# A Late Miocene Reduction in the Spatial Breadth of Marine Tephra Occurrence: A Five-Basin Test of the Volcanic-Pulse Hypothesis

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## Abstract

Episodic "pulses" of explosive volcanism have been widely invoked to explain climatic and biotic events across the Phanerozoic, but rarely tested against a high-resolution, multi-basin occurrence record. I tested for non-random temporal clustering of explosive volcanism using VOLCORE, a compilation of 34,696 visible tephra layers recovered by ocean drilling from across the world's ocean basins. Using a site-presence statistic designed to resist distortion from unusually prolific sites and correcting for sampling effort via independently dated age-control points, I find no evidence for discrete global pulses of anomalously high activity: every candidate excess identified during exploratory analysis failed to replicate across basins or did not survive correction for a bin-edge artifact. I instead find a robust, inter-basin reduction in the spatial breadth of tephra occurrence—the fraction of independent drill sites recording any ash layer—spanning approximately 6.5-13 Ma. This narrower geographic footprint of tephra occurrence is present in the West Pacific, East Pacific, Indian Ocean, and Southern Ocean, and in the Atlantic once one geologically atypical site is excluded and survives block-bootstrap resampling at the level of independent drilling expeditions. A parallel analysis using raw occurrence counts rather than site presence does not produce the same signal, a discrepancy traced to a single expedition supplying over half of one region's window-period layers from a single locality. I interpret this as evidence that the marine tephra record does not support discrete volcanic pulses, but does support a genuine, multi-basin decline in the spatial extent of explosive volcanism during the Late Miocene, distinct from any change in eruptive magnitude.

## 1. Introduction

The hypothesis that explosive volcanism occurs in discrete temporal pulses at a global scale, rather than at a constant background rate, has a long history and continues to be invoked to explain specific climatic and biotic events. A mechanistic link between Late Ordovician super-eruptions and the onset of Hirnantian icehouse conditions has been argued from tephra geochronology (Sell, 2011; Sell et al., 2013; Buggisch et al., 2010) and modeled quantitatively (Longman et al., 2021). At the scale of the entire Phanerozoic, a ~27.5-Myr periodicity in coordinated geological events, including pulses of intraplate volcanism, has been proposed from a curated compilation of well-dated events (Rampino et al., 2021). Most recently, intensified Central Andean explosive volcanism has been proposed as a driver of Late Miocene ocean fertilization and global cooling (Carrapa et al., 2026).

These studies operate at very different resolutions: single-interval case studies, or coarse, curated compilations of the largest, best-dated eruptions. A test built directly from a large, high-resolution compilation of individual tephra occurrences—rather than a short list of curated "major" events—requires a large, well-sampled occurrence dataset; explicit correction for uneven sampling effort; and a way to tell a genuine multi-region signal apart from one driven by a few prolific sites or by analytical choices that are not truly independent of the data. I apply such a test to VOLCORE (Mahony et al., 2020), the most complete existing compilation of marine tephra occurrences, as a proof-of-concept before any attempt to extend comparable analysis to lower-resolution, pre-Cenozoic land-based tephra compilations.

Direct tests using compiled tephra-layer counts are less common. Marine tephra records from Japan show a documented increase in large-magnitude eruption rates at ~8 Ma, attributed to a change in subduction dynamics (Mahony et al., 2016). This is the clearest existing regional precedent for tephra-count-based rate change in the interval examined here. At the global scale, temporal clustering of eruption timing has been proposed from historical and Holocene eruption catalogs (Gusev, 2008; De la Cruz-Reyna, 1991), though such catalogs are known to suffer substantial, magnitude- and time-dependent under-recording (Deligne et al., 2010; Kiyosugi et al., 2015). This is a bias with a similar structure to the sampling-effort problem addressed here for marine drilling cores. The question of whether arc volcanism is globally synchronous at all has itself been directly challenged (Cambray and Cadet, 1996), a skepticism this analysis's own results support.

## 2. Methods

VOLCORE_2021 (Mahony et al., 2021) compiles 34,696 visible tephra layers from Deep Sea Drilling Project, Ocean Drilling Program, and International Ocean Discovery Program cores, with ages estimated for 29,485 of them. I restricted analysis to ages 0-150 Ma (the approximate age limit of surviving oceanic crust) and to five ocean regions with adequate site density: West Pacific, East Pacific, Atlantic, Indian Ocean, and Southern Ocean. Caribbean, Mediterranean, and Gulf of Mexico were assessed and found too data-sparse to support a meaningful test.

The premise that apparent event-bed frequency is not a fixed property of a stratigraphic record but depends on how much of that record has actually been sampled and dated is a general one, established for stratigraphic completeness broadly by Sadler (1981) and developed further by Sadler and Strauss (1990). The effort-normalization approach used here is a direct application of that principle to a compiled marine tephra occurrence dataset. Age-depth control points, derived from biostratigraphy, magnetostratigraphy, and isotope stratigraphy and independent of the tephra record itself, served as the sampling-effort proxy. For each region, a baseline site-presence prevalence—the fraction of independent-site, time-bin opportunities with at least one tephra occurrence—was established across the full 0-150 Ma record using uniform, externally-fixed 0.25-Myr time bins. Bin edges derived from a region's own control-point distribution were tested during exploratory analysis and found capable of manufacturing spurious sustained significance not reproduced by externally-fixed bins; all reported results use fixed bins only. Multiple boreholes at one physical site were collapsed to a single site identifier throughout.

Candidate windows of anomalous prevalence were tested for (1) geographic concentration within a basin, using site latitude, longitude, and LaMEVE volcanic source region (Crosweller et al., 2012); (2) replication in independently sampled basins, using each basin's own baseline; and (3) robustness to non-independence among tephra layers, via block-bootstrap resampling at the level of individual drilling expeditions (2000 resamples), the more conservative of two resampling units tested (the other being physical site). The initial exploratory scan that led to the dismissed result below, and the additional windows examined, are reported in full in the Results, in the interest of transparency about the analytical process.

An initial analysis using raw tephra layer counts per equal-effort bin, tested against effort-proportional expectation with a chi-square goodness-of-fit statistic, produced very large apparent deviations (chi-square = 21,925, df = 69, full 0-150 Ma range). Inspection showed the largest-residual bins were driven by individual drill holes that contributed a disproportionate share of layers. In the most extreme case, two holes associated with Site 3573/3574 accounted for 65-

95% of tephra count in three separate bins spanning 22.8-46.5 Ma. Because a single prolific locality is not evidence of a globally synchronous process, raw layer counts normalized only by effort were judged inappropriate as the primary test statistic, motivating the site-presence approach used throughout.

The Atlantic 6.5-10.0 Ma result depended on a similar check. Site 907 (69.2 degrees N, Norwegian-Greenland Sea, at the junction of the Iceland mantle plume and the Mid-Atlantic Ridge) was found to contribute 10 of the Atlantic's 17 total window-period site-bin presences. Site 907 was flagged using the same disproportionate-single-site-contribution criterion applied throughout this analysis, independent of what direction excluding it would move the result. This has independent geological justification for exclusion as an atypical, persistently active hotspot-ridge intersection distinct from the broader passive-margin Atlantic. With Site 907 included, Atlantic 6.5-10.0 Ma prevalence was 19.8% against a 22.5% baseline ($z = -0.61$, not significant); excluding it, prevalence was 9.3% ($z = -2.73$, significant), matching the direction and approximate magnitude of the other four basins.

## 3. Results

An initial scan of the West Pacific record using the equal-effort quantile bins described above identified a sustained-looking deficit across eleven consecutive bins spanning approximately 1.7-5.0 Ma (pooled site-presence prevalence 18.6% versus the 38.0% basin-wide baseline). This result was initially considered a finding and appeared to replicate in the East Pacific when the identical West Pacific bin edges were applied there (pooled prevalence 13.6% versus 27.5% baseline).

Before testing this result against a third basin, the West and East Pacific basins were re-examined using uniform, externally-fixed 0.25-Myr bins spanning 0-10 Ma, rather than the data-derived equal-effort bin edges. Under this fixed binning, the 1.7-5.0 Ma interval showed no sustained pattern of significant deficit in either basin: standardized residuals were scattered and mostly within +/-1.5, with none of the eleven original bins reaching the $|z| > 2$ threshold. The most likely explanation is that the equal-effort quantile bin edges, being derived from each basin's own control-point distribution, happened to align with local sampling noise in a way not reproduced by an externally-fixed bin scheme unrelated to the underlying data. This finding is accordingly dismissed; it is reported here, rather than silently omitted, because it was an intermediate result of this analysis before further testing superseded it (Fig. 5).

A second methodological error was identified and corrected during the same re-examination. Pooling across a wide age window by asking whether a site has a tephra occurrence "anywhere" within that window is not statistically comparable to a baseline computed from many narrow bins. This produces misleadingly different results depending on how pooling is performed. All reported pooled statistics sum the site-bin opportunity/presence pairs at a fixed, consistent bin width (0.25 Myr), rather than collapsing a wide range into a single presence-anywhere indicator.

The initial equal-effort-bin scan also showed an apparent excess at 22.8-32.9 Ma (28 of 49 independent West Pacific sites showing tephra occurrence, 57.1%, versus the 38.0% baseline). This apparent excess was checked for geographic concentration within the West Pacific and found to span multiple independent volcanic arc systems and a wide latitudinal range (39 degrees S to 51 degrees N), which was initially taken as evidence against a single-locality artifact. However, the same window tested in the East Pacific, using its own 27.5% baseline, showed no significant departure (24 opportunity-sites, 6 with tephra, prevalence 25.0%, $z = -0.27$). This apparent excess was not examined further and is not part of the reported result.

This re-examination further identified a distinct, previously unflagged deficit at 6.5-10.0 Ma, present independently in the West Pacific (site-presence prevalence 18.3% versus a 38.0% basin-wide baseline) and the East Pacific (15.2% versus 27.5%). Both results are geographically broad, spanning the full latitudinal range of each basin and multiple independent volcanic arc systems (Fig. 2). The same window was tested in the Indian Ocean, Southern Ocean, and Atlantic. Indian Ocean (4.4% versus 27.7%) and the Southern Ocean (10.3% versus 32.8%) independently showed the same deficit. The Atlantic showed no significant deficit at face value (19.8% versus 22.5%), but this depended on a single site (Site 907, at the Iceland mantle plume-Mid-Atlantic Ridge junction) that contributed 10 of 17 total window-period presences. Excluding this geologically atypical site yields a clear deficit (9.3%), giving all five tested basins the same signal (Fig. 1; Table 1).

Block-bootstrap resampling at the drilling expedition level confirmed the West and East Pacific deficits, in both the original 6.5-10.0 Ma window and an alternative 9.0-13.0 Ma window (identified during a subsequent robustness check, described below), with all four 95% confidence intervals excluding the respective regional baseline (Fig. 3; Table 1). A parallel test using raw occurrence counts rather than site presence, resampled at the same expedition level, did not show a significant reduction in either region. This discrepancy traces to Expedition 350, which supplied 983 of 1756 West Pacific window-period layers (56.0%) from a single site (1.9% of the window's 53 contributing sites; Fig. 4), IODP Site U1437, independently documented as recording orbitally-paced, climate-modulated explosive volcanism at high resolution (Schindlbeck et al., 2018). This is consistent with genuinely elevated local tephra preservation rather than a data artifact—but it is exactly the kind of single-site intensity a raw-count statistic cannot distinguish from a basin-wide signal. A raw-count statistic is directly exposed to this kind of single-locality dominance; the site-presence statistic used throughout is structurally insensitive to it, since a site is counted as present once regardless of layer abundance.

For the 6.5-10.0 Ma window, the West Pacific site-presence spans 45.5 degrees S to 51.5 degrees N across the full basin longitude range and six distinct LaMEVE volcanic source regions (Crosweller et al., 2012). The East Pacific spans 46.6 degrees S to 57.0 degrees N across the full East Pacific longitude range and six distinct regions. In both basins, suppressed prevalence is distributed across most represented regions rather than concentrated in one, which argues against a single-arc-system explanation.

For the 22.8-32.9 Ma excess (subsequently found not to replicate), sites with tephra spanned a similarly broad range (39 degrees S to 51 degrees N, 123-179 degrees E longitude) across four distinct volcanic regions, illustrating that passing a within-basin geographic-breadth check is not equivalent to surviving cross-basin replication.

As an internal robustness check, an independently-designed reanalysis was performed in a separate session with no access to the analysis above, working from the raw VOLCORE workbook only, given the open-ended brief of testing for non-random temporal clustering in the tephra record. This reanalysis restricted itself to the best-sampled interval (0-5 Ma; 15,001 layers, 390 sites) and used core-meters of recovered section per 100-kyr time bin, derived from freshly-built per-hole age-depth models, as an independent effort proxy rather than control-point counts.

After normalizing by this proxy, the reanalysis found significant overdispersion relative to a Poisson null (Pearson dispersion approximately 24, runs test $z = -4.51$, p approximately 7x10^-6, with slowly-decaying lag-1 through lag-5 autocorrelation indicating persistent, non-white-noise temporal structure). This result was robust to removing the three most heavily-sampled IODP expeditions in the West Pacific. Splitting into three independent regions (West Pacific, East Pacific, Mediterranean+Atlantic combined), two of three region-pair correlations in the timing of excess/deficit periods were statistically significant (West Pacific-Mediterranean+Atlantic $r = 0.61$, $p < 0.001$; East Pacific-Mediterranean+Atlantic $r = 0.49$, $p = 0.021$); West Pacific-East Pacific was positive but not significant ($r = 0.36$, $p = 0.21$).

This reanalysis targeted a different window (0-5 Ma, general clustering) than the 6.5-10.0 Ma or 9.0-13.0 Ma windows discussed above and should be read as a complementary corroboration that real, effort-corrected temporal structure exists in this record and survives an independently-chosen effort proxy and expedition-exclusion check, not as a direct replication of either specific window.

A second reanalysis was performed in a separate session, again with no access to prior results, specifically directed at testing the 6.5-10.0 Ma window in West and East Pacific. This reanalysis used raw occurrence counts (an exact conditional-binomial rate-ratio test) rather than site presence, built independent per-hole age-depth models from raw (non-interpolated) tie points, tested two effort proxies (depth-based and time-based) and three baseline definitions, and resampled at the level of individual drilling expeditions via cluster bootstrap.

Under this approach, no significant reduction survived expedition-level resampling in either the West or East Pacific under any tested combination of effort proxy, baseline, or occurrence definition. Where the exact test showed nominal significance in West Pacific (depth-normalized proxy), it pointed toward a local increase rather than a decrease, and this reversed further upon excluding a single dominant expedition (Expedition 350, 64.9% of window occurrences). This reanalysis suggested that if a genuine low-occurrence interval exists in West Pacific, it is better centered on approximately 9.0-13.0 Ma than 6.5-10.0 Ma.

As noted above, this single-site concentration (Expedition 350) is exactly what the site-presence statistic is structurally insensitive to. To test whether the site-presence result itself survives the stricter expedition-level resampling scheme used by this reanalysis, the analysis was rerun with expedition-level (rather than site-level) block-bootstrap resampling (2,000 resamples), for both the original 6.5-10.0 Ma window and the alternative 9.0-13.0 Ma window this reanalysis proposed. Results are reported in Table 1 and Figure 3. In all four combinations, the 95% confidence interval on pooled site-presence prevalence excludes the regional baseline, with the 9.0-13.0 Ma window showing an equal or somewhat larger deficit than 6.5-10.0 Ma in both regions.

## 4. Discussion

The site-presence approach used throughout this analysis—recording whether a site shows any tephra occurrence in a given interval, independent of how many individual layers it contains—parallels long-standing field practice in stratigraphic mapping, where geologists assess the spatial distribution of ash-bearing versus ash-barren exposures across a region rather than tallying beds within the most accessible or thickest sections. A statistic built from raw bed counts across available outcrop would be similarly vulnerable to distortion by one exceptionally prolific, well-exposed, or well-studied locality, as demonstrated quantitatively above.

The robust signal identified here is a reduction in the geographic extent of tephra occurrence—fewer independent sites recording any ash at all—rather than a demonstrated reduction in total eruptive or depositional magnitude, which a raw-count-based test remains better positioned to evaluate once it is free of distortion from a single-locality. This reduced spatial breadth interval is best characterized as a broad ~6.5-13 Ma stretch rather than a sharply bounded window. Basins showing this signal span circum-Pacific subduction arcs, a passive-margin/mid-ocean-ridge system, and basins bordering multiple independent plate systems, arguing against a regional tectonic explanation specific to any one setting.

The Japan-specific rate increase reported by Mahony et al. (2016) at ~8 Ma—within the broader West Pacific basin examined here—illustrates the same point directly. A rate increase attributed to one arc system's subduction dynamics is not inconsistent with a reduction in the fraction of basin-wide sites recording any tephra. This finding does not conflict with Carrapa et al. (2026), who link intensified Andean explosive volcanism (peaking ~8.4 to ~7 Ma) to Southern Ocean fertilization and cooling. Their strongest evidence—productivity spikes tied to specific dated eruptions—falls mostly at 6 and 4.5 Ma, which is largely outside the window identified here and is consistent with locally intensified activity at a single, well-studied arc system. More broadly, beyond the range of single, intra-basin systems, this analysis found no support for inter-basin discrete positive pulses anywhere in the tested record, a result that pushes back against the pulse-based framing common in this literature (Rampino et al., 2021; Sell, 2011). VOLCORE is close to the best-available case for detecting a signal like this: radiometrically anchored ages, dense global coverage, and a method that survived repeated adversarial testing. This alone makes it unlikely that a comparable signal would be recoverable from lower-resolution, pre-Cenozoic, land-based tephra compilations, where age control is coarser and sampling biases are likely more severe. Such biases have been a documented concern for claims of temporal periodicity in the geological record since at least Raup and Sepkoski (1984). A causal link between volcanism and climate is not assumed here. In some studies, an increase rather than a decrease in explosive volcanism has been proposed as a driver of icehouse conditions (Soreghan et al., 2019, for the late Paleozoic). This underscores that no single expected relationship should be assumed a priori between eruption frequency and climate state. A further caution is warranted on the effort-normalization approach itself as applied to event beds: recent work on Holocene paleofire records, another archive of discrete event beds subject to sampling and completeness biases, has shown that rate-versus-duration relationships can partly reflect spurious self-correlation, since accumulation rate is mathematically a ratio with duration in its denominator (Wilkinson and Vachula, 2023). The site-presence statistic used throughout this analysis is structurally different from a rate-duration regression in this respect—it records a binary outcome per site-bin, not a ratio tested against its own denominator. This distinction is a reason for the specific approach taken here, not a guarantee against every possible form of preservation-driven bias. As such, two related limitations are worth stating directly rather than leaving implicit. First, the baseline used throughout is empirical, drawn from the same compiled dataset being tested, rather than an independently constructed mechanistic null that separately models formation and subsequent preservation probability through time, of the kind used to define metallogenic epochs in ore-deposit records (Wilkinson and Kesler, 2009); an empirical baseline cannot rule out biases shared across the whole dataset. Second, the control-point effort proxy measures the dating and sampling intensity, not the physical availability of appropriately-aged oceanic crust itself, which declines with age independent of drilling effort as older crust is progressively subducted.

Standardizing for sampling intensity does not guarantee that this deeper availability bias is fully removed, a distinction previously shown to matter for outcrop-area effects on terrestrial diversity records even after it is accounted for (Wall et al., 2009).

## 5. Conclusions

Explosive volcanism recorded in the global marine tephra record does not show discrete positive pulses under rigorous multi-basin testing, but does show a robust, cross-basin reduction in the spatial or geographical breadth of tephra occurrence during the Late Miocene (~6.5-13 Ma), distinct from any demonstrated change in eruptive magnitude. These results are not employed toward discerning causal links in either direction. In other words, the potential causes of a globally reduced geographic footprint of tephra were not tested, explored, or implied. Likewise, any links with the biosphere and Earth's climate system are not assumed here. The explicit goal was to test whether tephra occurrence records can tell us anything about the existence of real and statistically robust pulses of explosive volcanic activity. The goal was achieved with the finding that global pulses are not readily apparent in the best-preserved records. This was unexpected because simplistic raw counts of tephra occurrence binned by age had previously suggested clear clustering of tephra-rich time intervals. Furthermore, another unexpected result showed the opposite of the tested clustering, which is a period of decreased tephra occurrence across the Earth's oceans. These results should be helpful toward informing the design of any future test of volcanic episodicity in lower-resolution compilation records.

## Acknowledgments

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## Figures

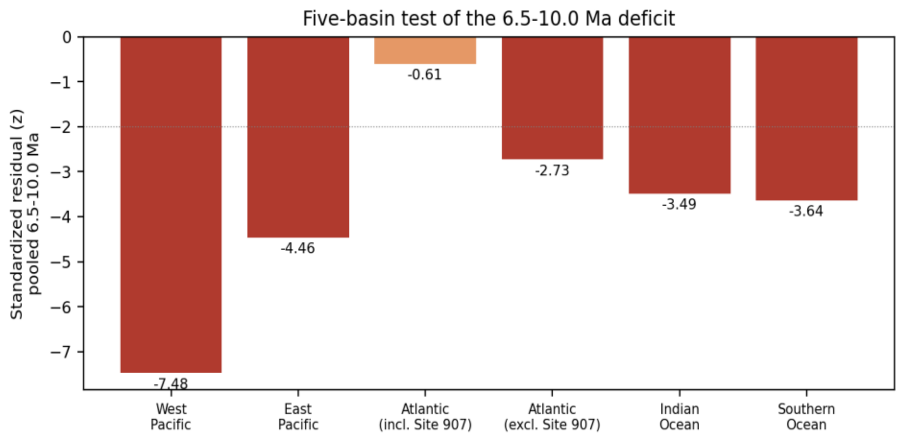


*Figure 1. Standardized site-presence prevalence, 6.5–10.0 Ma, across five ocean basins, relative to each basin's own baseline. Atlantic shown with and without Site 907.*

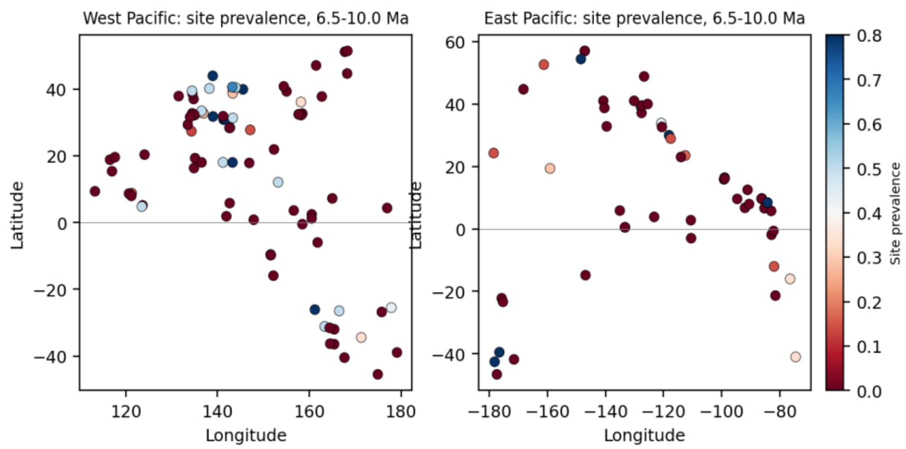


*Figure 2. Per-site prevalence within the 6.5–10.0 Ma window, West Pacific and East Pacific, showing broad geographic distribution across multiple independent volcanic arc systems.*

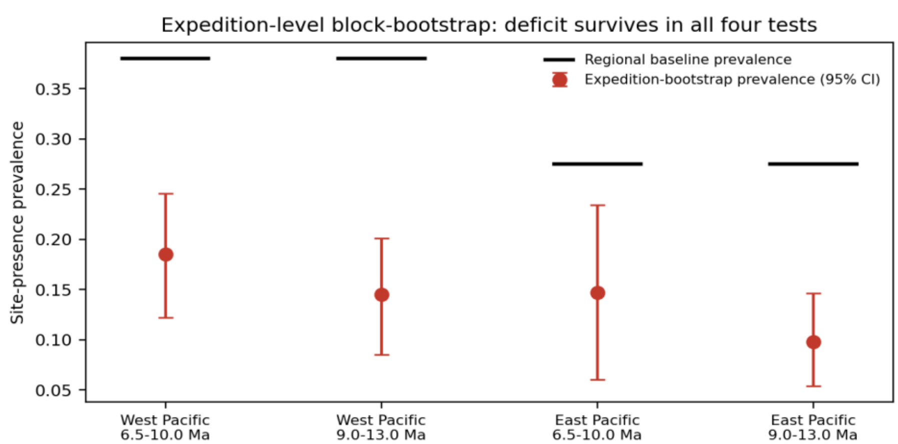


*Figure 3. Expedition-level block-bootstrap 95% confidence intervals on site-presence prevalence, West and East Pacific, both candidate windows, against regional baseline (black bars).*

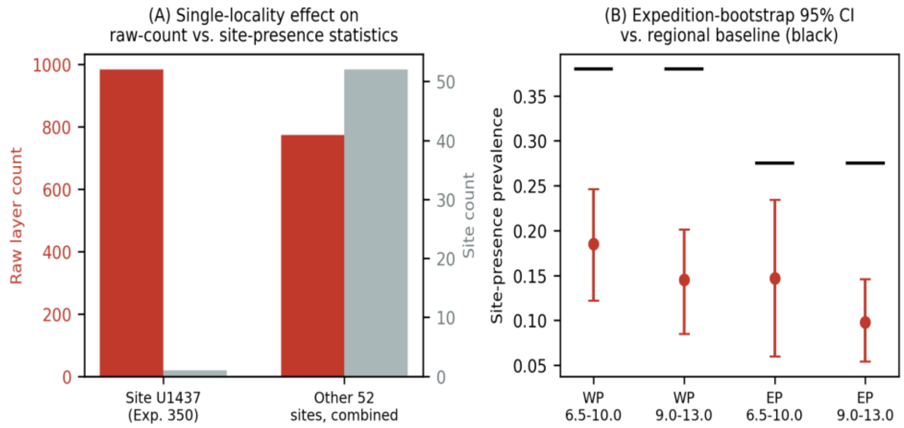


*Figure 4. (A) Expedition 350 supplies the majority of raw West Pacific window-period tephra layers from a single site, illustrating vulnerability of a raw-count statistic; contributes one data point among 53 to a site-presence tally. (B) Expedition-bootstrap validation, as in Figure 3.*

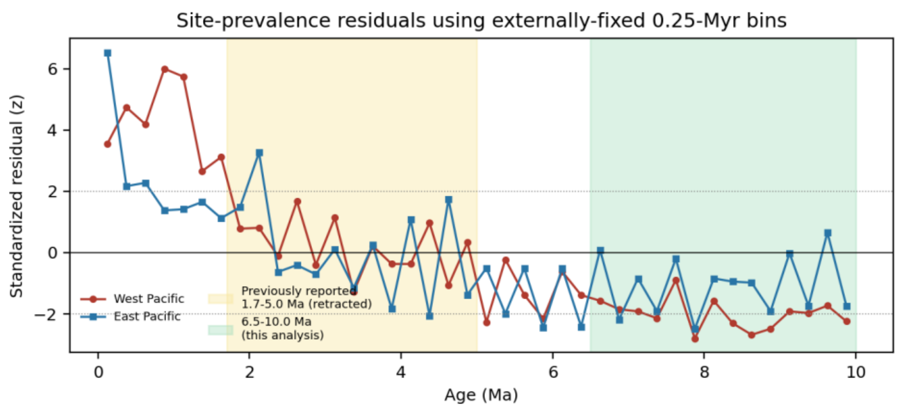


*Figure 5. Standardized site-prevalence residuals using externally-fixed 0.25-Myr bins, West and East Pacific, 0–10 Ma. The initial candidate window at 1.7–5.0 Ma (yellow) is not supported under this stricter test; a distinct deficit at 6.5–10.0 Ma (green) is visible in both basins.*

## Table 1. Summary of site-presence results by basin and window.

| Basin / window | Prevalence | Baseline | Result |
|---|---|---|---|
| West Pacific, 6.5–10.0 Ma | 18.3% | 38.0% | Deficit, CI excludes baseline |
| West Pacific, 9.0–13.0 Ma | 14.7% | 38.0% | Deficit, CI excludes baseline |
| East Pacific, 6.5–10.0 Ma | 14.7% | 27.5% | Deficit, CI excludes baseline |
| East Pacific, 9.0–13.0 Ma | 10.2% | 27.5% | Deficit, CI excludes baseline |
| Indian Ocean, 6.5–10.0 Ma | 4.4% | 27.7% | Deficit |

Southern Ocean, 6.5–10.0 Ma | 10.3% | 32.8% | Deficit

Atlantic, 6.5–10.0 Ma (incl. Site 907) | 19.8% | 22.5% | Not significant

Atlantic, 6.5–10.0 Ma (excl. Site 907) | 9.3% | 22.5% | Deficit

## Data Availability

VOLCORE_2021 is freely available via PANGAEA (doi:10.1594/PANGAEA.934363). The complete analytical code used to produce Table 1 and Figures 1–5 is provided as a supplementary file (volcore_analysis.py) accompanying this article at Zenodo (10.5281/zenodo.21476855).

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