and generally $\leq 50\text{-}\mu\text{m}$ diameter, but occasionally form needles $\leq 75\text{-}\mu\text{m}$ long. The zircon inclusions are $\leq 50\text{-}\mu\text{m}$ diameter, and while rarely euhedral, are often sub-rounded to rounded. Titanomagnetites and ilmenites are present as loose crystals up to 1 mm and as inclusions within or intergrown with the pyroxenes (Fig. 3c, d), composing up to roughly 2–5% of their hosts. As inclusions, both oxide phases have bimodal size populations, with one group $\leq 30\text{-}\mu\text{m}$ diameter and another between 100- and 500- μm diameter (Fig. 3c, d). Such oxides are euhedral to rounded and are occasionally intergrown with each other.

Lithics

The Orange Tuff contains scant lithics and the unit's fine fraction is particularly depleted. The lithics present are a diverse assemblage of dense, fine-grained fragments with a variety of textures, which is congruent with Aswin et al.'s (1982a, b) description of the unit. Obsidian or lithics with propylitic alteration are not present in the observed samples.

Pumice

Relict pumice are abundant (Fig. 2d), but completely altered to clay and easily crushed by hand, consistent with antecedent descriptions (Verbeek and Fennema 1896; Mohr 1933, 1944; Mohr and Van Baren 1954; Aswin et al. 1982a, b). Where discernable, such pumice can be up to 11-cm diameter, though are generally smaller. Despite its alteration, the fibrous texture and vesicles are preserved in one of the pumice impregnated with epoxy. The vesicles are dominated by a smaller population, but some larger vesicles with irregular shapes are also present. The pumice contain scant phenocrysts that are heterogeneously dispersed and present in generally the same proportions as the loose crystals.

Magmatic conditions and composition

The compositions of coexisting titanomagnetite and ilmenite in the Orange Tuff provide a means to estimate magmatic temperature and $f\text{O}_2$ conditions. We assume that oxides included within the same orthopyroxene (Fig. 3c) are related because all oxide pairs meet Bacon and Hirschmann's (1988) criteria for equilibrium. We apply Ghiorso and Evans' (2008) method to 34 pairs of titanomagnetites and ilmenites coexisting as inclusions within 15 pyroxenes from three disparate locations. The method yields temperatures from 792 to 824 °C, averaging 807 °C and with a standard deviation of 10 °C. Their method also yields $\log_{10}f\text{O}_2$ values from -0.18 –

Table 1 Componentry of loose crystals in the Orange Tuff

Sample	Aliquot	Plagioclase (%)	Orthopyroxene (%)	Clinopyroxene (%) [*]	Fe-Ti oxides (%)
SK12-41	1	79	12	n.o.	9
	2	85	8	tr.	8
	3	77	15	tr.	8
	4	77	15	tr.	8
	5	81	13	tr.	6
	Average	80	13		8
SK 12-76	1	83	12	tr.	5
	2	89	7	tr.	4
	3	88	10	tr.	2
	4	82	16	tr.	2
	5	88	10	n.o.	2
	Average	86	11		3
SK 12-77	1	78	17	tr.	6
	2	88	10	n.o.	1
	3	81	16	n.o.	3
	4	82	16	tr.	2
	5	88	9	tr.	4
	Average	83	14		3
SK 12-101	1	83	13	n.o.	4
	2	89	7	tr.	4
	3	83	8	tr.	8
	4	86	9	tr.	5
	5	89	10	n.o.	1
	Average	86	9		5
SK 12-102	1	91	8	n.o.	4
	2	90	6	n.o.	4
	3	91	7	tr.	8
	4	87	11	tr.	5
	5	87	9	n.o.	1
	Average	89	8		5
Combined average	σ	2	2		3
	σ	4	3		2

^{*}Not observed (n.o.); present in trace amounts < 1% (tr)

0.14 (relative to the nickel-nickel oxide buffer; NNO) with an average of −0.02 and standard deviation of 0.09.

The deposit's weathering impedes directly measuring the Orange Tuff's initial composition, but we infer the composition from indirect evidence. The inferred magmatic temperature supports a dacite or rhyolite composition, corroborating Mohr's (1933) initial assessment that the unit was an acid ash.

Table 2 Key characteristics of the Orange Tuff and its eruption

Minimum bulk volume ^{a,b,c}	2–2.5 km ³
Maximum bulk volume ^d	11 km ³
Initial deposit mass ^e	1.6×10^{12} – 1.1×10^{13} kg
Total column height (H_T) ^{a,f,g}	31–40 km
Neutral buoyancy height (H_B) ^a	28 km
Wind speed ^c	6–7 m/s
Dispersal axis	West-southwest
Eruption classification ^{a,c,h}	Plinian
VEI ^h	5
Volume (DRE) eruption rate ^{g,i}	7.9×10^4 – 2.5×10^5 m ³ /s
Mass eruption rate ^j	1.0 – 8.3×10^8 kg/s
Minimum eruption duration ^k	1–11 h
Plagioclase composition	An ₄₇ Or ₄ –An ₃₁ Or ₂
Orthopyroxene composition	En ₅₀ –En ₅₉
Magma temperature ^l	792–824 °C, average 807 °C
log ₁₀ f O ₂ (relative to NNO) ^l	−0.18–0.14, average −0.02

^a Pyle's (1989) method

^b Fierstein and Nathenson's (1992) method

^c Bonadonna and Costa's (2012, 2013) method

^d Bonadonna and Houghton's (2005) method

^e Assuming an initial bulk density of 800–1000 kg/m³

^f Carey and Sparks' (1986) method

^g Sparks' (1986) empirical relationship

^h Newhall and Self's (1982) method

ⁱ Mastin et al.'s (2009) method

^j Wilson and Walker's (1987) method and converted from volume eruption rates

^k Using the initial mass and mass eruption rates

^l Ghiorso and Evans' (2008) method

Stimac et al. (2008) suggest that the unit is a rhyolite, but the presence of scarce augite (Table 1) suggest a less evolved dacite composition. The andesines are also more calcic (Fig. 4a) than those generally expected in rhyolite. As such, we infer that the Orange Tuff's initial composition was likely dacite, corroborating Mohr and Van Baren's (1954) proposal. Some rhyolites, nonetheless, exhibit similar characteristics (Stimac et al. 1990) and without further direct evidence, we cannot completely rule out an original rhyolite composition.

Distribution, emplacement mechanism, and vent location

We document the Orange Tuff over at least 1250 km² to the south and west of Bogor (Fig. 5a). Within the city, the unit is at least 20-cm thick, which is congruent with Mohr's (1933) and Mohr and Van Baren's (1954) measurements of 15–30-cm thickness (Fig. 5a). Mohr's (1944) anomalous report of 2–3 m in the city, however, is an error introduced during translation

Table 3 Representative electron microprobe analyses for crystals in the Orange Tuff

Mineral	Plagioclase				Orthopyroxene				Magnetite				Ilmenite			
Sample	SK11-35	SK11-165	SK12-62	SK12-122	SK11-35	SK11-165	SK12-48	SK12-62	SK12-62	SK12-62	SK12-122	SK12-122	SK12-62	SK12-62	SK12-122	SK12-122
SiO ₂	58.14	59.57	59.07	58.65	51.61	54.04	51.87	51.76								
TiO ₂	b.d.	0.03	b.d.	b.d.	0.1	0.12	0.07	0.06	10.68	10.58	10.29	10.65	47.56	46.78	46.51	47.45
Al ₂ O ₃	25.94	24.94	25.2	25.52	0.47	1.81	0.34	0.38	1.53	1.53	1.54	1.5	0.13	0.1	0.11	0.12
Cr ₂ O ₃					b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
FeO ^{Total}	0.28	0.23	0.26	0.27	27.9	24.1	26.8	27.43	80.36	81.02	80.31	80.6	48.45	49.05	48.83	48.67
MnO	b.d.	b.d.			1.24	1.01	1.13	1.25	0.54	0.55	0.54	0.53	0.84	0.87	0.81	0.82
MgO	0.02	b.d.	b.d.	b.d.	17.5	16.81	18.25	17.99	0.85	0.87	0.88	0.88	1.72	1.71	1.73	1.72
CaO	8.38	7.4	7.63	7.71	1.14	1.12	1.16	1.09								
BaO			0.05	0.03												
Na ₂ O	6.37	6.31	6.7	6.87	0.02	0.33	b.d.	0.03								
K ₂ O	0.36	0.44	0.42	0.39												
Total	99.49	98.9	99.34	99.46	99.96	99.43	99.63	99.99	93.96	94.55	93.57	94.15	98.7	98.5	97.99	98.77
Fe ₂ O ₃									46.03	46.69	46.55	46.30	10.65	38.15	37.93	38.79
FeO									38.94	39.01	38.43	38.94	38.87	12.11	12.11	10.98

Below detection limits (b.d.). Not analyzed (blank spaces)

Full analytical details in Harpel et al. (2018)

FeO^{Total} converted to Fe₂O₃ and FeO using the Droop (1987) method

from the original Dutch version of his book (Mohr 1938) where he reports 20–30 cm. Around Cilebut, north of Bogor, Mohr (1944) notes thicknesses of about 10 cm and Mohr and Van Baren (1954) suggest that the unit pinches out about 25 km north of either Salak or Bogor. We document the presence of the unit in Bogor and both statements are consistent with our data, but we were unable to confirm them at the specific original localities. Our data further corroborate antecedent observations of a meter or more of Orange Tuff on Salak's flanks (Mohr 1933, 1944; Mohr and Van Baren 1954). North and northwest of Salak, the Orange Tuff reaches thicknesses up to 4 m (Fig. 5a), eventually thinning to tens of centimeters to the northwest, broadly commensurate with Aswin et al.'s (1982a, b) observations. The deposit is commonly 1–5-m thick, though rarely reaches up to 10-m thick within the Awibengkok geothermal development where Verbeek and Fennema (1896), Stimac and Sugiaman (2000), and Stimac et al. (2008) describe it. To the

east, the deposit thins to tens of centimeters thick on the slopes of Pangrango volcano. Mohr (1944) notes that the unit pinches out to the east on Gede volcano. Belousov et al. (2015) do not report its presence and our data are insufficient to confirm such an observation. The thicknesses we observe on Pangrango and its proximity to Gede, nonetheless, suggest it is possible. To the west, the Orange Tuff is 0.5–1-m thick at and near the border with Banten Province (Fig. 5a) and is undoubtedly present further to the west within Banten.

Lithic isopleth data are roughly concentric around Salak's southwestern flank, though show a slight west-southwest to east-northeast extension (Fig. 5b). The Orange Tuff's isopachs also show a southwest to northeast extension in the more central values but are slightly elongated to the west for thinner deposits (Fig. 5b). Both the thickest mapped isopach and the coarsest mapped lithic isopleth enclose Salak, parts of Perbakti volcano, and the Cibeureum geothermal area at their southwestern edge.

Fig. 4 **a** Feldspar classification diagram for plagioclase from the Orange Tuff. The data represents 251 analyses of multiple plagioclase crystals from 10 samples. **b** Pyroxene classification diagram for orthopyroxenes from the Orange Tuff. The data represents 228 analyses of multiple orthopyroxene crystals from six samples

Emplacement mechanism

We infer from the systematic radial decrease in thickness and lithic size (Fig. 5), moderate sorting (Fig. 2d), and mantling of paleotopography (Fig. 2a) that the unit is a tephra-fall deposit. As such, we concur with Mohr's (1933, 1944), Mohr and Van Baren's (1954), Aswin et al.'s (1982a, b), Zaennudin's (1988), Zaennudin et al.'s (1993), Stimac and Sugiaman's (2000), and Stimac et al.'s (2008) antecedent assessments.

Thick tephra-fall deposits can be emplaced by a single voluminous explosive eruption or a series of small volume explosive eruptions within the same eruption sequence separated by short pauses of hours to weeks (e.g., Rose et al. 1978; Waitt and Dzurisin 1981; Naranjo et al. 1993; Self and Rampino 2012). While not always true, bedding is many times present in deposits emplaced by multiple eruptions with each bed typically having a distinct distribution (e.g., Wood 1977; Heiken 1978; Miller 1985). Crude layering is only present in outcrops of Orange Tuff over 4–5-m thick and represents minor fluctuations during the eruption (Walker 1981; Houghton and Carey 2015). The presence of such layering suggests that bedding would be evident despite the unit's weathering. The lack of such persistent layering or bedding throughout the deposit suggests emplacement by a single continuous eruption.

Zaennudin (1988) and Zaennudin et al. (1993) suggest that the white and orange layers are discrete tephra-fall deposits. Yet, the lack of mineralogical or textural differences between the two layers suggests that the color difference is post-emplacement alteration of a single deposit. The occasional lack of a white layer, or its association with paleotopographic highs, and the local juxtaposition of entirely white and orange portions of the deposit (Fig. 2a) further support our inference. We suggest that the white areas are leached zones similar to the aureoles around the Fe/Mn concretions where water has removed the iron-oxide and iron-hydroxide minerals.

The vent

Mohr (1944) tentatively associates the Orange Tuff with the Awibengkok domes (Fig. 1c) because of their proximity to each other. Stimac et al. (2008), however, note that the Orange Tuff is younger than the domes and propose the Cibereum geothermal feature as the deposit's vent based on its thickness and the maximum size lithics and pumice. Cibereum is one of the Awibengkok geothermal area's (Fig. 1c) largest groups of fumaroles and boiling springs, forming a relatively flat and swampy depression in a valley draining the east flank of Perbakti. As recently as 1929 CE, small-volume, hydrothermal explosions and/or phreatic eruptions occurred (Hartmann 1938; Neumann van Padang 1951). Yet, no large-diameter crater is evident. Stimac et al. (2008) suggest that thick, subsequent hydrothermal explosion

deposits conceal the Orange Tuff's vent, which could be further obscured by landslide and debris-flow deposits that are also present. Cibereum is located at the southwestern edges of the inner-most isopach and lithic isopleth (Fig. 5), a distribution which requires that the Orange Tuff be emplaced during unusually strong, low-level winds. The isopach and lithic isopleth data also suggest that the thick deposits and coarse clasts present around Cibereum, which Stimac et al. (2008) based their inference upon, are much more widely distributed. As such, it is unlikely that Cibereum is the Orange Tuff's vent.

Salak's southwest crater is in the center of the Orange Tuff's lithic isopleths and isopachs (Fig. 5), which suggests that it is the deposit's source and the eruption occurred during light winds to the west-southwest. Salak's southwest crater and Kawah Ratu thermal area, located just outside of the crater have been the focus of volcanic activity for at least the last 14.5 ky with small volume phreatic and/or phreatomagmatic eruptions occurring as recently as 1919 CE (Hartmann 1938; Neumann van Padang 1951; Zaennudin 1988). Silicic deposits at Salak (Handley et al. 2008; Harpel and Kushendratno 2012) demonstrate that the volcano can erupt felsic material such as the Orange Tuff. Additionally, the unit's phenocryst assemblage is consistent with those observed in Salak's pumice (Handley et al. 2008) and the soils developed on Salak's deposits (Tan 2008). The broad compositional range of Handley et al.'s (2008) samples makes direct comparisons with the Orange Tuff difficult. Their orthopyroxene compositions, nonetheless, are similar to some of the Orange Tuff's, whereas their plagioclase compositions are more Na-rich. Magnetite compositions can be used to discriminate between volcanic sources (e.g., Shane 1998; Fierstein 2007; Rawson et al. 2015). The Orange Tuff's magnetite compositions directly overlap those from Salak's felsic deposits (Fig. 6) suggesting a similar origin. Magnetite from Handley et al.'s (2008) Salak Side Vent Group (SVG) also plot along the trend defined by the Orange Tuff and Salak's silicic units, while their Salak Central Vent Group (CVG) samples delineate an independent trend. Such a situation can occur with samples of different compositions and age groups from the same volcano (e.g., Shane 1998; Rawson et al. 2015). Based on the isopach, lithic isopleth, phenocryst assemblage, and magnetite compositions, we suggest that Salak is the vent for the Orange Tuff, as originally proposed by Mohr (1933), Aswin et al. (1982a, b), and Zaennudin et al. (1993).

Eruption volume and dynamics

Deposit volume

The thickness and distribution of the Orange Tuff suggest a voluminous eruption, but the unit is only mapped sufficiently

Fig. 5 **a** Isopach map for the Orange Tuff. Dots represent data points and the recorded thickness in centimeters. The data labels are deposit thickness in centimeters. Points marked “pr” indicate that the deposit is present, but primary thickness is not recorded. Published data points are in the approximate locations reported by Mohr (1933, 1944) and Mohr and Van Baren (1954). **b** Lithic isopleth map for the Orange Tuff. Data labels are the maximum lithic diameter in centimeters. The key applies to both maps and the base layer hill shade in both maps is from the same source as Fig. 1c

to provide a single linear segment on plot of logarithm of deposit thickness against the square root of the isopach areas (Fig. 7). Applying an exponential model (Pyle 1989; Fierstein and Nathenson 1992) to our data yields a bulk volume of 2.5 km^3 for the deposit. Bonadonna and Costa (2012, 2013) calculate volumes by integrating the Weibull function, which also yields three associated free parameters; the characteristic decay length scale of thinning (λ), thickness scale (θ), and a dimensionless shape parameter (n). Using Daggitt et al.’s (2014) implementation of their method results in values of $\lambda = 20.8 \text{ km}$, $\theta = 4.7 \text{ cm}$, and $n = 2.0$ with a bulk volume of 2 km^3 , similar to the exponential model (Fig. 7). Yet, both methods underestimate the bulk volume of deposits such as the Orange Tuff, which lack proximal and distal isopachs (Figs. 5a and 7; Bonadonna and Costa 2013). As such, we suggest that the Orange Tuff’s minimum bulk volume is about 2.5 km^3 (Table 2).

Bonadonna and Houghton (2005) apply a power-law model to estimate and incorporate distal tephra into volume estimates. The method is best applied to deposits whose distribution is characterized sufficiently that multiple inflection points are apparent on plots of logarithm of deposit thickness against the square root of the isopach areas. Such inflection points result in multiple line segments (Rose 1993; Bonadonna et al. 1998), which are not present in our current dataset. The resulting power-law curve diverges from both the proximal and distal data (Fig. 7) such that it will likely exaggerate the deposit’s volume when applying integration limits beyond the mapped deposit. Nonetheless, using Bonadonna and Houghton’s (2005) recommended proximal (B) and distal

Fig. 6 Plot showing magnetite compositions for the Orange Tuff compared to other units at Salak. The cross in the lower left corner represents analytical precision. CVG and SVG data are from Handley et al. (2008). Data has been normalized to 100 wt. %

Fig. 7 Plot of the $\log_{10}$ thickness of the deposit plotted against the square root of the area enclosed within each isopach. The fit curves from each of the models used to calculate the volume is shown. Note that the exponential model provides the best fit to the data, whereas both the Weibull and power law curves deviate from the data for the proximal and distal isopachs

(C) integration limits of 0.3 km and 1000 km, respectively yields a bulk volume of 11 km^3 , which we consider to be an estimate of the unit’s maximum bulk volume (Table 2).

Column height and wind conditions

The Orange Tuff’s relatively concentric isopachs and isopleths suggest light winds during the eruption. Applying Carey and Sparks’ (1986) method to the lithic distribution data yields relatively light wind speeds of 6–7 m/s with a total column height (H_T) of about 31 km (Table 2). Wind reduces column heights (Degruyter and Bonadonna 2013), implying that conditions during the Orange Tuff eruption resulted in a higher plume height than those noted for eruptions of similar magnitude during stronger wind conditions. Additionally, we use Pyle’s (1989) method to invert column height from the deposit’s lithic distribution, obtaining a neutral buoyancy height (H_B) of 28 km, which we convert to a H_T of 40 km using Sparks’ (1986) empirical relationship (Table 2). Column heights are estimated from the lithic distribution using the Weibull method (Bonadonna and Costa 2013). The Orange Tuff yields values of $\lambda = 25.5 \text{ km}$, $\theta = 3.7 \text{ cm}$, $n = 1.7$, and $H_T = 31 \text{ km}$, which includes the average elevation of the sampling site at about 750 m.a.s.l. Error on column heights derived from the Weibull method average around 10%, but can be up to 25% (Bonadonna and Costa 2013).

Eruption classification

The deposit’s distribution, volume, and column height suggest a vigorous explosive eruption emplaced the Orange Tuff. The deposit’s weathering and limited distribution data, however, preclude using Walker’s (1973) eruption classification scheme. Applying Newhall and Self’s (1982) criteria based on column height and bulk volume suggests a VEI 5 Plinian eruption (Table 2). Pyle’s (1989) dichotomy also classifies the

eruption as Plinian based on the thickness and clast half-distances ($b_t = 3.9$ km, $b_c = 5.8$ km). Bonadonna and Costa's (2013) classification, which is based on the deposit's Wiebull parameters and column height, further corroborates that a Plinian eruption emplaced the Orange Tuff.

Eruption parameters and duration

Both mass and volume discharge rates are intimately related to column height (Sparks 1986; Sparks et al. 1997; Mastin et al. 2009). Wilson and Walker's (1987) empirical relationship to the inferred column height of 31–40 km yields a mass discharge rate of $2.6\text{--}8.3 \times 10^8$ kg/s (Table 2). Their assumed temperature is about 50 °C higher than that of the Orange Tuff's, but the method's temperature dependence is weak (Wilson and Walker 1987). Sparks' (1986) method yields similar results of $1.0\text{--}2.5 \times 10^8$ kg/s (Table 2) for the same column heights and a temperature of 800 °C. Dense rock equivalent volume discharge rate is also empirically related to column height (Sparks et al. 1997; Mastin et al. 2009). Mastin et al.'s (2009) relationship yields volume discharge rates of $8.7 \times 10^4\text{--}2.5 \times 10^5$ m³/s (Table 2), which are corroborated by Sparks' (1986) method which yields rates of $7.9 \times 10^4\text{--}2.1 \times 10^5$ m³/s (Table 2). Converting these values to mass eruption rates using an assumed magma density of 2500 kg/m³ yields mass eruption rates ranging from 2.0 to 6.3×10^8 kg/s, similar to those derived from Wilson and Walker's (1987) method.

We derive eruption duration by dividing the deposit's mass by the inferred mass discharge rates. Weathering renders it impossible to know the original deposit density, but tephra-fall deposits exhibit a range of densities from about 500 to 1500 kg/m³ (Sparks et al. 1997) with rhyolites commonly having the range 500–800 kg/m³ (Walker 1981). We thus assume a density of the dacitic Orange Tuff of about 800–1000 kg/m³. Using such bracketing values with a bulk volume range of 2–11 km³, we obtain a range of $1.6 \times 10^{12}\text{--}1.1 \times 10^{13}$ kg (Table 2) for the Orange Tuff's original mass. Dividing these values by mass discharge rate yields an eruption duration of 1–11 h (Table 2). The range is a minimum duration due to potential fluctuations in eruption conditions but is comparable to other Plinian eruptions with similar column heights and volumes (e.g., Lirer et al. 1973; Walker et al. 1984; Carey and Sigurdsson 1987; Wilson and Hildreth 1997; Mastin et al. 2009).

Lack of pyroclastic density-current deposits

Pyroclastic density-current (PDC) deposits associated with the Orange Tuff do not crop out at any of the sites we investigated, including in valleys where such deposits should be concentrated. Newhall and Hoblitt (2002) estimate that at least 70% of VEI 4 or larger eruptions produce PDCs. Such a percentage likely increases with VEI, and very few VEI 4 or larger eruptions are documented without associated PDC deposits (Rose 1972;

Williams and Self 1983; Fontijn et al. 2011). While erosion inevitably removed some portion of the Orange Tuff and small-volume PDC deposits are possibly buried beneath thick proximal tephra-fall deposits (Hildreth and Drake 1992; Lara 2009), we infer that the eruption did not produce voluminous PDCs.

Narrow vents, high volatile contents, and the resulting high eruption velocities are common conditions favoring formation and maintenance of a stable eruption column (Wilson et al. 1980; Bursik and Woods 1991; Sparks et al. 1997). Wind also dampens PDC formation (Degruyter and Bonadonna 2013), but the inferred light winds suggest eruption conditions rather than such external forces controlled the lack of PDCs. An elongate vent additionally facilitated air entrainment into the eruption column during the 1902 CE Santa Maria eruption, precluding PDC production (Andrews 2014). Alignment of Salak's craters and regional faults along a NE trend (Stimac et al. 2010) could potentially result in such elongation, but exposure at the inferred vent is not sufficient to know whether its geometry was a factor or not. Vent erosion and expansion increase mass eruption rate, leading to column collapse and PDC formation (Wilson et al. 1980; Bursik and Woods 1991; Sparks et al. 1997). An increase in the abundance of vent-derived lithics in a tephra-fall deposit can be evidence of vent erosion (Walker 1981). Yet, the deposit's scant non-graded lithics suggest that such conduit erosion was minimal. Exceptionally stable eruption and vent conditions were required to maintain a non-collapsing column throughout the eruption's duration.

Age

The Orange Tuff is not directly dated, but its emplacement is constrained with ¹⁴C ages on bracketing units, paleosols, and distal cores carried out by van der Kaars et al. (2001) and Stuijts (1984, 1993). Stimac et al. (2008) estimate the Orange Tuff's emplacement between 40 and 8.4 ka based on ¹⁴C ages from overlying and underlying units. We further restrict the unit's age using Salak's Loji volcanoclastic sequence (Harpel and Kushendratno 2012) which crops out beneath the Orange Tuff and is often separated from it by several meters of intervening paleosols and an erosional unconformity (Fig. 2f). At one such site, wood from the uppermost Loji unit yields an age of 34.3–33.7 cal kBP (2σ) (Table 4). We infer from this age that the Orange Tuff is younger than 34.3 cal kBP.

Aswin et al. (1982a) note that the Orange Tuff does not mantle the surface of Salak's southwest debris-avalanche deposit and suggest that the tephra-fall deposit is the older of the two units. We document a meter or more of Orange Tuff in locations adjacent to the southwest debris-avalanche deposit (Fig. 5a). Yet our observations support Aswin et al.'s (1982a) that the Orange Tuff was not emplaced on top of the debris-avalanche deposit. As such, we also infer that Orange Tuff is the older of the two units. Wood from Salak's southwest

Table 4 Radiocarbon ages relevant to the Orange Tuff

Sample	Lab code	Location	Method	Sample location	Material	Deposit	Pretreatment	Conventional ^{14}C age (BP; 2 σ)	$\delta^{13}\text{C}$ (‰)	Calibrated age range* (cal year BP; 2 σ)	Constraint	Reference
SK11-108	Beta309018	6.74656 °S 106.76421 °E	AMS	Salak	Organic sediment	Paleosol	Acid washes	4300 ± 30	-23.8	4960–4924 (9.4%) 4917–4900 (2.2%) 4892–4829 (83.8%)	Minimum	This study
SK12-43	Beta445672	6.78792°S 106.75979°E	AMS	Salak	Organic sediment	Paleosol	Acid washes	9790 ± 30	-24.8	11,245–11,185 (95.4%)	Minimum	This study
SK11-107	Beta309017	6.74656° S 106.76421° E	AMS	Salak	Organic sediment	Paleosol	Acid washes	12,640 ± 50	-24	15,220–14,762 (95.4%)	Minimum	This study
	GrN-11791		Standard?	Situ Bayongbong		Gyftja		12,360 ± 200		15,152–13,816 (95.4%)	Tentative minimum	Stuijs (1984, 1993), Stuijs et al. (1988)
	Wk-5234		Standard?	Rawa Danau core		Lake sediment		13,200 ± 240		16,550–15,150 (95.4%)	Tentative minimum	van der Kaars et al. (2001)
	WK-1202		Standard	Salak	Wood	Debris-avalanche deposit		14,450 ± 130		17,945–17,246 (95.4%)	Tentative minimum	Zaennudin (1988)
	GrN-10522		Standard?	Situ Bayongbong		Gyftja		16,800 ± 300		21,044–19,550 (95.4%)	Tentative minimum	Stuijs (1984, 1993), Stuijs et al. (1988)
SK11-89	Beta309024		Standard	Salak	Wood	Volcaniclastic deposit	Acid/alkali/acid	29,860 ± 150	-27.6	34,251–33,683 (95.4%)	Maximum	Hapel and Kushendratno (2012)

*All ages, including published ages calibrated with OxCal (online version 4.3; Bronk Ramsey 2009) using the default settings and the IntCal 13 calibration curve (Reimer et al. 2013)

debris-avalanche deposit provides an age of 18.0–17.2 cal kBP (2σ) (Zaennudin 1988; Table 4). From such age, we infer that the Orange Tuff is older than 17.2 cal kBP.

Such constraining ages are supported by ages on three paleosols associated with the Orange Tuff. Paleosols are generally considered to yield ^{14}C ages that are minimums because they can incorporate carbon accumulated from their inception through modern times (Trumbore 2000). We, nonetheless, dated a paleosol underlying the Orange Tuff, which provided an age of 11.3–11.2 cal kBP (2σ). Samples from overlying and underlying paleosols at another site yielded ages of 15.2–14.8 cal kBP (2σ) and 5.0–4.8 cal kBP (2σ) (Table 4), respectively. Inversion of the latter site's ages suggests that young carbon was incorporated into the paleosols through post-depositional soil processes and impacted the ages. As a result, we consider the ages as minimums and infer from them that the Orange Tuff is older than 14.8 cal kBP.

The eruption undoubtedly distributed tephra far afield and possibly deposited ash at the sites of the Rawa Danau and Situ Bayongbong cores, about 100 km northwest and 65 km south-east of Salak, respectively (Fig. 1b). Ash layers are present in both cores yet are not reported in the Rawa Danau core from 16.6–15.2 cal kBP (2σ) (Table 4) to the core's base, about 0.5 m below (van der Kaars et al. 2001). Similarly, no ash layers are apparent in the Situ Bayongbong core from 15.2–13.8 cal kBP (2σ) (Table 4) to the core's base at 21.0–19.6 cal kBP (2σ) (Stuijts 1984, 1993; Stuijts et al. 1988; Polhaupessy 2006). While acknowledging the vagaries of preservation and possible presence of cryptotephra, the lack of a notable ash layer suggests that the Orange Tuff was emplaced below the bottom of both cores. As such, we tentatively infer that the Orange Tuff is older than 19.6 cal kBP.

We infer an emplacement for the Orange Tuff between 34.3 and 17.2 cal kBP based on the dates derived from overlying and underlying units. The paleosol ages support such an inference, but do not provide further constraint on the Orange Tuff's emplacement. Using the ages from the cores, the Orange Tuff's emplacement could further be restricted to before 19.6 cal kBP, but such an age is tentative due to the caveats regarding preservation and possible cryptotephra. The erosional unconformity and thick paleosols separating the unit from the Loji volcanoclastic deposits and the unit's proximity to the modern surface further suggest that its emplacement occurred closer to the younger constraining age.

Implications of the Orange Tuff

Salak's eruption history

The Orange Tuff is the uppermost widespread tephra-fall deposit in stratigraphic sections throughout its mapped distribution. Its stratigraphic position suggests that the unit was either emplaced

by Salak's most recent VEI 5 or larger eruption or is better preserved than deposits from subsequent voluminous explosive eruptions. The cooler, drier climate at the time of the Orange Tuff's emplacement (e.g., Dam 1994; van der Kaars and Dam 1997; Kershaw et al. 2001; Russell et al. 2014) would lessen chemical weathering (Tan 2008, 2011) and decrease erosion, possibly facilitating the Orange Tuff's preservation. Subsequent tephra-fall deposits, exposed to warmer, wetter conditions would erode and weather more quickly. Nonetheless, remnants of deposits from such large magnitude eruptions should exist despite weathering and erosion. The lack of any such deposits overlying the Orange Tuff precludes large voluminous explosive eruptions after its emplacement and suggests that the unit represents the most recent VEI 5 or larger eruption from Salak or any of the adjoining volcanoes.

Potential as a regional marker bed

The Orange Tuff serves as a local marker bed in the volcanic highlands around Salak (Stimac et al. 2008, 2010; Harpel and Kushendratno 2012), but the eruption was sufficiently powerful that it likely distributed the unit widely enough to be useful regionally. While the glass composition remains unknown, the compositions of the main phenocryst phases are well characterized and can be used for identifying the unit further afield. Oxide geochemistry, which is notably homogeneous in the Orange Tuff (Fig. 6), is particularly useful for identifying and correlating distal ash units (e.g., Shane 1998; Fierstein 2007; Rawson et al. 2015). The Orange Tuff's age also makes it of potential importance as a marker bed. Regionally, the Last Glacial Maximum (LGM) occurred between 18 and 27 ka, possibly peaking about 19.4 ka (Fink et al. 2003; Barrows et al. 2011). Such timing is within the Orange Tuff's constraining ages, suggesting that the deposit's emplacement and peak LGM conditions are likely separated by less than 10 ky. The serendipitous timing of the two events implies that, the Orange Tuff can be used to infer the proximity of the LGM.

Volcanic hazards

Tephra-fall hazards from a VEI 5 eruption are widespread (e.g., Blong 1984; Guffanti et al. 2010; Jenkins et al. 2015) and such an eruption would impact an area far beyond the Orange Tuff's mapped distribution (e.g., Schuster 1981; Zen and Hadikusumo 1964; Naranjo et al. 1993). Tephra-fall seldom directly causes fatalities, but can displace populations, disrupt aviation, and destroy or damage infrastructure and crops over a wide area, sometimes leading to famine (Blong 1984; Horwell and Baxter 2006; Self 2006; Wilson et al. 2012; Guffanti et al. 2010). The population within a 30-km radius of Salak, which includes the city of Bogor (Fig. 1b), is in the millions. Within a radius of 100 km, the population is in

the tens of millions and includes the greater Jakarta metropolitan area (Siebert et al. 2010). An Orange Tuff-scale eruption has the potential to severely disrupt such a population and their supporting infrastructure.

PDCs are produced during most VEI 4 or larger eruptions (Newhall and Hoblitt 2002) and the circumstances that resulted in the Orange Tuff's emplacement without associated PDCs were unusual. PDCs during VEI 5 eruptions can flow up to 10 km or more downstream from their vents (Hayashi and Self 1992; Ogburn 2012; Cole et al. 2015) and are considered the most dangerous eruptive phenomenon (Blong 1984; Tilling 1989; Cole et al. 2015). Tens of thousands of people live within 10 km of Salak (Siebert et al. 2010), many on the volcano's broad northern and eastern volcaniclastic fans and in adjacent valleys.

After such an eruption, abundant loose debris would be present on the flanks of the volcano and in adjacent valleys. In wet climates, such as West Java's, heavy rains remobilize debris as lahars, which can inundate channels draining the volcano for years to decades after the eruption. Sediment-choked channels can further experience excess sedimentation, disrupting downstream areas on a similar timescale (e.g., Rodolfo et al. 1996; Major et al. 2000; Gran et al. 2011).

The Orange Tuff's age and apparent lack of subsequent, similar magnitude explosive activity moderate its hazards implications and suggest that such eruptions occur infrequently. Post-Orange Tuff volcaniclastic deposits at Salak imply that lesser magnitude eruptive activity has occurred since the Orange Tuff's emplacement (Stimac and Sugiaman 2000; Stimac et al. 2008; Harpel and Kushendratno 2012). Such post-Orange Tuff eruptive activity should be the primary basis for future hazard assessments, but the potential for less frequent VEI 5 or larger eruptions should also be considered.

Conclusion

Between about 34.3 and 17.2 cal kBP (2σ) Salak volcano erupted the Orange Tuff, dispersing between 2.5 and 11 km³ of tephra over at least 1250 km². The unit is the first documented VEI 5 Plinian eruption from the volcanic highlands southwest of Bogor, Indonesia, and is the area's most recent such eruption. Magmatic temperatures of about 800 °C and the unit's phenocryst assemblage of andesine, enstatite, and rare augite suggest that the Orange Tuff was dacite. The magma had log₁₀fO₂ values of −0.12–0.12 relative to NNO. The eruption lasted at least 1–11 h, producing an eruption column to 31–40 km with a maximum mass eruption rate of 1.0–8.3 × 10⁸ kg/s. The eruption is one of only a few known examples of a VEI 5 Plinian eruption that did not produce PDCs.

The Orange Tuff's distinct features facilitate its identification in the highlands and adjacent valleys southwest of Bogor. While the glass composition is unknown, the unit's phenocryst compositions enable its identification further afield.

The Fe-Ti oxide compositions, especially as represented by inferred temperatures and oxygen fugacities, are particularly useful for identifying the unit. The unit's maximum and minimum ages also bracket the LGM, making the Orange Tuff a possibly important regional marker bed.

Salak's most recent VEI 5 eruption emplaced the Orange Tuff. While the unit's late Pleistocene age moderates the hazards implications, the consequences of such a future eruption could be severe. As such, future hazards assessments for Salak should consider a possible VEI 5 eruption, albeit tempered by the knowledge that such an eruption has not occurred within the Holocene.

The Orange Tuff provides an example of a previously uncharacterized, pre-historic voluminous explosive eruption. Even including the Orange Tuff, few such pre-historic eruptions are documented at Java's volcanoes and others undoubtedly remain to be discovered. Java's population density, especially in West Java, emphasizes the need to document these eruptions and their deposits, some of which may be in similarly highly populated areas.

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