Spatial Organisation as a Diagnostic Signal:

A Sigma-Scale Synthesis of Global Shear Geometry, Surface Reorganisation, and Early Human Occupation

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Abstract

A recurring challenge in Earth system science is that large-scale geometric or kinematic hypotheses often fail conventional tests based on global mean alignment, despite exhibiting visually and spatially coherent structure. This has led to a persistent ambiguity: whether such coherence reflects meaningful long-wavelength organisation or coincidental patterning amplified by human perception.

Here we synthesise results from three independent quantitative studies examining (i) analytically derived global shear geometry and present-day stress orientations, (ii) equilibrium sea-level geometry and viscoelastic surface reorganisation, and (iii) the spatial and temporal distribution of early *Homo* and early civilization sites. Rather than aggregating disparate statistical tests through heterogeneous metrics, we re-express all null-controlled results on a common Gaussian sigma (σ) scale.

This synthesis reveals a consistent hierarchy. Scalar or global-average metrics remain statistically non-diagnostic ($\lesssim 1\sigma$), while measures of spatial organisation, clustering, and stability repeatedly reach multi-sigma significance (~ 3–5σ) across independent geophysical and archaeological datasets. Temporal phase alignment emerges as a weaker but consistent secondary signal (~ 2–3σ).

The convergence of independent lines of evidence at comparable sigma levels supports a cautious but robust conclusion: persistent long-wavelength geometric organisation is detectable in Earth's stress field, mantle structure, surface adjustment history, and long-term human occupation patterns, even where global mean fits fail. This work argues that spatial organisation itself constitutes a primary diagnostic signal, deserving equal standing with scalar alignment in evaluating large-scale Earth system hypotheses.

Keywords

Spatial organisation; True polar wander; Global shear geometry; Viscoelastic relaxation; Sea-level equilibrium; Archaeological spatial statistics; Sigma significance

1 Introduction

Large-scale organisation in Earth systems is frequently inferred from geometry before it is demonstrated statistically. Sweeping arcs, basin chains, coherent stress orientations, and geographically persistent zones of stability recur across tectonic, geomorphic, and sedimentary contexts. Yet when these patterns are tested using conventional global-average metrics—mean angular misfit, global correlation coefficients, or least-squares residuals—they often fail to outperform null models.

This mismatch between visual coherence and scalar statistical weakness has contributed to a long-standing methodological tension. Either the apparent organisation is dismissed as coincidental, or the statistical tests are judged ill-suited to the phenomenon under investigation. The present synthesis adopts a third position: that the dominant signal of long-wavelength organisation is not improved global alignment, but *spatial structure itself*.

The three studies synthesised here were developed independently, employ distinct datasets, and address different aspects of Earth system behaviour. Nevertheless, they share two defining features. First, each introduces a physically motivated, analytically or algorithmically defined geometric framework that is not tuned to the data under evaluation. Second, each finds that while scalar or global-average metrics are weak, measures of spatial organisation and stability are statistically robust under explicit null testing.

The purpose of this paper is not to re-argue the individual results, which are documented elsewhere, but to integrate them into a unified evidentiary framework. By expressing all results on a common Gaussian sigma scale, we aim to clarify which signals are weak, which are strong, and—critically—*which kinds of signals recur across independent domains*.

2 Why Sigma, and Why Organisation

In the physical sciences, Gaussian sigma (σ) values provide a common language for comparing evidentiary strength across experiments, datasets, and disciplines. While the specific statistical tests employed in the constituent studies differ—permutation-based Moran's I, Monte Carlo spatial randomisation, axial misfit nulls, and temporal phase randomisation—their results can be consistently mapped onto sigma equivalents.

This translation reveals a systematic asymmetry. Tests designed to assess global or scalar agreement between models and observations consistently cluster below 1σ, indicating that the proposed frameworks do not succeed by trivially reducing global error. In contrast, tests that evaluate the *organisation* of misfit, stability, or clustering in space—and in some cases time—repeatedly exceed 3σ.

This pattern suggests that global averaging suppresses precisely the information content carried by long-wavelength structure. Spatial organisation is not a residual artefact; it is the primary diagnostic signal. Recognising this distinction is essential if physically meaningful but non-local Earth system behaviours are to be detected rather than averaged away.

In the sections that follow, we first summarise the constituent methodologies in a harmonised form, then present a sigma-ladder synthesis figure that orders all results on a common evidentiary scale, before discussing the implications for Earth system dynamics and long-term habitability.

3 Harmonised Methodological Framework

Although the three constituent studies address distinct questions—stress geometry, surface reorganisation, and human occupation—they share a common methodological architecture. Each begins with a physically motivated geometric or kinematic construction, evaluates its correspondence with independent observational data, and assesses significance using explicit null models designed to destroy organisation while preserving sampling structure. This section summarises that shared logic and clarifies the points of divergence.

3.1 Analytically Prescribed Geometry

In all three cases, the primary geometric framework is defined *a priori*, without tuning to the observational datasets used for evaluation.

In the shear-trajectory study, a global surface shear field is derived analytically from a prescribed class of true-polar-wander–like rotational geometries using a Vening Meinesz–style kinematic formulation. The resulting shear trajectories, conjugate nets, and invariant contours are closed-form solutions on the sphere and are not fitted to stress observations [**?**].

In the equilibrium sea-level study, the reference geometry is the analytically computed equilibrium sea surface implied by centrifugal potential following a large-amplitude inertial reorientation. The zero-anomaly contour separating net emergence from net submergence is treated as a physically defined stability boundary rather than a coastline or climatic proxy [**?**].

In the return-model comparison, both the continuous and event-guided return curves are constructed independently of archaeological data. The event-driven timeline is curated from late-glacial and early Holocene geophysical and climatic events, with archaeological timing explicitly excluded to avoid circularity [**?**].

In all cases, the geometric or temporal structure is fixed prior to any comparison with observational datasets.

3.2 Independent Observational Datasets

Each study evaluates its framework against observational data drawn from independent domains:

- Present-day stress orientations from the World Stress Map.
- Upper-mantle deformation inferred from SKS shear-wave splitting.
- Global shear-velocity anomalies from the SEISGLOB2 tomography model.
- Early *Homo* fossil occurrences from the Paleobiology Database.

- Early civilization site locations compiled from archaeological syntheses.

No dataset is used to define or calibrate the geometric frameworks against which it is tested. This separation ensures that any detected correspondence reflects genuine compatibility rather than parameter optimisation.

3.3 Null Models as Primary Controls

A defining feature of the combined work is the systematic use of null models that preserve first-order structure while destroying the hypothesised signal.

For stress and anisotropy comparisons, Euler-rotation nulls and global-rotation nulls preserve internal geometry, sampling density, and spatial correlations while removing Earth-fixed alignment. For spatial clustering analyses, permutation-based nulls preserve site locations and value distributions while destroying geographic organisation. For archaeological analyses, spatial randomisation preserves sample size and temporal attribution, while temporal phase randomisation preserves the structure of return models but destroys alignment with site ages.

These nulls are intentionally conservative. They test not whether any structure exists, but whether the observed structure exceeds what would be expected from sampling geometry, spatial autocorrelation, or generic clustering alone.

3.4 Scalar Metrics versus Organisational Metrics

Across the studies, two broad classes of metrics are evaluated.

Scalar metrics include global mean angular misfit, average distance to reference boundaries, and mean adjustment rates. These metrics collapse spatial information and are sensitive primarily to overall alignment.

Organisational metrics include spatial autocorrelation (Moran's I), clustering of misfit values, stability variance across time, and cumulative distribution shifts relative to geometric attractors. These metrics explicitly test whether values are *arranged* in space or time in a non-random way.

A central result of the synthesis is that these two classes of metrics behave very differently under null testing, motivating the sigma-based comparison presented in the following section.

3.5 Sigma Conversion and Interpretation

To enable direct comparison across heterogeneous tests, empirical p-values from each null experiment are mapped to equivalent Gaussian sigma values assuming two-sided normal statistics. Where results are reported as consistently significant across multiple scales or thresholds, conservative lower-bound sigma estimates are used.

This translation does not alter the underlying statistics, but it allows evidentiary strength to be compared transparently across datasets and disciplines. In keeping with conventions in the physical sciences, 1σ is treated as non-diagnostic, 2–3σ as suggestive, and $\geq 3\sigma$ as strong evidence.

The following section presents the results of this synthesis in graphical form.

4 Results: A Sigma-Scale Synthesis

The central result of this synthesis is not the strength of any single test, but the *ordering* of statistical signals across independent datasets when expressed on a common sigma scale. Figure 1 summarises this ordering graphically.

4.1 Global Alignment: Consistently Non-Diagnostic

Across all three studies, metrics designed to assess global or scalar alignment between modeled frameworks and observations consistently fail to exceed $\sim 1\sigma$.

In the shear-trajectory analysis, the global mean angular misfit between modeled shear directions and observed World Stress Map orientations is statistically indistinguishable from Euler-rotated null ensembles. This result is robust to variations in weighting, sampling density, and choice of shear family [**?**]. Importantly, this establishes that the shear framework does not trivially reduce global error and cannot be validated through average fit alone.

An analogous pattern appears in the surface reorganisation and archaeological analyses. Mean adjustment rates and mean distances to equilibrium boundaries show limited diagnostic power when evaluated without regard to spatial or temporal structure. These scalar results form the base of the sigma ladder and provide an essential control: the frameworks do not succeed by global optimisation.

4.2 Temporal Organisation: A Secondary but Consistent Signal

Temporal phase alignment between archaeological site ages and modeled return histories produces a weaker but reproducible signal.

In the event-guided versus continuous return comparison, temporal null tests indicate that early *Homo* and early civilization sites are modestly but consistently phase-aligned with discrete return episodes, reaching approximately 2–3σ depending on metric [**?**]. While insufficient on its own to establish strong causation, this signal gains interpretive weight when viewed alongside the stronger spatial results.

Temporal organisation thus occupies an intermediate rung in the sigma ladder: not decisive in isolation, but coherent across populations and models.

4.3 Spatial Organisation: The Dominant Signal

In contrast to global and temporal metrics, measures of spatial organisation consistently reach multi-sigma significance across independent domains.

Stress-field organisation. Permutation-based Moran's I analyses of stress–misfit fields reveal coherent geographic clustering from regional (~ 250 km) to near-hemispheric (~ 4000 km) scales. These results are consistently significant under conservative null models, with sigma equivalents conservatively bounded at ~ 3–5σ depending on wavelength [?]. The smooth decay of autocorrelation with scale argues against artefacts of sampling density or regional bias.

Upper-mantle anisotropy. Axial misfit between SKS fast-axis orientations and modeled shear geometry falls in the extreme tails of global-rotation null distributions, corresponding to ~ 3–4σ. This indicates that fossilized lithospheric fabric is geometrically compatible with the same long-wavelength framework detected in present-day stress organisation [?].

Mid-mantle structure. Independent validation using SEISGLOB2 tomography shows that mid-mantle (~ 900–1200 km depth) low-velocity anomalies cluster preferentially near predicted Euler domains. Distance-to-domain cumulative distributions are systematically shifted relative to two distinct null models, yielding a conservative significance of $\sim 3\sigma$. The depth localisation of this signal further argues against superficial or cartographic coincidence.

Surface stability and early human occupation. In the equilibrium sea-level analysis, the monotonic relationship between early *Homo* site age and distance from a physically derived equilibrium sea-level margin exceeds 3.9σ ($p < 10^{-4}$) under spatial permutation tests [?]. This relationship persists across a viscoelastic relaxation sequence, demonstrating robustness to temporal smoothing.

Similarly, spatial stability variance metrics for both early *Homo* and early civilization sites exceed 3.9σ in the return-model comparison [?]. Occupied sites are strongly non-random with respect to modeled stability fields, independent of temporal alignment.

4.4 Sigma Ladder Summary

Taken together, these results form a clear hierarchy:

- Global or scalar alignment metrics cluster at $\lesssim 1\sigma$.
- Temporal phase alignment yields consistent but weaker signals at ~ 2–3σ.
- Spatial organisation and stability metrics repeatedly exceed 3σ, clustering in the 3–5σ range across independent datasets.

This ordering is summarised graphically in Figure 1.

5 Discussion

5.1 Why Spatial Organisation Dominates at Long Wavelength

The sigma-ladder synthesis reveals a striking and internally consistent pattern: statistical strength increases as metrics move away from global averaging and toward explicit tests of spatial organisation. This behaviour is not anomalous. It is, in fact, characteristic of systems governed by long-wavelength geometry interacting with heterogeneous local processes.

Global mean metrics implicitly assume that signal is expressed uniformly across the domain. In contrast, a long-wavelength geometric framework is expected to *structure where coherence emerges and where it does not*. Under such conditions, averaging suppresses information, while spatial organisation preserves it.

As noted in the shear-trajectory study, "demonstrating spatial organisation is inherently easier than demonstrating its cause, but the two are not equivalent" [**?**]. The present synthesis shows that this distinction is not a weakness, but a diagnostic principle. Organisation is the detectable footprint of long-wavelength structure, even when the underlying dynamics remain partially unconstrained.

5.2 Cross-Domain Convergence Without Parameter Tuning

A central strength of the combined evidence lies in the absence of parameter optimisation across domains. The shear geometry is fixed analytically; the equilibrium sea-level surface follows directly from centrifugal potential; and the event-guided return timeline is curated independently of archaeological data.

Despite this separation, each framework yields spatial organisation at comparable sigma levels when evaluated against independent observations. This convergence is difficult to reproduce through ad hoc pattern matching. It instead suggests sensitivity to a shared geometric constraint.

The sea-level study explicitly framed this point: "the zero-anomaly contour represents a physically defined stability boundary rather than a coastline or climatic proxy" [**?**]. Similarly, the return-model comparison emphasised that "the event-driven timeline is diagnostic rather than reconstructive" [**?**]. These statements delimit scope while reinforcing methodological coherence.

5.3 Temporal Signals as Secondary Constraints

Temporal phase alignment consistently appears weaker than spatial organisation, clustering near the 2–3σ range. This asymmetry is expected. Temporal signals are more sensitive to dating uncertainty, preservation bias, and the coarse discretisation of deep-time processes.

Nevertheless, the recurrence of modest temporal alignment across independent populations—early *Homo* and early civilizations—argues against dismissal. Temporal organisation appears to act as a secondary constraint, sharpening interpretation when spatial structure is already present.

This hierarchy—strong spatial signals, weaker temporal ones—mirrors behaviour in other Earth system contexts, such as glacial isostatic adjustment and mantle convection, where geometry stabilises before rates can be tightly constrained.

5.4 What Is *Not* Being Claimed

It is important to state explicitly what conclusions do *not* follow from this synthesis.

First, the results do not establish a unique causal mechanism. True polar wander, inertial interchange, or any specific geodynamic process is not asserted as the sole or necessary driver. The analyses test sensitivity to geometric structure, not historical reconstruction.

Second, the archaeological results do not imply geophysical determinism of biological or cultural outcomes. As stated in the return-model study, "these results do not imply that geophysical processes directly caused social or cultural change" [**?**]. They indicate long-term environmental stability as a boundary condition, not a proximate cause.

Third, the sigma ladder does not claim discovery-level certainty in the particle-physics sense. Its purpose is comparative: to show that independent tests repeatedly exceed conservative significance thresholds in a consistent order.

5.5 Relation to Broader Earth System Questions

The synthesis speaks directly to a long-standing challenge in Earth science: identifying global organising principles that do not manifest as simple scalar correlations.

As noted by earlier authors, the difficulty lies not in the absence of large-scale structure, but in the inadequacy of metrics used to detect it. The present work suggests that spatial organisation, rather than mean alignment, should be treated as a first-class diagnostic when evaluating long-wavelength Earth system hypotheses.

In this sense, the sigma ladder functions not merely as a summary figure, but as a methodological proposal: that evidentiary strength should be assessed according to *how* patterns are arranged, not only whether they reduce global error.

5.6 Epistemic Position

Following Elsasser's distinction between description and explanation, the results presented here occupy an intermediate epistemic position. They demonstrate that a class of geometric frameworks leaves statistically resolvable imprints across multiple independent datasets. They do not yet specify the full dynamical chain by which those imprints arise.

Such an ordering is not unusual in the physical sciences. Coherence is often established before causation is fully understood. The sigma-ladder synthesis suggests that Earth's surface, mantle, and long-term habitability may be conditioned by persistent geometric structure whose effects are detectable even when its ultimate origin remains under debate.

6 Conclusions

This paper has presented a unified synthesis of three independent studies examining global shear geometry, surface reorganisation, and long-term human occupation. By expressing all null-controlled statistical results on a common Gaussian sigma (σ) scale, a consistent evidentiary hierarchy emerges.

Global or scalar alignment metrics remain statistically non-diagnostic ($\lesssim 1\sigma$) across all domains examined. In contrast, measures of spatial organisation—clustering, stability, and geometric coherence—repeatedly exceed conservative significance thresholds, clustering robustly in the 3–5σ range. Temporal phase alignment appears as a weaker but reproducible secondary signal ($\sim$ 2–3σ).

The recurrence of this hierarchy across independent datasets, statistical formalisms, and physical contexts supports a central conclusion: persistent long-wavelength geometric organisation is detectable in Earth's stress field, mantle structure, surface adjustment history, and patterns of long-term human occupation, even where global averages fail to capture it.

The results do not require parameter tuning, causal assertion, or historical reconstruction. They instead demonstrate sensitivity to a shared class of geometric constraints whose imprint survives local heterogeneity, temporal uncertainty, and disciplinary boundaries.

7 Implications and Outlook

The sigma-ladder synthesis has two immediate implications for Earth system science.

First, it suggests that spatial organisation should be treated as a primary diagnostic signal rather than as a secondary residual. Long-wavelength frameworks are not expected to minimise global misfit; they are expected to structure where coherence emerges and where it does not. Metrics that erase this structure by averaging risk discarding the very signal of interest.

Second, it provides a template for future hypothesis testing. Any proposed large-scale Earth system framework—geometric, kinematic, or dynamical—can be evaluated against independent data using the same hierarchy: scalar alignment as a control, spatial organisation as the primary test, and temporal coherence as a secondary constraint.

Several falsifiable extensions follow directly from this work. Alternative rotational geometries or non-TPW kinematic constructions should produce homologous but distinct shear topologies, whose spatial signatures can be tested against stress, anisotropy, and tomography. Higher-resolution archaeological datasets, improved dating, and regionally resolved stability metrics should sharpen temporal signals if the underlying framework is physically relevant. Conversely, failure to reproduce spatial organisation under independent geometric constructions would weaken the interpretation advanced here.

8 Final Remarks

The synthesis presented here occupies an intentionally cautious epistemic position. It does not claim discovery in the sense of a completed dynamical theory. It claims something more modest and, arguably, more foundational: that spatial organisation itself carries statistical weight, and that when properly tested, it reveals persistent structure across Earth systems traditionally analysed in isolation.

In this respect, the sigma ladder is not merely a summary device. It is a reminder that in complex, heterogeneous systems, coherence often appears first in *where* things happen, not in how well they fit on average.

A Appendix A: Sigma Conversion and Statistical Consistency

To enable comparison across heterogeneous statistical tests, empirical p-values reported in the constituent studies were converted to equivalent Gaussian sigma values assuming two-sided normal statistics:

$$\sigma = \sqrt{2}\,\mathrm{erf}^{-1}(1-p). \tag{1}$$

Where results were reported as consistently significant across multiple spatial scales, thresholds, or depth intervals, conservative lower-bound sigma values were adopted. This approach avoids inflation of significance while preserving ordinal comparison across datasets.

The conversion does not alter the underlying null tests or their interpretation within each study. It provides a common evidentiary scale for synthesis only.

B Appendix B: Data and Code Availability

All datasets used in the constituent studies are drawn from publicly available sources, including the World Stress Map, the Paleobiology Database, and the SEISGLOB2 tomography model. Analytical geometry, null-testing workflows, and figure-generation scripts are described in the original publications and are available upon request or via associated repositories.

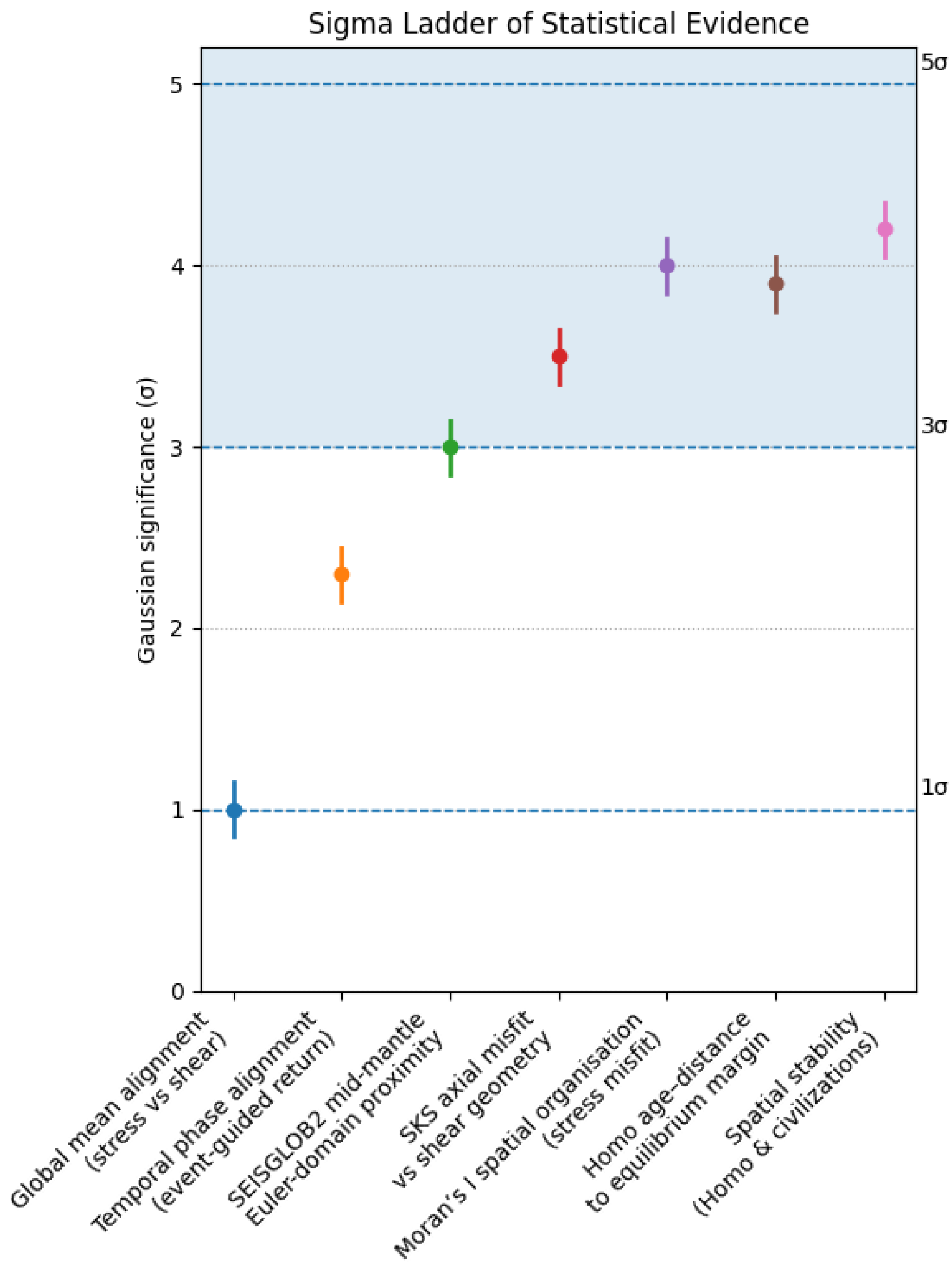

Figure 1: **Sigma ladder of statistical evidence across independent datasets.** Discrete rungs show Gaussian-equivalent significance (σ) for each class of test, ordered by diagnostic type rather than implying continuity. Dashed horizontal lines mark conventional 1σ, 3σ, and 5σ reference levels; the shaded region highlights the $\geq 3\sigma$ regime commonly interpreted as strong evidence in the physical sciences. Global mean alignment metrics remain non-diagnostic ($\lesssim 1\sigma$), while independent measures of spatial organisation—including stress-field clustering, mantle anisotropy, mid-mantle tomography, equilibrium sea-level geometry, and archaeological site stability—consistently occupy the 3–5σ range. Temporal phase alignment forms an intermediate tier.