

¹ Multi-Site Calibration of Volcanic Sedimentation
² Rates and Implications for Archaeological Visibility in
³ Java, Indonesia

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⁵ **Abstract**

Active volcanism in Indonesia has historically been viewed as a catalyst for catastrophic site preservation, yet cumulative, non-catastrophic volcanic sedimentation presents a more pervasive taphonomic challenge by systematically burying the material record of early Javanese polities. This paper presents a new *empirical calibration framework* for estimating archaeological burial depths using four independent empirical calibration points across two distinct volcanic systems: the Kelud system (Dwarapala Singosari, ~1268 CE) and the Merapi system (Candi Sambisari, Kedulan, and Kimpulan, 9th century CE). Despite differences in eruption frequency and local topography, we identify a remarkably consistent mean sedimentation rate of 4.4 ± 1.2 mm/yr over a 1,200-year horizon. We apply this rate to the “absence” of early archaeological evidence in Java, demonstrating that remains from the Kanjuruhan period (~760 CE) likely lie beneath 4.0–7.8 meters of overburden (based on calibrated rates of 2.4–6.2 mm/yr)—exceeding the detection limits of standard surface surveys and conventional ground-penetrating radar. Spatial analysis of 666 known sites in East Java confirms that the observable record is dominated by survey history and survivorship bias toward monumental stone architecture. Our findings suggest that the apparent chronological primacy of non-volcanic regions, such as

23 Kutai in Kalimantan, may partly reflect differential preservation conditions rather
24 than a genuine historical reality. This framework provides a quantitative baseline
25 for prioritizing future subsurface investigations in volcanic island arcs.

26 **Keywords:** volcanic taphonomy; sedimentation rates; archaeological visibility; East
27 Java; multi-site calibration; survey bias

28 1 Introduction

29 The Indonesian archipelago sits at the confluence of three major tectonic plates, producing
30 one of Earth's densest concentrations of active volcanoes alongside a deep record of human
31 habitation stretching back to *Homo erectus*. Java alone hosts 45 active volcanoes across
32 approximately 129,000 km², yielding a volcanic density unmatched by any comparably
33 sized landmass (van Bemmelen, 1949). Hindu-Buddhist kingdoms flourished on the island
34 from at least the 4th century CE, yet the material evidence of early Javanese polities
35 remains strikingly sparse compared to contemporaneous societies in mainland Southeast
36 Asia. The kingdom of Kutai in Kalimantan—a region devoid of active volcanism—is
37 conventionally regarded as Indonesia's oldest polity (~400 CE), its Yupa inscriptions found
38 near the modern ground surface (Vogel, 1918; Coedès, 1968). This paper argues that
39 such apparent chronological primacy may partly reflect differential preservation conditions
40 rather than genuine historical precedence.

41 Volcanic eruptions are widely recognized as agents of catastrophic archaeological preser-
42 vation: Pompeii, Akrotiri, and Cerén demonstrate how single events can seal entire settle-
43 ments in extraordinary detail (Sigurdsson et al., 1985; Doumas, 1983; Sheets, 1992). Far
44 less attention has been paid to the inverse process: the *cumulative* taphonomic effect of
45 repeated, non-catastrophic eruptions that gradually bury surface-level remains beneath
46 meters of overburden over centuries. In volcanically active regions, this ongoing sedi-
47 mentation systematically removes the material record from the observable archaeological
48 landscape—not through destruction, but through concealment (Torrence and Grattan,
49 2002; Grattan, 2006). Figure 1 provides striking photographic evidence of this process at
50 the Dwarapala guardian statues of Candi Singosari, East Java.



(a)



(b)

Figure 1: Direct photographic evidence of cumulative volcanic sedimentation at Candi Singosari. (a) Colonial-era photograph (c. 1860) from the Leiden University Library archives, captioned *Hindoe Oudheden—Singosari*, showing the Dwarapala guardian statue partially buried beneath volcanic sediment approximately six centuries after its construction (~1268 CE). Only the head, shoulders, and hands remain visible above the accumulated overburden. (b) The same statue today, fully excavated and displayed at its original seated height of 370 cm. At the calibrated sedimentation rate of 3.6 mm/yr derived from this site (Section 3.2), approximately 185 cm of volcanic overburden accumulated between construction and the statue’s rediscovery in 1803 CE.

51 The distinction is consequential. Catastrophic preservation creates spectacular but
 52 spatially localized windows into the past. Cumulative burial, by contrast, operates at
 53 landscape scale, affecting entire volcanic basins and potentially rendering whole centuries
 54 of habitation invisible to conventional surface survey. In Java, where no point on the
 55 island lies more than approximately 27 km from the nearest active volcano, the cumulative
 56 process is not a localized anomaly but an island-wide taphonomic regime.

57 Geoarchaeological approaches to understanding post-depositional site formation have
 58 a well-established methodological tradition (French, 2003), and the problem of surface vis-
 59 ibility in archaeological survey has been recognized for decades (Wandsnider and Camilli,
 60 1992). However, these perspectives have rarely been applied systematically to volcanic
 61 landscapes in island Southeast Asia, where the dominant research tradition has focused
 62 on monumental stone architecture—precisely the class of evidence most resistant to burial
 63 (de Groot, 2009). The result is a circular observational bias: we find stone temples because
 64 they protrude through sediment; we interpret their distribution as reflecting settlement

65 patterns; and we overlook the wooden settlements that constituted the overwhelming
66 majority of historical habitation.

67 This paper presents an empirical approach to quantifying the cumulative burial prob-
68 lem. We exploit four independent archaeological sites—each with known construction
69 dates and measured burial depths—as calibration points spanning two distinct volcanic
70 systems: the Kelud system in East Java (Dwarapala Singosari, ~1268 CE) and the Mer-
71 api system in Central Java (Candi Sambisari, Kedulan, and Kimpulan, 9th century CE).
72 These yield cumulative volcanic sedimentation rates that are remarkably consistent across
73 sites separated by hundreds of kilometers, establishing that mm/yr-scale burial is a sys-
74 tematic, Java-wide phenomenon. Kelud alone has produced 37 confirmed eruptions since
75 1000 CE (Global Volcanism Program, 2024), and the Merapi system is among the world’s
76 most persistently active stratovolcanoes (Gertisser et al., 2012).

77 We apply the calibrated rates to project expected burial depths for remains of succe-
78 sive historical periods, demonstrating that Kanjuruhan-era (~760 CE) sites in the Malang
79 basin likely lie beneath 4.0–7.8 m of overburden—exceeding the effective range of both
80 surface survey and standard ground-penetrating radar (Putra and Setyastuti, 2019). We
81 further examine the spatial distribution of 666 known archaeological sites in East Java,
82 showing that the observable record is dominated by survey history and survivorship bias
83 rather than genuine settlement patterns. The paper concludes by identifying priority zones
84 for future subsurface investigation where high terrain suitability coincides with deep pre-
85 dicted burial, offering a quantitative framework for directing archaeological fieldwork in
86 volcanic island arcs.

87 2 Background

88 2.1 Java as a volcanic burial zone

89 Java hosts 45 active volcanoes across approximately 129,000 km²—a volcanic density of
90 0.35 per 1,000 km², the highest of any major Indonesian island and approximately six
91 times that of Sumatra (0.06/1,000 km²) (van Bemmelen, 1949). The average spacing

92 between volcanic centers is \sim 54 km, meaning that no point on Java is more than approx-
93 imately 27 km from the nearest active volcano. Since tephra from VEI 3–4 eruptions can
94 deposit measurable ash at 50–100+ km from the source (Newhall and Self, 1982), the en-
95 tire island lies within the depositional range of at least one—and often multiple—volcanic
96 centers.

97 This density has a fundamental implication for archaeological preservation: Java is not
98 an island where some sites happen to be near volcanoes—it is an island where volcanic
99 sedimentation is an inescapable, island-wide taphonomic process. The relevant question
100 is not *whether* burial occurs at any given location, but *how deep*—a function of proximity
101 to active vents, eruption frequency, prevailing wind patterns, and local topography.

102 East Java province alone encompasses seven major active centers: Kelud, Semeru,
103 Arjuno-Welirang, Bromo, Lamongan, Raung, and Ijen. The Brantas River basin—which
104 hosted the Singosari (1222–1293 CE) and Majapahit (1293– \sim 1500 CE) kingdoms—sits in
105 the depositional path of Kelud (35 km east), Arjuno-Welirang (25 km north), and Semeru
106 (60 km southeast). Kelud alone has produced 37 confirmed eruptions since 1000 CE
107 (Global Volcanism Program, 2024; Maeno et al., 2019).

108 In Central Java, Mount Merapi—one of the world’s most active stratovolcanoes—has
109 buried a cluster of 9th-century Hindu-Buddhist temples to depths of 3–7 m (Lavigne
110 and Thouret, 2000; Thouret et al., 2000). These buried temples (Sambisari, Kedulan,
111 Kimpulan) were discovered accidentally during modern construction and mining activities,
112 not through systematic archaeological survey.

113 2.2 The observable archaeological record in East Java

114 Our compilation of known archaeological sites in East Java (Section 3.1) identified 666
115 unique entries, of which only 391 (59%) have usable spatial coordinates. The dataset is
116 dominated by stone monuments (*candi*) from the Singosari and Majapahit periods (13th–
117 15th centuries CE) (Kinney et al., 2003). Earlier periods are poorly represented: pre-10th
118 century sites constitute less than 5% of the geocoded total.

119 This temporal distribution is consistent with two complementary explanations: (a) ar-

¹²⁰ chaeological survey has historically concentrated on the Singosari-Majapahit heartland
¹²¹ around Blitar, Malang, and Mojokerto; and (b) older sites are more deeply buried, hav-
¹²² ing accumulated more overburden, making them less likely to be discovered by surface
¹²³ methods.

¹²⁴ 2.3 Volcanic taphonomy

¹²⁵ Taphonomy—the study of post-mortem processes affecting the archaeological and fossil
¹²⁶ records—has a well-established literature in sedimentary and fluvial contexts (Schiffer,
¹²⁷ 1987). Volcanic taphonomy is comparatively understudied outside of catastrophic preser-
¹²⁸ vation events (Pompeii, Akrotiri/Santorini, Cerén in El Salvador) (Sigurdsson et al., 1985;
¹²⁹ Doumas, 1983; Sheets, 1992). These high-profile cases involved rapid burial by single
¹³⁰ eruptions, preserving sites in extraordinary detail.

¹³¹ The process we describe is fundamentally different: *cumulative* volcanic taphonomy,
¹³² where repeated small-to-moderate eruptions over centuries gradually bury sites layer by
¹³³ layer. This produces the same end result—sites invisible from the surface—but through
¹³⁴ a slower, less dramatic mechanism. The key distinction is that cumulative burial is spa-
¹³⁵ tially pervasive (affecting entire volcanic basins, not just eruption-proximal zones) and
¹³⁶ temporally continuous (ongoing, not one-time events).

¹³⁷ 2.4 The Kutai comparison

¹³⁸ The oldest known kingdom in the Indonesian archipelago is Kutai Martadipura (~400 CE),
¹³⁹ located in East Kalimantan—a region with zero active volcanoes across 544,000 km²
¹⁴⁰ (Vogel, 1918). Its Yupa inscriptions were found near the present ground surface.

¹⁴¹ The contrast is stark: Java has 45 active volcanoes in 129,000 km²; Kalimantan has
¹⁴² zero in 544,000 km². At the mean Javanese sedimentation rate of 4.4 mm/yr, a Kutai-era
¹⁴³ (~400 CE) inscription in the Malang basin would now lie beneath 4–10 m of volcanic
¹⁴⁴ overburden—invisible to any surface survey. The same inscription in Kalimantan sits
¹⁴⁵ exactly where it was placed 1,600 years ago, because there is no volcanic sedimentation
¹⁴⁶ to bury it.

147 Kutai’s apparent chronological primacy over Javanese polities of similar or greater
148 antiquity may therefore reflect differential preservation conditions rather than genuine
149 temporal precedence (Coedès, 1968; Miksic, 2004). The “oldest kingdom” is simply the
150 most *visible* one—a direct consequence of volcanic density asymmetry between islands.

151 3 Data and Methods

152 3.1 Archaeological site dataset

153 We compiled a database of known archaeological sites in East Java province from three
154 complementary sources. First, we queried the OpenStreetMap Overpass API for all fea-
155 tures tagged with `historic=*` within the Jawa Timur administrative boundary (bounding
156 box: 6.5–9.0°S, 111.0–115.0°E), yielding 281 geolocated features. Second, we queried the
157 Wikidata SPARQL endpoint for entities with coordinate property P625 within the same
158 bounding box, recovering 16 precisely located sites. Third, we scraped the Indonesian-
159 language Wikipedia article “Daftar candi di Indonesia” for 369 additional entries.

160 To increase spatial coverage, we geocoded the 369 coordinate-less entries using the
161 OpenStreetMap Nominatim API with progressive query refinement. Of 369 queries, 94
162 returned valid coordinates within the study area (25.5% success rate). After spatial
163 deduplication within a 100 m radius, the final dataset contains 666 unique site entries,
164 of which 391 have usable coordinates (58.7% geocoding rate). Within the East Java
165 analytical bounds, 383 geocoded sites were used for spatial analysis.

166 **Limitation:** The dataset is heavily biased toward stone monuments (*candi*) that
167 survived volcanic burial due to their monumental scale. Wooden settlements, which likely
168 constituted the vast majority of historical habitation, are systematically absent—precisely
169 the pattern predicted by the taphonomic bias hypothesis.

170 3.2 The Dwarapala calibration

171 The primary empirical anchor for our burial depth framework is the pair of Dwarapala
172 guardian statues at Candi Singosari, Malang Regency, East Java.

173 **Known parameters:**

- 174 • Construction date: ~1268 CE (reign of Kertanegara, Singosari Kingdom)
- 175 • Discovery date: 1803 CE, by Nicolaus Engelhard
- 176 • Physical dimensions: 370 cm seated height, ~40 tonnes, monolithic andesite
- 177 • Condition at discovery: “*separuh tubuh terpendam*” (half the body buried)
- 178 • Estimated burial depth: ~185 cm
- 179 • Elapsed time: $1803 - 1268 = 535$ years (or ~510 years using estimated completion)

180 **Calculated sedimentation rate:**

$$R = \frac{185 \text{ cm}}{510 \text{ yr}} = 0.36 \text{ cm/yr} = 3.6 \text{ mm/yr} \quad (1)$$

181 **Cross-validation:** Gunung Kelud erupted approximately 20 times between 1268 and
182 1803 CE. Documented VEI 3–4 eruptions deposit 2–20 cm of ash at Malang distance
183 (~35 km). Twenty eruptions at an average of ~5 cm per event would account for ~100 cm
184 of the 185 cm total burial. The remainder (~85 cm) is attributable to secondary remobi-
185 lization (lahars, reworked tephra), contributions from Semeru and Arjuno-Welirang, and
186 non-volcanic aggradation (Global Volcanism Program, 2024; Maeno et al., 2019). We note
187 that the rates reported here represent *total landscape aggradation* in volcanic terrain, not
188 pure primary tephra accumulation; for archaeological burial, however, the total rate is
189 the operationally relevant metric regardless of depositional source.

190 Figure 2 illustrates the Dwarapala burial timeline from construction to present.

191 3.3 Secondary calibration points

192 To assess whether the Dwarapala rate is a local anomaly or representative of a Java-wide
193 phenomenon, we compiled three additional calibration points from Central Java’s Merapi
194 volcanic system (Table 1).

Dwarapala Singosari: Empirical Calibration of Volcanic Sedimentation Rate

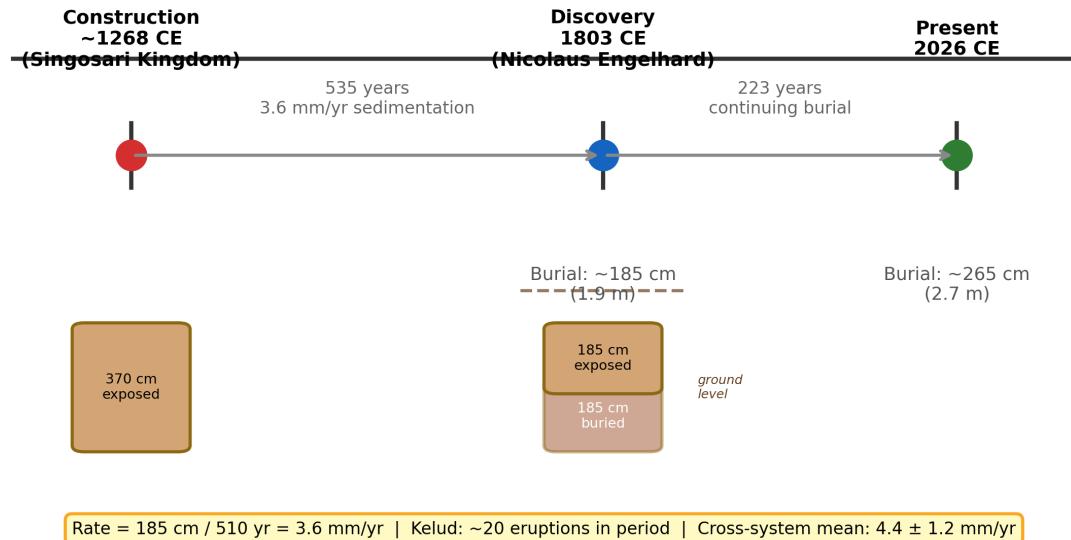


Figure 2: Dwarapala Singosari burial timeline. The statues were constructed \sim 1268 CE at full height (370 cm) and discovered in 1803 CE with approximately half (185 cm) buried by volcanic sedimentation, yielding a cumulative rate of 3.6 mm/yr. The cross-system mean from four calibration points is 4.4 ± 1.2 mm/yr.

Table 1: Empirical calibration points for volcanic sedimentation rates at archaeological sites in Java.

Site	Built (CE)	Discovered	Depth (cm)	System	Rate (mm/yr)	Source
Dwarapala Singosari	~1268	1803	~185	Kelud	3.5	BPCB Jatim
Candi Sambisari	~835	1966	500–650	Merapi	4.4–5.7	BPCB DIY
Candi Kedulan	~869	1993	600–700	Merapi	5.3–6.2	BPCB DIY
Candi Kimpulan	~900	2009	270–500	Merapi	2.4–4.5	Putra and Setyastuti (2019)

195 Across all four sites, the computed rates span 2.4–6.2 mm/yr with a mean of $4.4 \pm$
 196 1.2 mm/yr. The consistency across two independent volcanic systems—Kelud in East Java
 197 and Merapi in Central Java—demonstrates that mm/yr-scale burial of archaeological sites
 198 is systematic and Java-wide, not a local anomaly (Figure 3).

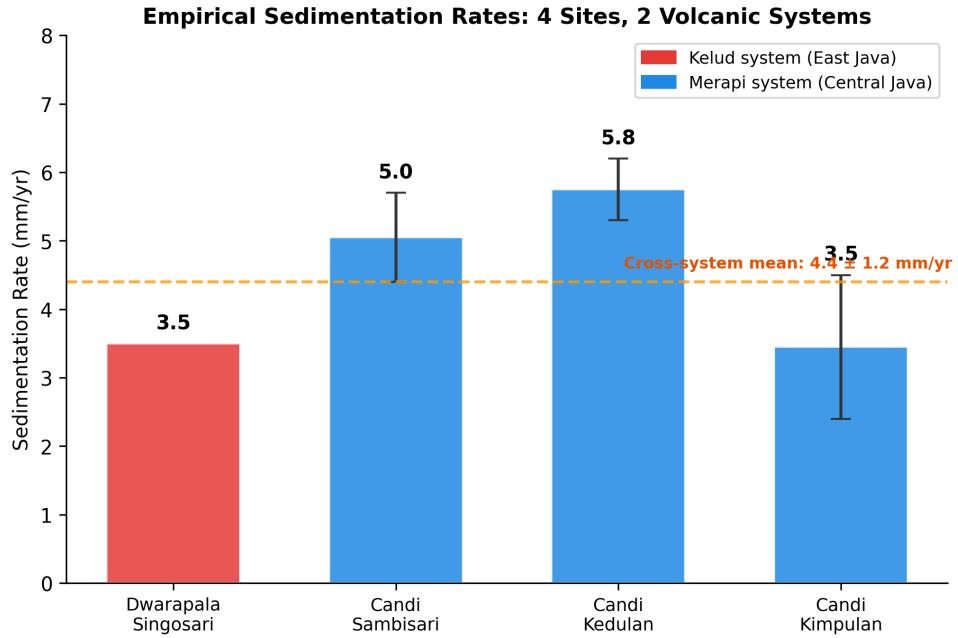


Figure 3: Empirical sedimentation rates from four archaeological sites across two volcanic systems. Error bars show the range from reported depth uncertainty. The cross-system mean is 4.4 ± 1.2 mm/yr.

199 3.4 Burial depth projection model

200 Using the empirically-derived rate range, we estimate expected overburden depth by era:

$$D(\text{era}) = R \times (T_{\text{present}} - T_{\text{era}}) \quad (2)$$

201 where R ranges from 2.4 to 6.2 mm/yr and $T_{\text{present}} = 2026$ CE. Results are presented
 202 in Figure 4.

203 3.5 Spatial analysis methods

204 **E004—Raw site density vs volcanic proximity.** We computed the minimum great-
 205 circle distance from each geocoded site to the nearest of seven reference volcanoes. Sites

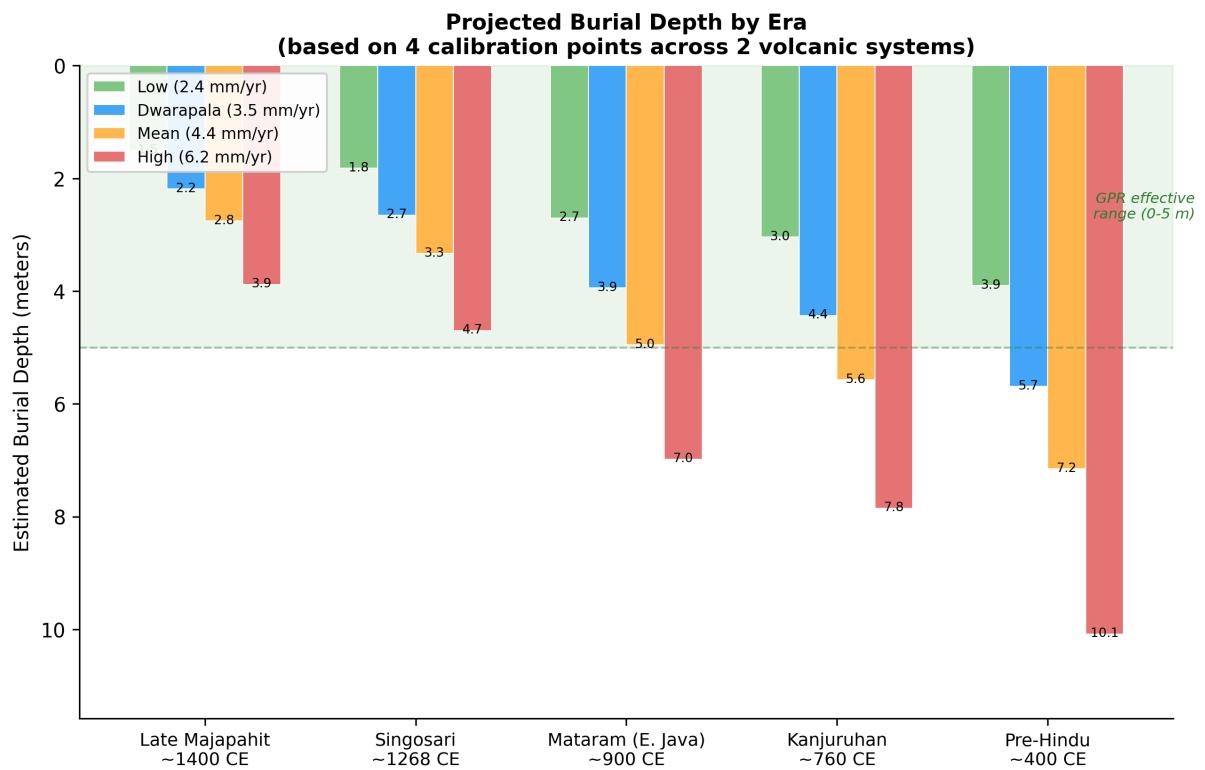


Figure 4: Projected burial depth by historical era using four empirically-derived sedimentation rates. The green band indicates the effective range of ground-penetrating radar in volcanic sediment (0–5 m). Kanjuruhan-era and earlier remains may exceed GPR detection limits.

206 were binned into seven distance bands (0–25, 25–50, 50–75, 75–100, 100–150, 150–200,
207 and 200+ km). Site density was expressed as sites per 1,000 km². Spearman’s rank
208 correlation between distance band midpoint and site density tests whether sites are found
209 preferentially near or far from volcanoes.

210 **E005—Terrain-controlled analysis.** To separate the effect of terrain suitability
211 from volcanic proximity, we constructed a terrain suitability index combining four DEM-
212 derived features (slope, elevation, TWI, and a river proximity proxy). The study area
213 was divided into a 25 km × 25 km grid (187 cells). For each cell, we computed the
214 residual between observed and terrain-predicted site count. Spearman correlation between
215 residual density and distance to nearest volcano tests the taphonomic bias hypothesis after
216 controlling for terrain preference.

217 4 Results

218 4.1 The Dwarapala calibration (RQ1)

219 The Dwarapala sedimentation calculation yields a rate of 3.6 mm/year (Section 3.2). This
220 rate is internally consistent with documented Kelud eruption histories, which account for
221 approximately 100 of the 185 cm total burial through direct tephra deposition alone. The
222 remaining 85 cm is attributable to secondary remobilization and contributions from other
223 volcanic systems.

224 The secondary calibration points yield rates of 2.4–6.2 mm/yr across the Merapi sys-
225 tem, consistently higher than the Dwarapala rate (3.5 mm/yr) from the Kelud system.
226 This difference is physically plausible: Merapi erupts more frequently than Kelud, and
227 the Central Java sites are closer to their volcanic source. The cross-system mean of
228 4.4 ± 1.2 mm/yr establishes that ongoing volcanic burial is a Java-wide phenomenon with
229 quantifiable, consistent rates.

230 4.2 Burial depth projections (RQ3)

231 Key projections for the Malang basin using the full rate range:

Table 2: Projected burial depth by era using empirically-derived sedimentation rates.

Era	Date (CE)	Elapsed (yr)	Low (2.4)	Dwarapala (3.5)	Mean (4.4)	High (6.2)
Late Majapahit	~1400	626	1.5 m	2.2 m	2.8 m	3.9 m
Singosari	~1268	758	1.8 m	2.7 m	3.3 m	4.7 m
Mataram (E. Java)	~900	1,126	2.7 m	3.9 m	5.0 m	7.0 m
Kanjuruhan	~760	1,266	3.0 m	4.4 m	5.6 m	7.9 m
Pre-Hindu	~400	1,626	3.9 m	5.7 m	7.2 m	10.1 m

232 These depths exceed standard archaeological surface survey capabilities (0–1 m) and
 233 approach or exceed the effective range of ground-penetrating radar (2–5 m in volcanic sed-
 234 ient) (Conyers, 2004; Goodman and Piro, 2013). Detection of Kanjuruhan-era or earlier
 235 remains will likely require deep GPR, borehole coring, or fortuitous exposure through
 236 modern construction.

237 4.3 Cautionary analysis: why distribution data cannot test H1

238 We conducted two spatial analyses to examine whether the distribution of known sites
 239 reflects taphonomic bias. In E004, analysis of 383 geocoded sites revealed a strong *negative*
 240 correlation between site density and distance from the nearest active volcano (Spearman’s
 241 $\rho = -0.955$, $p = 0.0008$, $n = 7$ distance bands; Table 3, Figure 5). Known sites cluster
 242 *near* volcanoes—the opposite of what a naive reading of the taphonomic bias hypothesis
 243 would predict.

Table 3: Site density by distance to nearest active volcano.

Distance Band (km)	Sites	Area (km ²)	Density (/1,000 km ²)
0–25	147	11,343	12.96
25–50	136	18,034	7.54
50–75	37	18,528	2.00
75–100	22	16,373	1.34
100–150	41	28,523	1.44
150–200	0	25,507	0.00
200+	0	73,740	0.00

244 In E005, a terrain-controlled analysis using a composite terrain suitability index (slope,
 245 elevation, TWI, river proximity) across 187 grid cells of 25 km × 25 km yielded Spear-
 246 man’s $\rho = -0.358$ ($p < 0.0001$). Terrain suitability explains part of the clustering, but
 247 the remaining signal reflects survey intensity concentrated on the Singosari-Majapahit

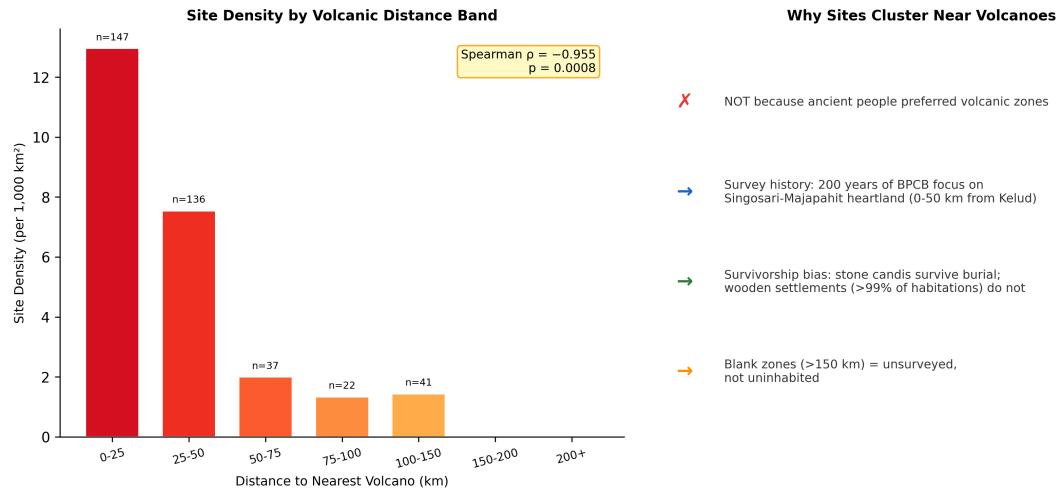


Figure 5: Left: Site density by volcanic distance band showing strong near-volcano clustering ($\rho = -0.955$). Right: Interpretive framework explaining why this pattern reflects survey history, not settlement preference.

248 heartland. Repeating both analyses after geocoding 94 additional sites (E006; increasing
 249 from 297 to 391 geocoded entries) produced negligible change: E004 ρ shifted from -0.991
 250 to -0.955 ; E005 ρ from -0.364 to -0.358 . The pattern is robust.

251 Critically, these results do *not* test the taphonomic bias hypothesis. The fundamental
 252 limitation is circular: the sites in our dataset are those that *survived* burial and were *dis-*
 253 *covered* by archaeologists. Both processes systematically favor low-burial-depth locations:

254 1. **Survivorship bias:** Stone temples dominate the dataset because they are large
 255 enough to protrude through meters of sediment. Wooden and bamboo structures—
 256 >99% of historical habitation—leave no surface trace after burial.

257 2. **Survey bias:** Indonesian archaeological survey has concentrated on regions of
 258 known historical kingdoms for over two centuries. “Blank” areas on the archaeo-
 259 logical map are blank because they are unsurveyed, not uninhabited.

260 3. **Discovery mechanism bias:** Most deeply buried temples were found accidentally
 261 during modern construction (Sambisari: farmer’s plow, 1966; Kimpulan: university
 262 excavation, 2009; Liangan: sand mining, 2008) (Putra and Setyastuti, 2019; Abbas,
 263 2016).

264 The taphonomic bias hypothesis therefore cannot be confirmed or denied from dis-

²⁶⁵ tribution data alone. It remains a hypothesis requiring subsurface investigation to test.
²⁶⁶ This is itself a contribution: the “archaeological absence” of pre-Majapahit evidence in
²⁶⁷ volcanic zones cannot be interpreted as evidence of cultural absence.

²⁶⁸ 5 Discussion

²⁶⁹ 5.1 Multi-point calibration as the core contribution

²⁷⁰ The central finding is not a statistical test of H1 but an empirical calibration: four inde-
²⁷¹ pendent archaeological sites across two volcanic systems yield cumulative sedimentation
²⁷² rates of 2.4–6.2 mm/yr (mean 4.4 ± 1.2 mm/yr). This consistency across sites separated
²⁷³ by hundreds of kilometers and sourced from different volcanic centers establishes that
²⁷⁴ ongoing burial is a systematic feature of volcanic Java.

²⁷⁵ The Dwarapala rate (3.5 mm/yr) sits at the lower end. Merapi-system sites show
²⁷⁶ higher rates (mean ~ 4.8 mm/yr), consistent with Merapi’s higher eruption frequency.
²⁷⁷ This variation is itself informative: burial rates are site-specific and depend on distance
²⁷⁸ from volcanic vents, topographic position, and local hydrology. A spatially-resolved burial
²⁷⁹ depth model must account for this heterogeneity.

²⁸⁰ 5.2 The informative “negative” result

²⁸¹ Our spatial analysis shows known sites clustering *near* volcanoes. We argue this is itself
²⁸² evidence for the hypothesis: the observable record maps *where we have looked* (Majapahit-
²⁸³ Singosari heartland, 0–50 km from Kelud/Arjuno) rather than *where sites exist*. Stone
²⁸⁴ monuments that dominate the dataset are precisely those large enough to resist burial—
²⁸⁵ the kind that would survive in high-deposition zones (Verhagen and Whitley, 2012).

²⁸⁶ The negligible change upon adding 29% more sites (E006) confirms the pattern is
²⁸⁷ saturated: the observable record has reached a ceiling imposed by survey history, not by
²⁸⁸ genuine settlement distributions.

289 **5.3 Practical implications for fieldwork**

290 The burial depth projections have direct operational implications:

- 291 • **GPR applicability:** Ground-penetrating radar is effective to ~2–5 m in volcanic
292 ash. Late Majapahit-era remains (1.5–3.9 m) are detectable; Kanjuruhan-era re-
293 mains (3.0–7.9 m) may exceed GPR range (Conyers, 2004).
- 294 • **Priority zones:** Areas with high terrain suitability AND high expected burial
295 depth are where settlement remains are most likely preserved yet invisible.
- 296 • **Discovery mechanism:** Accidental discoveries during construction illustrate that
297 deeply buried sites exist but systematic subsurface survey has never been conducted.

298 **5.4 The Kutai comparison (H2)**

299 At 4.4 mm/yr, a Kutai-era (~400 CE) artifact in the Malang basin would now lie be-
300 neath 7 m of overburden. The same artifact in Kalimantan (zero volcanism) sits at the
301 original ground surface. The perceived chronological primacy of Kutai over Javanese poli-
302 ties of similar antiquity may reflect this differential preservation, not genuine temporal
303 precedence (Coedès, 1968).

304 **5.5 Limitations**

- 305 1. **Calibration sample size:** Four points, while spanning two volcanic systems, re-
306 main a small sample. Rates carry uncertainty from imprecise construction dates
307 and variable depth measurements.
- 308 2. **Rate constancy:** We treat sedimentation as temporally uniform, smoothing over
309 episodic large eruptions. The Dwarapala rate is a cumulative average over ~510
310 years.
- 311 3. **Depth measurement uncertainty:** Published depths vary across sources (e.g.,
312 Sambisari: “5 m” to “6.5 m”). We report ranges rather than point estimates.

313 4. **Spatial extrapolation:** Rates derive from two specific volcanic basins. Extrapolation to other Java regions requires additional calibration.
314

315 5. **Survey bias unquantified:** We argue that survey history dominates distribution
316 data but cannot quantify this without systematic coverage maps.

317 5.6 Future work

318 Three follow-up studies are planned: (1) a machine learning settlement suitability model
319 independently tested against volcanic burial zones (Paper 2); (2) a spatially-resolved burial
320 depth model calibrated against all four anchor points (Paper 3); and (3) targeted GPR
321 survey at 5–10 locations in high-suitability, high-burial-depth zones to test for subsurface
322 anomalies.

323 6 Conclusions

324 We have presented a quantitative framework for estimating volcanic taphonomic bias in
325 the Indonesian archaeological record. Four empirical calibration points from two inde-
326 pendent volcanic systems yield cumulative sedimentation rates of 2.4–6.2 mm/yr (mean
327 4.4 ± 1.2 mm/yr), establishing that multi-meter burial is a systematic, Java-wide phe-
328 nomenon.

329 The spatial distribution of known sites in East Java cannot test the taphonomic bias
330 hypothesis because the observable record is dominated by survey history and survivorship
331 bias. This is itself a contribution: the “archaeological absence” of pre-Majapahit evidence
332 in volcanic zones cannot be interpreted as evidence of cultural absence.

333 Our projections indicate that Kanjuruhan-era (~760 CE) remains in the Malang basin
334 lie beneath 3.0–7.9 m of overburden, and pre-Hindu (~400 CE) remains beneath 3.9–
335 10.1 m. These depths exceed conventional survey capabilities and approach the limits
336 of ground-penetrating radar. Future investigation in volcanic Java should incorporate
337 subsurface detection methods in zones identified as having both high settlement suitability
338 and high expected burial depth.

339 Data Availability Statement

340 The archaeological site dataset, DEM derivatives, and analysis scripts are available at
341 [https://github.com/\[repository\]](https://github.com/[repository]) (to be made public upon acceptance). Raw DEM
342 data from Copernicus GLO-30 are publicly available.

343 Code Availability Statement

344 All analysis scripts (E001–E006) are available in the project repository under `experiments/`.

345 Author Contributions

346 Conceptualization, M.A.; methodology, M.A.; software, M.A.; validation, M.A.; formal
347 analysis, M.A.; investigation, M.A.; data curation, M.A.; writing—original draft, M.A.;
348 writing—review and editing, M.A.; visualization, M.A.

349 Funding

350 This research received no external funding.

351 Conflicts of Interest

352 The author declares no conflict of interest.

353 Acknowledgments

354 The author thanks the Global Volcanism Program (Smithsonian Institution) for open
355 eruption data, and the OpenStreetMap and Wikidata communities for structured geospa-
356 tial data.

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